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Chemical and Physical Hydrogeology of Coal, Mixed Coal-Sandstone and Sandstone Aquifers from Coal-Bearing Formations in the Alberta Plains Region, Alberta

Alberta Energy and Utilities Board
Alberta Geological Survey

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Alberta Geological Survey

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Executive Summary

Unconventional gas resources will become increasingly important as demand for natural-gas supplies continues to increase. One such unconventional gas resource receiving more and more attention from oil and gas exploration and development companies in Alberta is natural gas from coal (NGC). The potential size of the resource makes it an attractive target. Nevertheless, NGC development in Alberta faces several challenges. These include technical and economic issues, land access and tenure, water disposal and diversion and access to information. In addition, since exploration and development within Alberta are just beginning, very little information is available to base exploration, development and regulatory strategies on. Such baseline data are critical for informed and responsible decisions.

Sampling of water wells completed in coal, mixed coal-sandstone and sandstone aquifers throughout Alberta has helped fill an important information gap. The resulting analyses indicate that some of the samples collected from Paskapoo-Scollard Formation aquifers may exceed Canadian water quality guideline values in terms of

- aesthetic objectives for pH (1 of the 7 samples), sodium (4 of 7), manganese (3 of 7), chloride (1 of 7) and total dissolved solids (TDS; 4 of 7); and
- irrigation-water quality values for sodium adsorption ratio (SAR; 4 of 7) and chromium (2 of 7).

Some of the water samples collected from Horseshoe Canyon Formation aquifers may exceed Canadian water quality guideline values in terms of

- aesthetic objectives for pH (2 of 21), sodium (20 of 21), sulphate (7 of 21), chloride (2 of 21), manganese (4 of 21) and TDS (20 of 21);
- irrigation-water quality values for SAR (18 of 21) and chromium (13 of 21); and
- livestock-water quality values for total phenols and sulphate (1 of 21).

Some of the samples collected from Belly River Group aquifers may exceed Canadian water quality guideline values in terms of

- aesthetic objectives for pH (6 of 16), chloride (2 of 16), sulphate (1 of 16), sodium (13 of 16), manganese (5 of 16) and TDS (14 of 16);
- irrigation-water quality values for SAR (11 of 16), chromium (4 of 16) and boron (9 of 16);
- livestock-water quality values for As (1 of 16), total phenols (2 of 16) and TDS (1 of 16); and
- interim maximum acceptable concentrations for human consumption for arsenic (1 of 16).

Management of produced water from NGC activities will require careful consideration of the water quality to ensure responsible disposal practices are followed, as certain of the parameters listed above will limit the available disposal or reuse options for the produced water.

The geochemical processes responsible for the observed chemical compositions are varied. Stable and radiogenic isotopic analyses and Cl/Br ratios indicate that the observed chemical compositions of the water samples are most likely the result of mixing between meteoric and formation water, water-rock interactions and biological processes.

As with the chemical hydrogeology of the coal and sandstone aquifers, the nature of the flow regimes present within these aquifers is complex. Preliminary analyses of the information available for pump tests conducted within these aquifers reveal both simple and more complicated processes controlling groundwater flow. These include

- pseudo-homogeneous conditions leading to the development of a radial flow regime;

- boundary conditions, such as constant pressure and closed reservoir flow regimes; and
- processes, such as fracture flow or the development of dual porosity systems, that create a heterogeneity-influenced flow regime.

This study focused on the chemical and physical characteristics of coal, mixed coal-sandstone and sandstone aquifers in use for either domestic or agricultural purposes. Depths were generally less than 100 m except in a couple of cases. The majority of NGC exploration and development wells will be drilled and completed to greater depths. Because few such wells currently exist in the province, and because of the confidential nature of the work currently being conducted at the sites, collection of data from them is difficult. Future work should focus on collecting water samples from these wells and integrating the information from the deeper and shallower portions of the formations, in order to

- more clearly understand the chemical and biological processes occurring within the aquifers and the potential link between these processes and gas generation;
- develop exploration strategies using the knowledge gained from the chemical and physical hydrogeology; and
- develop mitigation and disposal strategies for any produced water.

1 Introduction

Natural gas from coal (NGC) exploration in Alberta is increasing as new technology and economic factors combine to enhance the attractiveness of this unconventional gas resource. Although development of NGC is just beginning in Alberta, development of this resource in Montana, Wyoming, Colorado, Utah, New Mexico and Alabama has been ongoing for many years. Many of the most fundamental issues identified during those years of development relate to water production.

Production of NGC generally requires dewatering of coal seams. Reduction in water pressure results in desorption of the methane from the coal matrix. The methane flows toward the wellbore and is captured at the surface. The initial phase of dewatering will induce drawdown within the coal aquifer and will produce significant quantities of water that must be disposed of. The effects of dewatering are well documented in the United States, and all of the NGC-producing states have drafted regulations to deal with NGC development. Produced water is disposed of in many ways, including deep well injection, evaporation, surface disposal and through co-operative agreements between resource companies and landowners in which some of the water is used for irrigation or livestock watering purposes. However, concerns still abound regarding the effects of dewatering on aquifer sustainability and the effects that produced water will have on the various disposal receptors. Increased volumes of water and changes in water chemistry have been identified as areas of concern for surface disposal. Water-quality issues are of concern for irrigation, livestock watering and re-injection. State and federal agencies in the United States are conducting ongoing research to assess the effect of NGC production on water resources, as well as evaluating and developing new technology for water disposal.

In Canada, provincial governments are responding to the interest in NGC by reviewing regulations governing gas and water-resource development, as well as royalty structures. The provinces of Alberta and British Columbia are benefiting from the lessons learned by American NGC producers and are trying to answer key questions before extensive development occurs. For instance, the government of Alberta is funding research to better understand the NGC resource potential within the province, the technological challenges of NGC development, the application of new technology to the development of NGC, the physical properties of coal and sandstone aquifers, the water chemistry of coal and sandstone aquifers, and the possibility of enhanced recovery of NGC through the sequestration of the greenhouse gas CO_2. With approximately 20 NGC pilot projects underway in the province and many more likely to come, the need for this information is growing. Because NGC resource development is just beginning in Alberta, few sources of information on produced water are available. The nature of the oil and gas industry further complicates the matter, since most companies, for reasons of confidentiality, prefer not to participate in public research projects.

Information on the physical properties and water chemistry of coal and sandstone aquifers can be obtained, however, from publicly available information. Alberta Environment maintains a database of all water wells drilled in the province. This database contains information on well completion details, sediment and rock types encountered during drilling, hydraulic testing of the aquifer, water chemistry and observations made during drilling. Figure 1 shows the locations, by formation, of wells reportedly completed in coal and mixed coal-sandstone aquifers in the Alberta Basin. Figure 2 shows the locations, by formation, of aquifer tests completed in coal aquifers in the Alberta Basin that are on file with Alberta Environment. Likewise, Figure 3 shows the locations of such wells where gas was noted during drilling, well development or water sampling. Information on well tests is also available for wells completed in sandstone aquifers within the province (Figure 4, Figure 5, Figure 6).

It must be noted that these water wells will generally be less than 100 m in depth and most NGC development wells will be drilled to substantially greater depths. Water chemistry and physical

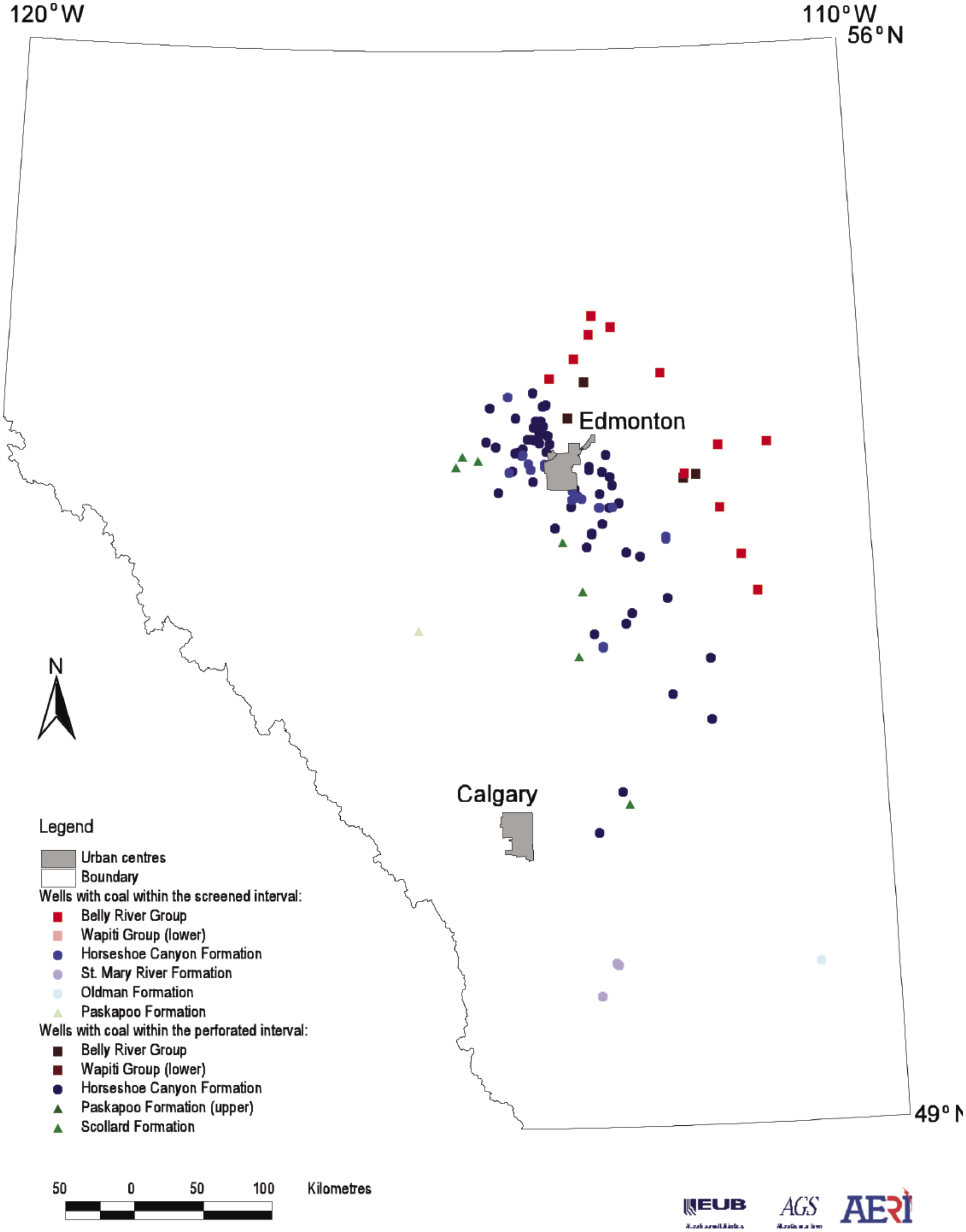


Figure 1. Locations of wells completed in coal and mixed coal-sandstone aquifers

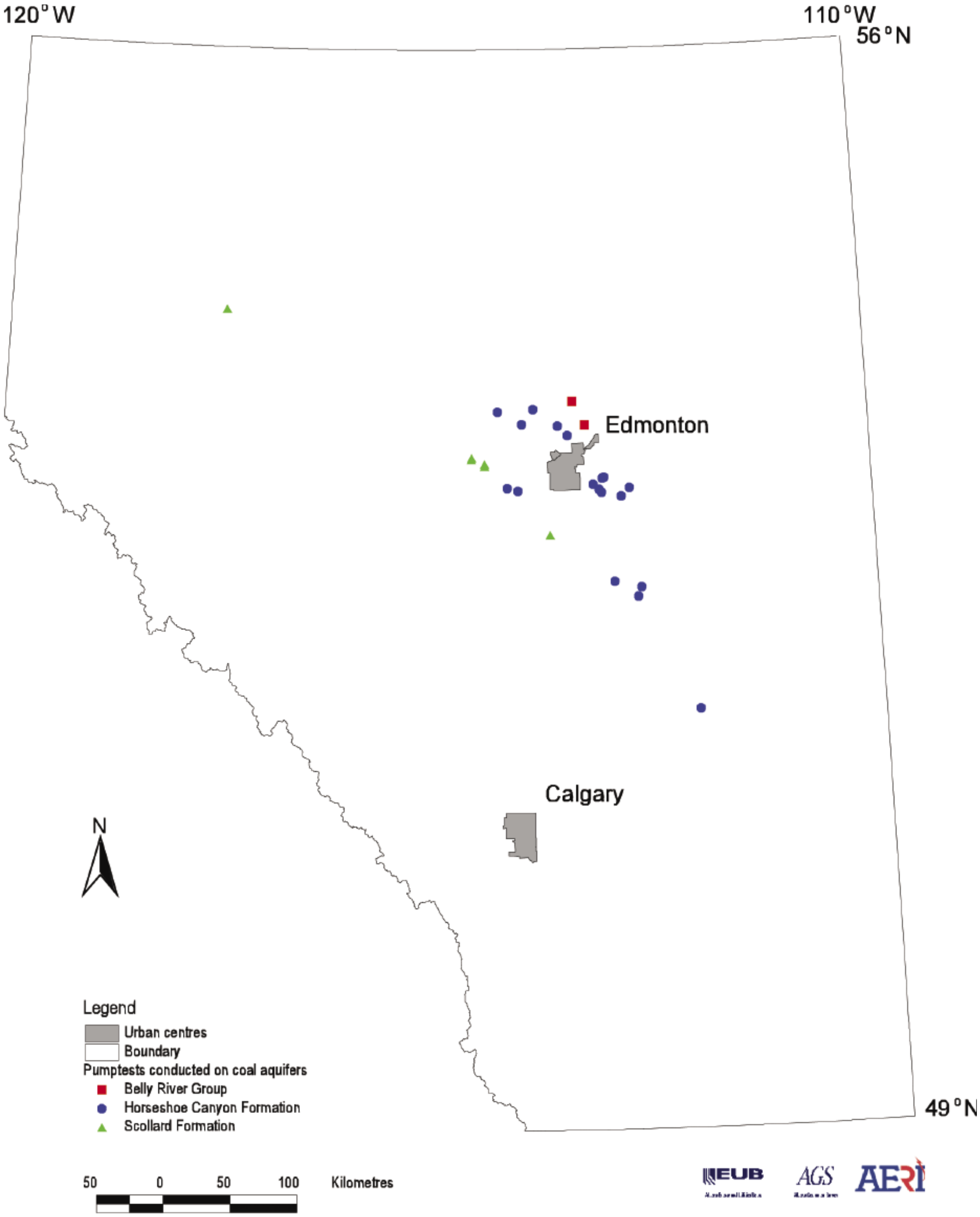


Figure 2. Locations of coal aquifer tests.

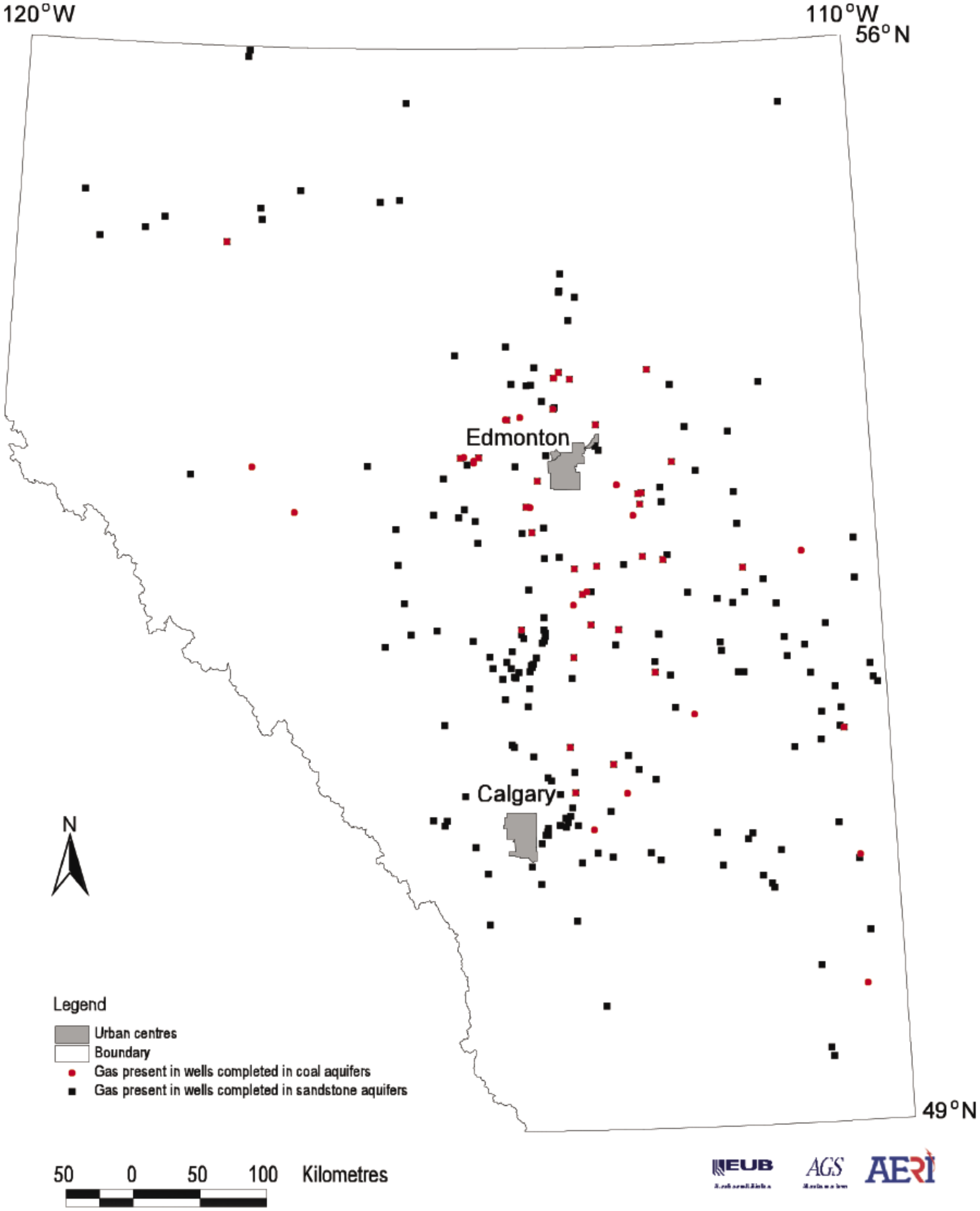


Figure 3. Locations of wells where gas was noted.

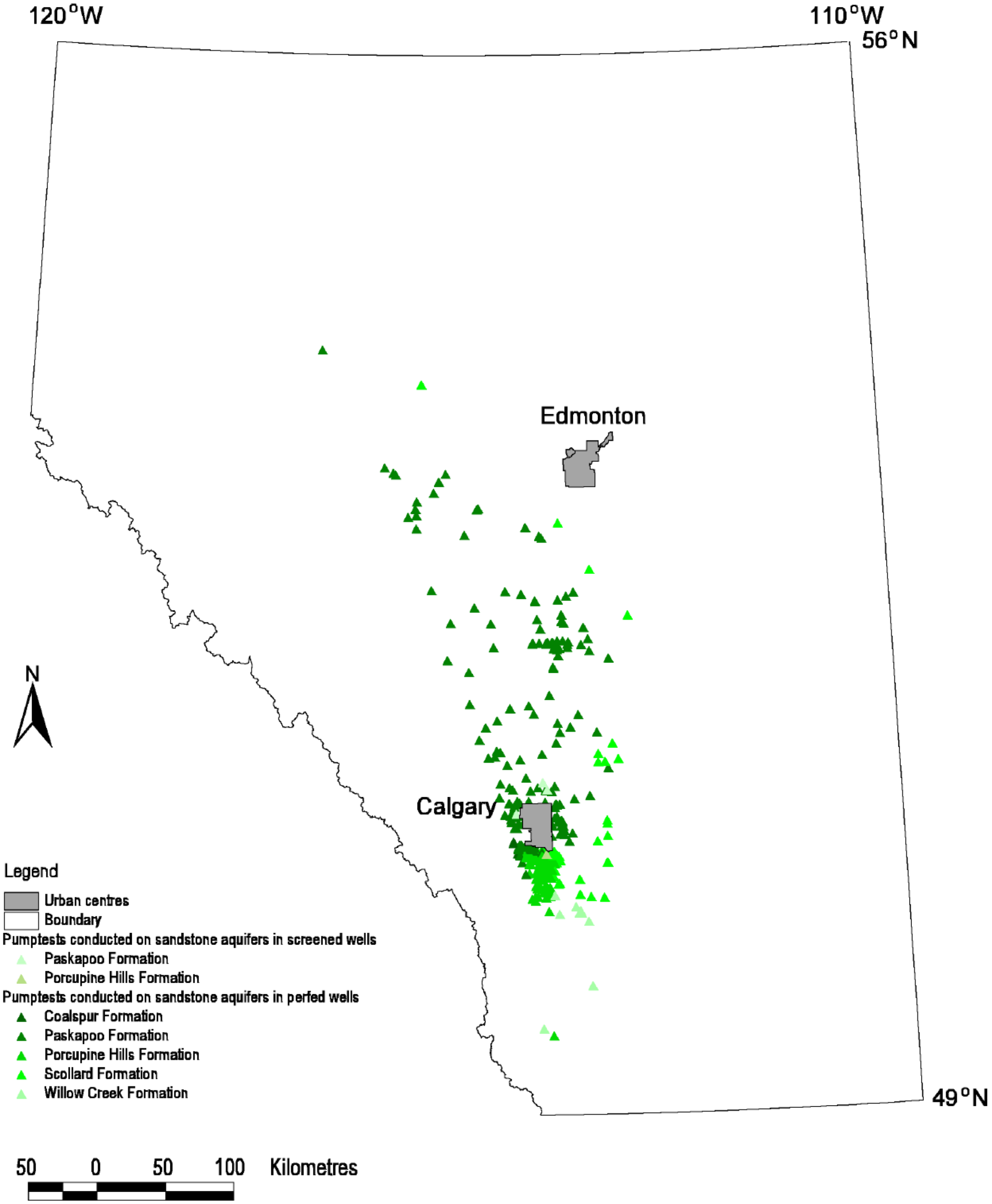


Figure 4. Locations of Tertiary-Upper Cretaceous sandstone aquifer tests.

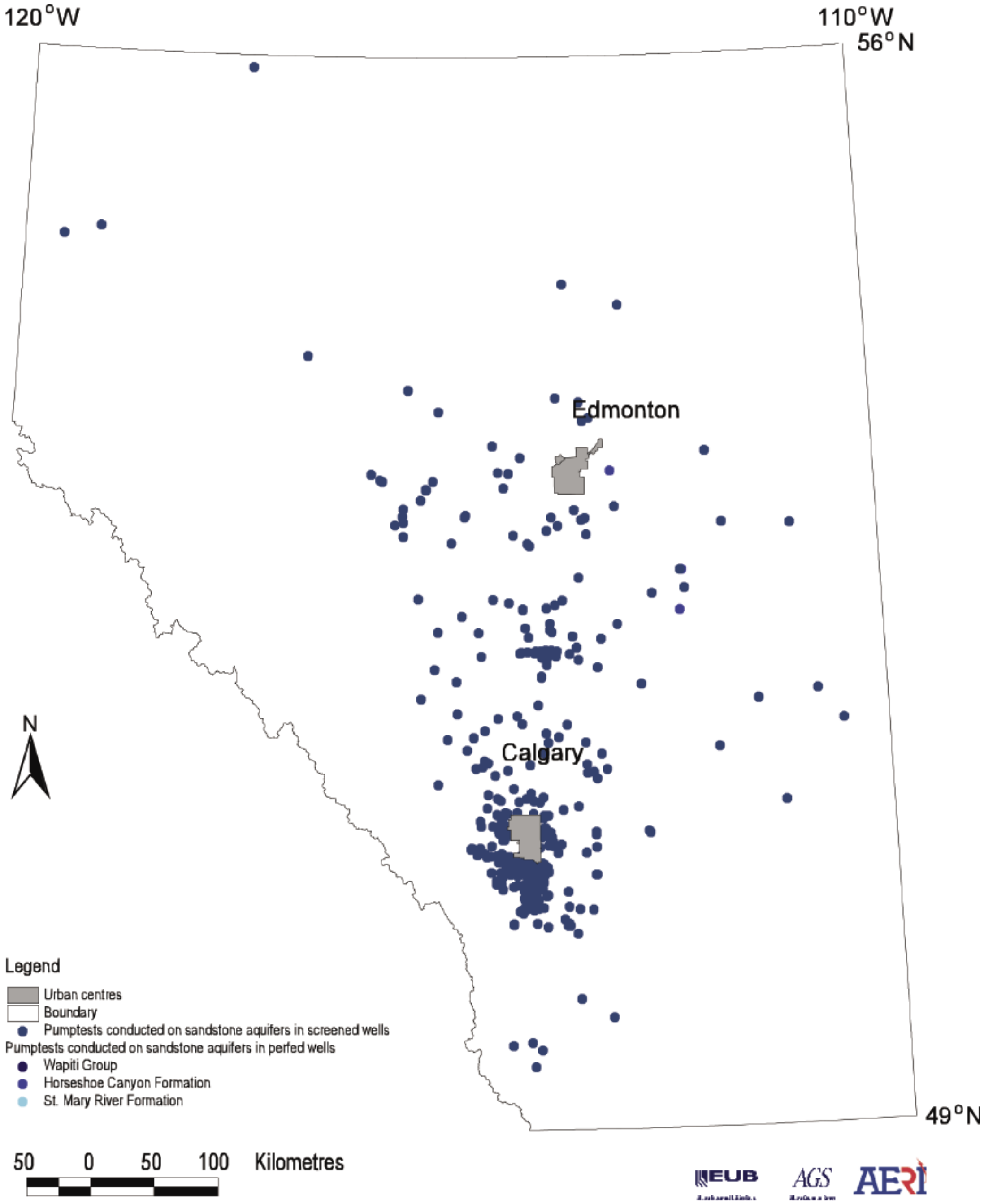


Figure 5. Location of Edmonton group sandstone aquifer tests.

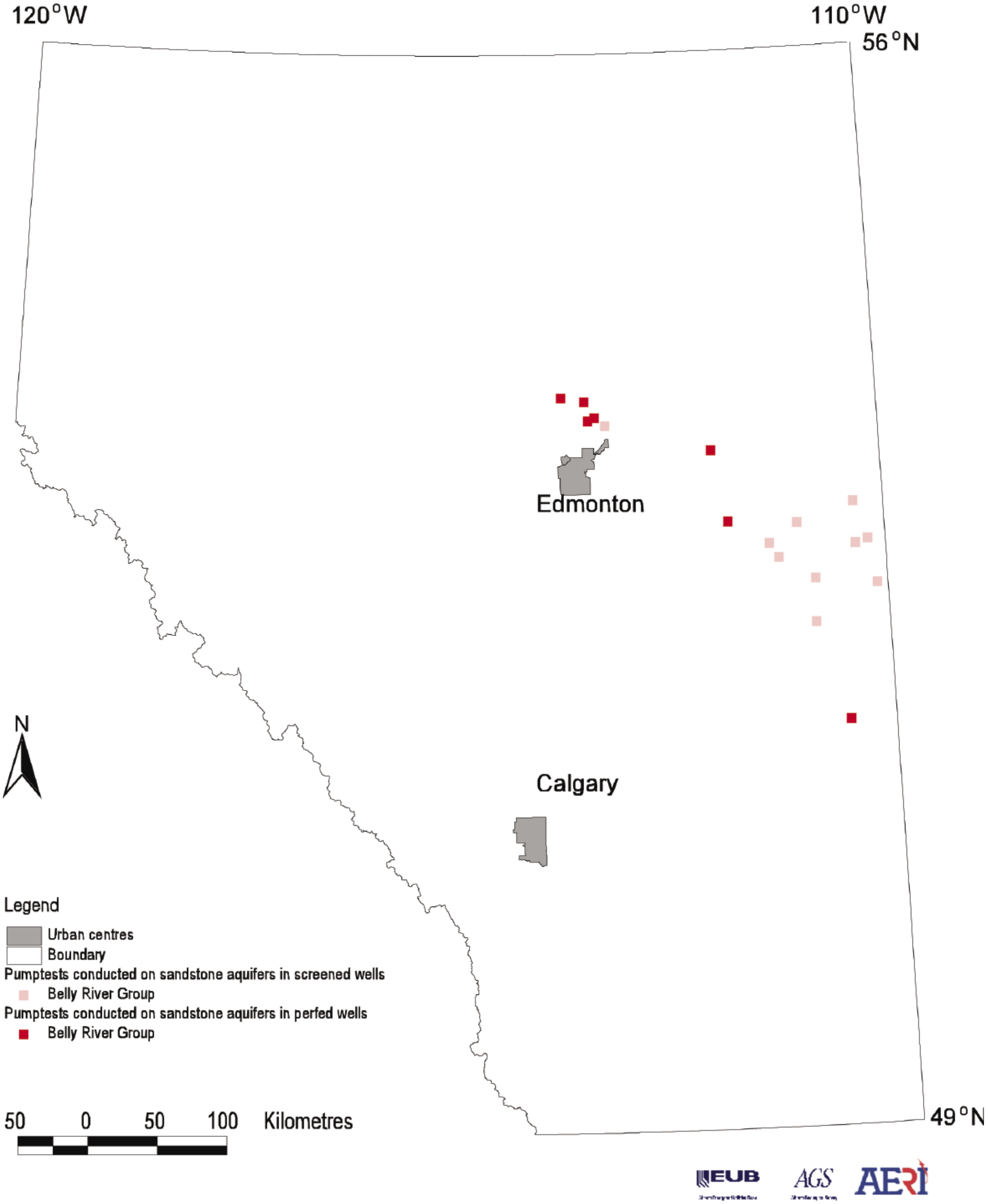


Figure 6. Locations of Belly River Group sandstone aquifer tests.

characteristics of these aquifers might therefore be different in these two classes of wells. Regional hydrogeological assessments (Bachu and Michael, 2002), however, suggest there is a regional hydraulic continuity between deeper portions of NGC formations and shallower portions of the formations where coal units are used as aquifers.

The purpose of this study is to provide information on the physical properties and water chemistry of coal and sandstone aquifers within the Alberta Basin. An important contribution of this study is a catalogue of aquifer tests undertaken in coal and sandstone aquifers. To that end, examples of the various flow regimes conducted in coal and sandstone aquifers within the Alberta Plains region are presented. In addition, a list of Alberta Environment site identifications, together with the likely formation in which the well is completed, will also be provided for anyone interested in conducting further analyses on the well tests. The data can be obtained from Alberta Environment.

Another important contribution of this study is a dataset of baseline geochemistry for coal, mixed coal-sandstone and sandstone aquifers within the Tertiary–Upper Cretaceous succession of the Alberta Basin. This extensive dataset includes major-, minor- and trace-element concentrations, polycyclic aromatic hydrocarbon (PAH) concentrations, nonhalogenated aromatic hydrocarbon (BTEX) concentrations, hydrocarbon concentrations, phenol concentrations, adsorbable organic halide concentrations, stable isotopic composition (focusing on the O, H, C and S stable isotopes), and radiogenic isotopic composition (focusing on ^{87}Sr/^{86}Sr and naturally occurring radioactive materials).

The knowledge generated by the interpretation of this data will be of use not only in understanding the physical properties of coal and sandstone aquifers and the nature and evolution of water chemistry within the Alberta Basin, but may also provide information on NGC potential within the Alberta Basin and highlight areas as development targets.

1.1 Study Area

The study area is bounded on the east by the Alberta-Saskatchewan provincial boundary, to the south by the Canada–United States border, to the west by the edge of the Rocky Mountain deformation front, and to the north by latitude 56°N (Figure 7). This area was selected because it marks the approximate limit of the extent of coal-bearing formations in the Alberta Basin. The majority of the water-sample locations fall within the subcrop areas of the various formations. The distribution of the sample points is therefore along arcuate bands stretching from north to south along the subcrop areas. The concentration of water wells around Edmonton indicates the greater dependency on coal and mixed coal-sandstone aquifers as water sources in this portion of the province.

2 Geological Setting

The formation of the Alberta Basin was initiated during the late Proterozoic by rifting of the North America craton. The original depositional environment of the basin was that of a passive or continental margin, dominated by carbonate and evaporite deposition with some intervening shale (Porter et al., 1982). Pre-Cretaceous erosion occurring at various times during the Paleozoic, as well as during the Triassic and Jurassic partially removed older strata, resulting in an incomplete rock record, for these eras, over much of the Alberta Basin.

Uplift and erosion of sedimentary rocks during the Columbian orogeny (early Cretaceous) and subsequent late Cretaceous tectonism shed sediments into the developing foreland basin, resulting in deposition of fluvial sand and shale. Following the tectonic events described above, sea level rises and falls also resulted in deposition of marine shale but also of coal-bearing fluvial sandstone. Peat accumulation during

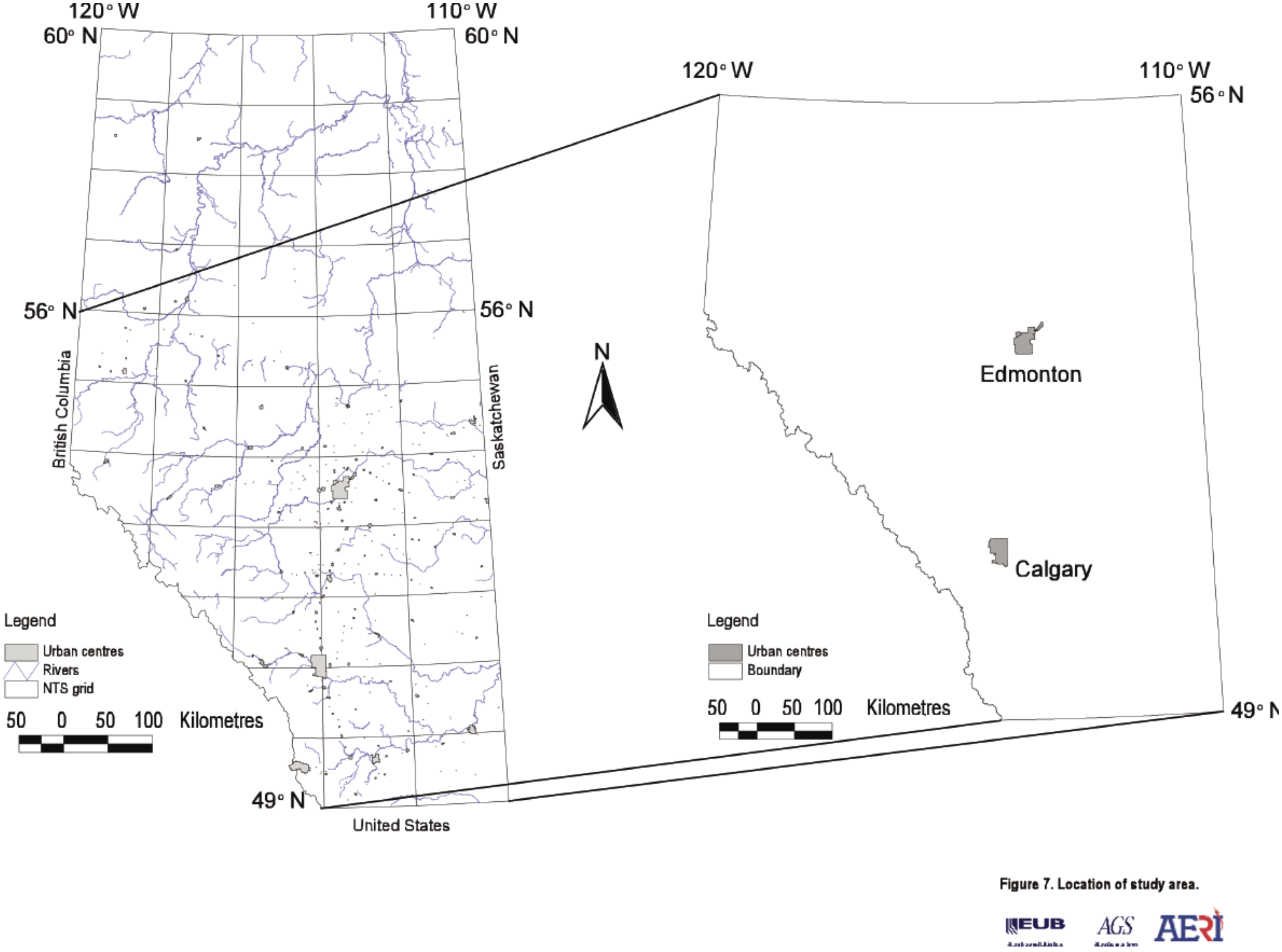


Figure 7. Location of Study area.

this time provided the source material for the coal found in rocks of these ages. The major coal-bearing units of this interval include the Mannville, Belly River–Wapiti and Edmonton groups.

Coarse clastic deposition continued into the early Tertiary. Subsequent to this cycle, a period of tectonic compression and uplift in the early Tertiary (the Laramide orogeny), led to deposition of fluvial channel sandstone, siltstone and shale (Bachu and Michael, 2002). Peat accumulations during this time period provided the material for coal development. The major coal-bearing units of this interval include the Cretaceous Scollard Formation and Tertiary Paskapoo Formation. Subsequent erosion during the Paleocene removed a substantial portion of the Tertiary succession.

Glaciation during the Quaternary period resulted in erosion of the bedrock and subsequent deposition of unconsolidated sediments covering most of the basin.

2.1 Geology of the Coal-Bearing Formations

The following geological description of the coal-bearing formations in Alberta is broken down by geographic area, beginning with southeastern Alberta, followed by south-central Alberta and concluding with north-central Alberta. The rationale for describing the coal-bearing formation geology by geographic area is based on the fact that stratigraphic nomenclature changes across the province, as does the presence of coals within a given member, formation or group.

A stratigraphic table of formations for the various geographic areas is given in Figure 8. The formation boundaries are shown in Figure 9.

2.1.1 Southeastern Alberta

In southeastern Alberta, coal-bearing zones are primarily found within the Belly River Group succession. This stratigraphic package occurs between the overlying Bearpaw Formation and the underlying Pakowki Formation (Figure 8). The following section describes this interval.

2.1.1.1 Pakowki Formation

The marine shale of the Pakowki Formation was deposited following tectonism during the late Cretaceous. The formation thins toward the west and thickens toward the east. The Pakowki Formation is equivalent to the upper Lea Park Formation of south-central and north-central Alberta.

2.1.1.2 Belly River Group

The Belly River Group is composed of three distinct lithological units. The Basal Belly River Group is found at the base of the Belly River Group. It represents a marine-nonmarine transitional coastal system and has been divided into a series of regressive cycles (Hamblin and Abrahamson, 1996).

The middle unit, the Foremost Formation, is a succession of amalgamated fluvial channels (Beaton et al., 2002). The McKay and Taber coal zones mark the base and top of the formation, respectively. Both the McKay and Taber coal zones accumulated in a coastal-plain environment.

The third unit, the Oldman Formation, overlies the Foremost Formation. It consists of fine-grained floodplain and lacustrine deposits (Beaton et al., 2002). The Oldman Formation is informally divided into the Comrey Member sandstone and an ‘upper siltstone’ member (Hamblin, 1997a). The Dinosaur Park Formation, also part of the third lithological unit, is found at the top of the Belly River Group and is dominated by thick, multistoried sandstone units in its lower portion and coal in the upper portion

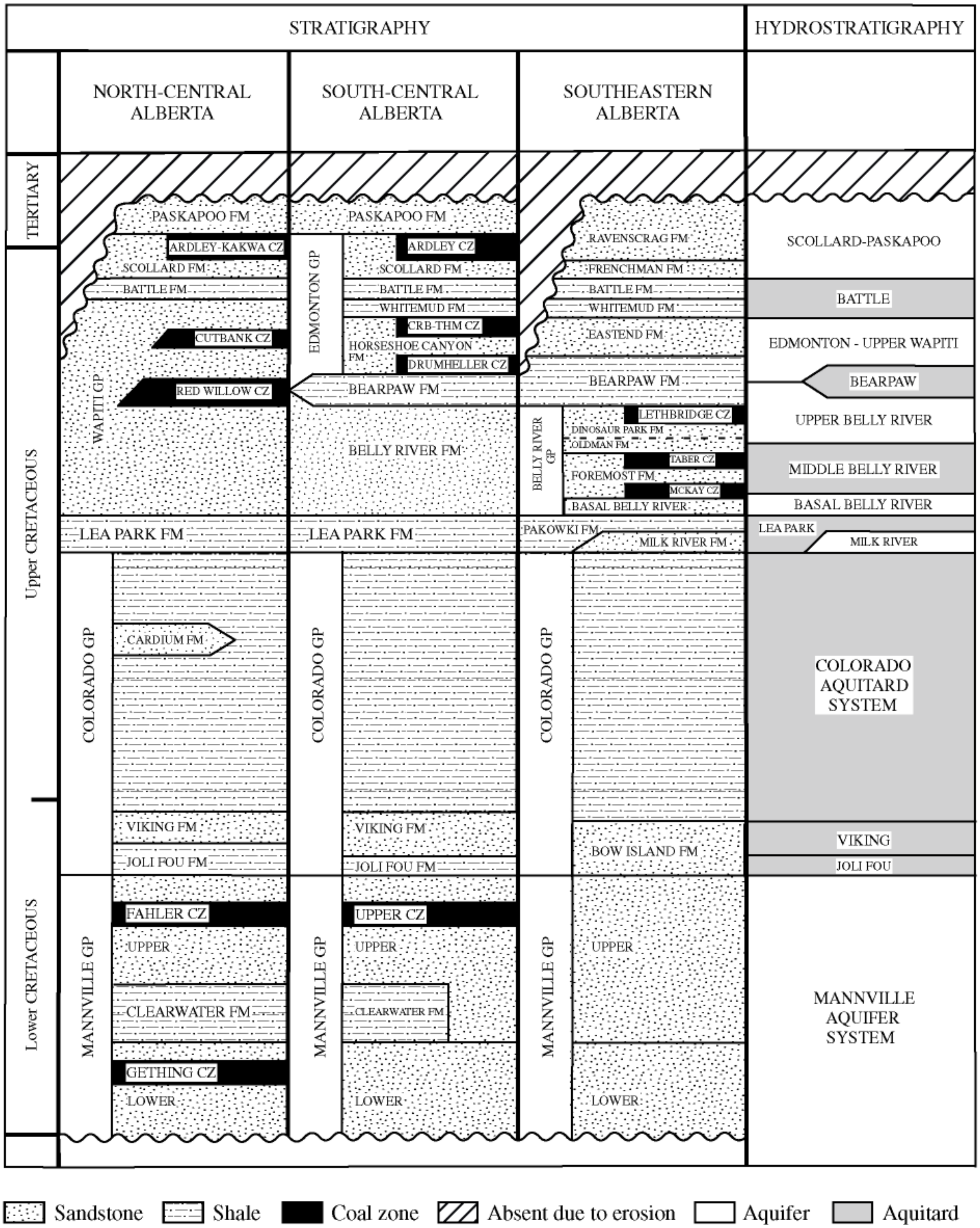


Figure 8. Stratigraphic table of formations (hydrostratigraphy of the pre-Lea Park sucession after Bachu, 1995). Abbreviations: CRB-THM, Carboson; CZ, Coal Zone; FM, Formation.

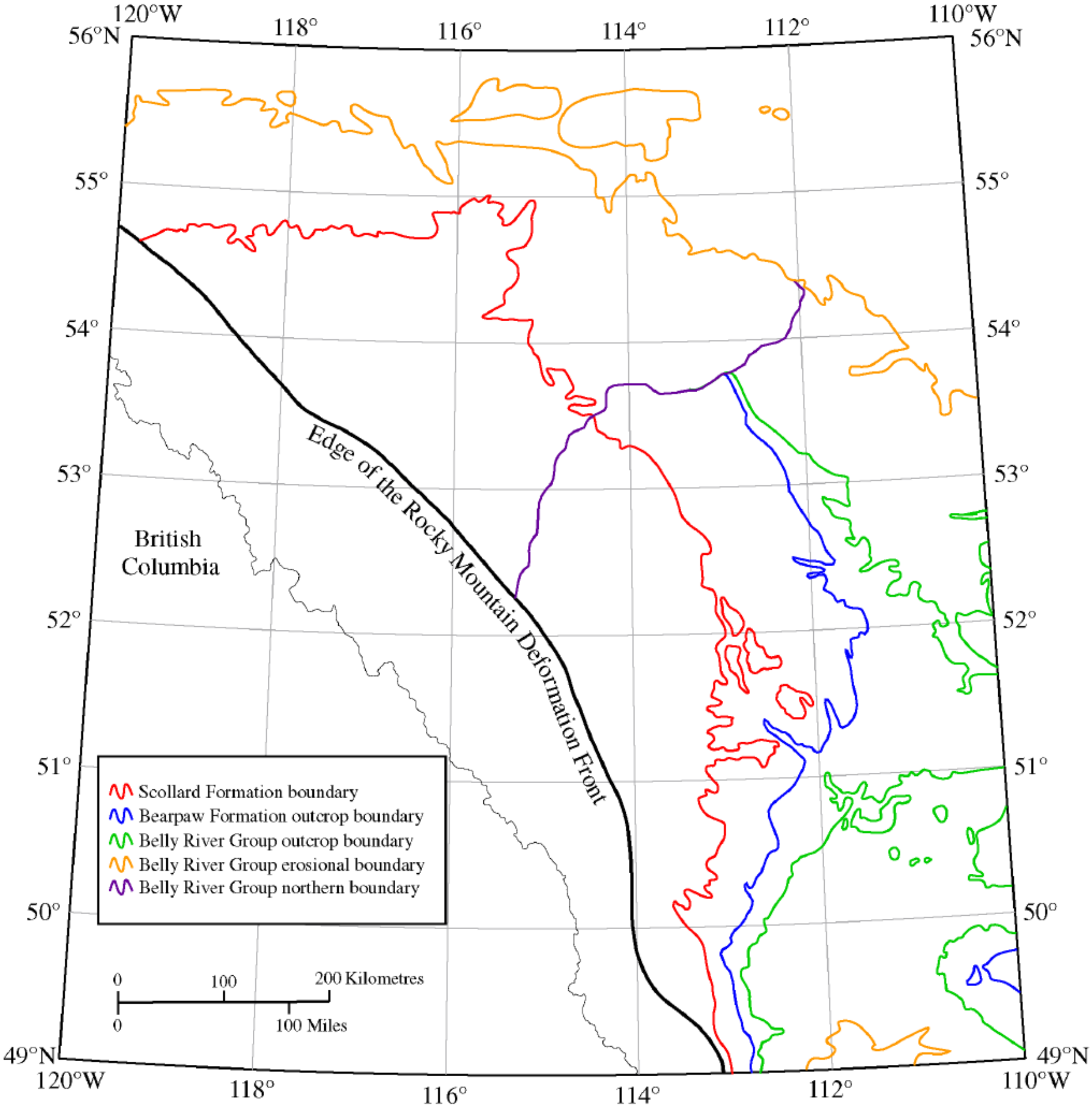


Figure 9. Formation boundaries in the study area.

(Hamblin, 1997b). The Lethbridge Coal Zone marks the top of the Dinosaur Park Formation. This coal zone developed as a result of rising regional water-table levels associated with the advancing sea that led to deposition of the Bearpaw Formation (Beaton et al., 2002).

The Belly River Group is equivalent to the Belly River Group of south-central Alberta and to the lower portion of the Wapiti Group in north-central Alberta.

2.1.1.3 Bearpaw Formation

During late Cretaceous time, a marine transgression deposited fine-grained marine strata of the Bearpaw Formation on the coarser-grained clastic sedimentary rocks of the Belly River Group. These fine-grained marine strata consist primarily of laminated shale and siltstone with some sandstone beds and lenses of kaolinitic claystone (Habib, 1981; Macdonald et al., 1987).

The Bearpaw Formation is present throughout southeastern Alberta and most of south-central Alberta, but is absent in north-central Alberta.

2.1.2 South-Central Alberta

In south-central Alberta, coal-bearing zones are found primarily within the Edmonton Group succession. This stratigraphic package occurs between the overlying Paskapoo Formation and the underlying Bearpaw Formation. The following section describes this interval.

2.1.2.1 Bearpaw Formation

The depositional environment of the Bearpaw Formation in south-central Alberta is very much the same as in southeastern Alberta. The presence of the marine shale units helps to differentiate the younger Edmonton Group from the underlying Belly River Group. The Bearpaw Formation is absent in portions of the central Alberta Basin, making stratigraphic correlations between the Edmonton Group and Belly River Group challenging.

The Bearpaw Formation is present throughout southeastern Alberta and most of south-central Alberta, but is absent in north-central Alberta.

2.1.2.2 Edmonton Group

The Edmonton Group comprises four formations, from oldest to youngest: the Horseshoe Canyon Formation, the Whitemud Formation, the Battle Formation and the Scollard Formation.

The Horseshoe Canyon Formation was deposited as the sea responsible for depositing the Bearpaw Formation shale regressed. The clastic sedimentary rocks of the Horseshoe Canyon Formation then prograded into the basin in an east-southeasterly direction (Nadon, 1988). The lower portion of the Horseshoe Canyon Formation is considered to have been formed in a deltaic environment (Rahmani, 1988), whereas the upper portions of the formation appear to have been deposited in a fluvial environment that represents the inland extension of the aforementioned deltaic environment (Beaton et al., 2002). The Horseshoe Canyon Formation is characterized by great lateral and vertical facies variability, bentonite, and abundant thin coal beds found in the Drumheller, Daly and Carbon Thomson coal zones (Hamblin and Lee, 1997). The Horseshoe Canyon Formation is equivalent to the Eastend Formation of southeastern Alberta and to the middle to upper Wapiti Group of north-central Alberta.

The Drumheller Coal Zone is found near the base of the Horseshoe Canyon Formation. Peat accumulation, leading to the development of the Drumheller Coal Zone, occurred in conjunction with intermittent regressive-transgressive pulses of the sea, where water table levels allowed peat accumulation for short periods in shoreline-parallel mires (Rottenfusser et al., 1991). The Drumheller Coal Zone is considered equivalent to the Red Willow Coal Zone of the Wapiti Group in north-central Alberta (Beaton et al., 2002).

The Daly Weaver Coal Zone is located in the middle portion of the Horseshoe Canyon Formation. The organic-matter source material for the Daly Weaver Coal Zone is thought to have accumulated in an alluvial-plain setting (McCabe et al., 1989). The Carbon Thomson Coal Zone is found near the top of the Horseshoe Canyon Formation. The peat accumulation that led to the development of the Carbon Thomson Coal Zone was associated with lacustrine and fluvial depositional environments (Beaton et al., 2002). The Daly Weaver and Carbon Thomson coal zones may be equivalent to the Cutbank Coal Zone of the Wapiti Group.

The fluvial, white, kaolinitic, silty sand of the Whitemud Formation conformably overlies the Horseshoe Canyon Formation. The Whitemud Formation is equivalent to the Whitemud Formation in southeastern Alberta and to the upper Wapiti Group in north-central Alberta.

The Battle Formation, which conformably overlies the Whitemud Formation, is composed of both lacustrine and paleosol facies throughout the plains (Binda, 1991). Several thin tuff beds are found throughout the formation. This formation is widespread and has been identified in southeastern and north-central Alberta.

The Scollard Formation disconformably overlies the Battle Formation and consists of thick, grey to buff sandstone and siltstone interbedded with thin, olive green mudstone beds and coal (Beaton et al., 2002). It is equivalent to the Frenchman and lower Ravenscrag formations of southeastern Alberta, and to the Scollard Formation of north-central Alberta. The Scollard Formation is divided into lower and upper units by the basin-wide Cretaceous-Tertiary boundary (Sweet and Braman, 1992). The lower unit is barren of coal and is composed of thin, fine-grained sandstone (Dawson et al., 1994). The upper unit is a medium to dark grey mudstone or greenish grey siltstone (Dawson et al., 1994), and contains the Ardley Coal Zone. This coal zone consists of four individual packages of coal seams and related interburden, associated with fluvial and lacustrine continental clastic sedimentary rocks (Beaton et al., 2002). The Ardley Coal Zone has been correlated with the Ardley-Kakwa Coal Zone of the Wapiti Group in north-central Alberta.

2.1.2.3 Paskapoo Formation

The Paskapoo Formation unconformably overlies the Ardley Coal Zone and clastic sedimentary rocks of the Scollard Formation. The Paskapoo Formation is made up of nonmarine, tabular, stacked successions of sandstone beds overlain by interbedded siltstone and mudstone (Beaton et al., 2002). The lower portion of the Paskapoo Formation contains minor coal. The Paskapoo Formation of south-central Alberta is equivalent to the Paskapoo Formation of north-central Alberta and to the upper Ravenscrag Formation of southeastern Alberta.

2.1.3 North-Central Alberta

In north-central Alberta, coal-bearing zones are primarily found within the Wapiti Group and the Scollard Formation. The Wapiti Group is overlain by the Battle Formation and overlies the Lea Park Formation. The Scollard Formation is overlain by the Paskapoo Formation and overlies the Battle Formation. The following sections describe these intervals. First, the Lea Park Formation–Wapiti Group–Battle Formation interval will be discussed, followed by a discussion of the Battle Formation–Scollard Formation–Paskapoo Formation interval.

2.1.3.1 Lea Park, Wapiti and Battle Formations

The Lea Park Formation consists of fine-grained, dark grey to brown mudstone and siltstone (Rosenthal et al., 1984) deposited during a marine transgression in late Cretaceous time. It is found in both south-central and north-central Alberta. The Lea Park Formation can be divided into lower and upper units. The lower unit is coarser grained and is equivalent to the Milk River Formation in southeastern Alberta. The upper unit is finer grained and represents a rapid marine transgression on the coarser grained sedimentary rocks of the lower unit. This upper unit is equivalent to the Pakowki Formation of southeastern Alberta.

The Wapiti Group is made up of terrestrial rocks that overlie the Lea Park Formation. The group is composed of basal, lower and upper units. The basal unit consists of a thick, coarse-grained sandstone capped by a thin coal horizon. This basal unit is equivalent to the basal Belly River Group of southeastern Alberta and to the lower portion of the Belly River Group in south-central Alberta. The lower unit consists of several cycles of sandstone and siltstone. This unit contains the Red Willow Coal Zone, which is equivalent to the Drumheller coal zone of the Horseshoe Canyon Formation of south-central Alberta. The lower unit itself is equivalent to portions of the Belly River, Bearpaw and Horseshoe Canyon formations of south-central Alberta, and to the Foremost, Oldman, Dinosaur Park and Bearpaw formations, and potentially the lower Eastend Formation of southeastern Alberta. The upper Wapiti Group is composed of interbedded sandstone and mudstone, and contains the Cutbank coal zone. The Cutbank coal zone may be equivalent to the Daly Weaver and Carbon Thomson coal zones of the Horseshoe Canyon Formation in south-central Alberta. The upper Wapiti Group is equivalent to portions of the Horseshoe Canyon Formation and to the Whitemud Formation of south-central Alberta. The upper Wapiti Group is also equivalent to portions of the Eastend Formation and to the Whitemud Formation in southeastern Alberta.

The Battle Formation, which conformably overlies the Wapiti Group, is composed of both lacustrine and paleosol facies throughout the plains (Binda, 1991). Several thin tuff beds are found throughout the formation. This formation is widespread and has been identified in southeastern and south-central Alberta.

2.1.3.2 Battle, Scollard and Paskapoo Formations

The Battle Formation is described in the previous section.

The Scollard Formation disconformably overlies the Battle Formation and consists of thick, grey to buff sandstone and siltstone interbedded with thin, olive green mudstone beds and coal (Beaton et al., 2002). It is equivalent to the Frenchman and lower Ravenscrag formations of southeastern Alberta, and to the Scollard Formation of north-central Alberta. The Scollard Formation is divided into lower and upper units by the basin-wide Cretaceous-Tertiary boundary (Sweet and Braman, 1992). The lower unit is barren of coal and is composed of thin, fine-grained sandstone (Dawson et al., 1994). The upper unit is a medium to dark grey mudstone or greenish grey siltstone (Dawson et al., 1994), and contains the Ardley Coal Zone. This coal zone consists of four individual packages of coal seams and related interburden, associated with fluvial and lacustrine continental clastic sedimentary rocks (Beaton et al., 2002). The Ardley Coal Zone has been correlated with the Ardley-Kakwa Coal Zone of the Wapiti Group in north-central Alberta.

The Paskapoo Formation unconformably overlies the Ardley Coal Zone and clastic sedimentary rocks of the Scollard Formation. The Paskapoo Formation is made up of nonmarine, tabular, stacked successions of sandstone beds overlain by interbedded siltstone and mudstone (Beaton et al., 2002). The lower portion of the Paskapoo Formation contains minor coal. The Paskapoo Formation of south-central Alberta is equivalent to the Paskapoo Formation of north-central Alberta and to the upper Ravenscrag Formation of southeastern Alberta.

3 Chemical Hydrogeology

3.1 Previous Work

Regional chemical hydrogeological studies of portions of the Upper Cretaceous–Tertiary coal-bearing formations have been undertaken by a number of researchers. Billings et al. (1969) and Hitchon et al. (1971) assessed the major-, minor- and trace-element geochemistry of the same formation-water samples from the Alberta Basin. Hitchon and Friedman (1969) analyzed these same formation-water samples for their stable oxygen and hydrogen isotopic compositions. These samples were collected from aquifers within the Lower Devonian–Upper Cretaceous stratigraphic interval, although only 3 of the 78 samples were from coal-bearing formations.

A number of regional groundwater assessments throughout the province by the Alberta Research Council mention coal aquifers. These include reports by Tóth (1966), Le Breton (1971), Borneuf (1972, 1973, 1979), Ozoray (1972), Tokarsky (1974, 1977a, b), Ozoray and Lytviak (1974), Bibby (1974), Gabert (1975), Hackbarth (1975), Stevenson and Borneuf (1977), Stein (1976), Ozoray and Barnes (1978), Ceroici (1979) and Ozoray et al. (1980). Coal-aquifer water chemistry is not described separately, but is included in the description of the formation-water chemistry.

Schwartz et al. (1981) confirmed some of the ideas of Billings et al. (1969), Hitchon and Friedman (1969) and Hitchon et al. (1971) regarding the dilution of formation water by meteoric water. Through the use of stable isotopes of oxygen and hydrogen, Schwartz et al. (1981) suggested that the mixing effect is occurring in Cretaceous aquifers of southern Alberta.

Connolly et al. (1990a, b) sampled formation water from central Alberta. Samples were analyzed for major ions, stable isotopic compositions of oxygen and hydrogen, and radiogenic isotopic ratios of Sr. Their work showed that formation waters within their study area fell into one of three groups that can in turn be associated with two hydrological regimes. Formation water from coal-bearing formations in the Alberta Basin fall into their Group III, indicating that rocks within this group have undergone flushing by meteoric water. Four of the 43 formation-water samples collected during this study were from coal-bearing formations.

Michael (2002) assessed water chemistry of Cretaceous to Tertiary formation water in west-central Alberta and proposed mechanisms responsible for the observed total dissolved solids (TDS), HCO_3, Na and Ca concentrations. He concluded that water chemistry within the coal-bearing formations is controlled by mixing of deep formation water with shallow meteoric groundwater to various degrees.

Bachu and Michael (2002) utilized the chemistry of formation waters collected by the energy industry and submitted to the Alberta Energy and Utilities Board (EUB) to assess aquifer water quality and to infer fluid flow between and within the Upper Cretaceous–Tertiary coal-bearing aquifers of the Alberta Basin. They found that, for all units, low-salinity areas generally coincided with subcrop beneath the unconsolidated Quaternary cover, whereas the higher salinity areas are located in the centre of the basin. They also noted that all units display lower salinity in the northern part of the basin. Through the use of chemical and hydraulic information, Bachu and Michael (2002) proposed a hydrostratigraphy for the Alberta Basin.

Goodarzi (2002) sampled water from 60 sites in the Lake Wabamun area of central Alberta. Twenty-one of these water samples were collected from wells completed in coal aquifers, 32 were completed in mixed sandstone-coal aquifers and two were completed in sandstone aquifers; the aquifer material in five of the wells was unknown. Goodarzi (2002) found that contents of As, Hg, Mo, Ni, Pb, U, Zn, Ba, Cr and Cu were either below the analytical detection limits or less than Canadian drinking water guideline values. Concentrations of Mn in coal-aquifer water samples were below Canadian drinking water guideline values except for five of the samples. Four of the mixed-aquifer water samples exceeded the drinking water guidelines. One of the water samples contained pyrene concentrations above the drinking water guideline value of 0.0002 mg/L.

3.2 Methodology

One of the goals of this project was to collect high-quality chemical information on coal-aquifer water samples in the Tertiary–Upper Cretaceous succession of the Alberta Basin. Because oil and gas exploration and development of coalbed methane resources in the Alberta Basin are in the early stages, collection of water samples from coalbed-methane development wells was not possible. Coal aquifers have been developed for domestic and industrial water use however and information exists regarding these wells. Information on domestic and industrial water wells is collected and input to a database administered by Alberta Environment. Searching this database reveals potential sampling candidates. Search criteria were defined so that the highest quality locations were selected. The criteria included the following:

- wells less than 20 years in age
- wells with stainless steel or plastic casing
- wells with a seal
- wells with either perforations or screens
- wells with coal making up at least 10% of the aquifer material within the completion interval

Once the list of wells was compiled, the water-well driller's reports were inspected to confirm the well completion details. If the details could be confirmed by examination of the report, individual well owners were contacted and asked some additional questions to confirm the wells as potential sampling locations. Owners were asked

- to confirm the location, completion date and approximate depth of the well;
- if some means, such as an outdoor tap or valve, was available so that the sampling apparatus could be connected to the well; and
- if any sort of filtration, aeration or treatment equipment was connected to the water system between the pump and the tap that would be used for sampling purposes

If the well details could not be confirmed, or if no means of sampling the water was available, or if treatment, aeration or filtration could not be bypassed or avoided, the well was rejected as a potential candidate. Once the list of wells was developed, a sampling schedule was completed.

The sampling occurred between September 30 and November 14, 2002. At each location, the following information was captured:

- latitude and longitude
- approximate elevation
- photographs of the well, the connection of sampling equipment and the condition of the area where wastewater was disposed of before and after sampling
- Field determinations of pH, temperature, oxidation-reduction potential, conductivity, dissolved oxygen and alkalinity

Water sampling and determination of field parameters were completed according to the methods given in Lemay (2002a, b). The steps detailed in these references were used to

- complete the sampling-equipment setup, including equipment calibration;
- determine when sufficient water had been pumped from the well to produce a representative sample;
- measure the above field parameters;
- collect water samples for analyses;
- collect quality-control and quality-assurance samples; and
- clean and decontaminate the sampling equipment.

3.3 Groundwater Geochemical Processes of Coal Aquifer Water

As water enters and moves through the hydrogeological system, the chemistry of the water changes. The variability is a function of geochemical processes active in the subsurface. Some of the more important processes are discussed below. Following this description, observations on the chemical composition of the various aquifer-water samples are presented and some preliminary conclusions on the geochemical characteristics of the water samples are discussed. Next, a detailed parameter-by-parameter summary is presented for each formation. These summaries provide information on the statistical parameters for each element and compound, and compare the statistical parameters with those obtained for datasets from other research conducted in Alberta and in NGC-producing basins in the United States.

3.3.1 Major-Ion Evolution Sequence

In most cases, groundwater originates as atmospheric precipitation. This water infiltrates through the soil zone, undergoing organic and inorganic chemical transformations. The first series of reactions involves the consumption of oxygen through the oxidation of organic matter. The result of this oxidation is the production of CO_2, which can either return to the atmosphere or be dissolved by H_2O to produce H_2CO_3 or aqueous CO_2. Residual O_2, as well as aqueous CO_2, will travel downward through advection and diffusion processes, resulting in the leaching and dissolution of mineral constituents and organic matter until it reaches the saturated zone. Groundwater continues to migrate along flow paths through the saturated zone, accompanied by an increase in the concentrations of total dissolved solids and most of the major ions.

Chebotarev (1955) noted that groundwater tends to evolve toward the composition of seawater, accompanied by regional changes in dominant anion species. As travel distance along the flow path increases, the dominant major anion shifts from HCO_3^- to HCO_3^-+SO_4^{2-} to SO_4^{2-}+HCO_3^- to SO_4^{2-}+Cl^- to Cl^-+SO_4^{2-} and finally to Cl^-. A similar progression is seen as the residence time of groundwater increases. An evolution sequence for the major cations has not been proposed because of the complications associated with cation movement along flow paths. Cation exchange reactions are more prevalent than anion exchange reactions and can commonly cause alterations or reversals in the cation sequences. The process of evolution from stage to stage is controlled by the availability of soluble carbonate, sulphate and chloride minerals along the groundwater flow paths and by mixing with waters of different types.

3.3.2 Electrochemical Evolution Sequence

Another evolution sequence takes place as water moves along its flow path. Oxidation-reduction (redox) potentials decrease along the flow path, as well as with depth and with residence time. This occurs initially because oxygen introduced during recharge is rapidly consumed by the oxidation of organic matter, forcing the redox potential to decline. Once all of the dissolved oxygen is consumed, reduction of NO_3^- and MnO_2 occurs, followed by a reduction of iron minerals that is accompanied by incremental decreases in the redox potential of the water. Once sufficiently negative redox potentials are reached, sulphate reduction occurs. The final step in the electrochemical evolution sequence involves the reduction of organic matter to methane. These reactions are biologically catalyzed, and it is thought that the evolution sequence is at least partially, if not totally, controlled by the ability for the necessary redox bacteria to thrive. Important factors controlling the electrochemical evolution of water therefore include the availability of nutrients, the availability of electron acceptors and donors, the pH and the temperature.

3.3.3 Hydrochemical Facies

Groundwater evolution is a complicated series of interactions and reactions. Several graphical methods have been developed for quickly representing the major-ion chemistry of water and to clarify the processes of geochemical evolution. Specialized trilinear plots, known as Piper plots, are particularly useful for describing differences in major-ion chemistry and are a convenient method of identifying groups or categories of water compositions. The concept of hydrochemical facies (Back 1961, 1966; Morgan and Winner, 1962; Seaber, 1962) was developed for this purpose. Hydrochemical facies are distinct zones that have cation and anion concentrations describable within defined composition categories (Figure 10). The composition category is based on the subdivisions of the trilinear diagram. The facies are useful for identifying recharge and discharge zones, and for tracing the evolution of groundwater composition.

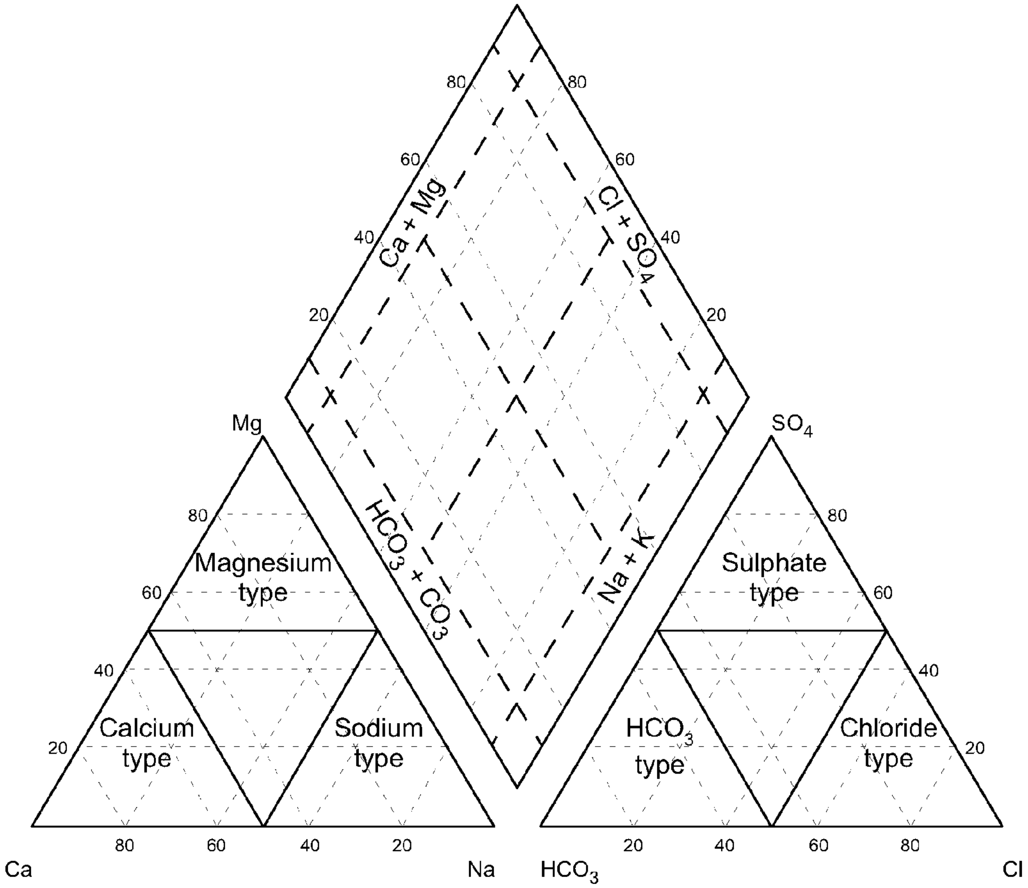


Figure 10. Hydrochemical-facies diagram.

3.4 Major-, Minor- and Trace-Element Chemistry

This section describes the observations made with respect to the chemical composition of the various water samples collected during this study. The hydrochemical facies are assigned, and any trends in the data are highlighted. The results are grouped by formation.

3.4.1 Observations - Paskapoo-Scollard Formation

The data are presented in Appendix A (Table 183). Samples 29, 45 and 46 belong to the Ca-HCO_3 water type (Figure 11); samples 23, 42 and 44 belong to the Na-HCO_3 type (Figure 11); and sample 22 belongs to the Na-Cl-HCO_3 type (Figure 11). In comparison, analyses presented by Bachu and Michael (2002) belong to the full range of water types (Figure 12). The associated water-well locations from this study and that of Bachu and Michael (2002) are presented in Figure 13 and Figure 14, respectively. Most of the samples have Ca and Mg as the dominant cations, and Na is present as the dominant cation in a significant number. Most of the samples have HCO_3 as the dominant anion, SO_4 is the second most common dominant anion and Cl is the dominant anion in just two cases. The distributions of the samples from this study (Figure 11) and the Bachu and Michael (2002) study (Figure 12) are consistent.

Correlation coefficients were calculated to assess possible correlations between elements, compounds and calculated parameters. Positive correlations in the data ($R > 0.5$) were observed between 1) depth and Na, TDS, sodium adsorption ratio (SAR) and B; 2) elevation and field-measured temperature, Li and Sc; 3) Ca and well-completion elevation, field-measured dissolved oxygen (DO), field-measured Eh, K, SO_4, turbidity, Si, Ba, Sr and $^{87}Sr/^{86}Sr$; 4) Mg and field-measured DO, field-measured Eh, Ca, K, SO_4, turbidity, Si, Ba, Sr and $^{87}Sr/^{86}Sr$; 5) Na and depth, field-measured pH, field-measured conductivity, field-measured temperature, HCO_3, total alkalinity, TDS and SAR; 6) SO_4 and field-measured DO, field-measured Eh, Ca, Mg and K; 7) HCO_3 and field-measured pH, Na, total alkalinity and SAR; 8) TDS and depth, field-measured pH, field-measured conductivity, field-measured temperature, Na and total alkalinity; 9) B and depth, Na, field-measured total alkalinity, TDS, Cr and Li; 10) Cr and field-measured conductivity, Na, TDS, B, SO_4 and Li; and 11) SAR and depth, field-measured conductivity, TDS and Li. Positive correlations ($R > 0.5$) in the data used by Bachu and Michael (2002) were observed between 1) depth and Na, Cl, TDS and SAR; 2) Na and depth, Cl, TDS and SAR; 3) Ca and Mg; 4) Mg and Ca; 5) Cl and depth, Na and TDS; 5) SAR and depth, temperature and TDS; and 6) TDS and depth, Na, Cl and SAR.

Negative correlations in the data ($R < -0.5$) were observed between 1) depth and Li and Sc; 2) elevation and HCO_3 and total alkalinity; 3) well-completion elevation and field-measured conductivity, Na, TDS, SAR and Cr; 4) Ca and field-measured pH, field-measured conductivity, Na, HCO_3, total alkalinity, SAR, B and Cr; 5) Mg and field-measured pH, field-measured conductivity, Na, HCO_3, total alkalinity, TDS, SAR, B, Cr and Li; 6) Na and well-completion elevation, field-measured DO, field-measured Eh, Ca, Mg, K, SO_4, turbidity, Si, Ba, Sr and $^{87}Sr/^{86}Sr$; 7) SO_4 and field-measured pH, field-measured conductivity, field-measured temperature, Na, HCO_3, total alkalinity, TDS, SAR, B, Cr and Li; 8) HCO_3 and well-completion elevation, field-measured DO, field-measured Eh, Ca, Mg, K, SO_4, Si, Ba and $^{87}Sr/^{86}Sr$; 9) TDS and well-completion elevation, field-measured DO, field-measured Eh, Ca, Mg, K, SO_4, Si, Ba, Sr and $^{87}Sr/^{86}Sr$; 10) B and field-measured Eh, Ca, Mg, K, SO_4, Si, Ba and $^{87}Sr/^{86}Sr$; 11) Cr and well-completion elevation, Ca, Mg, K and Si; and 12) SAR and well-completion elevation, field-measured Eh, Ca, Mg, K, SO_4, turbidity and Si. No negative correlations ($R < -0.5$) were observed in the data used by Bachu and Michael (2002).

3.4.2 Observations - Horseshoe Canyon Formation

Samples collected during this study belong to three water types (Figure 15): sample 24 is of Na-Ca-HCO_3-SO_4 type; sample 28 is of Na-Ca-SO_4-HCO_3 type; and the remaining samples are of Na-HCO_3 type. Samples selected by Bachu and Michael (2002) belong to all water-type categories (Figure 16). The sample locations for the two studies are presented in Figure 17 and Figure 18. The dominant cation, in most cases, appears to be Na, and Ca is generally the second most dominant cation. The dominant anion, in most cases, appears to be HCO_3, SO_4 is generally the second most common dominant anion and Cl is the third most common anion. The distributions of the samples from this study (Figure 15) and the Bachu

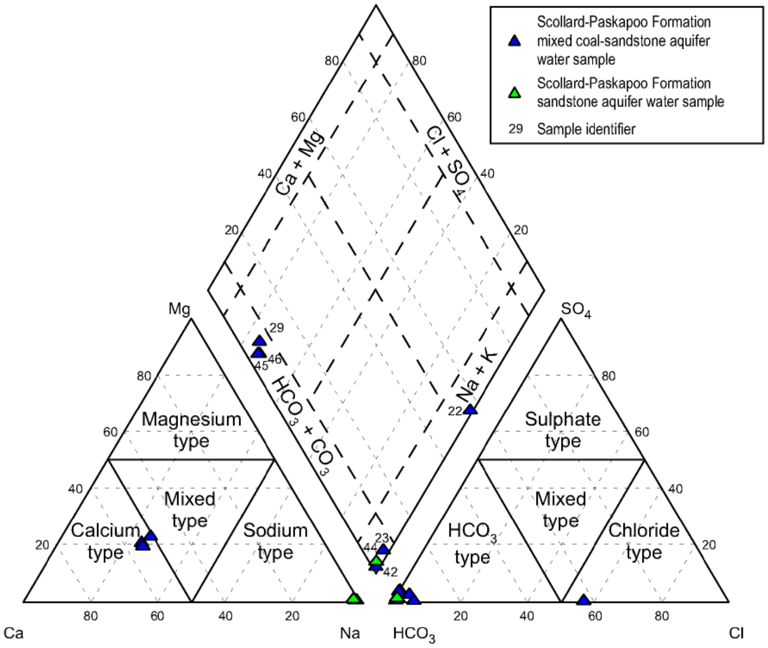


Figure 11. Paskapoo-Scollard Formation: hydrochemical-facies plot

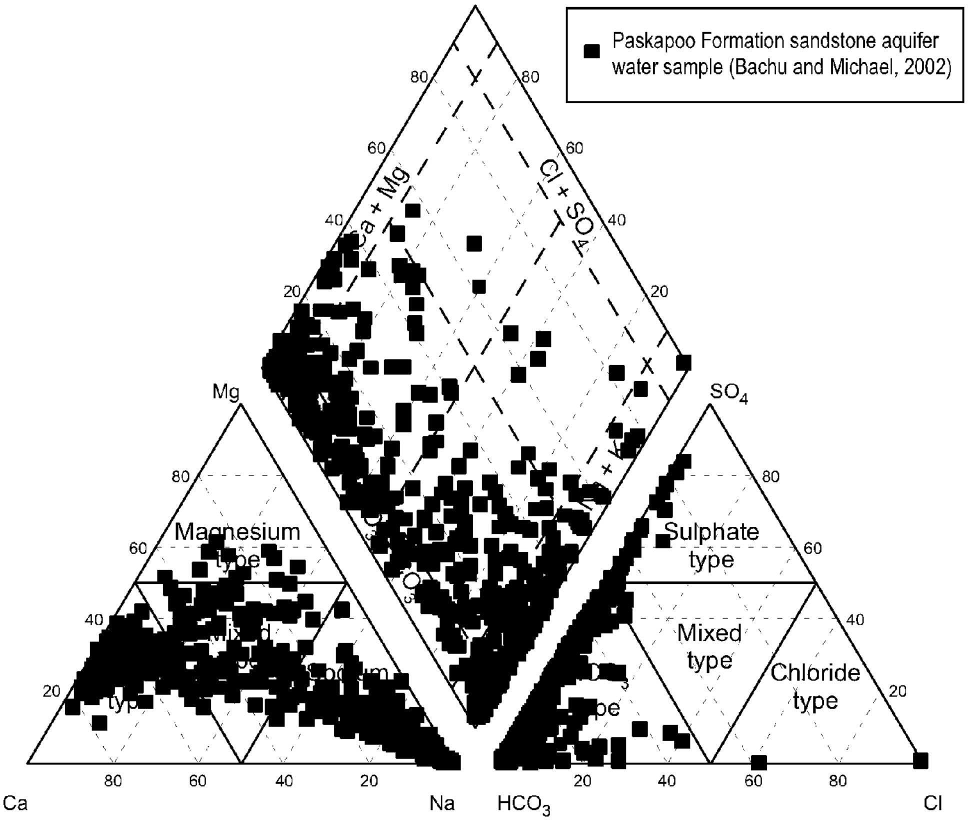


Figure 12. Tertiary-Upper Cretaceous: hydochemical-facies plot of sample points used by Bachu and Michael (2002).

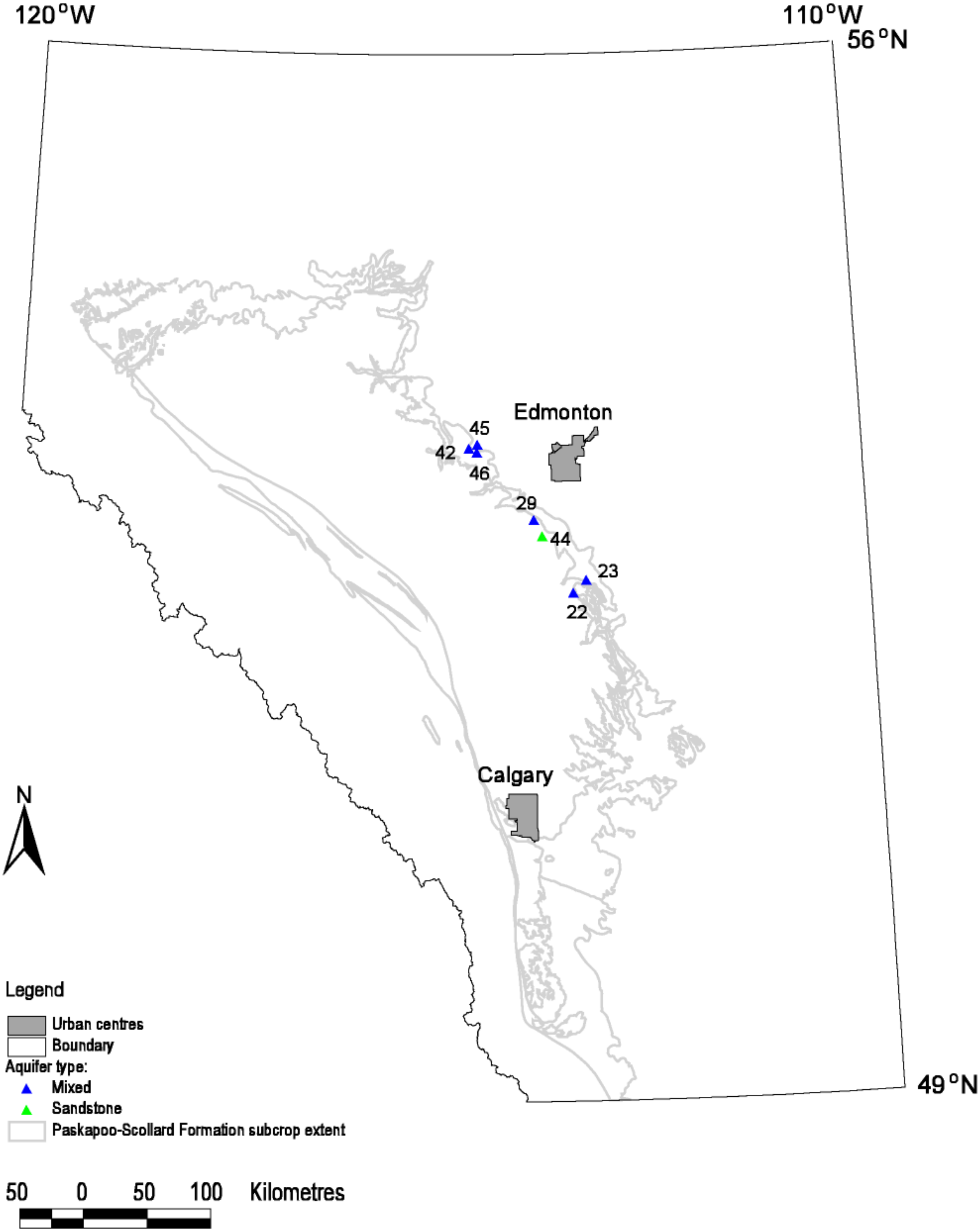


Figure 13. Paskapoo-Scollard Formation: sample locations (this study).

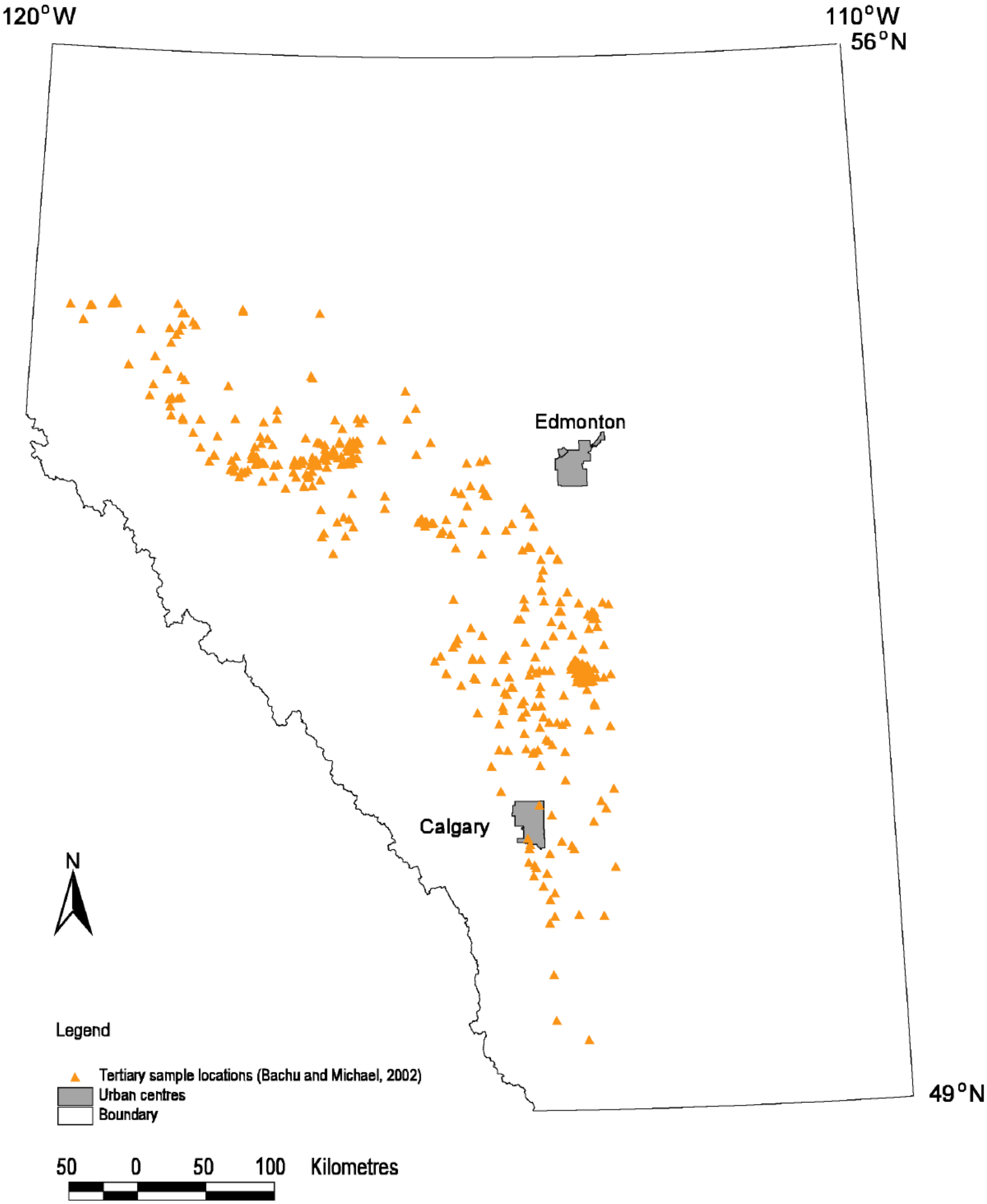


Figure 14. Tertiary-Upper Cretaceous: sample locations (Bachu and Michael, 2002).

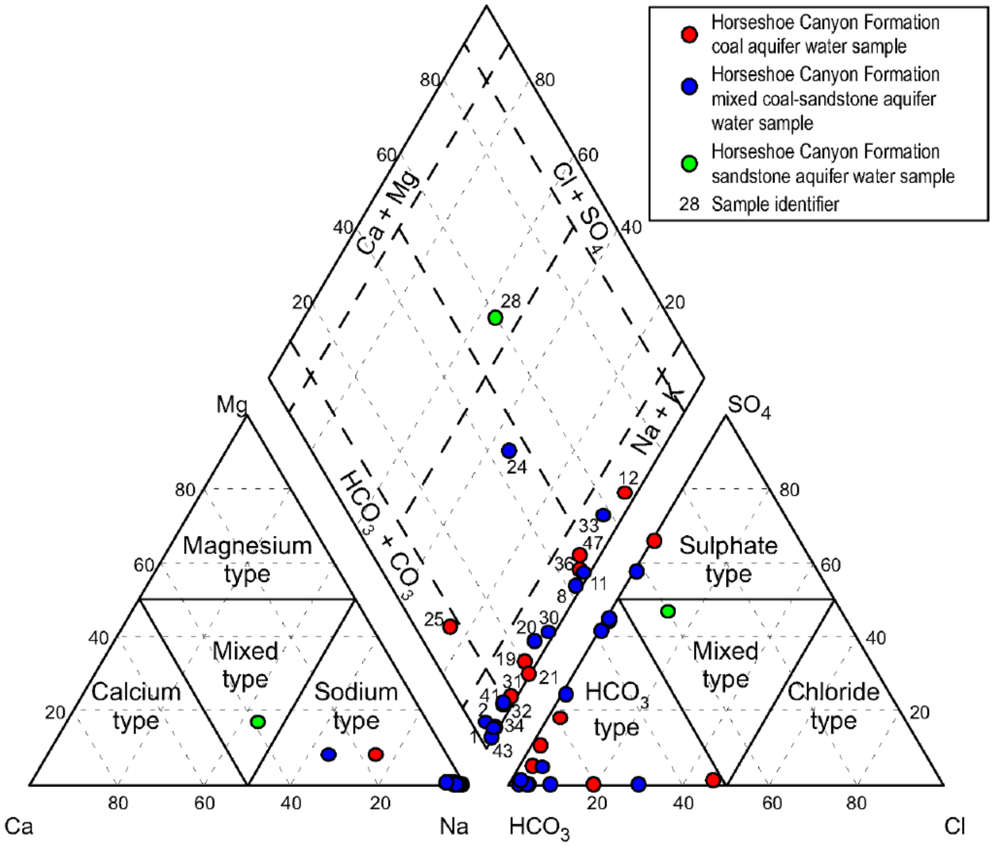


Figure 15. Horseshoe Canyon Formation: hydrochemical-facies plot.

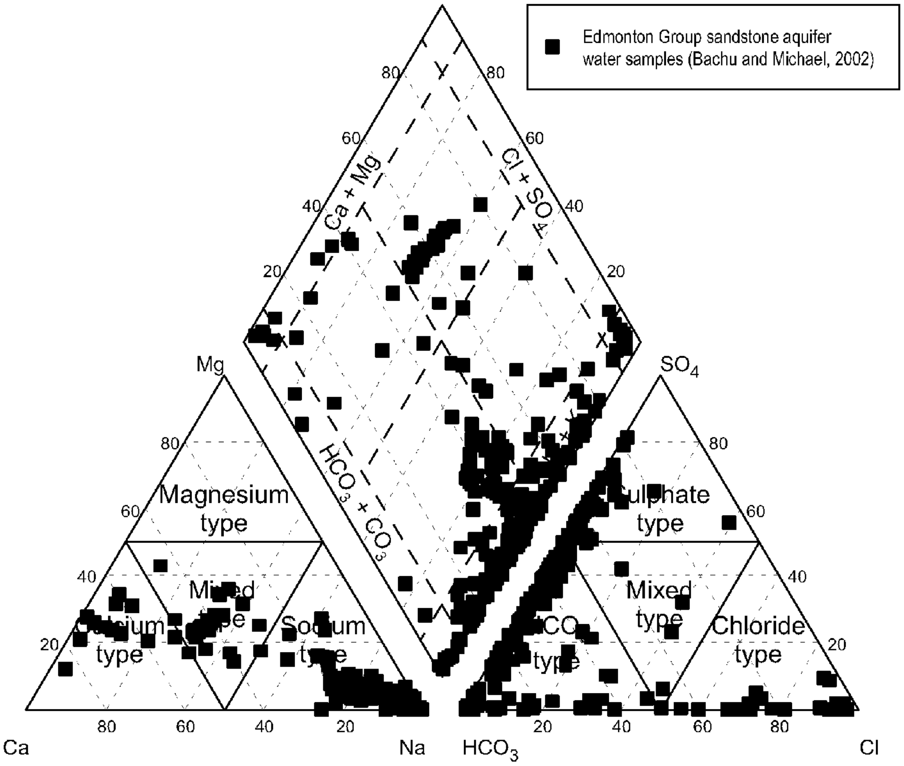


Figure 16. Edmonton Group: hydrochemical-facies plot of sample points used by Bachu and Michael (2002).

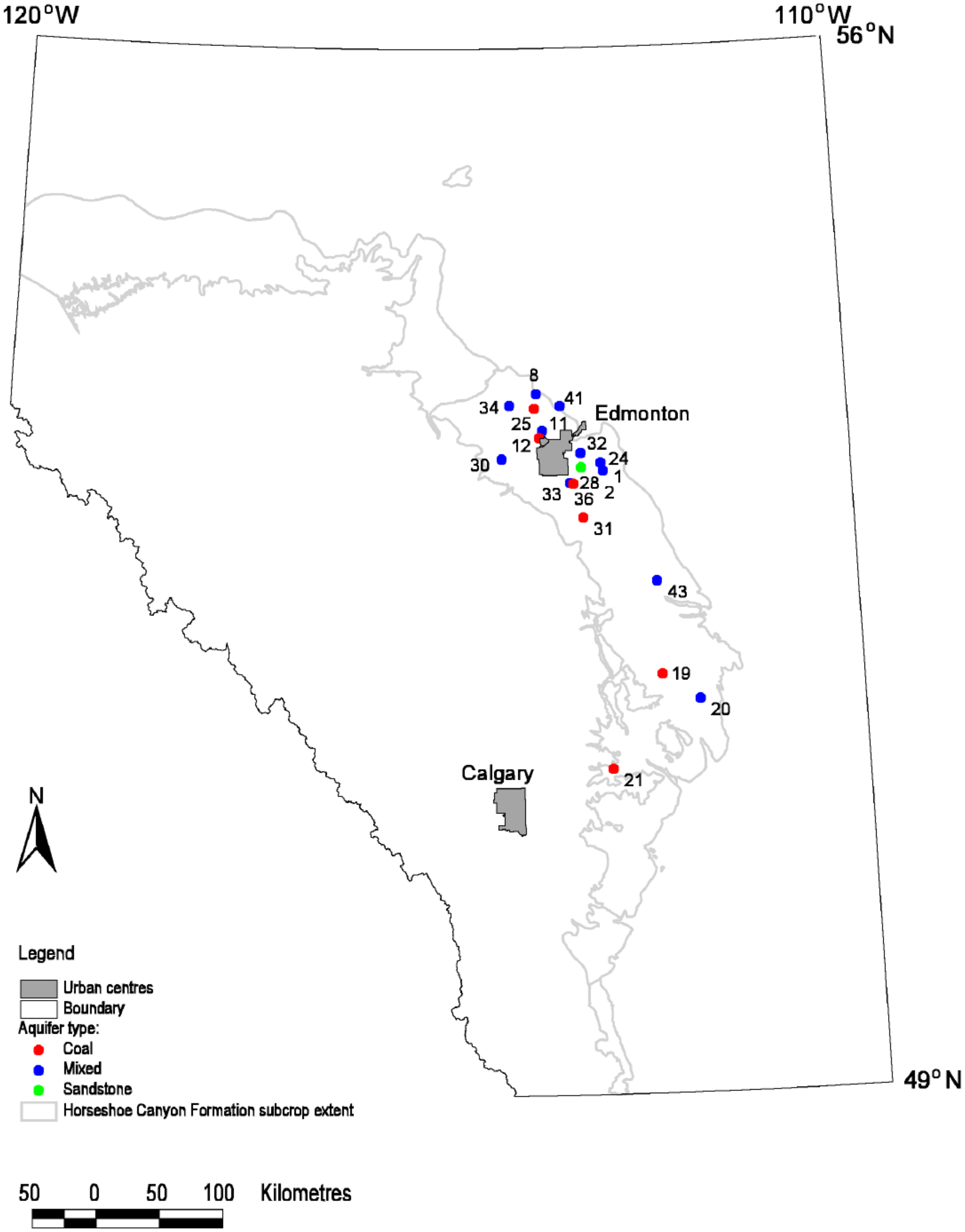


Figure 17. Horseshoe Canyon Formation: sample locations (this study).

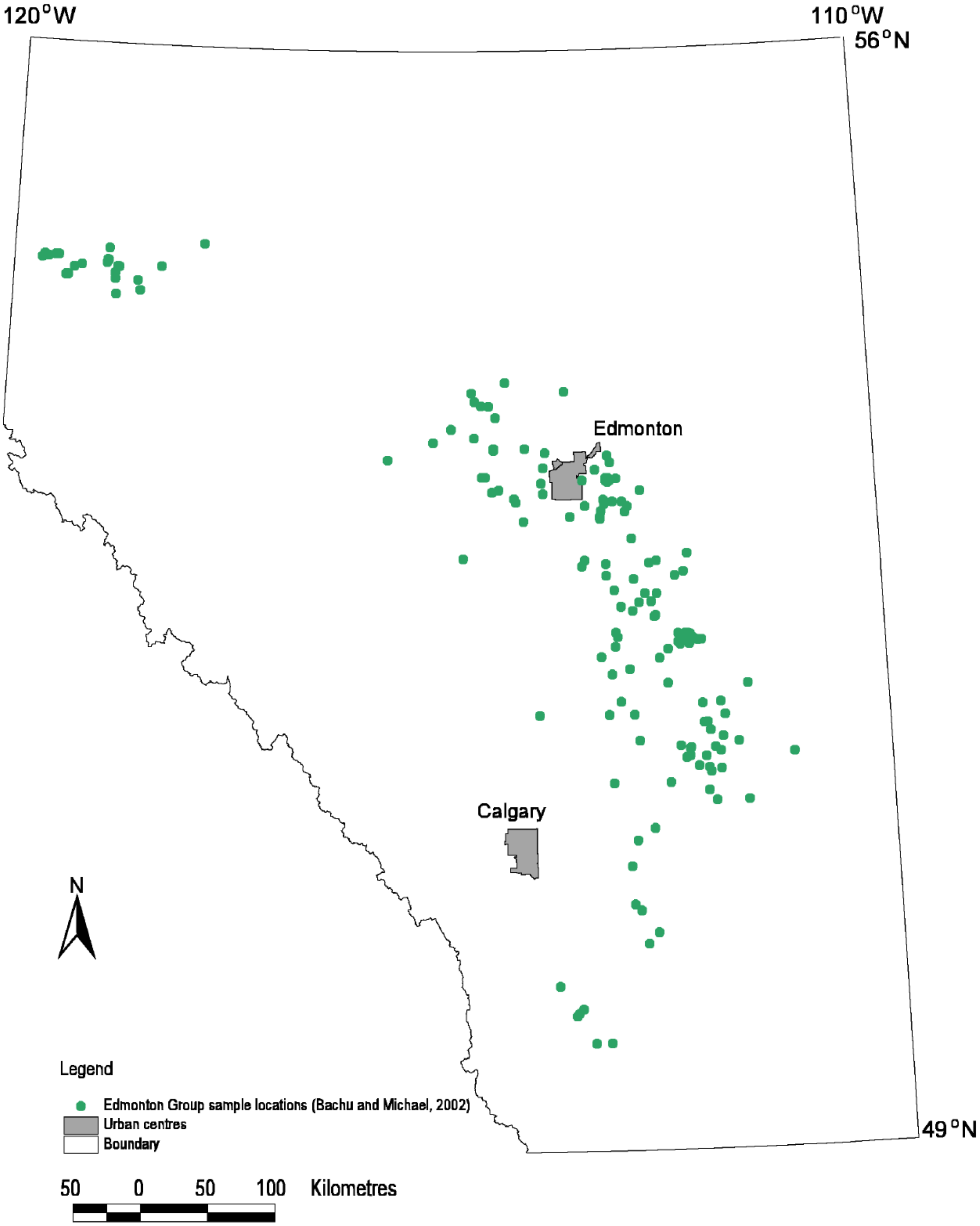


Figure 18. Edmonton Group: sample locations (Bachu and Michael, 2002).

and Michael (2002) study (Figure 16) are consistent.

Positive correlations in the data ($R > 0.5$) were observed between 1) depth and SAR; 2) ground surface elevation and field-measured temperature, Li and Sc; 3) well-completion elevation and Sr; 4) Ca and field-measured DO, Mg, K, Mn, turbidity, Sr and $^{87}Sr/^{86}Sr$; 5) Mg and field-measured DO, Ca, K, Mn, turbidity, Sr and $^{87}Sr/^{86}Sr$; 6) Na and field-measured conductivity, HCO_3, total alkalinity, TDS, SAR, Ti and Sc; 7) SO_4 and field-measured conductivity, TDS and Ti; 8) Cl and Cr, Br and I; 9) HCO_3 and Na, total alkalinity, Ba, Cr, Li and Sc; 10) TDS and field-measured conductivity, Na, SO_4, Li and Ti; 11) B and Li, Sc and well-completion elevation; 12) Cr and HCO_3, Ba, Br and I; 13) SAR and depth, field-measured pH and Na; and 14) Zn and adsorbable organic halides and $^{87}Sr/^{86}Sr$. Positive correlations ($R > 0.5$) in the data used by Bachu and Michael (2002) were observed between 1) depth and temperature, Na, Cl and TDS; 2) temperature and depth; 3) Na and depth, Ca, Mg, Cl, SO_4 and TDS; 4) Ca and Na, Mg, Cl, SO_4 and TDS; 5) Mg and Na, Ca, Cl, SO_4 and TDS; 6) Cl and depth, Na, Ca, Mg and TDS; 7) SO_4 and Na, Ca, Mg and TDS; 8) TDS and depth, Na, Ca, Mg, Cl and SO_4; 9) pH and SAR; and 10) SAR and pH.

Negative correlations in the data ($R < -0.5$) were observed between 1) depth and field-measured DO, field-measured Eh, Mg, Zn and $^{87}Sr/^{86}Sr$; 2) Ca and field-measured pH and SAR; 3) Mg and depth, field-measured pH and SAR; 4) Na and Fe; 5) HCO_3 and Fe; 6) turbidity and SAR; and 7) SAR and Ca, Mg, K, Mn and $^{87}Sr/^{86}Sr$. Negative correlations ($R <-0.5$) in the data used by Bachu and Michael (2002) were observed between 1) well-completion elevation and temperature, Na, Ca, Mg, Cl and TDS; 2) temperature and well-completion elevation; 3) Na and well-completion elevation; 4) Ca and well-completion elevation; 5) Mg and well-completion elevation; 6) Cl and well-completion elevation; and 7) TDS and well-completion elevation.

3.4.3 Observations - Belly River Group

Samples collected during this study belong to a number of water type categories, representing a variety of geochemical environments and processes (Figure 19). Samples 5 and 16 belong to the Ca-Mg-HCO_3 water type category. Sample 17 belongs to the Mg-Ca-HCO_3 water type category. Sample 35 belongs to the Na-Ca-HCO_3 water type category. Samples 6 and 9 belong to the Na-HCO_3 water type category. Samples 7, 10, 15, 26, 37, 38 and 40 belong to the Na-HCO_3-SO_4 water type category. Sample 39 belongs to the Na-SO_4-HCO_3 water type category. Sample 18 belongs to the Na-HCO_3-Cl water type category. Sample 27 belongs to the Na-Cl water type category. Samples selected by Bachu and Michael (2002) belong to all water type categories (Figure 20). The distribution of the samples from this study (Figure 19) and the Bachu and Michael (2002) study (Figure 20) are consistent. The sample locations are presented in Figure 21 and Figure 22.

Positive correlations in the data ($R > 0.5$) were observed between: 1) depth and field-measured pH, SAR and B; 2) elevation and $^{87}Sr/^{86}Sr$; 3) well-completion elevation and field-measured Eh, Ca, Si and $^{87}Sr/^{86}Sr$; 4) Ca and well-completion elevation, Si, As, Co, $^{87}Sr/^{86}Sr$ and gross beta radiation; 5) Mg and SO_4, turbidity, Si and gross beta radiation; 6) Na and field-measured conductivity, TDS, SAR, Ba, Cr, Li and Sr; 7) Cl and field-measured conductivity, Na and TDS; 8) SO_4 and Mg, total alkalinity, turbidity and gross beta radiation; 9) HCO_3 and total alkalinity and Mo; 10) TDS and field-measured conductivity, Na, Ba, Cr, Li, Sr and Cl; 11) turbidity and Mg, SO_4, total alkalinity, Si and gross beta radiation; 12) As and Ca, Co, Si and $^{87}Sr/^{86}Sr$; 13) Cr and field-measured conductivity, Na, TDS, Ba, Cl, Li and Sr; 14) SAR and field-measured pH, Na and B; 15) B and depth, field-measured pH and SAR; and 16) gross beta radiation and Ca, Mg, SO4, total alkalinity, turbidity and Si. Positive correlations ($R > 0,5$) in the data used by Bachu and Michael (2002) were observed between: 1) Na and Ca, Cl, TDS and SAR; 2) Ca and Na, Cl and TDS; 3) Mg and HCO_3 and pH; 4) Cl and Na, Ca, TDS and SAR; 5) HCO_3 and Mg and pH; 6) TDS and Na, Ca, Cl and SAR; 7) SAR and Na, Cl and TDS.

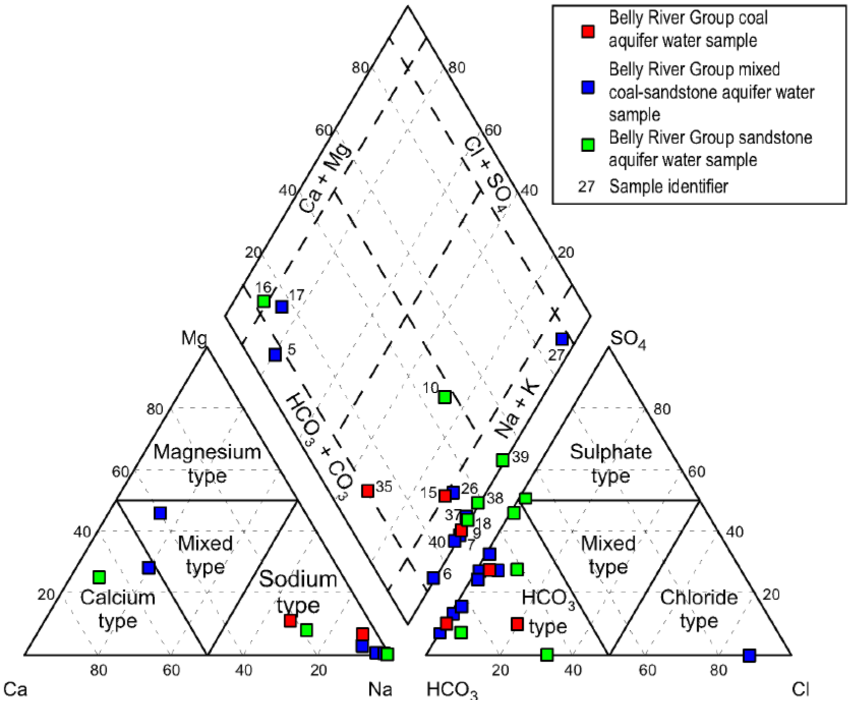


Figure 19. Belly River Group: hydrochemical-facies plot.

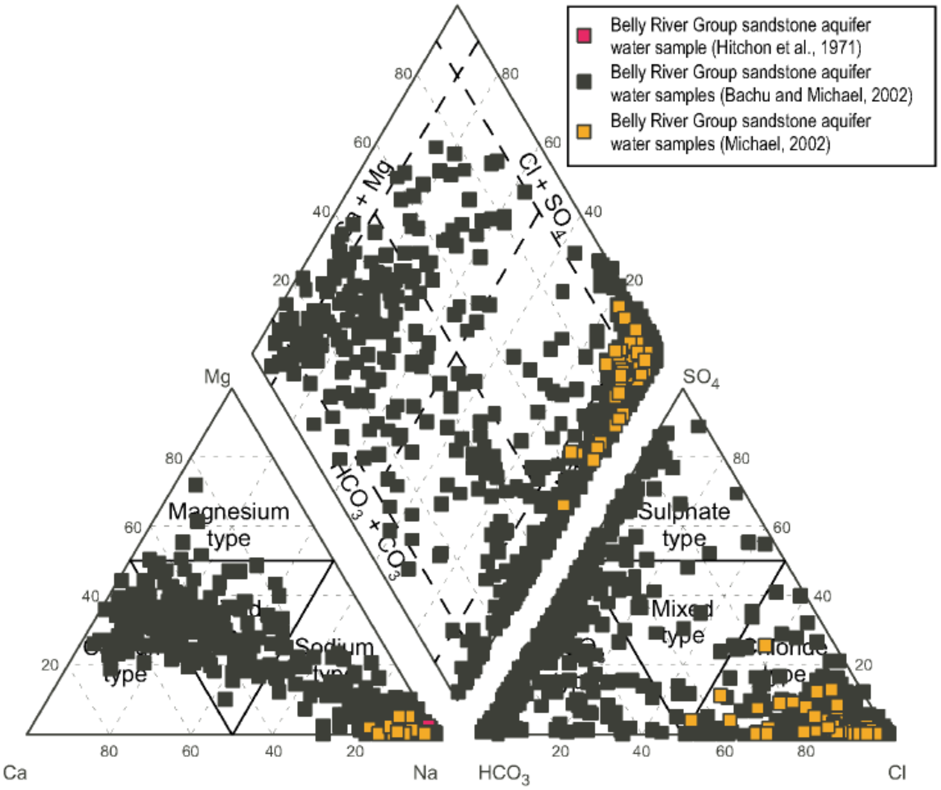


Figure 20. Belly River Group: hydrochemical-facies plot of sample points used by Bachu and Michael (2002).

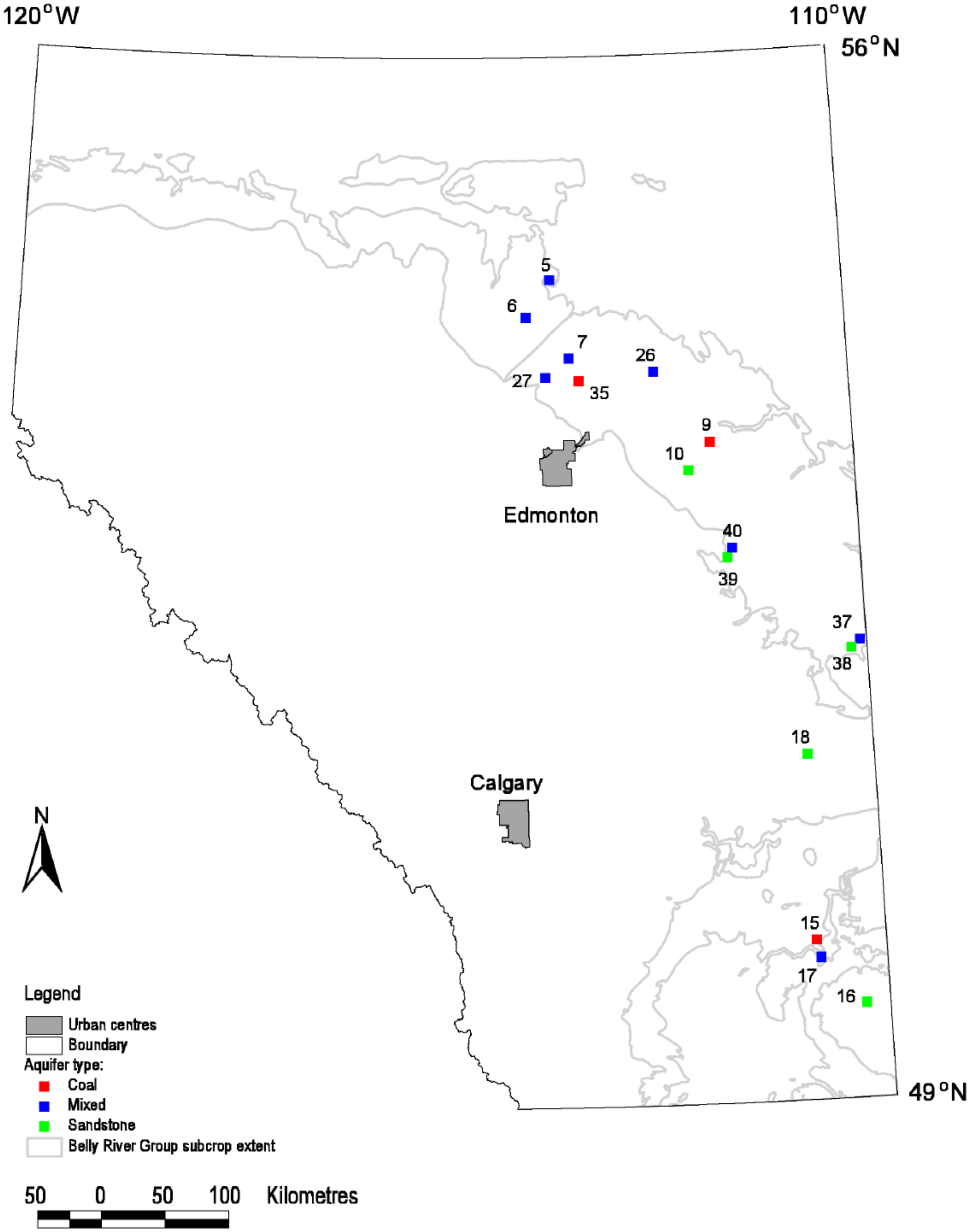


Figure 21. Belly River Group: sample locations (this study).

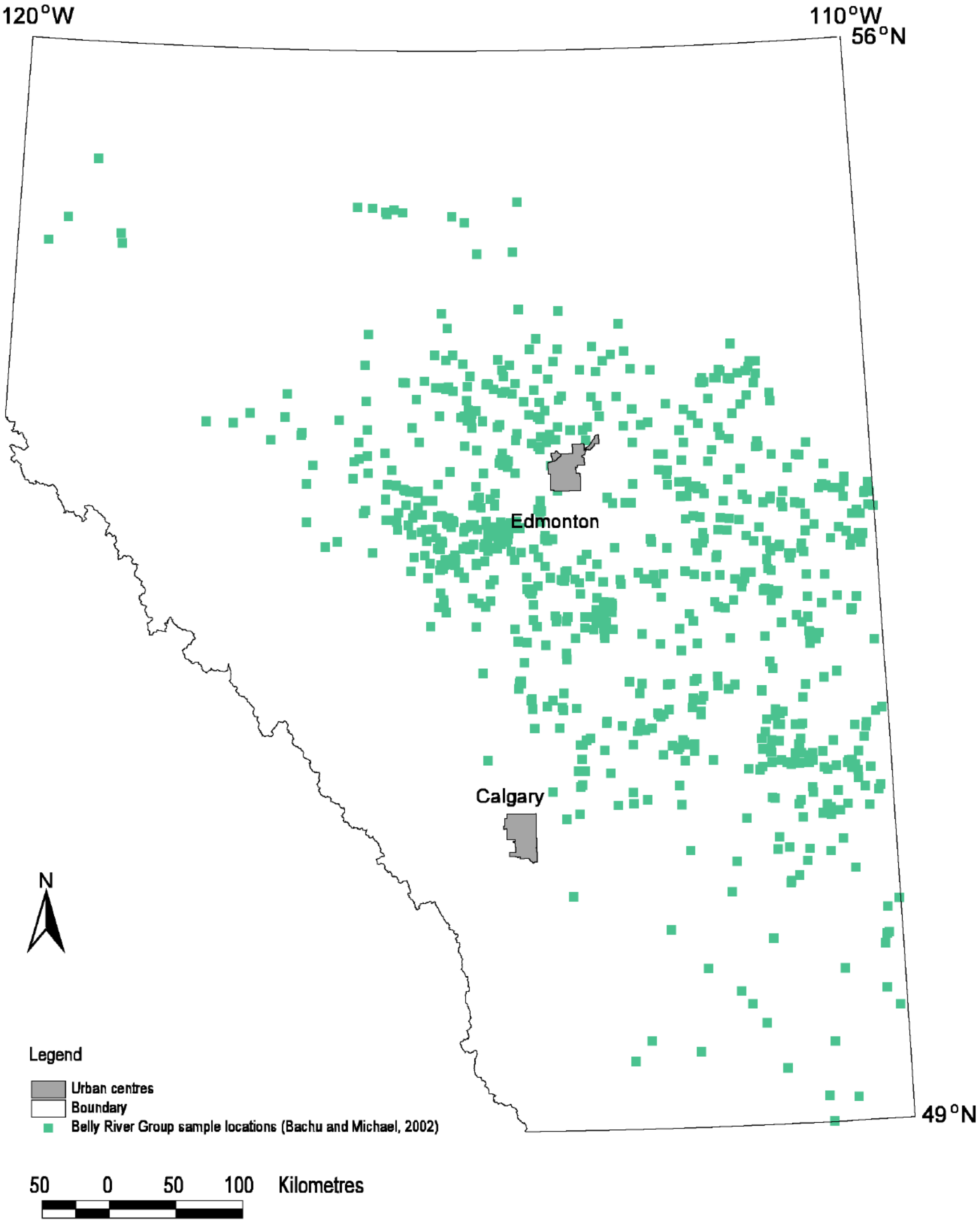


Figure 22. Belly River Group: sample locations (Bachu and Michael,002).

Negative correlations in the data (R < -0.5) were observed between: 1) depth and field-measured Eh, Ca, Mg, K, SO4, Si and gross beta radiation; 2) ground elevation and Ca and Co; 3) well-completion elevation and field-measured pH and Co; 4) Ca and field-measured pH, SAR and B; 5) Mg and field-measured pH and SAR; 6) Na and Si; 7) HCO_3 and Zn and adsorbable organic halides; 8) As and field-measured pH; 9) SAR and Ca, Mg, Si and $^{87}Sr/^{86}Sr$; 10) B and field-measured Eh, Ca, K, Si, $^{87}Sr/^{86}Sr$ and gross beta radiation; and 11) gross beta radiation and depth, field-measured pH, Mn, total alkalinity, SAR, B and Mo. No negative correlations (R < -0.5) were observed in the data used by Bachu and Michael (2002).

3.4.4 Preliminary Interpretations - Paskapoo-Scollard Formation

Samples 29, 45 and 46 are interpreted as being located near recharge areas. This interpretation is based on the observed geochemical facies, TDS values and field observations. Samples 22, 23, 42 and 44 are interpreted as being located farther along groundwater-flow paths within the Paskapoo-Scollard Formation. Values of TDS in these samples are greater than for those interpreted as being in recharge areas (Appendix A, Table 183). The water type is consistent with water that has undergone geochemical transformation typical of longer residence times in the flow system.

The distribution of the above water samples in Figure 11 is consistent with that of the samples used by Bachu and Michael (2002) for their geochemical description of major-ion concentrations in the Tertiary of the Alberta Basin (Figure 12). This suggests that similar geochemical processes are occurring within the Paskapoo-Scollard Formation aquifers throughout the Alberta Basin. Further supporting this idea is the observation that the same positive correlations are present between parameters such as depth, Na, Ca, Mg, Cl, TDS, SAR and temperature in the water samples collected during this study, and those compiled by Bachu and Michael (2002). In addition, the ranges of values for the various parameters in this study fall within those of the dataset of Bachu and Michael (2002).

The dominant cation in solution is either Ca or Na. The dominant anion in solution is HCO_3. Therefore, processes likely occurring within these aquifers include 1) water-rock interactions dissolving and exchanging ions in solution; 2) the precipitation of minerals; and possibly 3) bacterial action. The dissolution of carbonate, sulphate and silicate minerals releases into solution ions such as Ca, Mg, Ba, Sr, Li, K and Na, which can subsequently be exchanged on clay minerals. These processes first introduce Ca and Mg into solution and then remove it through exchange reactions, introducing Na into solution as it is replaced by the Ca or Mg on clay mineral surfaces. Once concentrations of mineral components reach the saturation point and thermodynamic criteria are met, mineral phases such as calcite, aragonite or dolomite may precipitate within the aquifer, further decreasing the Ca and Mg concentrations in solution. The dissolution of both carbonate and silicate minerals contributes HCO_3 to the solution through the reactions of carbonic acid with the minerals. Sulphate and HCO_3 concentrations are linked through processes such as sulphate reduction, in which reduced S and CO_2 are produced. Under most groundwater pH conditions this CO_2 will form HCO_3. This process is characterized by low SO_4 concentrations and much higher HCO_3 concentrations. The reaction can occur both abiologically and biologically.

3.4.5 Preliminary Interpretations - Horseshoe Canyon Formation

The samples collected during this study have geochemical facies typical of water that has undergone progressive geochemical changes consistent with water-rock interaction. The mean TDS is higher than the TDS of the overlying Paskapoo-Scollard Formation aquifer water samples (Table 10), consistent with the ideas presented in the section of geochemical evolution. The distribution of samples in Figure 15 is similar to that of samples compiled by Bachu and Michael (2002) in Figure 16. This may indicate that similar geochemical processes are occurring within Horseshoe Canyon Formation aquifers throughout the

Alberta Basin.

Similarities exist in the positive correlations between parameters determined for the water samples collected during this study and those compiled by Bachu and Michael (2002). Various positive correlations between TDS, Na, SO_4, pH and SAR point to similarities between the water contained within Horseshoe Canyon Formation aquifers throughout the Alberta Basin. Most of the major-ion concentrations determined for the samples collected during this project fall within the range of values compiled by Bachu and Michael (2002).

Geochemical reactions occurring within the Horseshoe Canyon Formation aquifers are likely similar to those discussed previously for the Paskapoo-Scollard Formation.

3.4.6 Preliminary Interpretations - Belly River Group

The geochemical facies of the water samples collected during this study represent a wide variety of environments and geochemical processes. Samples 5, 16 and 17 have a signature consistent with recharge areas; the elevation and TDS values appear to confirm this idea. Samples 6, 7, 9, 10, 15, 18, 26, 37, 38 and 40 belong to water types that indicate progressive geochemical changes consistent with water-rock interaction along groundwater-flow paths. Sample 27 has the highest TDS and also has a water type indicative of the final composition that water will attain along the groundwater-flow path. The distribution of the water samples collected during this study (Figure 19) is similar to that of the samples (Figure 20) compiled by Bachu and Michael (2002).

Positive correlations between Na, Cl and TDS, as well as between Na and SAR, exist in both the water samples collected during this study and those compiled by Bachu and Michael (2002). The ranges of values determined for the samples collected during this study fall within those of the samples compiled by Bachu and Michael (2002). This may indicate that similar geochemical processes are controlling the major-ion chemistry throughout the Belly River Group within the Alberta Basin.

Geochemical reactions occurring within the Belly River Group aquifers are likely similar to those discussed previously for the Paskapoo-Scollard Formation.

3.5 Chloride/Bromide Ratios

This section deals with just the Cl and Br data. As discussed below, these two halogens are useful in answering questions regarding water-rock interactions and water origin.

Both Cl and Br occur primarily as monovalent anions in natural water (Luong et al., 1983; Hem, 1989). Davis et al. (1998a) stated that Cl and Br tend to 1) behave conservatively when ionized in water; 2) do not occur in large concentrations in common rock-forming minerals, with the exception of evaporite minerals; and 3) form soluble compounds. Davis et al. (1998a) also listed differences in the geochemical characteristics of these halogens, including the following: 1) Cl is generally from 40 to 8000 times as abundant as Br; 2) Br compounds are more soluble than Cl compounds; 3) Br retention on clay, iron oxide and organic matter appears to be greater than that of Cl; and 4) bioaccumulation of Br appears to be greater than that of Cl.

Chloride and Br can enter groundwater through a number of possible mechanisms. Davis et al. (1998a) proposed a list that includes 1) atmospheric precipitation and dry fallout; 2) dissolution of evaporite minerals; 3) extrusion of brine from compacting clay deposits; 4) diffusion of ions out of saline fluid inclusions and micropores; 5) expulsion of water through recrystallization of minerals; 6) intrusion of seawater into coastal aquifers; and 7) introduction through anthropogenic sources. The differences in the geochemical characteristics of Br and Cl suggest that each source of Cl and Br in groundwater will generally have a distinct Cl/Br ratio. The mechanism of introduction and possible water-rock or water-water interaction can be determined through calculation and interpretation of this ratio.

3.5.1 Observations - Paskapoo-Scollard Formation

Only two of the six water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers have Br concentrations above the analytical detection limit (Appendix A, Table 183). The Cl/Br ratios for these samples (29, 42, 45 and 46) were therefore calculated assuming a Br concentration of half the detection limit.

The calculated or estimated Cl/Br ratios are generally less than 150, except for sample 29, which has an estimated Cl/Br ratio of 401.5. A well completed in a sandstone aquifer within the Paskapoo-Scollard Formation has a Cl/Br ratio of 44.1. For comparison purposes, seawater has a Cl/Br ratio of 287.5.

A linear trend appears to exist between the Cl/Br ratio and Cl concentration (Figure 23). As the ratio increases, so does the concentration of Cl.

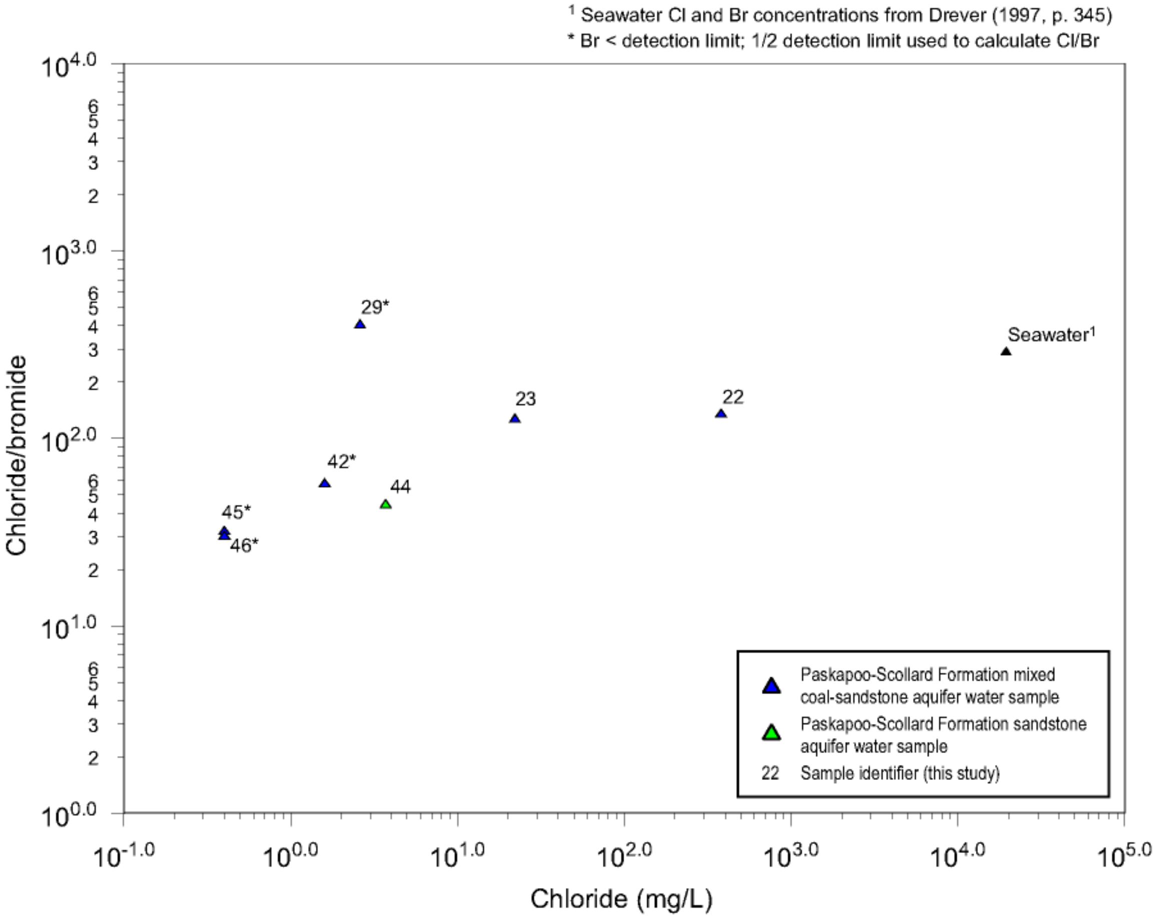


Figure 23. Paskapoo-Scollard Formation: chloride/bromide ratio vs. chloride.

The majority of the estimated or calculated Cl/Br ratios fall within the range of values (between 50 and 200) expected for atmospheric precipitation and for shallow groundwater (Davis et al., 1998a). Two of the samples (45 and 46) have ratios below 50. The estimated Cl/Br ratios for these samples are 31.8 and 30.0, respectively. The Cl/Br ratios below 50 have been determined for precipitation and for groundwater with similar chloride concentrations as the above samples (Davis et al., 1998a). The ratio for sample 29 (401.5) is beyond the expected values for groundwater and atmospheric precipitation (Davis et al., 1998a). Ratios of approximately 400 have, however, been observed in groundwater and atmospheric precipitation with Cl concentrations similar to that of sample 29 (Davis et al., 1998a). It should be noted that it was necessary to estimate the Cl/Br ratios for these samples because Br concentrations were below the analytical detection limits. The actual ratios could therefore be higher.

The Cl/Br ratio in the water sample (sample 44) from the sandstone aquifer is 44.1. This value falls slightly outside the range of ratios expected for atmospheric precipitation and groundwater (Davis et al., 1998a). Ratios in this range have, however, been reported for groundwater and atmospheric precipitation with Cl concentrations similar to that of sample 44 (Davis et al., 1998a).

The Paskapoo-Scollard Formation Cl/Br ratios and Cl concentrations are similar to some of the results observed for samples from the Horseshoe Canyon Formation (Figure 24) and Belly River Group (Figure 25).

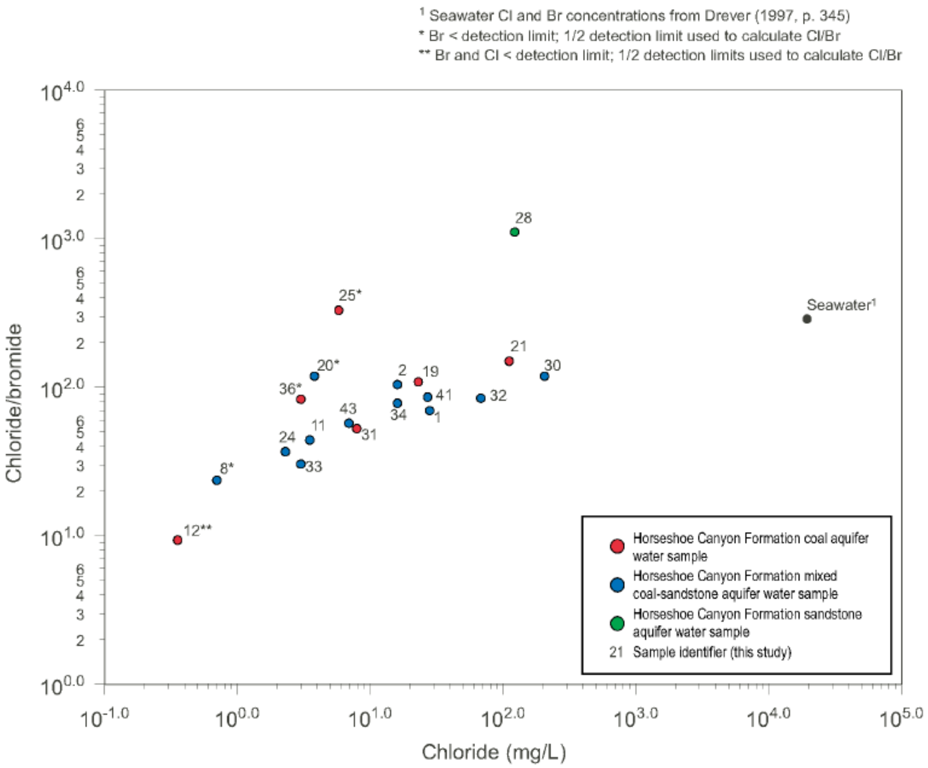

[1] Seawater Cl and Br concentrations from Drever (1997, p. 345)
* Br < detection limit; 1/2 detection limit used to calculate Cl/Br
** Br and Cl < detection limit; 1/2 detection limits used to calculate Cl/Br

Figure 24. Horseshoe Canyon Formation: chloride/bromide ratio vs. chloride.

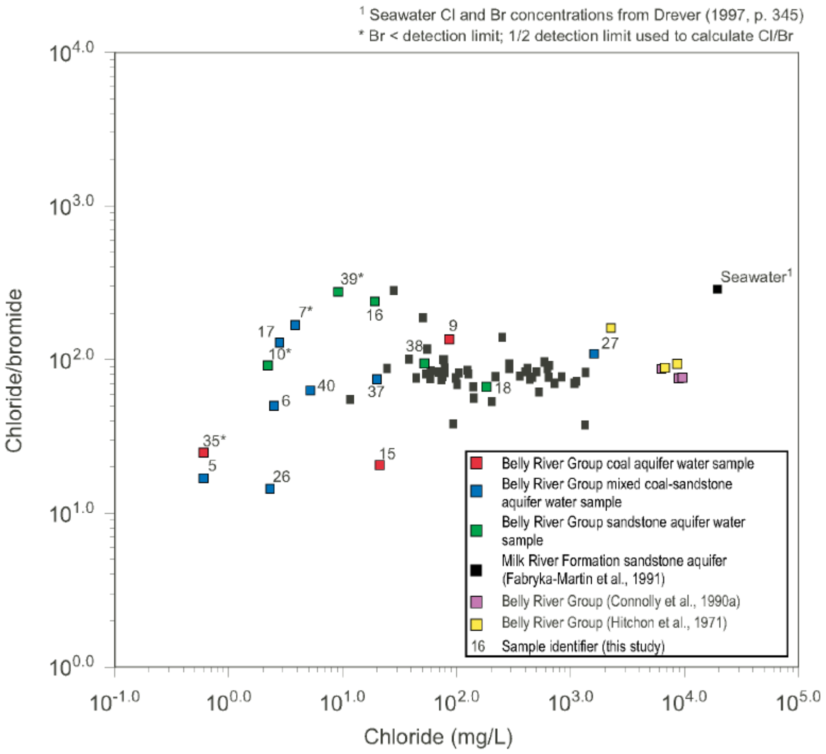


Figure 25. Belly River Group: chloride/bromide ratio vs. chloride.

3.5.2 Observations - Horseshoe Canyon Formation

Three of the six water samples (samples 12, 25, 36) from Horseshoe Canyon Formation coal aquifers and two of the twelve samples (samples 8, 20) from mixed coal-sandstone aquifers have Br concentrations below the analytical detection limit (Appendix A, Table 183). One of the six samples (sample 12) from Horseshoe Canyon Formation coal aquifers has a Cl concentration below the analytical detection limit. The Cl/Br ratios for these samples were calculated assuming Cl or Br concentrations equal to half of the relevant detection limit.

Most of the calculated or estimated Cl/Br ratios for coal aquifer water samples are below 150, except for sample 25, which has an estimated ratio of 329.1. All of the calculated or estimated ratios for mixed coal-sandstone aquifer water samples are below 120. One sample (28) from a Horseshoe Canyon Formation sandstone aquifer has a Cl/Br ratio value of 1109. For comparison purposes, seawater has a ratio of 287.5.

There appears to be a curvilinear trend in the plot of Cl/Br ratio vs. Cl concentration (Figure 24). As the ratio increases, so does the concentration of Cl.

Most of the estimated or calculated Cl/Br ratios for water samples from coal and mixed coal-sandstone aquifers fall within the range of values (between 50 and 200) expected for atmospheric precipitation and for shallow groundwater (Davis et al., 1998a). One of the water samples (12) from the coal aquifers and four of the samples (8, 11, 24 and 33) from the mixed coal-sandstone aquifers have ratios below 50. Chloride/bromide ratios below 50 have been determined for precipitation and for groundwater with Cl concentrations similar to the above samples (Davis et al., 1998a). The Cl/Br ratio value for coal aquifer water sample 25 (329.1) is beyond the expected Cl/Br ratio values for groundwater and atmospheric precipitation (Davis et al., 1998a). Ratios of approximately 300 have, however, been observed in groundwater and atmospheric precipitation with chloride concentrations similar to that of sample 25

(Davis et al., 1998a). It should be noted that it was necessary to estimate ratios for samples 8, 12 and 25 because Br concentrations were below the analytical detection limit. In the case of sample 12, the Cl concentration was also below the analytical detection limit. The actual Cl/Br ratios are therefore uncertain.

The Cl/Br ratio in the water sample (28) from the sandstone aquifer is 1109. This value falls outside the range of Cl/Br ratios expected for atmospheric precipitation and groundwater (Davis et al., 1998a). Ratios in this range have, however, been reported for groundwater with Cl concentrations similar to that of sample 28 (Davis et al., 1998a).

The Horseshoe Canyon Formation Cl/Br ratios and Cl concentrations are similar to some of the results observed for samples from the Paskapoo-Scollard Formation (Figure 23) and Belly River Group (Figure 25).

3.5.3 Observations - Belly River Group

One of the three Belly River Group coal aquifer water samples (sample 35) has a Br concentration below the analytical detection limit (Appendix A, Table 183). One of the eight mixed coal-sandstone aquifer water samples (sample 7) has a Br concentration below the analytical detection limit (Appendix A, Table 183). Two of the five sandstone aquifer water samples (samples 10, 39) have Br concentrations below the analytical detection limits (Appendix A, Table 183). The Cl/Br ratios for these samples were calculated assuming Cl or Br concentrations equal to half of the relevant detection limits.

The calculated or estimated coal aquifer water sample Cl/Br ratios are below 150. The calculated or estimated mixed coal-sandstone aquifer water sample Cl/Br ratios are below 170. The calculated or estimated sandstone aquifer water sample Cl/Br ratios are generally below 200, with the exception of two samples (samples 16, 39), which have calculated or estimated ratios of 239.2 and 276.7 respectively. For comparison purposes, seawater has a Cl/Br ratio of 287.5. Belly River Group samples collected by Hitchon et al. (1971), Connolly et al. (1990a) and Fabryka-Martin et al. (1991) have Cl/Br ratios generally less than 100.

Only a very general linear trend appears to exist between Cl/Br ratios and Cl concentration (Figure 25). An increase in Cl/Br ratios corresponds very generally to an increase in Cl concentrations. The majority of the sample Cl/Br ratio values are comparable to Cl/Br ratio values calculated from data collected by Hitchon et al. (1971), Connolly et al. (1990a) and Fabryka-Martin et al. (1991).

Most of the estimated or calculated coal and mixed coal-sandstone aquifer water sample Cl/Br ratios fall within the range of values (between 50 and 200) expected for atmospheric precipitation and for shallow groundwater (Davis et al., 1998a). Two of the coal aquifer water samples (samples 15, 35) and two of the mixed coal-sandstone aquifer water samples (samples 5, 26) have ratios below 50. Chloride/bromide ratio values below 50 have been determined for precipitation and for groundwater with similar Cl concentrations as the above samples (Davis et al., 1998a). It should be noted that it was necessary to estimate ratios for sample 35 because the Br concentration was below the analytical detection limit. The actual Cl/Br ratio for this sample is therefore uncertain.

Three of the sandstone aquifer water samples (samples 10, 18, 28) have Cl/Br ratios that fall within the range of values expected for atmospheric precipitation and for shallow groundwater (Davis et al., 1998a). However, two of the sandstone aquifer samples (samples 16, 39) have Cl/Br ratios that value fall outside the range of expected Cl/Br ratios. These Cl/Br ratio values do fall within the range of reported Cl/Br ratio values for atmospheric precipitation and groundwater with Cl concentrations similar to that of samples 16 and 39 (Davis et al., 1998a). It should be noted that it was necessary to estimate ratios for samples 10 and 39 because the Br concentrations were below the analytical detection limit. The actual Cl/Br ratio for these samples is therefore uncertain.

The sample Cl/Br and Cl concentrations are similar to results determined from samples collected by other researchers (Figure 25). The Belly River Group Cl/Br ratios and chloride concentrations are similar to some of the results observed for samples from the Paskapoo-Scollard Formation (Figure 23) and Horseshoe Canyon Formation (Figure 24).

3.5.4 Preliminary Interpretations - Paskapoo-Scollard Formation

The Cl/Br ratios determined for water samples from the Paskapoo-Scollard Formation mixed coal-sandstone aquifers and sandstone aquifer fall within the range of values reported for shallow groundwater and atmospheric precipitation. This suggests that the water within these aquifers is derived from a mixture of meteoric water and connate water that has not undergone any interaction with evaporite minerals.

Although the ratios fall within the range of values determined for atmospheric precipitation and groundwater, there may be other possible explanations for the ratio that exceeds, and those ratios that fall below, the expected ratios for shallow groundwater and atmospheric precipitation.

Hite and Cheng (1996) sampled groundwater from 18 piezometers installed in an artificial fen environment constructed in Ohio. The piezometers were installed to depths between 0.15 and 1.8 m below ground surface. Chloride and Br were measured in six groundwater samples. The depths of completion from which the samples were collected were between 0.15 and 0.60 m below ground surface. The Cl/Br ratios had a mean value of 28. This may suggest a link between organic matter and lower Cl/Br ratios. The ratios for Scollard Formation coal, mudstone, shale and shaly coal, determined from analyses by Gentzis and Goodarzi (1995) and Pollock et al. (2000), have mean values of 0.30 (N=82) and 41.3 (N=18), respectively. The lower Cl/Br values from coal and aquifer rock types could indicate that the Cl/Br ratios in samples 42, 45 and 46 are related to the Cl and Br content of the coal and other aquifer rock types from which the water samples were collected.

The mechanisms for developing Cl/Br ratios greater than the values expected for shallow groundwater or atmospheric precipitation usually involve either the dissolution of salt or evaporite minerals, the mixing of waters with different Cl/Br ratios, or possibly the retention of bromide on clay minerals or organic matter. Each possibility will be considered.

Whittemore (1993), in his work on groundwater geochemistry in Kansas, found that meteoric water influenced by salt dissolution has a mean Cl/Br ratio of between 148 and 461, with Cl concentrations of between 3.1 and 37 mg/L. The Cl/Br ratio and Cl concentration of sample 29 are 401.5 and 2.6 mg/L, respectively. This suggests that salt or evaporite-mineral dissolution is not responsible for the Cl/Br ratio and Cl concentration observed in sample 29.

Davis et al. (1998a) constructed a model to explain observed trends in Cl/Br ratios and Cl concentrations in southeastern Kansas, the Tucson basin and the Milk River aquifer of southern Alberta. The model involved the evaporation of one litre of rainwater with a Cl/Br ratio of 100 and a Cl concentration of 0.5 mg/L, followed by the addition of one litre of a brine solution with a Cl/Br ratio of 10 000 and a Cl concentration of 10 000 mg/L. Bachu and Michael (2002) noted a Paskapoo Formation formation-water sample with a Cl concentration of 16 953 mg/L. The Davis et al. (1998a) model may therefore be applicable to the Paskapoo Formation. In order to generate a Cl/Br ratio of approximately 400, however, the Davis et al. (1998a) model increases the Cl concentration by approximately 60 mg/L. It therefore appears unlikely that mixing of water is responsible for the observed Cl/Br ratio and Cl concentration.

Seaman et al. (1996) reported that the retardation of Br was increased, in column experiments using coarse sediments, by the presence of bivalent cations in solution, and that retardation increased as the concentration of Br decreased. A selective removal of Br over Cl will result in an increase in the Cl/Br ratio. The water type for sample 29 (Ca-Na-Mg-HCO_3) indicates that calcium is the dominant cation in solution. Therefore, a bivalent cation is present. The concentration of Br in solution is <0.013 mg/L; therefore, low concentrations of Br exist. The results of Seaman et al. (1996), however, were observed at pH values of between 6 and 4.4. The observed pH value during the collection of sample 29 was 7.2. Boggs and Adams (1992) documented a loss of Br from solution at a pH of 4.7, but no loss at near-neutral pH. Although retardation is a mechanism that could explain the observed Cl/Br value for sample 29, it cannot be advanced as the only one.

The apparent linear trend in the plot of Cl/Br ratio vs. chloride concentration (Figure 23) does not have any obvious explanation. Some of the relationships between points can be linked to factors such as depth, and location along the groundwater flow path.

Samples 22 and 23 have similar Cl/Br ratio values of 126.5 and 134.4, respectively. Sample 22, however, has a higher Cl concentration. This sample was collected from a well completed to a depth of 132.6 m, whereas sample 23 was collected from a well completed to a depth of 42.1 m. According to the distribution of hydraulic heads in the Scollard-Paskapoo aquifer (Bachu and Michael, 2002), sample 22 is downgradient of sample 23. According to geochemical convention, under closed-system conditions, and assuming sample locations penetrate aquifers that are part of the same flow system, the upgradient sample would likely have a greater concentration of Cl than the downgradient sample. The similar water types and Cl/Br ratios suggest that the water within these aquifers was derived from a similar source. The lower TDS value of sample 23, however, indicates that it has potentially undergone a greater amount of dilution than sample 22. The Cl/Br values are indicative of shallow groundwater or atmospheric precipitation. The most likely explanation for the difference in the observed Cl concentrations is the greater depth of sample 22, compared to sample 23.

Samples 42, 45 and 46 are located within the same general area, samples 45 and 46 having been collected from dewatering wells. Based on field observations, water types and TDS, these wells are likely located close to the recharge area for the aquifers penetrated by them. Using similar criteria as above, it is inferred that sample 42 is farther along the groundwater-flow path than samples 45 and 46. Therefore, Cl concentrations are likely to be higher in sample 42 than in samples 45 and 46. The Br concentration in the samples was below detection limit. It is therefore difficult to draw any firm conclusions regarding the differences between the estimated Cl/Br ratios. The values are similar, however, and, as mentioned previously, are within the reported ranges for groundwater and atmospheric precipitation. As was also previously mentioned, a link between Cl and Br concentrations in the coal may also be responsible for the observed ratios.

The observed Cl/Br ratios and Cl concentrations in samples from the Paskapoo-Scollard Formation are similar to ratios of samples from the Horseshoe Canyon Formation (Figure 24) Belly River Group (Figure 25). This implies that similar processes are responsible for the observed Cl/Br and chloride concentrations in these various aquifers.

3.5.5 Preliminary Interpretations - Horseshoe Canyon Formation

The calculated and estimated Cl/Br ratios for water samples from the coal, mixed coal-sandstone and sandstone aquifer fall within the range of values observed for shallow groundwater and atmospheric precipitation. This suggests that the water within these aquifers is derived from a mixture of meteoric water and connate formation water that has not undergone any interaction with evaporite minerals.

Although speculative, the possible explanations proposed for the Paskapoo-Scollard Formation water sample Cl/Br ratios that exceed and those that fall below the expected ratios for shallow groundwater and atmospheric precipitation may apply to Horseshoe Canyon Formation water samples that fall below or exceed these values.

The Cl/Br ratios that fall below the expected results could, as mentioned above, be caused by the interaction of the water with Br associated with organic matter, in this case coal. However, no supporting evidence regarding the Cl and Br concentrations of Horseshoe Canyon coals has been located to substantiate the possible effect of water-coal interaction on the Cl/Br ratio.

The Cl/Br ratios that exceed the expected Cl/Br ratios for groundwater and atmospheric precipitation could be derived through the interaction of brine with original precipitation-derived water. The mixing curve derived by Davis et al. (1998a) can explain the observed Cl/Br ratio and the chloride concentration of sample 28, but not those of sample 25. Dissolution of natural salt can also explain the observed Cl/Br ratio and chloride concentration of sample 28 (Whittemore, 1993), but once again, not the observed values for sample 25. It should be noted however, that the Br concentration in sample 25 was below the analytical detection limit, and as such the Cl/Br ratio is likely higher than presented.

The other possible means of increasing the Cl/Br ratio is through the relative increase of Cl over Br through the selective retention of Br. Seaman et al. (1996) observed that an increase of retention of Br was correlated to the presence of bivalent cations in solution and that retention was increased as the concentration of Br decreased. Boggs and Adams (1992) noted that increased retention of Br occurred at acidic pH values. The dominant cation in solution in samples 25 and 28 is sodium, a univalent cation, and the pH values are near neutral. It therefore appears unlikely that bromide retention is responsible for the observed increases in Cl/Br ratios.

A linear or curvilinear trend appears to exist between Cl/Br ratios and Cl concentration, with an increase in the Cl/Br ratio corresponding to an increase in Cl concentration (Figure 24). However, no obvious link appears to exist to explain the trend. Neither the Cl/Br ratios nor the Cl concentrations appear to be directly linked to well depth, well completion interval elevation or surface elevation. Groundwater flow in the Horseshoe Canyon Formation is toward the northeast (Bachu and Michael, 2002) with a component of flow toward the southwest. No obvious trend in Cl/Br ratios or Cl concentrations appear to coincide with the water well locations along inferred groundwater-flow paths.

There may be a geographic trend in the data. Samples 19, 20 and 21 form a loose cluster of locations to the northeast of Calgary (Figure 17). These three water samples have Cl/Br ratios of 109, 119 (estimated) and 150 respectively. Chloride concentrations are 23.0, 3.80 and 111 mg/L, respectively. The similar Cl/Br ratios and variable Cl concentrations indicate the possibility that water of similar origin or water that has undergone similar processes is present within the aquifers these water wells are completed in. The remainder of the samples is located to the southeast and northwest of Edmonton (Figure 17). The majority of these samples have Cl/Br ratios less than 100 over a wide range of Cl concentration values. A similar water source, or a similar geochemical process may be responsible for the estimated and calculated Cl/Br ratios.

The observed Cl/Br ratios and Cl concentration values from the Horseshoe Canyon Formation samples are similar to ratios and values determined for samples from the Paskapoo-Scollard Formation (Figure 23) and from the Belly River Group (Figure 25). This implies that similar processes are responsible for the observed Cl/Br and chloride concentrations in these various aquifers.

3.5.6 Preliminary Interpretations - Belly River Group

The calculated and estimated Cl/Br ratios for water samples from the coal, mixed coal-sandstone and sandstone aquifer fall within the range of values observed for shallow groundwater and atmospheric precipitation. This suggests that the water within these aquifers is derived from a mixture of meteoric water and connate formation water that has not undergone any interaction with evaporite minerals.

Although speculative, the possible explanations proposed for the Paskapoo-Scollard Formation and Horseshoe Canyon Formation water sample Cl/Br ratios that exceed and those that fall below the expected shallow groundwater and atmospheric Cl/Br ratio values may apply to Belly River Group water samples that fall below or exceed these values.

The Cl/Br ratios (samples 5, 15, 26, 35) that fall below the expected results could, as mentioned above, be caused by the interaction of the water with Br associated with organic matter, in this case coal. However, no supporting evidence regarding the Cl and Br concentrations of Belly River Group coals has been located to substantiate the possible effect of water-coal interaction on the Cl/Br ratio. It should be noted that sample 35 has a Br concentration below the analytical detection limit and as such, the Cl/Br ratio for this sample will be higher than the estimated value.

The Cl/Br ratios (samples 16, 39) that exceed the expected Cl/Br ratios for groundwater and atmospheric precipitation do not appear to be derived through the interaction of brine with original precipitation-derived water as described by the mixing curve determined by Davis et al. (1998a). Dissolution of natural salt may explain the observed Cl/Br ratios and Cl concentrations of samples 16 and 39 (Whittemore, 1993). It should be noted that sample 39 has a Br concentration below the analytical detection limit and as such, the Cl/Br ratio for this sample will be higher than the estimated value.

The other possible means of increasing the Cl/Br ratio is through the relative increase of Cl over Br through the selective retention of Br. Seaman et al. (1996) observed that an increase of retention of Br was correlated to the presence of bivalent cations in solution and that retention was increased as the concentration of Br decreased. Boggs and Adams (1992) noted that increased retention of Br occurred at acidic pH values. The dominant cation in solution in sample 16 is a divalent cation, but in sample 39 it is sodium, a univalent cation. The pH values are near neutral to basic respectively. It therefore appears unlikely that Br retention is responsible for the observed increases in Cl/Br ratios.

Regional groundwater flow in the Belly River Group is toward the north and northeast in the areas in which the sample locations are situated. Well depths vary between 15 and 193 m. Surface elevations vary between 602 and 1227 m asl. However, there do not appear to be any obvious reasons for the weakly linear trend in Cl/Br ratios and Cl concentrations. The number of sample locations in this study is likely insufficient to resolve patterns in the data in terms of well depth, geographic location, elevation or position along groundwater flow paths.

The observed Cl/Br ratios and Cl concentration values from the Belly River Group samples are similar to ratios and values determined for samples from the Paskapoo-Scollard Formation (Figure 23) and from the Horseshoe Canyon Formation (Figure 24). This implies that similar processes are responsible for the observed Cl/Br and Cl concentrations in these various aquifers.

There are a number of similarities in Cl/Br ratios between water samples collected during this study and those water samples collected by Connolly et al. (1990a) and Hitchon et al. (1971) from the Belly River Group (Figure 25). A similar water source, or a similar geochemical process may be responsible for the estimated and calculated Cl/Br ratios and the values determined from the work of Connolly et al. (1990a) and Hitchon et al. (1971). The Connolly et al. (1990a) and Hitchon et al. (1971) sample locations are close to the cluster of samples surrounding Edmonton (Figure 21).

There appear to be some similarities and some significant differences between the values of the Cl/Br ratios and Cl concentrations of the samples collected during this study and the work of others for the Milk River Formation. Hendry and Schwartz (1988) and Fabryka-Martin et al. (1991) collected water samples from the Milk River Formation of southern Alberta. This formation conformably underlies the Pakowki Formation and conformably overlies the Colorado Group. Like the Belly River Group, the Milk River Formation is part of the upper Cretaceous System. The samples located in southern Alberta are different from the results presented by Fabryka-Martin et al. (1991). Samples collected from the Belly River Group farther north as well as the samples collected by Connolly et al. (1990a) and Hitchon et al. (1971) show similarities to the results of Fabryka-Martin et al. (1991). For the Milk River Formation, Fabryka-Martin et al. (1991) stated that similar Cl/Br ratio values regardless of Cl concentrations in the Milk River Formation, suggests that a single subsurface source of these ions is likely and that the favoured hypothesis is that altered original seawater diffused from low-permeability units within the formation as the primary salt source. Hendry and Schwartz (1988) suggested, however, that aquitard diffusion controls Cl concentrations in the Milk River Formation. The similarities in the results from this study and from the results of the other researchers listed may indicate that similar processes are responsible for the observed Cl/Br and Cl concentrations.

3.6 Parameter-Specific Observations

The previous sections discussed the overall chemical characteristics of the various Tertiary–Upper Cretaceous coal-bearing formations in the Alberta Basin. This section provides a summary of each element or compound determined during this study. A description of the characteristics of each element is presented in Appendix B.

3.6.1 Paskapoo-Scollard Formation: Calcium

The mean concentration of Ca in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers is 45.2 mg/L, with a standard deviation of 45.9 mg/L (N=6). For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Ca concentration of 5.1 mg/L. The complete chemistry dataset is found in Appendix A, (Table 183).

The Canadian environmental water-quality guidelines for livestock purposes specify that Ca concentrations in water should be less than 1000 mg/L. The observed Ca concentrations do not exceed this value.

The summary statistics for water samples collected during this study are presented in Table 1. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 1. Paskapoo-Scollard Formation: Calcium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) – this study	45.2	45.9	6	96.3	3.6
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	37.0	32.7	640	198	0.8
U.S.A. – Powder River Basin[c] (Tertiary)	32.1	14.9	47	69	5.9
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	16.1	2.9	3	18.9	13.2
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	63.4	37.6	6	118.7	6.5
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	33.4	29.4	13	100	2.5
Coal samples (Scollard Formation)					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	12872	845.6	4	14100	12270
Ardley Coal Zone[f] – multiple locations by PES					
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.2 Paskapoo-Scollard Formation – Magnesium

The mean concentration of Mg in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples 10.4 mg/L, with a standard deviation of 11.0 mg/L (N=6). For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Mg concentration of 1.0 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

There are no Canadian environmental water quality guidelines for magnesium in drinking water, for the protection of freshwater aquatic life or for agricultural uses.

The summary statistics for water samples collected during this study are presented in Table 2. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 2. Paskapoo-Scollard Formation: Magnesium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min.(mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	10.4	11.0	6	22.1	0.3
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	16.0	18.0	639	192	0.1
U.S.A. – Powder River Basin[c] (Tertiary)	16.1	8.1	47	46	1.6
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	6.0		2	7.8	4.3
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	16.3	16.3	6	39	2.9
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	12.1	10.2	13	34	1.1
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	1668	950	4	3050	903
Ardley Coal Zone[f] – multiple locations by PES	1043	361	4	1542	730
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.3 Paskapoo-Scollard Formation – Sodium

The mean concentration of Na in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers is 216.7 mg/L, with a standard deviation of 196.7 mg/L (N=6). For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Na concentration of 339 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental water-quality guideline aesthetic objectives specify that Na concentrations in water for domestic water use should be less than or equal to 200 mg/L. Three of the six water samples (samples 22, 23, 42) have Na concentrations that exceed the aesthetic objective.

The summary statistics for water samples collected during this study are presented in Table 3. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 3. Paskapoo-Scollard Formation: Sodium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	216.7	196.7	6	503	42.7
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	181	454	640	10932	0.2
U.S.A. – Powder River Basin[c] (Tertiary)	305.3	175.5	47	800	110
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	2240	378.2	3	2673	1976
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	5339	841.8	6	5939	3674
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	1503	795.8	13	3100	570
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	1947	1258	4	3180	228
Ardley Coal Zone[f] – multiple locations by PES	2630	1460	3	3709	969
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.4 Paskapoo-Scollard Formation – Potassium

The mean concentration of K in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers is 2.1 mg/L, with a standard deviation of 1.2 mg/L (N=6). For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has a K concentration of 1.7 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

There are no Canadian environmental water quality guidelines for K concentrations for domestic use, for the protection of freshwater aquatic life or for agricultural uses.

The summary statistics for water samples collected during this study are presented in Table 4. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 4. Paskapoo-Scollard Formation: Potassium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	2.1	1.2	6	3.8	0.8
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	8.4	3.1	47	18	3.8
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	3.5	1.4	13	6	2
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	723	520	4	1460	352
Ardley Coal Zone[f] – multiple locations by PES	511	234	4	756	266
Ardley Coal Zone[g] – one location	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.5 Paskapoo-Scollard Formation – Iron

Iron concentrations from mixed coal-sandstone aquifer water samples from within the Paskapoo-Scollard Formation are almost all below the analytical detection limit of 0.01 mg/L. One well (sample 23) has a measured concentration of iron of 0.04 mg/L. For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has an iron concentration of 0.05 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The Canadian environmental water-quality guidelines for domestic water use specify Fe concentrations less than or equal to 0.3 mg/L as an aesthetic objective. A maximum concentration of 0.3 mg/L Fe has been established for the protection of freshwater aquatic life. A maximum concentration of 5 mg/L Fe has been established for use of water for irrigation purposes. None of the samples collected during this study exceed these guideline concentration values.

The summary statistics for water samples collected during this study are presented in Table 5. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 5. Paskapoo-Scollard Formation: Iron.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.04	<0.01
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.78	0.94	47	4.9	0.2
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.447	0.447	13	1.50	.050
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**St. Dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	4187	998	4	5070	2760
Ardley Coal Zone[f] – multiple locations by PES	4553	810	4	5250	3418
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.6 Paskapoo-Scollard Formation – Manganese

The mean concentration of Mn in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers is 0.101 mg/L, with a standard deviation of 0.171 mg/L (N=6). For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Mn concentration of <0.005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental guidelines for domestic water use suggest that Mn concentrations should be less than or equal to the aesthetic objective of 0.05 mg/L. A maximum concentration of 0.2 mg/L Mn has been established for use of water for irrigation purposes. Three of the samples (samples 29, 45, 46) exceed the aesthetic objective concentration. One of the samples (sample 45) exceeds the recommended maximum concentration value for use of water for irrigation purposes.

The summary statistics for water samples collected during this study are presented in Table 6. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 6. Paskapoo-Scollard Formation: Manganese.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	0.101*	0.171*	6	0.376	<0.005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.091*	0.26*	21	1.21	<0.001
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.032	0.026	47	0.101	0.002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.097	0.046	13	0.200	0.040
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	106.1	43.4	4	144	56.8
Ardley Coal Zone[f] – multiple locations by PES	111.9	34.8	3	151.6	86.8
Ardley Coal Zone[g] – one location	44.5	11.6	8	68	35
Ardley Coal Zone[h] – one location	92.5	133.3	82	1215	16.6
Ardley Coal Zone[i] – multiple locations	-	-	-	249	16
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.7 Paskapoo-Scollard Formation – Chloride

Chloride concentrations in water samples from Paskapoo-Scollard mixed coal-sandstone aquifers were determined by an automated ferricyanide method (FCM) and by neutron activation analysis (NAA). For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has chloride concentrations of 4.6 mg/L (FCM) and 3.7 mg/L (NAA). The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental water-quality guidelines for domestic water use suggest Cl concentrations should be less than or equal to the aesthetic objective of 250 mg/L. A maximum concentration of between 100 and 700 mg/L Cl has been established for use of water for irrigation purposes. The Cl concentration of sample 22 exceeds the aesthetic objective concentration and falls within the maximum concentration range values for use of water for irrigation purposes.

The summary statistics for water samples collected during this study are presented in Table 7. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 7. Paskapoo-Scollard Formation: Chloride.

Water samples

Location	Mean (mg/L)	Std. dev (mg/L)	N	Max. (mg/L)	Min. (mg/L)
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study – Ferricyanide Method	52.8*	195*	6	425	<0.5
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study – NAA	67.6	153	6	379	0.4
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	37.0	702	583	16953	0.5
U.S.A. – Powder River Basin[c] (Tertiary)	13.2	12.1	47	64	5.2
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	204.7	343	3	600	4
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	1187	734	6	2499	668
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	1828	1149	13	4200	450

Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	4	-	<200
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	21.5	3.25	8	27	18
Ardley Coal Zone[h] – one location	77.7	41.0	82	231	35
Ardley Coal Zone[i] – multiple locations	-	-	-	212	12
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.8 Paskapoo-Scollard Formation – Sulphate

The mean concentration of SO_4 in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers is 6.33 mg/L, with a standard deviation of 6.62 mg/L (N=6). For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has a SO_4 concentration of 6.7 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective of ≤500 mg/L SO_4 for domestic water use has been established. A maximum concentration of 1000 mg/L SO_4 has been established for use of water for livestock purposes. None of the samples exceed the guideline values.

The summary statistics for water samples collected during this study are presented in Table 8. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 8. Paskapoo-Scollard Formation: Sulphate.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	6.33	6.62	6	12.3	0.3
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	95.9	169	640	2075	0.7
U.S.A. – Powder River Basin[c] (Tertiary)	2.41	3.63	47	17	0.01
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	56.2	69.2	3	135.5	8.32
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	51.3	66.5	6	166.8	0
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	<0.5
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.9 Paskapoo-Scollard Formation – Bicarbonate

The mean concentration of HCO_3 in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers is 591.2 mg/L, with a standard deviation of 160.9 mg/L (N=6). For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has a HCO_3 concentration of 912 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for bicarbonate.

The summary statistics for water samples collected during this study are presented in Table 9. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 9. Paskapoo-Scollard Formation: Bicarbonate.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) This study	591.2	160.9	6	854	408
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	471	234	640	4000	54
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	5737	759	3	6612	5250
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	11833	2961	6	14701	6083
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	883	125	13	1120	670
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.10 Paskapoo-Scollard Formation – Total Dissolved Solids (TDS)

The mean value of TDS in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers is 670.5 mg/L, with a standard deviation of 342.5 mg/L (N=6). A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a TDS of 815 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental water-quality guidelines for domestic use suggest TDS values less than or equal to 500 mg/L as an aesthetic objective. Three of the six samples (samples 22, 23, 42) exceed this objective. A recommended range of TDS values has been established for water for irrigation purposes. The maximum recommended value is between 500 mg/L and 3500 mg/L. Three of the six samples (samples 22, 23, 42) fall within this range. A recommended maximum TDS value of 3000 mg/L has been established for water to be used for livestock purposes. None of the TDS values determined during this study exceed the guideline value for water to be used for livestock purposes.

The summary statistics for water samples collected during this study are presented in Table 10. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 10. Paskapoo-Scollard Formation: Total Dissolved Solids.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	591.2	160.9	6	854	408
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	605	1154	640	28409	51
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	5737	759	3	6612	5250
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	11833	2961	6	14701	6083
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	883	125	13	1120	670
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					

3.6.11 Paskapoo-Scollard Formation – Turbidity

The mean value of turbidity in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers is 1.38 NTU, with a standard deviation of 1.94 NTU (N=6). For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has a turbidity value of 0.1 NTU. The complete chemistry dataset is found in Appendix A, Table 183.

Both an aesthetic objective of turbidity ≤5 NTU and a maximum acceptable value of 1 NTU have been established for water for domestic use. Sample 29 exceeds the maximum acceptable value. Sample 42 exceeds both values.

The summary statistics for water samples collected during this study are presented in Table 11. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 11. Paskapoo-Scollard Formation: Turbidity.

Water samples					
Location	**Mean (NTU)**	**Std. dev (NTU)**	**N**	**Max. (NTU)**	**Min. (NTU)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	1.38	1.94	6	5.3	0.2
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.12 Paskapoo-Scollard Formation – Sodium Adsorption Ratio (SAR)

Soils with high concentration of Na^+ in solution generally have poor physical structures (Appelo and Postma, 1994, p. 191). Sodium's large ionic size, single electrical charge and hydration status tends to cause physical separation of soil particles (Warrence et al., 2002). When this separation occurs, repulsive forces begin to dominate and the soil disperses potentially leading to plugging of soil pores (Warrence et al., 2002). Repeated wetting and drying and associated dispersion can lead to the formation of cement-like soil with little or not structure (Warrence et al., 2002). Permeability can be greatly reduced and heavy machinery may not be supported (Appelo and Postma, 1994, p. 191). In order to predict the effects of irrigation water quality on soil properties, the exchangeable sodium ratio (ESR) is calculated.

(1) $ESR = \beta_{Na} / 1- \beta_{Na}$ where β_{Na} is the fraction of exchangeable Na^+

This ESR is related to the activity of Na^+ over the square root of the sum of the Ca^{2+} and Mg^{2+} activities and becomes:

(2) $ESR = 0.5 \times 1000/\sqrt{1000} \times m_{Na+}/(\sqrt{}m_{Ca2+} + m_{Mg2+})$ where m_X is activity in mmol/L

The ratio of $m_{Na+}/(\sqrt{}m_{Ca2+} + m_{Mg2+})$ is given a specific name, the sodium adsorption ratio or SAR.

Equation 2 upon simplification then becomes:

(3) $ESR = 0.0158 \times SAR$

The critical ESR is equal to 0.15 (Appelo and Postma, 1994, p. 193) and corresponds to an SAR value of 10. Alberta Agriculture Food and Rural Development specifies that irrigation water with an SAR value greater than 9 may be hazardous for irrigation purposes (Hecker, 2002).

SAR is not an absolute predictor of the suitability of water for irrigation, and will depend on soil conditions since the ratio of Na^+ over the square root of $Ca^{2+} + Mg^{2+}$ may change as a result of reactions in the soil, on the concentrating effect of evapotranspiration and on the water composition (Appelo and Postma, 1994, p. 193).

The mean value of SAR in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers is 25.3 $(mmol/L)^{0.5}$, with a standard deviation of 27.2 $(mmol/L)^{0.5}$ (N=6). For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has a SAR of 36 $(mmol/L)^{0.5}$. The complete chemistry dataset is found in Appendix A, Table 183.

Three of the samples (samples 22, 23, 42) have SAR values that exceed the Alberta Agriculture Food and Rural Development irrigation water guideline of 9 $(mmol/L)^{0.5}$.

The summary statistics for water samples collected during this study are presented in Table 12. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 12. Paskapoo-Scollard Formation: Sodium Adsorption Ratio.

Water samples					
Location	Mean (mmol/L)$^{0.5}$	Std. dev (mmol/L)$^{0.5}$	N	Max. (mmol/ L)$^{0.5}$	Min. (mmol/ L)$^{0.5}$
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	25.3	27.2	6	60	1.16
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	14.4	19	639	207	0.01
U.S.A. – Powder River Basin[c] (Tertiary)	11.7	7.3	47	32	5.7
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	131	21	3	144	107
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	149	45	6	199	111
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	64	18	13	108	43
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.13 Paskapoo-Scollard Formation – Silicon

Silicon concentration was determined by two methods, ICP-MS and APHA ICP method 3120B. The mean concentrations of Si in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers are 7.49 mg/L, with a standard deviation of 3.93 mg/L (N=6) and a mean of 7.05 mg/L with a standard deviation of 3.56 mg/L (N=6) for the two methods listed above respectively. For comparison purposes, a well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Si concentration of 7.11 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Si.

The summary statistics for water samples collected during this study are presented in Table 13. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 13. Paskapoo-Scollard Formation: Silicon.

Water samples					
Location	Mean (mg/L)	Std. dev (mg/L)	N	Max. (mg/L)	Min. (mg/L)
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study – ICP-MS	7.49	3.93	6	14.4	4.45
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study – ICP	7.05	3.56	6	13.2	4.2
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)					
U.S.A. – Powder River Basin[c] (Tertiary)	4.76	0.62	47	7.1	3.7
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Data sources for Table 13.:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.14 Paskapoo-Scollard Formation – Mercury

Mercury concentrations from mixed coal-sandstone aquifer water samples from within the Paskapoo-Scollard Formation are all below the analytical detection limit of 0.0001 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer also has a Hg concentration of <0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been established for Hg concentrations for domestic purposes as well as for the protection of freshwater aquatic life and for the use of water for livestock purposes. A maximum acceptable concentration of 0.001 mg/L has been established for domestic water use. A maximum concentration of 0.0001 mg/L has been established for the protection of freshwater aquatic life. A maximum concentration of 0.003 mg/L has been established for the use of water for livestock purposes.

The summary statistics for water samples collected during this study are presented in Table 14. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 14. Paskapoo-Scollard Formation: Mercury.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	0.000913	<0.000002
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.00025	<0.000005
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	0.082	0.16	8	0.46	0.01
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.15 Paskapoo-Scollard Formation – Aluminum

Only one of the water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers (sample 22) has an Al concentration above the detection limit of 0.005 mg/L. The concentration at this location is 0.013 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has an Al concentration of <0.005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An interim recommended aluminum concentration of 0.1 mg/L has been recommended for domestic water use. A maximum concentration of between 0.005 and 0.100 mg/L has been established for the protection of freshwater aquatic life. A maximum concentration of 5.0 mg/L has been established for the use of water for irrigation and livestock purposes. The Al concentration of sample 22 falls within the maximum concentration range for the protection of freshwater aquatic life.

The summary statistics for water samples collected during this study are presented in Table 15. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 15. Paskapoo-Scollard Formation: Aluminum.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.013	<0.005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.05
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	17800	3243	4	20700	14700
Ardley Coal Zone[f] – multiple locations by PES	20247	6402	4	29050	15420
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.16 Paskapoo-Scollard Formation – Antimony

None of the water samples from the Paskapoo-Scollard Formation mixed coal-sandstone aquifers has Sb concentrations above the detection limit of 0.0002 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has an Sb concentration of 0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been established for Sb concentrations for domestic water use. An interim maximum acceptable concentration of 0.006 mg/L has been recommended for this purpose. All of the water samples analyzed have concentrations that fall below this guideline value.

The summary statistics for water samples collected during this study are presented in Table 16. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 16. Paskapoo-Scollard Formation: Antimony.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	-	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	2	0.61	0.29
Ardley Coal Zone[f] – multiple locations by PES					
Ardley Coal Zone[g] – one location	0.764	1.03	8	3.05	0.0
Ardley Coal Zone[h] – one location	0.743	0.858	82	3.39	<0.10
Ardley Coal Zone[i] – multiple locations	-	-	-	2.5	0.1
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.17 Paskapoo-Scollard Formation – Arsenic

Four of the six water samples from the Paskapoo-Scollard Formation mixed coal-sandstone aquifers have As concentrations above the analytical detection limit of 0.0002 mg/L. The mean concentration is 0.0004 mg/L with a standard deviation of 0.0010 mg/L (N=6). A well completed in a Paskapoo-Scollard Formation sandstone aquifer has an As concentration of 0.0011 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.025 mg/L has been established for domestic water use. A maximum concentration of 0.005 mg/L has been established for the protection of freshwater aquatic life. Maximum concentrations of 0.100 mg/L and 0.025 mg/L have been established for the use of water for irrigation and livestock uses respectively. All of the water samples analyzed have concentrations that fall below these guideline values.

The summary statistics for water samples collected during this study are presented in Table 17. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 17. Paskapoo-Scollard Formation: Arsenic.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	0.0004*	0.0010*	6	0.0022	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	0.0249	<0.0004
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.0004*	0.0004*	47	0.0026	<0.0002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.0183	0.0302	13	0.110	0.001
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	3.93	5.20	4	11.65	0.62
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	1.44	1.62	8	5.4	0.6
Ardley Coal Zone[h] – one location	5.12	12.9	82	116	1.53
Ardley Coal Zone[i] – multiple locations	-	-	-	21	1.5
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.18 Paskapoo-Scollard Formation – Barium

The mean concentration of Ba in mixed coal-sandstone aquifer water samples from the Paskapoo-Scollard Formation is 0.176 mg/L with a standard deviation of 0.097 mg/L (N=6). A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Ba concentration of 0.105 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 1.0 mg/L has been established for domestic water use. All of the water samples analyzed have concentrations that fall below these guideline values.

The summary statistics for water samples collected during this study are presented in Table 18. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 18. Paskapoo-Scollard Formation: Barium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	0.176	0.097	6	0.299	0.065
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.149	0.169	21	0.761	0.007
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.617	0.300	47	1.60	0.14
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal Samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	518	171	4	623	264
Ardley Coal Zone[f] – multiple locations by PES	533	84	4	597	415
Ardley Coal Zone[g] – one location	761	447	8	1600	470
Ardley Coal Zone[h] – one location	714	218	82	1269	288
Ardley Coal Zone[i] – multiple locations	-	-	-	261	987
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.19 Paskapoo-Scollard Formation – Beryllium

None of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples contain Be above the analytical detection limit of 0.0001 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Be concentration < 0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.100 mg/L has been established for the use of water for irrigation and livestock purposes. All of the water samples analyzed have concentrations that fall below these guideline values.

The summary statistics for water samples collected during this study are presented in Table 19. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 19. Paskapoo-Scollard Formation: Beryllium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	0.767	0.473	3	1.3	0.4
Ardley Coal Zone[g] – one location	1.65	2.36	8	7.3	0.5
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.20 Paskapoo-Scollard Formation – Bismuth

None of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples contain Bi concentrations above the analytical detection limit of 0.0005 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Bi concentration < 0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have not been developed for Bi.

The summary statistics for water samples collected during this study are presented in Table 20. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 20. Paskapoo-Scollard Formation: Bismuth.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	-	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.032	<0.020
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.21 Paskapoo-Scollard Formation – Boron

The mean concentration of B in mixed coal-sandstone aquifer water samples from the Paskapoo-Scollard Formation is 0.195 mg/L with a standard deviation of 0.175 mg/L (N=6). A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a B concentration of 0.271 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An interim maximum acceptable concentration of 5 mg/L has been established for domestic water use. The range of maximum concentrations for water to be used for irrigation purposes is between 0.500 and 6 mg/L. The maximum concentration for water to be used for livestock purposes is 5 mg/L. None of the water samples exceeds the guideline values.

The summary statistics for water samples collected during this study are presented in Table 21. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 21. Paskapoo-Scollard Formation: Boron.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) This study	0.195	0.175	6	0.457	0.041
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.217	<0.100
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	1129	256	3	1413	917
Ardley Coal Zone[g] – one location	73.1	12.4	8	90	51
Ardley Coal Zone[h] – one location	27.1	11.8	82	63	7
Ardley Coal Zone[i] – multiple locations	-	-	-	50	14
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.22 Paskapoo-Scollard Formation – Cadmium

Only one of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples (sample 29) contains Cd above the analytical detection limit of 0.00001 mg/L. The value determined in this water sample is 0.00008 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Cd concentration of <0.00001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.005 mg/L has been established for domestic water use. A maximum concentration value of 0.000017 mg/L has been established for the protection of freshwater aquatic life. The maximum concentration for water to be used for irrigation purposes is 0.0051 mg/L. The maximum concentration for water to be used for livestock purposes is 0.080 mg/L. One of the water samples (sample 29) exceeds the guideline values for the protection of freshwater aquatic life.

The summary statistics for water samples collected during this study are presented in Table 22. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 22. Paskapoo-Scollard Formation: Cadmium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.00008	<0.00001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	0.00011	<0.00005
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.0009*	0.0002*	13	0.001	<0.001
Table 22. Paskapoo-Scollard Formation: Cadmium, continued					
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	2	7.9	7
Ardley Coal Zone[g] – one location	0.375	0.495	8	1.60	0.200
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992).					

3.6.23 Paskapoo-Scollard Formation – Chromium

The mean Cr concentration in mixed coal-sandstone aquifer water samples from the Paskapoo-Scollard Formation is 0.0047 mg/L with a standard deviation of 0.0043 mg/L (N=6). A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Cr concentration of 0.0059 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.050 mg/L has been established for domestic water use. A maximum concentration value of 0.0089 mg/L has been established for the protection of freshwater aquatic life. The maximum concentration for water to be used for irrigation purposes is 0.0049 mg/L. The maximum concentration for water to be used for livestock purposes is 0.050 mg/L. One of the water samples (sample 22) exceeds the guideline values for the protection of freshwater aquatic life as well as the maximum concentration for water to be used for irrigation purposes.

The summary statistics for water samples collected during this study are presented in Table 23. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 23. Paskapoo-Scollard Formation: Chromium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	0.0047	0.0043	6	0.0133	0.0019
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	-	<0.001
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.0009*	0.0002*	13	0.001	<0.001
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	2	3.01	2.29
Ardley Coal Zone[f] – multiple locations by PES	8.12	5.40	4	16	4.4
Ardley Coal Zone[g] – one location	28.5	21.1	8	67	9
Ardley Coal Zone[h] – one location	13.8*	20.5*	82	107	<2.50
Ardley Coal Zone[i] – multiple locations	-	-	-	802	0.7
Data sources for Table 23.:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.24 Paskapoo-Scollard Formation – Cobalt

The majority of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water sample Co concentrations are below the analytical detection limit of <0.0001 mg/L (N=4). Two of the water samples (samples 22, 23) have Co concentrations of 0.0003 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Co concentration of 0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The maximum concentration for water to be used for irrigation purposes is 0.050 mg/L. The maximum concentration for water to be used for livestock purposes is 1.00 mg/L. None of the water samples exceed the guideline values.

The summary statistics for water samples collected during this study are presented in Table 24. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 24. Paskapoo-Scollard Formation: Cobalt.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.0003	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.0002	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	1.85	0.52	4	2.41	1.39
Ardley Coal Zone[f] – multiple locations by PES	-	-	1	16.2	-
Ardley Coal Zone[g] – one location	1.99	0.70	8	3.50	1.20
Ardley Coal Zone[h] – one location	2.80	2.99	82	23.4	0.54
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.25 Paskapoo-Scollard Formation – Copper

Only one of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water sample Cu concentrations is above the analytical detection limit of <0.001 mg/L. Sample 42 has a Cu concentration of 0.001 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Cu concentration <0.001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective concentration of ≤1.00 mg/L has been established for domestic water use. The range of maximum acceptable concentrations of Cu for the protection of freshwater aquatic life is between 0.002 and 0.004 mg/L. The range of maximum concentrations for water to be used for irrigation purposes is between 0.200 and 1.00 mg/L. The range of maximum concentrations for water to be used for livestock purposes is between 0.500 and 5.00 mg/L. None of the water samples exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 25. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 25. Paskapoo-Scollard Formation: Copper.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.001	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.009*	0.0042*	21	0.148	<0.002
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	5.36	4.26	47	28.6	1.5
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	7.1	2.89	4	9.7	4.4
Ardley Coal Zone[g] – one location	16.5	31.1	8	93	2
Ardley Coal Zone[h] – one location	24.7	14.2	82	68.9	6.2
Ardley Coal Zone[i] – multiple locations	-	-	-	23.2	0.7
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.26 Paskapoo-Scollard Formation – Lead

Only one of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water sample Pb concentrations is above the analytical detection limit of <0.0001 mg/L. Sample 23 has a Pb concentration of 0.0003 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Pb concentration <0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.010 mg/L has been established for domestic water use. The range of maximum acceptable concentrations of Pb for the protection of aquatic life is between 0.001 and 0.007 mg/L. The maximum Pb concentration for water to be used for irrigation purposes is 0.200 mg/L. The maximum Pb concentration for water to be used for livestock purposes is 0.100 mg/L. None of the water samples exceeds these guideline values.

The summary statistics for water samples collected during this study are presented in Table 26. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 26. Paskapoo-Scollard Formation: Lead.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.0003	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.00043*	0.00060*	21	0.0027	<0.00001
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.00043	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.00028*	0.00031*	13	0.100	<0.001
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	10.7	6.21	4	19.4	5.5
Ardley Coal Zone[g] – one location	22	42	8	125	2
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.27 Paskapoo-Scollard Formation – Lithium

The mean Li concentration in the mixed coal-sandstone aquifer water samples from the Paskapoo-Scollard Formation is 0.049 mg/L with a standard deviation of 0.03 mg/L (N=6). A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Li concentration of 0.044 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The maximum Li concentration for water to be used for irrigation purposes is 2.50 mg/L. None of the water sample Li concentrations exceeds this value.

The summary statistics for water samples collected during this study are presented in Table 27. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 27. Paskapoo-Scollard Formation: Lithium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	0.049	0.003	6	0.11	0.014
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.052	0.036	47	0.208	0.018
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	7	4.3	8	17	4
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.28 Paskapoo-Scollard Formation – Molybdenum

The majority of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples have Mo concentration below the analytical detection limit of 0.001 mg/L (N= 4). Two of the samples (samples 23, 42) have Mo concentrations of 0.008 and 0.003 mg/L respectively. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Mo concentration of 0.003 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The maximum acceptable concentration for the protection of freshwater aquatic life is 0.073 mg/L. The range of maximum Mo concentrations for water to be used for irrigation purposes is between 0.010 and 0.050 mg/L. The maximum Mo concentration for water to be used for livestock purposes is 0.500 mg/L. None of the water samples exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 28. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 28. Paskapoo-Scollard Formation: Molybdenum.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.008	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.0013*	0.0013*	21	0.0043	<0.00005
Paskapoo wells[b] (Tertiary)					
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	4.87	3.80	8	13	2
Ardley Coal Zone[h] – one location	1.25*	2.33*	82	9.22	<0.25
Ardley Coal Zone[i] – multiple locations	-	-	-	90	0.5
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.29 Paskapoo-Scollard Formation – Nickel

The majority of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples have Ni concentrations below the analytical detection limit of 0.0005 mg/L (N=5). Sample 23 has a Ni concentration of 0.0007 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Ni concentration <0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The range of maximum acceptable concentrations of Ni for the protection of freshwater aquatic life is between 0.025 and 0.150 mg/L. The maximum Ni concentration for water to be used for irrigation purposes is 0.200 mg/L. The maximum Ni concentration for water to be used for livestock purposes is 1.00 mg/L. None of the water samples exceeds these guideline values.

The summary statistics for water samples collected during this study are presented in Table 29. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 29. Paskapoo-Scollard Formation: Nickel.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.0007	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.00037*	0.00055*	21	0.0021	<0.0002
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.0065*	0.0068*	47	0.0354	<0.0005
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	8.3	1.85	3	9.7	6.2
Ardley Coal Zone[g] – one location	13.5	9.44	8	29	5
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	491	2.5
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.30 Paskapoo-Scollard Formation – Selenium

The majority of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples have Se concentrations below the analytical detection limit of 0.0002 mg/L (N=5). Sample 23 has a Se concentration of 0.0002 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Se concentration <0.0002 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.010 mg/L has been established for domestic water use. The maximum acceptable concentration for the protection of freshwater aquatic life is 0.001 mg/L. The range of maximum Se concentrations for water to be used for irrigation purposes is between 0.020 and 0.050 mg/L. The maximum Se concentration for water to be used for livestock purposes is 0.050 mg/L. None of the water samples exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 30. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 30. Paskapoo-Scollard Formation: Selenium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.0002	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	4	-	<2
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	2.25	4.37	8	13	0
Ardley Coal Zone[h] – one location	0.753*	2.59*	82	5.86	<0.59
Ardley Coal Zone[i] – multiple locations	-	-	-	5.4	0.7
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.31 Paskapoo-Scollard Formation – Silver

All of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples have Ag concentrations below the analytical detection limit of 0.0001 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer also has a Ag concentration <0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The maximum acceptable concentration for the protection of freshwater aquatic life is 0.0001 mg/L. None of the water samples exceeds this guideline value.

The summary statistics for water samples collected during this study are presented in Table 31. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 31. Paskapoo-Scollard Formation: Silver.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	1	0.8	-
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.32 Paskapoo-Scollard Formation – Strontium

The mean concentration of Sr within Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples is 0.503 mg/L with a standard deviation of 0.649 mg/L (N= 6). A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Sr concentration of 0.086 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have not been developed for Sr.

The summary statistics for water samples collected during this study are presented in Table 32. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 32. Paskapoo-Scollard Formation: Strontium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	0.503	0.649	6	1.69	0.05
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.692	0.412	47	1.9	0.1
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	2.13	1.95	13	7.20	0.27
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	4	-	<400
Ardley Coal Zone[f] – multiple locations by PES	121.4	40.0	4	145.7	62
Ardley Coal Zone[g] – one location	201.5	38.4	8	284	162
Ardley Coal Zone[h] – one location	146.9	58.2	82	380	64.7
Ardley Coal Zone[i] – multiple locations	-	-	-	380	66
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.33 Paskapoo-Scollard Formation – Thallium

None of the water samples collected from Paskapoo-Scollard Formation mixed coal-sandstone aquifers have Tl concentrations that exceed the analytical detection limit of 0.00005 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer also has a Tl concentration <0.00005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been developed for maximum Tl concentrations for the protection of freshwater aquatic organisms. The value is 0.0008 mg/L. None of the water sample Tl concentrations exceed this guideline value.

The summary statistics for water samples collected during this study are presented in Table 33. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 33. Paskapoo-Scollard Formation: Thallium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	-	<0.00005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.00034	<0.0002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.34 Paskapoo-Scollard Formation – Titanium

Three of the six water samples (samples 22, 23, 42) collected from Paskapoo-Scollard Formation mixed coal-sandstone aquifers have Ti concentrations that exceed the analytical detection limit of 0.0005 mg/L. A mean of 0.104 mg/L and a standard deviation of 0.176 mg/L (N= 6) were determined. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Ti concentration <0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have not been developed for Ti.

The summary statistics for water samples collected during this study are presented in Table 34. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta are presented for comparison purposes.

Table 34. Paskapoo-Scollard Formation: Titanium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	0.104*	0.176*	6	0.307	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.050
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	588	244	4	942	403
Ardley Coal Zone[f] – multiple locations by PES	637	243	4	1001	500
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.35 Paskapoo-Scollard Formation – Vanadium

One of the six water samples (sample 23) collected from Paskapoo-Scollard Formation mixed coal-sandstone aquifers has a V concentration that exceeds the analytical detection limit of 0.0001 mg/L. It has a concentration of 0.0014 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a V concentration <0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been developed for V concentrations in water for irrigation and livestock purposes. The maximum concentration for irrigation and livestock purposes is 0.100 mg/L. None of the observed V concentrations exceeds these guidelines.

The summary statistics for water samples collected during this study are presented in Table 35. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 35. Paskapoo-Scollard Formation: Vanadium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.0014	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.0002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	8.37	2.91	4	10.6	4.09
Ardley Coal Zone[f] – multiple locations by PES	10.3	3.65	4	15.2	6.5
Ardley Coal Zone[g] – one location	13.4	23.4	8	71	2
Ardley Coal Zone[h] – one location	21.4*	27.0*	82	140	<1.36
Ardley Coal Zone[i] – multiple locations	-	-	-	57	0.4
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.36 Paskapoo-Scollard Formation – Zinc

Four of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples (samples 23, 29, 45, 46) have Zn concentrations above the analytical detection limit of 0.001 mg/L. A mean of 0.004 mg/L and a standard deviation of 0.002 mg/L (N=6) were determined. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Zn concentration 0.002 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective concentration of ≤ 5.00 mg/L has been established for Zn concentrations in water for domestic use. A maximum concentration of 0.030 mg/L has been established for the protection of freshwater aquatic life. The range of maximum concentrations for use of water for irrigation purposes is between 1.00 and 5.00 mg/L. The maximum concentration for the use of water for livestock purposes is 50 mg/L. None of the observed Zn concentrations exceed these guidelines.

The summary statistics for water samples collected during this study are presented in Table 36. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 36. Paskapoo-Scollard Formation: Zinc.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	0.004*	0.002*	6	0.007	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.065	0.113	21	0.470	0.0007
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.0804	<0.001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.032*	0.063*	13	0.240	<0.005
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	15.6	5.65	4	22.9	9.2
Ardley Coal Zone[g] – one location	29.9	61.5	8	182	6
Ardley Coal Zone[h] – one location	-	-	82	182	<5.1
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.37 Paskapoo-Scollard Formation – Fluorine

Four of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples (samples 22, 23, 29 and 42) have fluorine concentrations above the analytical detection limit of 0.5 ppm. A mean of 1.5 ppm and a standard deviation of 1.4 ppm (N=6) were determined. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a fluorine concentration 2.0 ppm. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum allowable concentration of 1.5 mg/L has been established for fluoride concentrations in water for domestic use. The maximum recommended concentration of fluoride in water for use for irrigation purposes is 1.0 mg/L. The maximum recommended concentration of fluoride in water for use for livestock purposes is between 1.0 and 2.0 mg/L. Samples 22, 23, 42 and 44 may have observed F concentrations that exceed these guidelines.

The summary statistics for water samples collected during this study are presented in Table 37. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 37. Paskapoo-Scollard Formation: Fluorine.

Water samples					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	1.5*	1.4*	6	3.2	<0.5
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.92	0.32	47	1.7	0.42
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.38 Paskapoo-Scollard Formation – Bromine

Two of the six water samples (samples 22, 23) collected from Paskapoo-Scollard Formation mixed coal-sandstone aquifers have measurable Br concentrations. The measured values for these two samples are 2.82 and 0.17 mg/L respectively. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Br concentration 0.08 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Br.

The summary statistics for water samples collected during this study are presented in Table 38. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 38. Paskapoo-Scollard Formation: Bromine.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	2.82	<0.013
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.11*	0.18*	47	0.85	<0.02
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	6.98*	7.81*	4	16.2	<1
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	1.45	0.62	8	2.6	0.9
Ardley Coal Zone[h] – one location	420	402	82	1850	23
Ardley Coal Zone[i] – multiple locations	-	-	-	639	78
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.39 Paskapoo-Scollard Formation – Iodine

Three of the six water samples (samples 22, 23, 42) collected from Paskapoo-Scollard Formation mixed coal-sandstone aquifers have measurable I concentrations. The measured values for these samples are 0.82, 0.09 and 0.04 mg/L respectively. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has an I concentration 0.06 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for I.

The summary statistics for water samples collected during this study are presented in Table 39. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 39. Paskapoo-Scollard Formation: Iodine.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.82	<0.0048
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	4	-	<20
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.40 Paskapoo-Scollard Formation – Scandium

The mean Sc concentration in water samples collected from mixed coal-sandstone aquifers in the Paskapoo-Scollard Formation is 0.00006 mg/L with a standard deviation of 0.00003 mg/L (N = 6). A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Sc concentration 0.00004 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Sc.

The summary statistics for water samples collected during this study are presented in Table 40. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 40. Paskapoo-Scollard Formation: Scandium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	0.00006	0.00003	6	0.00011	0.00003
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.00120*	0.00079*	47	0.003	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	2.08	0.77	4	3.20	1.51
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	3.14	3.49	8	11.1	0.598
Ardley Coal Zone[h] – one location	3.70	3.19	82	16.0	0.610
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.41 Paskapoo-Scollard Formation – Rubidium

None of the Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples have measurable Rb concentrations. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Rb concentration <0.0045 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Rb.

The summary statistics for water samples collected during this study are presented in Table 41. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 41. Paskapoo-Scollard Formation: Rubidium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	-	<0.0052
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.0118	0.0061	47	0.0382	0.0041
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	-	-	8	5.7	0
Ardley Coal Zone[h] – one location	-	-	82	92.5	<3.78
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.42 Paskapoo-Scollard Formation – Gross Alpha and Gross Beta Radiation

One of the six Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples (sample 46) has measurable gross alpha radioactivity of 0.1 Bq/L. Three of the six Paskapoo-Scollard Formation coal aquifer water samples (samples 29, 45, 46) have measurable gross beta radioactivity of 0.1, 0.2 and 0.1 Bq/L respectively. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has gross alpha and gross beta radioactivity levels of <0.01 Bq/L and 0.1 Bq/L respectively. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for gross alpha and gross beta radioactivity levels in water.

The summary statistics for water samples collected during this study are presented in Table 42. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 42 Paskapoo-Scollard Formation Summary Table Gross Alpha and Gross Beta

Water samples – Gross alpha					
Location	**Mean (Bq/L)**	**St. Dev (Bq/L)**	**N**	**Max. (Bq/L)**	**Min. (Bq/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) This study	-	-	6	0.1	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[b] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[d] (Pennsylvanian)	-	-	-	-	-
Water samples –Gross beta					
Location	**Mean (Bq/L)**	**St. Dev (Bq/L)**	**N**	**Max. (Bq/L)**	**Min. (Bq/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) This study	0.086*	0.07*	6	0.2	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[b] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[d] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.43 Paskapoo-Scollard Formation – Thorium

Two of the six Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples (samples 42, 45) have measurable Th concentrations of 0.0002 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a Th concentration of less than 0.00015 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for total concentration of Th in water. A maximum acceptable level of radioactivity of 0.1 Bq/L has been established in water for domestic use. None of the radioactivity levels for Th is above this value.

The summary statistics for water samples collected during this study are presented in Table 43. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 43. Paskapoo-Scollard Formation: Thorium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.0002	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.020
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	3.60	1.72	4	6.17	2.55
Ardley Coal Zone[f] – multiple locations by PES	4.45	3.14	4	9	1.8
Ardley Coal Zone[g] – one location	7.94	10.2	8	29.2	0.6
Ardley Coal Zone[h] – one location	8.89	7.26	82	30.5	0.86
Ardley Coal Zone[i] – multiple locations	-	-	-	25	1
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					

3.6.44 Paskapoo-Scollard Formation – Uranium

One of the six Paskapoo-Scollard Formation mixed coal-sandstone aquifer water samples (sample 46) has a measurable U concentration of 0.001 mg/L. A well completed in a Paskapoo-Scollard Formation sandstone aquifer has a U concentration of less than 0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of uranium of 0.100 mg/L has been established for water for domestic purposes. A maximum concentration of 0.010 mg/L has been established for water used for irrigation purposes. A maximum concentration of 0.200 mg/L has been established for water used for livestock purposes. None of the observed U concentrations are above these guideline values. Maximum acceptable levels of radioactivity of 4 Bq/L for ^{234}U, ^{235}U and ^{238}U have been established for uranium in water for domestic use. None of the observed radioactivity levels exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 44. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 44. Paskapoo-Scollard Formation: Uranium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.001	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.0014*	0.0023*	21	0.0078	<0.000005
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	0.89	0.29	4	1.11	0.49
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	7.3	15.7	8	46.1	0.4
Ardley Coal Zone[h] – one location	3.5	2.8	82	33	0.54
Ardley Coal Zone[i] – multiple locations	-	-	-	6	0.5
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.45 Paskapoo-Scollard Formation – Phenols

Two of the six mixed coal-sandstone aquifer water samples (samples 23, 29) from the Paskapoo-Scollard Formation have phenols concentrations above the analytical detection limit of 0.001 mg/L. Both samples have a concentration of 0.001 mg/L. A water sample from a sandstone aquifer within the Paskapoo-Scollard Formation has a phenols concentration less than 0.001 mg/L.

Canadian environmental water quality guideline maximum concentrations for the protection of freshwater aquatic life and for the use of water for livestock purposes of 0.004 mg/L and 0.002 mg/L respectively have been established. None of the measured concentrations of phenols exceeds these values. The complete chemistry dataset is found in Appendix A, Table 183.

The summary statistics for water samples collected during this study are presented in the table below (Table 45). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 45. Paskapoo-Scollard Formation: Phenols.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-	-	6	0.001	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[b] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[d] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.46 Paskapoo-Scollard Formation – Non-halogenated Aromatic Hydrocarbons (BTEX)

None of the six mixed coal-sandstone aquifer water samples from the Paskapoo-Scollard Formation have BTEX concentrations above the analytical detection limits of 0.001 mg/L. A water sample from a sandstone aquifer within the Paskapoo-Scollard Formation has BTEX concentrations less than 0.001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The table below (Table 46) lists the Canadian environmental water quality guideline maximum concentrations for benzene, toluene, ethylbenzene and xylene. None of the measured concentrations of BTEX exceeds these values.

Table 46. Canadian environmental water-quality guidelines for BTEX concentrations.

Parameter	Domestic Water Use		Aquatic Life – Freshwater (mg/L)	Agriculture	
	MAC,IMAC (mg/L)	AO (mg/L)		Irrigation (mg/L	Livestock (mg/L)
Benzene	0.005	-	0.370	-	-
Toluene	-	≤ 0.024	0.002	-	0.024
Ethylbenzene	-	≤ 0.0024	0.090	-	0.0024
Xylene	-	≤ 0.300	-	-	-

The summary statistics for water samples collected during this study are presented in the table below (Table 47). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 47. Paskapoo-Scollard Formation: BTEX.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study – Benzene	-	-	6		<0.001
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study – Toluene	-	-	6		<0.001
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study – Ethylbenzene	-	-	6		<0.001
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study – Xylene	-	-	6		<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[b] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[d] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.47 Paskapoo-Scollard Formation – Purgeable and Extractable Hydrocarbons

One of the six mixed coal-sandstone aquifer water samples (sample 42) from the Paskapoo-Scollard Formation has a purgeable hydrocarbon concentration above the analytical detection limits of 0.01 mg/L. The purgeable hydrocarbon concentration in this water sample is 0.02 mg/L. A water sample from a sandstone aquifer within the Paskapoo-Scollard Formation has a purgeable hydrocarbons concentration less than 0.01 mg/L.

Two of the six mixed coal-sandstone aquifer water samples (samples 29, 42) have extractable hydrocarbons concentrations at or above the analytical detection limit of 0.1 mg/L. The concentrations of extractable hydrocarbons in these water samples are 0.2 and 0.1 mg/L respectively. A water sample from a sandstone aquifer within the Paskapoo-Scollard Formation has an extractable hydrocarbons concentration of 0.4 mg/L.

No specific Canadian environmental quality guidelines have been established for purgeable and extractable hydrocarbons in water. The complete chemistry dataset is found in Appendix A, Table 183.

The summary statistics for water samples collected during this study are presented in the table below (Table 48). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 48. Paskapoo-Scollard Formation: Purgeable and Extractable Hydrocarbons.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study – Purgeable hydrocarbons	-	-	6	0.02	<0.01
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study – Extractable hydrocarbons	-	-	6	0.2	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[b] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[d] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

The nature of the peaks in the chromatograms of samples 29 and 42 may in fact suggest that the observed concentrations of hydrocarbons may in reality be polycyclic aromatic hydrocarbons (Fowler, pers. comm. 2003,).

3.6.48 Paskapoo-Scollard Formation – Polycyclic Aromatic Hydrocarbons (PAH)

Two of the six mixed coal-sandstone aquifer water samples (samples 45, 46) from the Paskapoo-Scollard Formation have PAH concentrations above the analytical detection limits. The specific PAH in question is naphthalene. The concentrations are 0.0004 and 0.0003 mg/L respectively. A water sample from a sandstone aquifer within the Paskapoo-Scollard Formation has PAH concentrations below the analytical detection limits. The complete chemistry dataset is found in Appendix A, Table 183.

The table below (Table 49) lists the Canadian environmental water quality guideline maximum concentrations for PAHs in water. None of the measured concentrations of PAHs exceeds these values.

Table 49. Canadian environmental water-quality guidelines for PAH concentrations.

Parameter	Domestic Water Use		Aquatic Life – Freshwater (mg/L)	Agriculture	
	MAC,IMAC (mg/L)	AO (mg/L)		Irrigation (mg/L	Livestock (mg/L)
Naphthalene	-	-	0.0011	-	-
Acenaphthylene	-	-	-	-	-
Acenaphthene	-	-	0.0058	-	-
Fluorene	-	-	0.003	-	-
Phenanthrene	-	-	0.0004	-	-
Anthracene	-	-	0.00012	-	-
Acridine	-	-	0.0044	-	-
Fluoranthene	-	-	0.00004	-	-
Pyrene	-	-	0.000025	-	-
Benzo(a)anthracene	-	-	0.000018	-	-
Chrysene	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-
Benzo(k)fluoranthene	0.005	-	0.370	-	-
Benzo(a)pyrene	0.00001	-	0.000015	-	-
Indeno(1,2,3-c,d)pyrene	-	≤ 0.0024	0.090	-	0.0024
Dibenzo(a,h)anthracene	-	-	-	-	-
Benzo(g,h,I)perylene	-	-	-	-	-

The summary statistics for water samples collected during this study are presented in the table below (Table 50). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 50. Paskapoo-Scollard Formation: PAH.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study					
Naphthalene	-	-	6	0.0004	<0.0001
Acenaphthylene	-	-	6	-	<0.0001
Acenaphthene	-	-	6	-	<0.0001
Fluorene	-	-	6	-	<0.0001
Phenanthrene	-	-	6	-	<0.0001
Anthracene	-	-	6	-	<0.0001
Acridine	-	-	6	-	<0.00005
Fluoranthene	-	-	6	-	<0.0001
Pyrene	-	-	6	-	<0.00002
Benzo(a)anthracene	-	-	6	-	<0.00001
Chrysene	-	-	6	-	<0.0001
Benzo(b)fluoranthene	-	-	6	-	<0.00001
Benzo(k)fluoranthene	-	-	6	-	<0.00001
Benzo(a)pyrene	-	-	6	-	<0.00001
Indeno(1,2,3-c,d)pyrene	-	-	6	-	<0.0001
Dibenzo(a,h)anthracene	-	-	6	-	<0.00001
Benzo(g,h,I)perylene	-	-	6	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)					
Pyrene	-	-	21	-	<0.0001
Benzo(b,j,k)fluoranthene	-	-	21	-	<0.0001
Benzo(a)pyrene	-	-	21	-	<0.0001
Indeno(1,2,3-cd)pyrene	-	-	21	-	<0.0001
Dibenz(ah,ai,aj)pyrene	-	-	21	-	<0.0001
U.S.A. – Black Warrior Basin[d] (Pennsylvanian)					
Naphthalene	-	-	1	-	<0.30
Acenaphthylene	-	-	1	-	<0.50
Acenaphthene	-	-	1	-	<1.00
Fluorene	-	-	1	-	<0.07
Phenanthrene	-	-	1	-	<0.03
Anthracene	-	-	1	-	<0.02
Fluoranthene	-	-	1	-	<0.10
Pyrene	-	-	1	-	<0.10
Benzo(a)anthracene	-	-	1	-	<0.05
Benzo(k)fluoranthene	-	-	1	-	<0.20
Benzo(a)pyrene	-	-	1	-	<0.07
Dibenzo(a,h)anthracene	-	-	1	-	<0.20
Benzo(g,h,I)perylene	-	-	1	-	<0.20
Indeno(1,2,3-c,d)pyrene	-	-	1	-	<0.20
Chrysene	-	-	1	-	<0.03
Benzo(b)fluoranthene	-	-	1	-	<0.20
Data sources:					
[a] Goodarzi (2002)					
[d] O'Neil et al. (1989)					

3.6.49 Paskapoo-Scollard Formation – Adsorbable Organic Halides

The mean concentration of adsorbable organic halides from water samples taken from mixed coal-sandstone aquifers within the Paskapoo-Scollard Formation is 0.0042 mg/L with a standard deviation of 0.0070 mg/L (N= 6). A water sample from a sandstone aquifer within the Paskapoo-Scollard Formation has an adsorbable organic halides concentration of 0.0042 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have not been defined specifically for total adsorbable organic halides.

The summary statistics for water samples collected during this study are presented in the table below (Table 51). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 51. Paskapoo-Scollard Formation Summary Table Adsorbably Organic Halides

Water samples					
Location	**Mean (mg/L)**	**St. Dev (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) This study	0.0042*	0.0070*	6	0.016	<0.0025
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[b] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[d] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.50 Horseshoe Canyon Formation – Calcium

The mean concentration of Ca in Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples is 18.6 mg/L, with a standard deviation of 28.2 mg/L (N=18). For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a Ca concentration of 222 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

There are Canadian environmental water quality guidelines concentration values for Ca used for livestock purposes. These guidelines specify that Ca concentrations in water used for livestock purposes should be below 1000 mg/L. The observed Ca concentrations do not exceed this value.

The summary statistics for water samples collected during this study are presented in Table 52. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 52. Horseshoe Canyon Formation: Calcium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	18.6	28.2	18	128	2.7
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	62.4	114.3	241	1420	1.7
U.S.A. – Powder River Basin[c] (Tertiary)	32.1	14.9	47	69	5.9
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	16.1	2.9	3	18.9	13.2
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	63.4	37.6	6	118.7	6.5
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	33.4	29.4	13	100	2.5
Coal samples Horseshoe Canyon Formation					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	9147	1425	4	11030	7960
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.51 Horseshoe Canyon Formation – Magnesium

The mean Mg concentration from coal or mixed coal-sandstone aquifer water samples from within the Horseshoe Canyon Formation is 2.74 mg/L, with a standard deviation of 5.42 mg/L (N=18). For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a Mg concentration of 58.6 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

There are no Canadian environmental water quality guideline concentration values for Mg in drinking water, for the protection of aquatic life or for agricultural uses.

The summary statistics for water samples collected during this study are presented in Table 53. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 53. Horseshoe Canyon Formation: Magnesium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	2.74*	5.42*	18	23.5	<0.2
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	21.4	47.3	240	498	0.1
U.S.A. – Powder River Basin[c] (Tertiary)	16.1	8.13	47	46	1.6
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	6.03	3.89	3	7.77	0
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	16.3	16.3	6	39	2.88
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	12.1	10.2	13	34	1.1
Coal samples Horseshoe Canyon Formation					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Drumheller Coal Zone[f] – multiple locations by NAA	885*	726*	3	1690	<500
Drumheller Coal Zone[f] – multiple locations by PES	871	406	4	1440	482
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.52 Horseshoe Canyon Formation – Sodium

The mean concentration of Na in Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples is 533.9 mg/L, with a standard deviation of 186.4 mg/L (N=18). For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a Na concentration of 281 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective concentration value for sodium of 200 mg/L has been established. Seventeen of the eighteen water samples (samples 1, 2, 8, 11, 12, 19, 20, 21, 24, 30, 31, 32, 33, 34, 39, 41, 43) have sodium concentrations that exceed the aesthetic objective.

The summary statistics for water samples collected during this study are presented in Table 54. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 54. Horseshoe Canyon Formation: Sodium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	533.9	186.4	18	861	112
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	647.3	1419	241	16361	1.2
U.S.A. – Powder River Basin[c] (Tertiary)	305.3	175.5	47	800	110
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	2240	378.2	3	2673	1976
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	5339	841.8	6	5939	3674
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	1503	795.8	13	3100	570
Coal samples Horseshoe Canyon Formation					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Drumheller Coal Zone[f] – multiple locations by NAA	2375	1320	4	3830	1150
Drumheller Coal Zone[f] – multiple locations by PES	2833.5	-	2	3891	1776
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.53 Horseshoe Canyon Formation – Potassium

The mean concentration of K in Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples is 2.55 mg/L, with a standard deviation of 1.93 mg/L (N=18). For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a K concentration of 6.7 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

There are no Canadian environmental water quality guideline values for K concentration in drinking water, for the protection of aquatic life or for agricultural uses.

The summary statistics for water samples collected during this study are presented in Table 55. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 55. Horseshoe Canyon Formation: Potassium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	2.55*	1.93*	18	8.9	<2
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	8.4	3.1	47	18	3.8
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	3.5	1.4	13	6	2
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	621*	524*	4	1040	<100
Drumheller Coal Zone[f] – multiple locations by PES	511	234	4	756	266
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.54 Horseshoe Canyon Formation – Iron

Iron concentrations from coal or mixed coal-sandstone aquifer water samples from within the Horseshoe Canyon Formation are predominantly below the analytical detection limit of 0.01 mg/L. Eight water well samples (samples 1, 20, 21, 25, 30, 31, 32, 43) have a measured concentrations that exceed the detection limit. For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has an Fe concentration of less than 0.05 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective of less than or equal to 0.3 mg/L Fe for domestic water use has been established. A maximum concentration of 0.3 mg/L Fe has been established for the protection of freshwater aquatic life. A maximum concentration of 5 mg/L has been established for use of water for irrigation purposes. None of the samples collected during this study exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 56. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 56. Horseshoe Canyon Formation: Iron.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.16	<0.01
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.78	0.94	47	4.9	0.2
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.447	0.447	13	1.50	.050
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	3412	1024	4	4740	2520
Drumheller Coal Zone[f] – multiple locations by PES	3447	827	4	4347	2438
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.55 Horseshoe Canyon Formation – Manganese

The mean concentration of Mn in Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples is 0.0017 mg/L, with a standard deviation of 0.096 mg/L (N=18). For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a Mn concentration of 0.413 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective of less than or equal to 0.05 mg/L Mn for domestic water use has been established. A maximum concentration of 0.2 mg/L Mn has been established for use of water for irrigation purposes. Three of the coal or mixed coal-sandstone aquifer water samples (samples 24, 25, 36) exceed the aesthetic objective concentration. One of the mixed coal-sandstone aquifer water samples (sample 24) exceeds the recommended maximum concentration value for use of water for irrigation purposes.

The summary statistics for water samples collected during this study are presented in Table 57. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 57. Horseshoe Canyon Formation: Manganese.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.0017*	0.096*	18	0.295	<0.005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.091*	0.26*	21	1.21	<0.001
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.032	0.026	47	0.101	0.002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.097	0.046	13	0.200	0.040
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	63.1	39.6	4	113	26.9
Drumheller Coal Zone[f] – multiple locations by PES	82.2	58.1	3	154	25.1
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	524	15
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.56 Horseshoe Canyon Formation – Chloride

Chloride was determined by an automated ferricyanide method and by neutron activation analysis (NAA). For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a Cl concentration of 135 mg/L (ferricyanide method) and 122 mg/L (NAA). The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective of less than or equal to 250 mg/L Cl for domestic water use has been established. A maximum concentration of between 100 and 700 mg/L chloride has been established for use of water for irrigation purposes. Two of the coal or mixed coal-sandstone aquifer water samples (samples 21, 30) fall within the maximum concentration range values for use of water for irrigation purposes.

The summary statistics for water samples collected during this study are presented in Table 58. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 58. Horseshoe Canyon Formation: Chloride.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study – Ferricyanide Method	33.7*	57.8*	18	229	<0.5
Horseshoe Canyon wells (Upper Cretaceous) this study – NAA	29.5*	52.0*	18	205	<0.7
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	393	2094	239	24202	2
U.S.A. – Powder River Basin[c] (Tertiary)	13.2	12.1	47	64	5.2
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	204.7	343	3	600	4
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	1187	734	6	2499	668
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	1828	1149	13	4200	450
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	4	-	<100
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	165	19
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.57 Horseshoe Canyon Formation – Sulphate

The mean concentration of SO_4 in Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples is 293 mg/L, with a standard deviation of 382 mg/L (N=18). For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a SO_4 concentration of 670 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective of less than or equal to 500 mg/L SO_4 for domestic water use has been established. A maximum concentration of 1000 mg/L SO_4 has been established for use of water for livestock purposes. Six of the coal or mixed coal-sandstone aquifer water samples (samples 8, 11, 12, 24, 33, 36) exceed the aesthetic objective concentration of SO_4 in water for domestic use. One of the coal aquifer water samples (sample 12) exceeds the maximum concentration value for use of water for livestock purposes.

The summary statistics for water samples collected during this study are presented in Table 59. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 59. Horseshoe Canyon Formation: Sulphate.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	293	382	18	1320	1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	401.2	519.5	241	5670	1.2
U.S.A. – Powder River Basin[c] (Tertiary)	2.41	3.63	47	17	0.01
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	56.2	69.2	3	135.5	8.32
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	51.3	66.5	6	166.8	0
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	2.84	0.19
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.58 Horseshoe Canyon Formation – Bicarbonate

The mean concentration of HCO_3 in Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples is 1021 mg/L, with a standard deviation of 332 mg/L (N=18). For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a HCO_3 concentration of 723 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for HCO_3.

The summary statistics for water samples collected during this study are presented in Table 60. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 60. Horseshoe Canyon Formation: Bicarbonate.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	1021	332	18	1720	384
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	773	297	241	2157	63
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	5737	759	3	6612	5250
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	11833	2961	6	14701	6083
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	883	125	13	1120	670
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.59 Horseshoe Canyon Formation – Total Dissolved Solids (TDS)

The mean value of TDS in Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples is 1398 mg/L, with a standard deviation of 533 mg/L (N=18). A well completed in a Horseshoe Canyon Formation sandstone aquifer has a TDS of 1730 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective of TDS ≤ 500 mg/L has been established for water for domestic use. Only one of the eighteen samples (sample 25) does not exceed the aesthetic objective. A recommended range of TDS values has been established for the use of water for irrigation purposes. The maximum recommended values are between 500 mg/L and 3500 mg/L. Once again, only one of the eighteen samples (sample 25) falls below this range. A recommended maximum TDS value of 3000 mg/L has been established for water to be used for livestock purposes. None of the TDS values determined during this study exceed the guideline value for water to be used for livestock purposes.

The summary statistics for water samples collected during this study are presented in Table 61. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 61. Horseshoe Canyon Formation: Total Dissolved Solids.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	1398	533	18	2620	354
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	1954	3921	241	46435	162
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	5737	759	3	6612	5250
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	11833	2961	6	14701	6083
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	883	125	13	1120	670
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.60 Horseshoe Canyon Formation – Turbidity

The mean value of turbidity in Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples is 1.55 NTU, with a standard deviation of 3.13 NTU (N=18). For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a turbidity value of 0.1 NTU. The complete chemistry dataset is found in Appendix A, Table 183.

Both an aesthetic objective of turbidity less than or equal to 5 NTU and a maximum acceptable value of 1 NTU have been established for water for domestic use. Four of the eighteen coal or mixed coal-sandstone aquifer water samples (samples 24, 25, 31, 34) exceed the maximum acceptable value. Two of the coal or mixed coal-sandstone aquifer water samples (samples 24, 31) exceed both the maximum acceptable value and the aesthetic objective value.

The summary statistics for water samples collected during this study are presented in Table 62. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 62. Horseshoe Canyon Formation: Turbidity.

Water samples					
Location	**Mean (NTU)**	**Std. dev. (NTU)**	**N**	**Max. (NTU)**	**Min. (NTU)**
Horseshoe Canyon wells (Upper Cretaceous) this study	1.55*	3.13*	18	11.3	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.61 Horseshoe Canyon Formation – Sodium Adsorption Ratio (SAR)

Soils with high concentration of Na^+ in solution generally have poor physical structures (Appelo and Postma, 1994, p. 191). Sodium's large ionic size, single electrical charge and hydration status tends to cause physical separation of soil particles (Warrence et al., 2002). When this separation occurs, repulsive forces begin to dominate and the soil disperses potentially leading to plugging of soil pores (Warrence et al., 2002). Repeated wetting and drying and associated dispersion can lead to the formation of cement-like soil with little or not structure (Warrence et al., 2002). Permeability can be greatly reduced and heavy machinery may not be supported (Appelo and Postma, 1994, p. 191). In order to predict the effects of irrigation water quality on soil properties, the exchangeable sodium ratio (ESR) is calculated.

(1) $ESR = \beta_{Na} / 1- \beta_{Na}$ where β_{Na} is the fraction of exchangeable Na^+

This ESR is related to the activity of Na^+ over the square root of the sum of the Ca^{2+} and Mg^{2+} activities and becomes:

(2) $ESR = 0.5 \times 1000/\sqrt{1000} \times m_{Na+}/(\sqrt{}m_{Ca2+} + m_{Mg2+})$ where m_X is the activity in mmol/L

The ratio of $m_{Na+}/(\sqrt{}m_{Ca2+} + m_{Mg2+})$ is given a specific name, the sodium adsorption ratio or SAR.

Equation 2 upon simplification then becomes:

(3) $ESR = 0.0158 \times SAR$

The critical ESR is equal to 0.15 (Appelo and Postma, 1994, 193) and corresponds to an SAR value of 10. Alberta Agriculture Food and Rural Development specifies that irrigation water with an SAR value greater than 9 may be hazardous for irrigation purposes (Hecker, 2002).

SAR is not an absolute predictor of the suitability of water for irrigation, and will depend on soil conditions since the ratio of Na^+ over the square root of $Ca^{2+} + Mg^{2+}$ may change as a result of reactions in the soil, on the concentrating effect of evapotranspiration and on the water composition (Appelo and Postma, 1994, p. 193).

The mean value of SAR in Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples is 42.8 $(mmol/L)^{0.5}$, with a standard deviation of 16.1 $(mmol/L)^{0.5}$ (N=18). For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a SAR of 4 $(mmol/L)^{0.5}$. The complete chemistry dataset is found in Appendix A, Table 183.

Only two of the coal or mixed coal-sandstone aquifer water samples (samples 24, 25) have SAR values that are below the Alberta Agriculture Food and Rural Development irrigation water guideline of 9 $(mmol/L)^{0.5}$.

The summary statistics for water samples collected during this study are presented in Table 63. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 63. Horseshoe Canyon Formation: Sodium Adsorption Ratio.

Water samples					
Location	**Mean (mmol/L)$^{0.5}$**	**Std. dev. (mmol/L)$^{0.5}$**	**N**	**Max. (mmol/L)$^{0.5}$**	**Min. (mmol/L)$^{0.5}$**
Horseshoe Canyon wells (Upper Cretaceous) this study	42.8	16.1	18	63	5
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	32.1	25.4	240	111	0.04
U.S.A. – Powder River Basin[c] (Tertiary)	11.7	7.3	47	32	5.7
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	131	21	3	144	107
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	149	45	6	199	111
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	64	18	13	108	43
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.62 Horseshoe Canyon Formation – Silicon

Silicon concentration was determined by two methods, ICP-MS and APHA ICP method 3120B. The mean concentrations of Si in Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples are 8.35 mg/L, with a standard deviation of 4.00 mg/L (N=18) and a mean of 7.55 mg/L with a standard deviation of 3.65 mg/L for the two methods listed above, respectively. For comparison purposes, a well completed in a Horseshoe Canyon Formation sandstone aquifer has a Si concentration of 10.2 and 10.3 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Si.

The summary statistics for water samples collected during this study are presented in Table 64. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 64. Horseshoe Canyon Formation: Silicon.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study – ICP-MS	8.35	4.00	18	15.3	3.89
Horseshoe Canyon wells (Upper Cretaceous) this study – ICP	7.55	3.65	18	13.7	3.55
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	4.76	0.62	47	7.1	3.7
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.63 Horseshoe Canyon Formation – Mercury

Mercury concentrations from coal or mixed coal-sandstone aquifer water samples from within the Horseshoe Canyon Formation are all below the analytical detection limit of 0.0001 mg/L. A well completed in a Horseshoe Canyon Formation sandstone aquifer also has a Hg concentration of less than 0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been established for Hg concentrations for domestic purposes as well as for the protection of freshwater aquatic life and for livestock purposes. A maximum acceptable concentration of 0.001 mg/L has been established for domestic water use. A maximum concentration of 0.0001 mg/L has been established for the protection of freshwater aquatic life. A maximum concentration of 0.003 mg/L has been established for water to be used for livestock purposes.

The summary statistics for water samples collected during this study are presented in Table 65. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 65. Horseshoe Canyon Formation: Mercury.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	0.000913	<0.000002
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.00025	<0.000005
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.64 Horseshoe Canyon Formation – Aluminum

None of the coal or mixed coal-sandstone aquifer water samples from the Horseshoe Canyon Formation have an Al concentration above the detection limit of 0.005 mg/L. A well completed in a Horseshoe Canyon Formation sandstone aquifer has an Al concentration of less than 0.03 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An interim maximum acceptable Al concentration of 0.1 mg/L has been recommended for domestic water use. A maximum concentration of between 0.005 and 0.100 mg/L has been established for the protection of freshwater aquatic life. A maximum concentration of 5.0 mg/L has been established for the use of water for irrigation and livestock purposes.

The summary statistics for water samples collected during this study are presented in Table 66. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 66. Horseshoe Canyon Formation: Aluminum.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	-	<0.005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.05
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	10935	2592	4	13200	7640
Drumheller Coal Zone[f] – multiple locations by PES	12412	4457	4	17760	7078
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.65 Horseshoe Canyon Formation – Antimony

Two of the coal or mixed coal-sandstone aquifer water samples (samples 30, 31) from the Horseshoe Canyon formation have Sb concentrations above the detection limit of 0.0002 mg/L. The Sb concentrations in these two water samples are 0.0004 and 0.0002 mg/L respectively. A well completed in a Horseshoe Canyon Formation sandstone aquifer has an Sb concentration of less than 0.001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been established for Sb concentrations for domestic water use. An interim maximum acceptable concentration of 0.006 mg/L has been recommended for this purpose. All of the water samples analyzed have concentrations that fall below this guideline value.

The summary statistics for water samples collected during this study are presented in Table 67. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 67. Horseshoe Canyon Formation: Antimony.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.0004	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	4	0.93	<0.3
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	4.0	0.1
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.66 Horseshoe Canyon Formation – Arsenic

Ten of the coal or mixed coal-sandstone aquifer water samples from the Horseshoe Canyon Formation have As concentrations above the detection limit of 0.0002 mg/L. The mean concentration is 0.0002 mg/L with a standard deviation of 0.0007 mg/L (N=18). A well completed in a Horseshoe Canyon Formation sandstone aquifer has an As concentration of 0.0168 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.025 mg/L has been established for domestic water use. A maximum concentration of 0.005 mg/L has been established for the protection of freshwater aquatic life. Maximum concentrations of 0.100 mg/L and 0.025 mg/L have been established for the use of water for irrigation and livestock uses respectively. All of the coal or mixed coal-sandstone aquifer water samples analyzed have concentrations that fall below these guideline values.

The summary statistics for water samples collected during this study are presented in Table 68. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 68. Horseshoe Canyon Formation: Arsenic.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.0002*	0.0007*	18	0.0022	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	0.0249	<0.0004
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.0004*	0.0004*	47	0.0026	<0.0002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.0183	0.0302	13	0.110	0.001
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	4	1.14	<0.9
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	67	0.5
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.67 Horseshoe Canyon Formation – Barium

The mean concentration of Ba in coal or mixed coal-sandstone aquifer water samples from the Horseshoe Canyon Formation is 0.095 mg/L with a standard deviation of 0.089 mg/L (N=18). A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Ba concentration of 0.016 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 1.0 mg/L has been established for domestic water use. All of the water samples analyzed have concentrations that fall below these guideline values.

The summary statistics for water samples collected during this study are presented in Table 69. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 69. Horseshoe Canyon Formation: Barium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.095	0.089	18	0.368	0.007
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.149	0.169	21	0.761	0.007
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.617	0.300	47	1.60	0.14
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	518	171	4	623	264
Drumheller Coal Zone[f] – multiple locations by PES	533	84	4	597	415
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	261	987
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.68 Horseshoe Canyon Formation – Beryllium

None of the coal or mixed coal-sandstone aquifer water samples from the Horseshoe Canyon Formation contain Be above the analytical detection limit of 0.0001 mg/L. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Be concentration less than 0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.100 mg/L has been established for the use of water for irrigation and livestock purposes. All of the water samples analyzed have concentrations that fall below these guideline values.

The summary statistics for water samples collected during this study are presented in Table 70. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 70. Horseshoe Canyon Formation: Beryllium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.69 Horseshoe Canyon Formation – Bismuth

None of the coal or mixed coal-sandstone aquifer water samples from the Horseshoe Canyon Formation contain Bi concentrations above the analytical detection limit of 0.0005 mg/L. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Bi concentration less than 0.003 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have not been developed for Bi.

The summary statistics for water samples collected during this study are presented in Table 71. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 71. Horseshoe Canyon Formation: Bismuth.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	-	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.032	<0.020
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.70 Horseshoe Canyon Formation – Boron

The mean concentration of B in coal or mixed coal-sandstone aquifer water samples from the Horseshoe Canyon Formation is 0.294 mg/L with a standard deviation of 0.144 mg/L (N=18). A well completed in a Horseshoe Canyon Formation sandstone aquifer has a B concentration of 0.329 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An interim maximum acceptable concentration of 5 mg/L has been established for domestic water use. The range of maximum concentrations for water to be used for irrigation purposes is between 0.500 and 6 mg/L. The maximum concentration for water to be used for livestock purposes is 5 mg/L. One of the mixed coal-sandstone aquifer water sample B concentrations (sample 20) falls within the maximum concentration range for boron in water to be used for irrigation purposes. Sample 20 has a boron concentration of 0.707 mg/L.

The summary statistics for water samples collected during this study are presented in Table 72. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 72. Horseshoe Canyon Formation: Boron.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.294	0.144	18	0.707	0.099
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.217	<0.100
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	955	183	4	1225	834
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	628	10
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.71 Horseshoe Canyon Formation – Cadmium

Two of the mixed coal-sandstone aquifer water samples (samples 11, 20) from the Horseshoe Canyon Formation contain Cd above the analytical detection limit of 0.00001 mg/L. The values determined in these water samples are 0.00011 and 0.00092 mg/L respectively. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Cd concentration of less than 0.00005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.005 mg/L has been established for domestic water use. A maximum concentration value of 0.000017 mg/L has been established for the protection of freshwater aquatic life. The maximum concentration for water to be used for irrigation purposes is 0.0051 mg/L. The maximum concentration for water to be used for livestock purposes is 0.080 mg/L. Two of the mixed coal-sandstone aquifer water samples (samples 11, 20) exceed the guideline values for the protection of freshwater aquatic life.

The summary statistics for water samples collected during this study are presented in Table 73. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 73. Horseshoe Canyon Formation: Cadmium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.00092	<0.00001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	0.00011	<0.00005
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.0009*	0.0002*	13	0.001	<0.001
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.72 Horseshoe Canyon Formation – Chromium

The mean Cr concentration in coal or mixed coal-sandstone water samples from the Horseshoe Canyon Formation is 0.0056 mg/L with a standard deviation of 0.0025 mg/L (N=18). A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Cr concentration of 0.0059 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.050 mg/L has been established for domestic water use. A maximum concentration value of 0.0089 mg/L has been established for the protection of freshwater aquatic life. The maximum concentration for water to be used for irrigation purposes is 0.0049 mg/L. The maximum concentration for water to be used for livestock purposes is 0.050 mg/L. Samples 1, 2, 19, 21, 30, 31, 32, 33, 34, 37 and 41 exceed the guideline value for water to be used for irrigation purposes. Samples 30 and 32 exceed the guideline value for the protection of freshwater aquatic life.

The summary statistics for water samples collected during this study are presented in Table 74. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 74. Horseshoe Canyon Formation: Chromium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.0056	0.0025	18	0.0120	0.0012
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	-	<0.001
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.0009*	0.0002*	13	0.001	<0.001
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	4	-	<3
Drumheller Coal Zone[f] – multiple locations by PES	2.85	2.02	4	5.6	0.9
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	254	6
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.73 Horseshoe Canyon Formation – Cobalt

The majority of the Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water sample Co concentrations are below the analytical detection limit of 0.0001 mg/L (N=14). Four of the coal or mixed coal-sandstone aquifer water samples (samples 25, 30, 31, 34) have Co concentrations of 0.0002, 0.0002, 0.0005 and 0.0002 mg/L respectively. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Co concentration of 0.0008 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The maximum concentration of Co in water to be used for irrigation purposes is 0.050 mg/L. The maximum concentration for water to be used for livestock purposes is 1.00 mg/L. None of the water samples exceed the guideline values.

The summary statistics for water samples collected during this study are presented in Table 75. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 75. Horseshoe Canyon Formation: Cobalt.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.0005	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.0002	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	0.617	0.186	4	0.84	0.42
Drumheller Coal Zone[f] – multiple locations by PES	-	-	1	7.6	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	17	0.6
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.74 Horseshoe Canyon Formation – Copper

Three of the Horseshoe Canyon Formation mixed coal-sandstone aquifer water samples (samples 8, 20, 24) have Cu concentrations above the analytical detection limit of 0.001 mg/L. The Cu concentrations in these water samples are 0.036, 0.001 and 0.001 mg/L respectively. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Cu concentration less than 0.005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective concentration of less than or equal to 1.00 mg/L has been established for domestic water use. The range of maximum acceptable concentrations of Cu for the protection of aquatic life is between 0.002 and 0.004 mg/L. The range of maximum concentrations for water to be used for irrigation purposes is between 0.200 and 1.00 mg/L. The range of maximum concentrations for water to be used for livestock purposes is between 0.500 and 5.00 mg/L. The Cu concentration in mixed coal-sandstone aquifer water sample 8 exceeds the maximum Cu concentration range for the protection of freshwater aquatic life.

The summary statistics for water samples collected during this study are presented in Table 76. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 76. Horseshoe Canyon Formation: Copper.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.036	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.009*	0.0042*	21	0.148	<0.002
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	5.36	4.26	47	28.6	1.5
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	5.87	2.37	4	9.2	3.6
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	18	1
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.75 Horseshoe Canyon Formation – Lead

Two of the Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples (samples 8, 31) have Pb concentrations above the analytical detection limit of 0.0001 mg/L. Sample 8 has a Pb concentration of 0.0007 mg/L, whereas sample 31 has a Pb concentration of 0.0005 mg/L. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Pb concentration less than 0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.010 mg/L has been established for domestic water use. The range of maximum acceptable concentrations of Pb for the protection of aquatic life is between 0.001 and 0.007 mg/L. The maximum Pb concentration for water to be used for irrigation purposes is 0.200 mg/L. The maximum Pb concentration for water to be used for livestock purposes is 0.100 mg/L. None of the water samples exceeds these guideline values.

The summary statistics for water samples collected during this study are presented in Table 77. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 77. Horseshoe Canyon Formation: Lead.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.0007	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.00043*	0.00060*	21	0.0027	<0.00001
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.00043	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.00028*	0.00031*	13	0.100	<0.001
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	3.82	1.52	4	5.6	1.9
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.76 Horseshoe Canyon Formation – Lithium

The mean Li concentration in the coal or mixed coal-sandstone aquifer water samples from the Horseshoe Canyon Formation is 0.141 mg/L with a standard deviation of 0.086 mg/L (N=18). A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Li concentration of 0.204 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been developed for Li. The maximum Li concentration for water to be used for irrigation purposes is 2.50 mg/L. None of the water sample Li concentrations exceeds this value.

The summary statistics for water samples collected during this study are presented in Table 78. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 78. Horseshoe Canyon Formation: Lithium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.141	0.086	18	0.383	0.05
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.052	0.036	47	0.208	0.018
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.77 Horseshoe Canyon Formation – Molybdenum

The majority of the Horseshoe Canyon coal or mixed coal-sandstone aquifer water samples have Mo concentration below the analytical detection limit of 0.001 mg/L (N=13). Samples 21, 30, 31, 34 and 43 have Mo concentrations of 0.003, 0.002, 0.007, 0.004 and 0.004 mg/L respectively. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Mo concentration of 0.005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The maximum acceptable concentration for the protection of freshwater aquatic life is 0.073 mg/L. The range of maximum Mo concentrations for water to be used for irrigation purposes is between 0.010 and 0.050 mg/L. The maximum Mo concentration for water to be used for livestock purposes is 0.500 mg/L. None of the water samples exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 79. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 79. Horseshoe Canyon Formation: Molybdenum.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.007	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.0013*	0.0013*	21	0.0043	<0.00005
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	30	0.3
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.78 Horseshoe Canyon Formation – Nickel

The majority of the Horseshoe Canyon coal or mixed coal-sandstone aquifer water samples have Ni concentrations below the analytical detection limit of 0.0005 mg/L (N=14). Samples 19, 20, 31 and 33 have Ni concentrations of 0.016, 0.0035, 0.0006 and 0.011 mg/L respectively. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Ni concentration less than 0.0025 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The range of maximum acceptable concentrations of Ni for the protection of freshwater aquatic life is between 0.025 and 0.150 mg/L. The maximum Ni concentration for water to be used for irrigation purposes is 0.200 mg/L. The maximum Ni concentration for water to be used for livestock purposes is 1.00 mg/L. None of the water samples exceeds these guideline values.

The summary statistics for water samples collected during this study are presented in Table 80. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 80. Horseshoe Canyon Formation: Nickel.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.016	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.00037*	0.00055*	21	0.0021	<0.0002
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.0065*	0.0068*	47	0.0354	<0.0005
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	30	1
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.79 Horseshoe Canyon Formation – Selenium

The majority of the Horseshoe Canyon coal or mixed coal-sandstone aquifer water samples have Se concentrations below the analytical detection limit of 0.0002 mg/L (N=18). Sample 31 has a Se concentration of 0.0002 mg/L. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Se concentration <0.0010 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.010 mg/L has been established for domestic water use. The maximum acceptable concentration for the protection of freshwater aquatic life is 0.001 mg/L. The range of maximum selenium concentrations for water to be used for irrigation purposes is between 0.020 and 0.050 mg/L. The maximum Se concentration for water to be used for livestock purposes is 0.050 mg/L. None of the water samples exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 81. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 81. Horseshoe Canyon Formation: Selenium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.0002	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	4	-	<3
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	2.6	0.4
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.80 Horseshoe Canyon Formation – Silver

All of the Horseshoe Canyon coal or mixed coal-sandstone aquifer water samples have Ag concentrations below the analytical detection limit of 0.0001 mg/L. A well completed in a Horseshoe Canyon Formation sandstone aquifer also has a Ag concentration less than 0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been developed for silver. The maximum acceptable concentration for the protection of freshwater aquatic life is 0.0001 mg/L. None of the water samples exceeds this guideline value.

The summary statistics for water samples collected during this study are presented in Table 82. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 82. Horseshoe Canyon Formation: Silver.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	1.8	-	2	2.7	0.9
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.81 Horseshoe Canyon Formation – Strontium

The mean concentration of Sr within Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples is 0.255 mg/L with a standard deviation of 0.327 mg/L (N=18). A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Sr concentration of 1.7 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have not been developed for Sr.

The summary statistics for water samples collected during this study are presented in Table 83. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 83. Horseshoe Canyon Formation: Strontium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.255	0.327	18	1.5	0.04
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.692	0.412	47	1.9	0.1
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	2.13	1.95	13	7.20	0.27
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	211*	136*	4	374	<100
Drumheller Coal Zone[f] – multiple locations by PES	299	79	4	374	211
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	492	96
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.82 Horseshoe Canyon Formation – Thallium

Two of the water samples (samples 1, 2) collected from Horseshoe Canyon Formation mixed coal-sandstone aquifers have Tl concentrations that exceed the analytical detection limit of 0.00005 mg/L. The concentrations of Tl in these water samples are 0.0013 and 0.00038 mg/L respectively. A well completed in a Horseshoe Canyon Formation sandstone aquifer also has a Tl concentration less than 0.0003 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been developed for maximum Tl concentrations for the protection of freshwater aquatic life. The value is 0.0008 mg/L. Sample 1 exceeds this guideline value.

The summary statistics for water samples collected during this study are presented in Table 84. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 84. Horseshoe Canyon Formation: Thallium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.0013	<0.00005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.00034	<0.0002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.83 Horseshoe Canyon Formation –Titanium

Eleven of the coal or mixed coal-sandstone aquifer water samples from the Horseshoe Canyon Formation have Ti concentrations above the analytical detection limit of 0.0005 mg/L. A mean of 0.0015 mg/L and a standard deviation of 0.0069 mg/L (N=18) were determined. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Ti concentration 0.0071 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have not been developed for Ti.

The summary statistics for water samples collected during this study are presented in Table 85. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 85. Horseshoe Canyon Formation: Titanium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.0015*	0.0069*	18	0.018	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.050
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	273	153	4	500	161
Drumheller Coal Zone[f] – multiple locations by PES	272	88	4	389	194
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.84 Horseshoe Canyon Formation – Vanadium

One (sample 31) of the water samples collected from Horseshoe Canyon Formation coal aquifers has a V concentration that exceeds the analytical detection limit of 0.0001 mg/L. It has a concentrations of 0.0001 mg/L A well completed in a Horseshoe Canyon Formation sandstone aquifer has a V concentration less than 0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been developed for V concentrations in water for irrigation and livestock purposes. The maximum concentration for the use of water for irrigation and livestock purposes is 0.100 mg/L. None of the observed vanadium concentrations exceeds these guidelines.

The summary statistics for water samples collected during this study are presented in Table 86. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 86. Horseshoe Canyon Formation: Vanadium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.0001	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.0002
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	2.65	1.58	4	4.72	0.94
Drumheller Coal Zone[f] – multiple locations by PES	4.1	1.61	4	6.3	2.8
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	502	1.6
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.85 Horseshoe Canyon Formation – Zinc

Ten of the coal or mixed coal-sandstone aquifer water samples collected from the Horseshoe Canyon Formation have Zn concentrations above the analytical detection limit of 0.001 mg/L. A mean of 0.0004 mg/L and a standard deviation of 0.0213 mg/L (N=18) were determined. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Zn concentration 0.191 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective concentration of less than or equal to 5.00 mg/L has been established for Zn concentrations in water for domestic use. A maximum concentration of 0.030 mg/L has been established for the protection of freshwater aquatic life. The range of maximum concentrations for the use of water for irrigation purposes is between 1.00 and 5.00 mg/L. The maximum concentration for the use of water for livestock purposes is 50 mg/L. None of the observed Zn concentrations exceed these guidelines.

The summary statistics for water samples collected during this study are presented in Table 87. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 87. Horseshoe Canyon Formation: Zinc.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.0004*	0.0213*	18	0.05	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.065	0.113	21	0.470	0.0007
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	0.0804	<0.001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	0.032*	0.063*	13	0.240	<0.005
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	32.9	51.9	4	110.6	4.9
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.86 Horseshoe Canyon Formation - Fluorine

All of the Horseshoe Formation coal and mixed coal-sandstone aquifer water samples have fluorine concentrations above the analytical detection limit of 0.5 ppm. A mean of 2.1 ppm and a standard deviation of 0.7 ppm (N=18) were determined. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a fluorine concentration 1.0 ppm. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum allowable concentration of 1.5 mg/L has been established for fluoride concentrations in water for domestic use. Samples 1, 2, 8, 11, 12, 19, 21, 30, 31, 32, 33, 34, 36 and 43 may have observed fluorine concentrations that could exceed this guideline. The maximum recommended concentration of fluoride in water for use for irrigation purposes is 1.0 mg/L. The maximum recommended concentration of fluoride in water for use for livestock purposes is between 1.0 and 2.0 mg/L. Samples 1, 2, 8, 11, 12, 19, 20, 21, 30, 31, 32, 33, 34, 36, 41 and 43 may have observed fluorine concentrations that could exceed these agricultural guidelines.

The summary statistics for water samples collected during this study are presented in Table 88. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 88. Horseshoe Canyon Formation: Fluorine.

Water samples					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	2.1	0.71	18	3.2	0.6
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[b] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.92	0.32	47	1.7	0.42
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[g] – one location	-	-	-	-	-
Ardley Coal Zone[h] – one location	-	-	-	-	-
Ardley Coal Zone[i] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Pollock et al. (2000)					
[h] Gentzis and Goodarzi (1995)					
[i] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.87 Horseshoe Canyon Formation – Bromine

Thirteen of the water samples collected from Horseshoe Canyon Formation coal or mixed coal-sandstone aquifers have measurable Br concentrations. A mean of 0.155 mg/L with a standard deviation of 0.530 mg/L (N=18) was determined. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Br concentration 0.11 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Br.

The summary statistics for water samples collected during this study are presented in Table 89. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 89. Horseshoe Canyon Formation: Bromine.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.192*	0.538*	18	1.73	<0.035
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.11*	0.18*	47	0.85	<0.02
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	4	1.7	<0.5
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	4.3	0.5
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.88 Horseshoe Canyon Formation – Iodine

Thirteen of the water samples collected from Horseshoe Canyon Formation coal or mixed coal-sandstone aquifers have measurable I concentrations. The mean I concentration is 0.052 mg/L with a standard deviation of 0.151 mg/L (N=18). A well completed in a Horseshoe Canyon Formation sandstone aquifer has an I concentration less than 0.022 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for I.

The summary statistics for water samples collected during this study are presented in Table 90. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 90. Horseshoe Canyon Formation: Iodine.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.053*	0.151*	18	0.39	<0.013
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	4	-	<20
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.89 Horseshoe Canyon Formation – Scandium

The mean Sc concentration in water samples collected from coal or mixed coal-sandstone aquifers in the Horseshoe Canyon Formation is 0.00007 mg/L with a standard deviation of 0.00003 mg/L (N=18). A well completed in a Horseshoe Canyon Formation sandstone aquifer has a scandium concentration 0.00005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Sc.

The summary statistics for water samples collected during this study are presented in Table 91. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 91. Horseshoe Canyon Formation: Scandium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.00007	0.00003	18	0.00014	0.00003
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.00120*	0.00079*	47	0.003	<0.0001
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	1.11	0.26	4	1.49	0.92
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.90 Horseshoe Canyon Formation – Rubidium

Six of the 18 Horseshoe Canyon coal or mixed coal-sandstone aquifer water samples (samples 1, 2, 8, 19, 20, 24) have measurable Rb concentrations of 0.013, 0.013, 0.011, 0.011, 0.015 and 0.024 mg/L respectively. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Rb concentration <0.0084 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Rb.

The summary statistics for water samples collected during this study are presented in Table 92. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 92. Horseshoe Canyon Formation: Rubidium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.024	<0.0048
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	0.0118	0.0061	47	0.0382	0.0041
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.91 Horseshoe Canyon Formation – Gross Alpha and Gross Beta Radiation

Two of the Horseshoe Canyon Formation mixed coal-sandstone aquifer water samples (samples 8, 20) have measurable gross alpha radioactivity of 0.6 and 0.4 Bq/L respectively. Four of the Horseshoe Canyon coal or mixed coal-sandstone aquifer water samples (samples 8, 12, 20, 24) have measurable gross beta radioactivity of 0.3, 0.2, 0.6 and 0.2 Bq/L respectively. A well completed in a Horseshoe Canyon Formation sandstone aquifer has gross alpha and gross beta radioactivity levels of less than 0.2 and 0.2 Bq/L respectively. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for gross alpha and gross beta radioactivity levels in water.

The summary statistics for water samples collected during this study are presented in Table 93. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 93. Horseshoe Canyon Formation: Gross alpha and gross beta radiation.

Water samples – Gross alpha					
Location	**Mean (Bq/L)**	**Std. dev. (Bq/L)**	**N**	**Max. (Bq/L)**	**Min. (Bq/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.6	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Water samples –Gross beta					
Location	**Mean (Bq/L)**	**Std. dev. (Bq/L)**	**N**	**Max. (Bq/L)**	**Min. (Bq/L)**
Horseshoe Canyon wells (Tertiary-Cretaceous) this study	-	-	18	0.6	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)					
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					

3.6.92 Horseshoe Canyon Formation – Thorium

Two of the Horseshoe Canyon Formation coal or mixed coal-sandstone aquifer water samples (samples 19, 34) have measurable Th concentrations of 0.0003 and 0.0002 mg/L respectively. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a Th concentration less than 0.00018 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for total concentration of Th in water. A maximum acceptable level of radioactivity of 0.1 Bq/L has been established in water for domestic use. None of the radioactivity levels for Th are above this value.

The summary statistics for water samples collected during this study are presented in Table 94. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 94. Horseshoe Canyon Formation: Thorium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.0003	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.020
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	2.07	0.60	4	2.88	1.48
Drumheller Coal Zone[f] – multiple locations by PES	4.53	2.43	4	6.7	1.9
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	25	0.4
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					

3.6.93 Horseshoe Canyon Formation – Uranium

None of the Horseshoe Canyon coal or mixed coal-sandstone aquifer water samples has a measurable U concentration. A well completed in a Horseshoe Canyon Formation sandstone aquifer has a U concentration of 0.003 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of U of 0.100 mg/L has been established for water for domestic purposes. A maximum concentration of 0.010 mg/L has been established for water used for irrigation purposes. A maximum concentration of 0.200 mg/L has been established for water used for livestock purposes. None of the observed U concentrations are above these guideline values. Maximum acceptable levels of radioactivity of 4 Bq/L for ^{234}U, ^{235}U and ^{238}U have been established for U in water for domestic use. None of the observed radioactivity levels exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 95. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 95. Horseshoe Canyon Formation: Uranium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	-	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.0014*	0.0023*	21	0.0078	<0.000005
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	47	-	<0.020
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[f] – multiple locations by NAA	0.89	0.29	4	1.11	0.49
Drumheller Coal Zone[f] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[g] – multiple locations	-	-	-	8	0.2
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					
[f] Landheer et al. (1982)					
[g] Gentzis and Goodarzi (1998)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.94 Horseshoe Canyon Formation – Phenols

Four of the coal or mixed coal-sandstone aquifer water samples (samples 24, 25, 31, 41) from the Horseshoe Canyon Formation have phenols concentrations above the analytical detection limit of 0.001 mg/L. The samples have concentrations of 0.001, 0.001, 0.005 and 0.004 mg/L respectively. A water sample from a sandstone aquifer within the Horseshoe Canyon Formation has a phenols concentration 0.001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental water quality guideline maximum concentrations for the protection of freshwater aquatic life and for the use of water for livestock purposes of 0.004 mg/L and 0.002 mg/L respectively have been established. Samples 31 and 41 have phenols concentrations that exceed the maximum concentration for the use of water for livestock purposes. Sample 31 has a phenols concentration that exceeds the guideline value for the protection of aquatic life.

The summary statistics for water samples collected during this study are presented in the table below (Table 96). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 96. Horseshoe Canyon Formation: Phenols.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	-	-	18	0.005	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O’Neil et al. (1989)					

3.6.95 Horseshoe Canyon Formation – Non-halogenated aromatic hydrocarbons (BTEX)

One of the mixed coal-sandstone aquifer water samples (sample 1) from the Horseshoe Canyon Formation has a toluene concentration above the analytical detection limit of 0.001 mg/L. The concentration of toluene in sample 1 is 0.005 mg/L. A water sample from a sandstone aquifer within the Horseshoe Canyon Formation has BTEX concentrations less than 0.001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The table below (Table 97) lists the Canadian environmental water quality guideline maximum concentrations for benzene, toluene, ethylbenzene and xylene. The concentration of toluene in sample 1 exceeds the guideline value for the protection of freshwater aquatic life.

Table 97. Canadian environmental water-quality guideline for BTEX

Parameter	Domestic water use		Aquatic life – freshwater (mg/L)	Agriculture	
	MAC, IMAC (mg/L)	AO (mg/L)		Irrigation (mg/L	Livestock (mg/L)
Benzene	0.005	-	0.370	-	-
Toluene	-	≤ 0.024	0.002	-	0.024
Ethylbenzene	-	≤ 0.0024	0.090	-	0.0024
Xylene	-	≤ 0.300	-	-	-

The summary statistics for water samples collected during this study are presented in the table below (Table 98). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 98. Horseshoe Canyon Formation: BTEX.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study – Benzene	-	-	18	-	<0.001
Horseshoe Canyon wells (Upper Cretaceous) this study – Toluene	-	-	18	0.005	<0.001
Horseshoe Canyon wells (Upper Cretaceous) this study – Ethylbenzene	-	-	18	-	<0.001
Horseshoe Canyon wells (Upper Cretaceous) this study – Xylene	-	-	18	-	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.96 Horseshoe Canyon Formation – Purgeable and Extractable Hydrocarbons

Five of the coal or mixed coal-sandstone aquifer water samples (samples 1, 8, 12, 21, 36) from the Horseshoe Canyon Formation have a purgeable hydrocarbon concentration at or above the analytical detection limits of 0.01 mg/L. The purgeable hydrocarbon concentrations in these water samples are 0.01, 0.01, 0.01, 0.04 and 0.11 mg/L. A water sample from a sandstone aquifer within the Horseshoe Canyon Formation has a purgeable hydrocarbons concentration of 0.07 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Three of coal or mixed coal-sandstone aquifer water samples (samples 25, 30, 41) have extractable hydrocarbons concentrations at or above the analytical detection limit of 0.1 mg/L. The concentrations of extractable hydrocarbons in these water samples are 0.2, 0.2 and 0.5 mg/L respectively. A water sample from a sandstone aquifer within the Horseshoe Canyon Formation has an extractable hydrocarbons concentration less than 0.1 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

No specific Canadian environmental quality guidelines have been established for purgeable and extractable hydrocarbons in water.

The summary statistics for water samples collected during this study are presented in the table below (Table 99). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 99. Horseshoe Canyon Formation: Purgeable and extractable hydrocarbons.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study – Purgeable hydrocarbons	-	-	18	0.11	<0.01
Horseshoe Canyon wells (Upper Cretaceous) this study – Extractable hydrocarbons	-	-	18	0.5	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.97 Horseshoe Canyon Formation – Polycyclic Aromatic Hydrocarbons (PAH)

None of the coal or mixed coal-sandstone aquifer water samples from the Horseshoe Canyon Formation have PAH concentrations above the analytical detection limits. A water sample from a sandstone aquifer within the Horseshoe Canyon Formation also has PAH concentrations below the analytical detection limits. The complete chemistry dataset is found in Appendix A, Table 183.

The table below (Table 100) lists the Canadian environmental water quality guideline maximum concentrations for PAHs in water. None of the measured concentrations of PAHs exceeds these values.

Table 100. Canadian environmental water-quality guideline values for PAH

Parameter	Domestic water use		Aquatic life – freshwater (mg/L)	Agriculture	
	MAC, IMAC (mg/L)	AO (mg/L)		Irrigation (mg/L	Livestock (mg/L)
Naphthalene	-	-	0.0011	-	-
Acenaphthylene	-	-	-	-	-
Acenaphthene	-	-	0.0058	-	-
Fluorene	-	-	0.003	-	-
Phenanthrene	-	-	0.0004	-	-
Anthracene	-	-	0.00012	-	-
Acridine	-	-	0.0044	-	-
Fluoranthene	-	-	0.00004	-	-
Pyrene	-	-	0.000025	-	-
Benzo(a)anthracene	-	-	0.000018	-	-
Chrysene	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-
Benzo(k)fluoranthene	0.005	-	0.370	-	-
Benzo(a)pyrene	0.00001	-	0.000015	-	-
Indeno(1,2,3-c,d)pyrene	-	≤ 0.0024	0.090	-	0.0024
Dibenzo(a,h)anthracene	-	-	-	-	-
Benzo(g,h,I)perylene	-	-	-	-	-

The summary statistics for water samples collected during this study are presented in the table below (Table 101). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 101. Horseshoe Canyon Formation: PAH.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study					
Naphthalene	-	-	18	-	<0.0001
Acenaphthylene	-	-	18	-	<0.0001
Acenaphthene	-	-	18	-	<0.0001
Fluorene	-	-	18	-	<0.0001
Phenanthrene	-	-	18	-	<0.0001
Anthracene	-	-	18	-	<0.0001
Acridine	-	-	18	-	<0.00005
Fluoranthene	-	-	18	-	<0.0001
Pyrene	-	-	18	-	<0.00002
Benzo(a)anthracene	-	-	18	-	<0.00001
Chrysene	-	-	18	-	<0.0001
Benzo(b)fluoranthene	-	-	18	-	<0.00001
Benzo(k)fluoranthene	-	-	18	-	<0.00001
Benzo(a)pyrene	-	-	18	-	<0.00001
Indeno(1,2,3-c,d)pyrene	-	-	18	-	<0.0001
Dibenzo(a,h)anthracene	-	-	18	-	<0.00001
Benzo(g,h,I)perylene	-	-	18	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)					
Pyrene	-	-	21	-	<0.0001
Benzo(b,j,k)fluoranthene	-	-	21	-	<0.0001
Benzo(a)pyrene	-	-	21	-	<0.0001
Indeno(1,2,3-cd)pyrene	-	-	21	-	<0.0001
Dibenz(ah,ai,aj)pyrene	-	-	21	-	<0.0001
U.S.A. – Black Warrior Basin[d] (Pennsylvanian)					
Naphthalene	-	-	1	-	<0.30
Acenaphthylene	-	-	1	-	<0.50
Acenaphthene	-	-	1	-	<1.00
Fluorene	-	-	1	-	<0.07
Phenanthrene	-	-	1	-	<0.03
Anthracene	-	-	1	-	<0.02
Fluoranthene	-	-	1	-	<0.10
Pyrene	-	-	1	-	<0.10
Benzo(a)anthracene	-	-	1	-	<0.05
Benzo(k)fluoranthene	-	-	1	-	<0.20
Benzo(a)pyrene	-	-	1	-	<0.07
Dibenzo(a,h)anthracene	-	-	1	-	<0.20
Benzo(g,h,I)perylene	-	-	1	-	<0.20
Indeno(1,2,3-c,d)pyrene	-	-	1	-	<0.20
Chrysene	-	-	1	-	<0.03
Benzo(b)fluoranthene	-	-	1	-	<0.20
Data sources:					
[a] Goodarzi (2002)					
[d] O'Neil et al. (1989)					

3.6.98 Horseshoe Canyon Formation – Adsorbable Organic Halides

The mean concentration of adsorbable organic halides from water samples taken from coal or mixed coal-sandstone aquifers within the Horseshoe Canyon Formation is 0.016 mg/L with a standard deviation of 0.016 mg/L (N=18). A water sample from a sandstone aquifer within the Horseshoe Canyon Formation has an adsorbable organic halides concentration of 0.054 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have not been defined specifically for total adsorbable organic halides.

The summary statistics for water samples collected during this study are presented in the table below (Table 102). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 102. Horseshoe Canyon Formation: Adsorbable Organic Halides.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells (Upper Cretaceous) this study	0.016	0.016	18	0.053	0.0027
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[b] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[c] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[d] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[e] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Bachu and Michael (2002)					
[c] Rice et al. (2000)					
[d] Decker et al. (1987)					
[e] O'Neil et al. (1989)					

3.6.99 Belly River Group – Calcium

The mean concentration of Ca in Belly River Group coal or mixed coal-sandstone aquifer water samples is 27.9 mg/L, with a standard deviation of 30.3 mg/L (N=11). For comparison purposes, 5 wells completed in Belly River Group sandstone aquifers have a mean Ca concentration of 47 mg/L with a standard deviation of 65.1 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

There are Canadian environmental water quality guidelines for Ca concentration s in water used for livestock purposes. These guidelines specify that Ca concentrations in water used for livestock purposes should be below 1000 mg/L. The observed Ca concentrations do not exceed this value.

The summary statistics for water samples collected during this study are presented in Table 103. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 103. Belly River Group: Calcium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	27.9	30.3	11	85.9	1.8
Belly River wells (Upper Cretaceous) this study -sandstone	47	65.1	5	150	2.8
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	47.3	22.5	3	65	22
Belly River – Alberta Basin [c] (Upper Cretaceous)	163.2	27.3	4	186	125
Belly River – Alberta Basin [d] (Upper Cretaceous)	92.5	85.9	51	403	2
Belly River – Alberta Basin [e] (Upper Cretaceous)	103	131	1189	1666	1.3
U.S.A. – Powder River Basin[f] (Tertiary)	32.1	14.9	47	69	5.9
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	16.1	2.9	3	18.9	13.2
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	63.4	37.6	6	118.7	6.5
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	33.4	29.4	13	100	2.5
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.100 Belly River Group – Magnesium

The mean Mg concentration from coal or mixed coal-sandstone aquifer water samples from within the Belly River Group is 11 mg/L, with a standard deviation of 12.9 mg/L (N=11). For comparison purposes, five wells completed in Belly River Group sandstone aquifers have a mean Mg concentration of 8.55 mg/L with a standard deviation of 18.2 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

There are no Canadian environmental water quality guideline concentration values for Mg in drinking water, for the protection of aquatic life or for agricultural uses.

The summary statistics for water samples collected during this study are presented in Table 104. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 104. Belly River Group: Magnesium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	11.0	12.9	11	34.4	0.3
Belly River wells (Upper Cretaceous) this study -sandstone	8.55*	18.2*	5	33.8	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	54.0	-	2	87	21
Belly River – Alberta Basin[c] (Upper Cretaceous)	44.7	10.0	4	52	30
Belly River – Alberta Basin[d] (Upper Cretaceous)	7.69	8.39	51	36	0
Belly River – Alberta Basin[e] (Upper Cretaceous)	27.2	36.5	1186	581	0.1
U.S.A. – Powder River Basin[f] (Tertiary)	16.1	8.13	47	46	1.6
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	6.03	3.89	3	7.77	0
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	16.3	16.3	6	39	2.88
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	12.1	10.2	13	34	1.1
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.101 Belly River Group – Sodium

The mean concentration of Na in Belly River Group coal or mixed coal-sandstone aquifer water samples is 385.7 mg/L, with a standard deviation of 348.2 mg/L (N=11). For comparison purposes, wells completed in Belly River Group sandstone aquifer have a mean Na concentration of 353.9 mg/L with a standard deviation of 205.7 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

A domestic water use aesthetic objective concentration value for Na of 200 mg/L has been established. Nine of the eleven water samples (samples 6, 7, 9, 15, 26, 27, 35, 37, 40) have Na concentrations that exceed the aesthetic objective.

The summary statistics for water samples collected during this study are presented in Table 105. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 105. Belly River Group: Sodium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	385.7	348.2	11	1340	19.1
Belly River wells (Upper Cretaceous) this study -sandstone	353.9	205.7	5	562	19.5
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	4143	2356	3	6360	1670
Belly River – Alberta Basin[c] (Upper Cretaceous)	5485	864	4	6050	4210
Belly River – Alberta Basin[d] (Upper Cretaceous)	1596	784	51	3900	604
Belly River – Alberta Basin[e] (Upper Cretaceous)	2160	2028	1189	19857	1.3
U.S.A. – Powder River Basin[f] (Tertiary)	305.3	175.5	47	800	110
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	2240	378.2	3	2673	1976
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	5339	841.8	6	5939	3674
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	1503	795.8	13	3100	570
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O’Neil et al. (1989)					

3.6.102 Belly River Group – Potassium

The mean concentration of K in Belly River Group coal or mixed coal-sandstone aquifer water samples is 3.33 mg/L, with a standard deviation of 1.80 mg/L (N=11). For comparison purposes, wells completed in Belly River Group sandstone aquifers have a mean potassium concentration of 3.32 mg/L with a standard deviation of 1.89 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

There are no Canadian environmental water quality guideline values for K in drinking water, for the protection of aquatic life or for agricultural uses.

The summary statistics for water samples collected during this study are presented in Table 106. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 106. Belly River Group: Potassium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	3.33	1.80	11	6.6	1.2
Belly River wells (Upper Cretaceous) this study -sandstone	3.32	1.89	5	6.4	1.5
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	18.3	9.07	3	25	8
Belly River – Alberta Basin[c] (Upper Cretaceous)	46.5	18.2	4	72	33
Belly River – Alberta Basin[d] (Upper Cretaceous)	17.6	16.1	51	71	2
Belly River – Alberta Basin[e] (Upper Cretaceous)	31.6	40.3	353	250	0.99
U.S.A. – Powder River Basin[f] (Tertiary)	8.4	3.1	47	18	3.8
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	3.5	1.4	13	6	2
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O’Neil et al. (1989)					

3.6.103 Belly River Group – Iron

Seven of the eleven Belly River Group coal or mixed coal-sandstone aquifer water samples (samples 6, 7, 9, 15, 26, 37, 40) have measured Fe concentrations that exceed the analytical detection limit of 0.01 mg/L. For comparison purposes, two of the five wells completed in Belly River Group sandstone aquifers have an iron concentration that exceeds the analytical detection limit of 0.01 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective of less than or equal to0.3 mg/L Fe for domestic water use has been established. A maximum concentration of 0.3 mg/L Fe has been established for the protection of freshwater aquatic life. A maximum concentration of 5 mg/L has been established for use of water for irrigation purposes. None of the samples collected during this study exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 107. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 107. Belly River Group: Iron.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.017*	0.036*	11	0.09	<0.01
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	0.05	<0.01
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	2.35	1.65	3	3.8	0.55
Belly River – Alberta Basin [c] (Upper Cretaceous)	0.675	1.19	4	2.46	0.01
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.78	0.94	47	4.9	0.2
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	0.447	0.447	13	1.50	.050
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.104 Belly River Group – Manganese

The mean concentration of Mn in Belly River Group coal or mixed coal-sandstone aquifer water samples is 0.049 mg/L, with a standard deviation of 0.265 mg/L (N=11). For comparison purposes, wells completed in Belly River Group sandstone aquifers have a mean Mn concentration of 0.299 mg/L with a standard deviation of 1.05 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective of less than or equal to 0.05 mg/L manganese for domestic water use has been established. A maximum concentration of 0.2 mg/L Mn has been established for the use of water for irrigation purposes. Three of the coal aquifer water samples (samples 5, 27, 35) exceed the aesthetic objective concentration. Two of the coal or mixed coal-sandstone aquifer water samples (samples 5, 35) exceed the recommended maximum concentration value for the use of water for irrigation purposes.

The summary statistics for water samples collected during this study are presented in Table 108. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 108. Belly River Group: Manganese.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.049*	0.265*	11	0.714	<0.005
Belly River wells (Upper Cretaceous) this study -sandstone	0.299*	1.05*	5	2.02	<0.005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.091*	0.26*	21	1.21	<0.001
Belly River – Alberta Basin[b] (Upper Cretaceous)	0.107	0.012	3	0.12	0.1
Belly River – Alberta Basin[c] (Upper Cretaceous)	0.317	0.105	4	0.42	0.17
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.032	0.026	47	0.101	0.002
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	0.097	0.046	13	0.200	0.040
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.105 Belly River Group –Chlorine

Chlorine was determined by an automated ferricyanide method (FCM) and by neutron activation analysis (NAA). The mean concentration of Cl in Belly River Group coal or mixed coal-sandstone aquifer water samples is 196.5 mg/L, with a standard deviation of 595.5 mg/L (N=11) by FCM, whereas the mean concentration of Cl using the NAA method is 158.6 mg/L with a standard deviation of 479 mg/L (N=11). For comparison purposes, wells completed in Belly River Group sandstone aquifers have a mean Cl concentration of 61.2 mg/L with a standard deviation of 85.5 mg/L (N=5) by the FCM and 52.8 mg/L with a standard deviation of 74.7 mg/L (N=5) by the NAA method.

An aesthetic objective of less than or equal to 250 mg/L Cl for domestic water use has been established. A maximum concentration of between 100 and 700 mg/L Cl has been established for the use of water for irrigation purposes. One of the coal aquifer water samples (sample 27) Cl concentrations exceeds the aesthetic objective ands falls within the maximum concentration range for the use of water for irrigation purposes. The complete chemistry dataset can be found in Appendix A, Table 183.

The summary statistics for water samples collected during this study are presented in Table 109. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 109. Belly River Group: Chlorine.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max (mg/L)**	**Min (mg/L)**
Belly River wells (Upper Cretaceous) this study – FCM – coal and mixed coal-sandstone aquifers	196.5*	595.5*	11	1990	<0.5
Belly River wells (Upper Cretaceous) this study – NAA – coal and mixed coal-sandstone aquifers	158.6	479	11	1600	0.6
Belly River wells (Upper Cretaceous) this study – Ferricyanide Method – sandstone	61.2	85.5	5	209	3.5
Belly River wells (Upper Cretaceous) this study – NAA – sandstone	52.8	74.7	5	182	2.2
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	5877	3284	3	8650	2250
Belly River – Alberta Basin[c] (Upper Cretaceous)	8557	1569	4	9590	6250
Belly River – Alberta Basin[d] (Upper Cretaceous)	2250	1351	51	6256	564
Belly River – Alberta Basin[e] (Upper Cretaceous)	3049	3157	1186	34800	0.6
U.S.A. – Powder River Basin[f] (Tertiary)	13.2	12.1	47	64	5.2
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	204.7	343	3	600	4
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	1187	734	6	2499	668
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	1828	1149	13	4200	450
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.106 Belly River Group – Sulphate

The mean concentration of SO_4 in Belly River Group coal or mixed coal-sandstone aquifer water samples is 134.9 mg/L, with a standard deviation of 115.3 mg/L (N=11). For comparison purposes, wells completed in Belly River Group sandstone aquifers have a mean SO_4 concentration of 260.8 mg/L with a standard deviation of 254.5 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective of less than or equal to 500 mg/L SO_4 for domestic water use has been established. A maximum concentration of 1000 mg/L SO_4 has been established for the use of water for livestock purposes. None of the coal aquifer water samples SO_4 concentrations exceed the guideline values.

The summary statistics for water samples collected during this study are presented in Table 110. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 110. Belly River Group: Sulphate.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	134.9	115.3	11	340	27.8
Belly River wells (Upper Cretaceous) this study -sandstone	260.8	254.5	5	567	0.7
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	4.67	2.08	3	7	3
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	91.8	104	51	537	0
Belly River – Alberta Basin [e] (Upper Cretaceous)	165	363	1189	4990	0.5
U.S.A. – Powder River Basin[f] (Tertiary)	2.41	3.63	47	17	0.01
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	56.2	69.2	3	135.5	8.32
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	51.3	66.5	6	166.8	0
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O’Neil et al. (1989)					

3.6.107 Belly River Group – Bicarbonate

The mean concentration of HCO_3 in Belly River Group coal or mixed coal-sandstone aquifer water samples is 634.2 mg/L, with a standard deviation of 214.6 mg/L (N=11). For comparison purposes, wells completed in Belly River Group sandstone aquifers have a mean HCO_3 concentration of 658.2 mg/L with a standard deviation of 61.3 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for HCO_3.

The summary statistics for water samples collected during this study are presented in Table 111. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 111. Belly River Group: Bicarbonate.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	634.2	214.6	11	1040	321
Belly River wells (Upper Cretaceous) this study -sandstone	658.2	61.3	5	732	585
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	765	413	3	1220	413
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	495	271	51	1340	20
Belly River – Alberta Basin [e] (Upper Cretaceous)	538	595	1189	6586	4
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	5737	759	3	6612	5250
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	11833	2961	6	14701	6083
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	883	125	13	1120	670
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.108 Belly River Group – Total Dissolved Solids (TDS)

The mean value of TDS in Belly River Group coal or mixed coal-sandstone aquifer water samples is 1097 mg/L, with a standard deviation of 889 mg/L (N=11). Wells completed in Belly River Group sandstone aquifers have a mean TDS of 1093 mg/L with a standard deviation of 353 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective of TDS less than or equal to 500 mg/L has been established for water for domestic use. Only two of the 11 samples (samples 5, 17) do not exceed the aesthetic objective. A recommended range of TDS values has been established for the use of water for irrigation purposes. The maximum recommended values are between 500 mg/L and 3500 mg/L. Once again, only two of the eleven samples (samples 5, 17) fall below this range. A recommended maximum TDS value of 3000 mg/L has been established for the use of water to be used for livestock purposes. One of the TDS values determined during this study exceeds the guideline value for water to be used for livestock purposes. Sample 27 has a TDS value of 3610 mg/L.

The summary statistics for water samples collected during this study are presented in Table 112. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 112. Belly River Group: Total Dissolved Solids (TDS)

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	1097	889	11	3610	317
Belly River wells (Upper Cretaceous) this study -sandstone	1093	353	5	1520	555
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	14500	2380	4	16000	11000
Belly River – Alberta Basin [d] (Upper Cretaceous)	4347	2156	51	10420	1703
Belly River – Alberta Basin [e] (Upper Cretaceous)	5810	5279	1189	57104	132
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	5737	759	3	6612	5250
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	11833	2961	6	14701	6083
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	883	125	13	1120	670
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.109 Belly River Group – Turbidity

The mean value of turbidity in Belly River Group coal or mixed coal-sandstone aquifer water samples is 4.1 NTU, with a standard deviation of 9.4 NTU (N=11). For comparison purposes, wells completed in Belly River Group sandstone aquifers have a mean turbidity value of 0.8 NTU with a standard deviation of 1.0 NTU (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

Both an aesthetic objective of turbidity less than or equal to 5 NTU and a maximum acceptable value of 1 NTU have been established for water for domestic use. Five of the eleven coal aquifer water samples (samples 5, 6, 17, 27, 35) exceed the maximum acceptable value. Two of the coal aquifer water samples (samples 5, 27) exceed both the maximum acceptable value and the aesthetic objective value.

The summary statistics for water samples collected during this study are presented in Table 113. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 113. Belly River Group: Turbidity.

Water samples					
Location	**Mean (NTU)**	**Std. dev. (NTU)**	**N**	**Max. (NTU)**	**Min. (NTU)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	4.1	9.4	11	32	0.2
Belly River wells (Upper Cretaceous) this study -sandstone	0.8	1.0	5	2.5	0.2
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.110 Belly River Group – Sodium Adsorption Ratio (SAR)

Soils with high concentration of Na^+ in solution generally have poor physical structures (Appelo and Postma, 1994, p. 191). Sodium's large ionic size, single electrical charge and hydration status tends to cause physical separation of soil particles (Warrence et al., 2002). When this separation occurs, repulsive forces begin to dominate and the soil disperses potentially leading to plugging of soil pores (Warrence et al., 2002). Repeated wetting and drying and associated dispersion can lead to the formation of cement-like soil with little or not structure (Warrence et al., 2002). Permeability can be greatly reduced and heavy machinery may not be supported (Appelo and Postma, 1994, p. 191). In order to predict the effects of irrigation water quality on soil properties, the exchangeable sodium ratio (ESR) is calculated.

(1) $ESR = \beta_{Na} / 1- \beta_{Na}$ where β_{Na} is the fraction of exchangeable Na^+

This ESR is related to the activity of Na^+ over the square root of the sum of the Ca^{2+} and Mg^{2+} activities and becomes:

(2) $ESR = 0.5 \times 1000/\sqrt{1000} \times m_{Na+}/(\sqrt{m_{Ca2+}} + m_{Mg2+})$ where m_X is the activity in mmol/L

The ratio of $m_{Na+}/(\sqrt{m_{Ca2+}} + m_{Mg2+})$ is given a specific name, the sodium adsorption ratio or SAR.

Equation 2 upon simplification then becomes:

(3) $ESR = 0.0158 \times SAR$

The critical ESR is equal to 0.15 (Appelo and Postma, 1994, 193) and corresponds to an SAR value of 10. Alberta Agriculture Food and Rural Development specifies that irrigation water with an SAR value greater than 9 may be hazardous for irrigation purposes (Hecker, 2002).

SAR is not an absolute predictor of the suitability of water for irrigation, and will depend on soil conditions since the ratio of Na^+ over the square root of $Ca^{2+} + Mg^{2+}$ may change as a result of reactions in the soil, on the concentrating effect of evapotranspiration and on the water composition (Appelo and Postma, 1994, p. 193).

The mean value of SAR in Belly River Group coal or mixed coal-sandstone aquifer water samples is 32 $(mmol/L)^{0.5}$, with a standard deviation of 24 $(mmol/L)^{0.5}$ (N=11). For comparison purposes, wells completed in Belly River Group sandstone aquifers have a mean SAR of 39 $(mmol/L)^{0.5}$ with a standard deviation of 32 $(mmol/L)^{0.5}$ (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

Three of the coal or mixed coal-sandstone aquifer water samples (samples 5, 17, 35) have SAR values that are below the Alberta Agriculture Food and Rural Development irrigation water guideline of 9 $(mmol/L)^{0.5}$.

The summary statistics for water samples collected during this study are presented in Table 114. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 114. Belly River Group: Sodium Adsorption Ratio (SAR)

Water samples					
Location	**Mean (mmol/L)$^{0.5}$**	**Std. dev. (mmol/L)$^{0.5}$**	**N**	**Max. (mmol/L)$^{0.5}$**	**Min. (mmol/L)$^{0.5}$**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	32	24	11	63	0.5
Belly River wells (Upper Cretaceous) this study - sandstone	39	32	5	66	0.4
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	115	14	3	124	98
Belly River – Alberta Basin[c] (Upper Cretaceous)	98	7	4	103	88
Belly River – Alberta Basin[d] (Upper Cretaceous)	51	19	51	132	19
Belly River – Alberta Basin[e] (Upper Cretaceous)	57	37	1189	212	0.03
U.S.A. – Powder River Basin[f] (Tertiary)	11.7	7.3	47	32	5.7
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	131	21	3	144	107
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	149	45	6	199	111
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	64	18	13	108	43
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O’Neil et al. (1989)					

3.6.111 Belly River Group – Silicon

Silicon concentration was determined by two methods, ICP-MS and APHA ICP method 3120B. The mean concentrations of Si in Belly River Group coal or mixed coal-sandstone aquifer water samples are 5.36 mg/L, with a standard deviation of 1.80 mg/L (N=11) and a mean of 4.78 mg/L with a standard deviation of 1.72 mg/L (N=11) for the two methods listed above respectively. For comparison purposes, wells completed in Belly River Group sandstone aquifers have a mean Si concentration of 5.72 mg/L with a standard deviation of 2.01 mg/L (N=5) using the ICP-MS method and a mean of 6.52 mg/L with a standard deviation of 3.47 mg/L (N=5) using the ICP method. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Si.

The summary statistics for water samples collected during this study are presented in Table 115. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 115. Belly River Group: Silicon.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – ICP-MS – coal and mixed coal-sandstone aquifers	5.36	1.80	11	9.06	3.64
Belly River wells (Upper Cretaceous) this study – ICP – coal and mixed coal-sandstone aquifers	4.78	1.72	11	7.96	3.07
Belly River wells (Upper Cretaceous) This study – ICP-MS – sandstone	5.72	2.01	5	9.12	4.41
Belly River wells (Upper Cretaceous) This study – ICP – sandstone	6.52	3.47	5	11.6	3.44
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	4.76	0.62	47	7.1	3.7
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.112 Belly River Group – Mercury

Mercury concentrations from coal or mixed coal-sandstone aquifer water samples from within the Belly River Group are all below the analytical detection limit of 0.0001 mg/L. Wells completed in Belly River Group sandstone aquifers also have Hg concentrations of less than 0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.001 mg/L has been established for domestic water use. A maximum concentration of 0.0001 mg/L has been established for the protection of freshwater aquatic life. A maximum concentration of 0.003 mg/L has been established for the use of water livestock purposes. None of the water samples have Hg concentrations that exceed the guideline values.

The summary statistics for water samples collected during this study are presented in Table 116. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 116. Belly River Group: Mercury.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	-	<0.0001
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	0.000913	<0.000002
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	0.00025	<0.000005
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.113 Belly River Group – Aluminum

None of the coal or mixed coal-sandstone aquifer water samples from the Belly River Group has an Al concentration above the detection limit of 0.005 mg/L. Wells completed in Belly River Group sandstone aquifers also have Al concentrations of less than 0.005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An interim aluminum concentration of 0.1 mg/L has been recommended for domestic water use. A maximum concentration of between 0.005 and 0.100 mg/L has been established for the protection of freshwater aquatic life. A maximum concentration of 5.0 mg/L has been established for the use of water for irrigation and livestock purposes.

The summary statistics for water samples collected during this study are presented in Table 117. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 117. Belly River Group: Aluminum.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	-	<0.005
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	-	<0.005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.05
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.114 Belly River Group – Antimony

None of the coal or mixed coal-sandstone aquifer water samples from the Belly River formation have Sb concentrations above the detection limit of 0.0002 mg/L. One of the five wells completed in Belly River Group sandstone aquifers has an Sb concentration above the analytical detection limit of 0.0002 mg/L. The Sb concentration in this sample (sample 16) is 0.0009 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An interim maximum acceptable concentration of 0.006 mg/L has been recommended for domestic water use. All of the water samples have concentrations that fall below this guideline value.

The summary statistics for water samples collected during this study are presented in Table 118. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 118. Belly River Group: Antimony.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	-	<0.0002
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	0.0009	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.002
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.115 Belly River Group – Arsenic

Nine of the 11 coal or mixed coal-sandstone aquifer water samples from the Belly River Group have As concentrations above the detection limit of 0.0002 mg/L. The mean concentration is 0.0012 mg/L with a standard deviation of 0.0036 mg/L (N=11). Three of the five wells completed in Belly River Group sandstone aquifers have As concentrations above the detection limit of 0.0002 mg/L. The mean As concentration is 0.0009 mg/L with a standard deviation of 0.023 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.025 mg/L has been established for domestic water use. A maximum concentration of 0.005 mg/L has been established for the protection of freshwater aquatic life. Maximum concentrations of 0.100 mg/L and 0.025 mg/L have been established for the use of water for irrigation and livestock purposes respectively. None of the coal or mixed coal-sandstone aquifer water samples have As concentrations that exceed the guideline values.

The summary statistics for water samples collected during this study are presented in Table 119. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 119. Belly River Group: Arsenic.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.0012*	0.0036*	11	0.0109	<0.0002
Belly River wells (Upper Cretaceous) this study -sandstone	0.0009*	0.023*	5	0.0353	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	0.0249	<0.0004
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.0004*	0.0004*	47	0.0026	<0.0002
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	0.0183	0.0302	13	0.110	0.001
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.116 Belly River Group – Barium

The mean concentration of Ba in coal or mixed coal-sandstone aquifer water samples from the Belly River Group is 0.22 mg/L with a standard deviation of 0.60 mg/L (N=11). Wells completed in Belly River Group sandstone aquifers have a mean Ba concentration of 0.048 mg/L with a standard deviation of 0.057 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 1.0 mg/L has been established for domestic water use. One of the coal aquifer water samples (sample 27) has a Ba concentration of 2.02 mg/L and exceeds this guideline value.

The summary statistics for water samples collected during this study are presented in Table 120. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 120. Belly River Group Summary Table Barium

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.219	0.600	11	2.02	0.013
Belly River wells (Upper Cretaceous) this study -sandstone	0.048	0.057	5	0.146	0.009
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.149	0.169	21	0.761	0.007
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	39.5	8.7	4	47	27
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.617	0.300	47	1.60	0.14
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.117 Belly River Group – Beryllium

None of the coal or mixed coal-sandstone aquifer water samples from the Belly River Group contain Be above the analytical detection limit of 0.0001 mg/L. Wells completed in Belly River Group sandstone aquifers have Be concentrations less than the detection limit. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.100 mg/L has been established for the use of water for irrigation and livestock purposes. All of the water samples have concentrations that fall below these guideline values.

The summary statistics for water samples collected during this study are presented in Table 121. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 121. Belly River Group: Beryllium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	-	<0.0001
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.118 Belly River Group – Bismuth

None of the coal or mixed coal-sandstone aquifer water samples from the Belly River Group contain Bi concentrations above the analytical detection limit of 0.0005 mg/L. Wells completed in Belly River Group sandstone aquifers have Bi concentrations less than 0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental water-quality guidelines have not been developed for Bi.

The summary statistics for water samples collected during this study are presented in Table 122. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 122. Belly River Group: Bismuth.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	-	<0.0005
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	-	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	0.032	<0.020
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.119 Belly River Group – Boron

The mean concentration of B in coal or mixed coal-sandstone aquifer water samples from the Belly River Group is 0.666 mg/L with a standard deviation of 0.574 mg/L (N=11). Wells completed in Belly River Group sandstone aquifers have a mean B concentration of 0.706 mg/L with a standard deviation of 0.553 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

An interim maximum acceptable concentration of 5 mg/L has been established for domestic water use. The range of maximum concentrations for water to be used for irrigation purposes is between 0.500 and 6 mg/L. The maximum concentration for water to be used for livestock purposes is 5 mg/L. Six of the coal or mixed coal-sandstone aquifer water sample B concentrations (samples 6, 9, 15, 26, 27, 40) fall within the maximum concentration range for B in water to be used for irrigation purposes. Boron concentrations of 1.97, 1.41, 0.667, 0.666, 0.761 and 0.651 mg/L respectively were determined in these water samples.

The summary statistics for water samples collected during this study are presented in Table 123. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 123. Belly River Group: Boron.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.666	0.574	11	1.97	0.061
Belly River wells (Upper Cretaceous) this study -sandstone	0.706	0.553	5	1.45	0.021
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	4	-	2	5	3
Belly River – Alberta Basin[c] (Upper Cretaceous)	8.5	8.4	4	21	3
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	0.217	<0.100
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.120 Belly River Group – Cadmium

One of the 11 coal or mixed coal-sandstone aquifer water samples (sample 17) from the Belly River Group contains Cd above the analytical detection limit of 0.00001 mg/L. The value determined in this water sample was 0.00005 mg/L. One of five wells completed in Belly River Group sandstone aquifers has a Cd concentration above the detection limit of 0.00005 mg/L. The Cd concentration in this water well (sample 16) is 0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been developed for Cd. A maximum acceptable concentration of 0.005 mg/L has been established for domestic water use. A maximum concentration value of 0.000017 mg/L has been established for the protection of freshwater aquatic life. The maximum concentration in water to be used for irrigation purposes is 0.0051 mg/L. The maximum concentration in water to be used for livestock purposes is 0.080 mg/L. None of the coal or mixed coal-sandstone aquifer water samples exceed the guideline values.

The summary statistics for water samples collected during this study are presented in Table 124. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 124. Belly River Group: Cadmium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	0.00005	<0.00001
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	0.0001	<0.00001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	0.00011	<0.00005
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	0.0009*	0.0002*	13	0.001	<0.001
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.121 Belly River Group – Chromium

The mean Cr concentration in coal or mixed coal-sandstone water samples from the Belly River Group is 0.005 mg/L with a standard deviation of 0.005 mg/L (N=11). Wells completed in Belly River Group sandstone aquifers have a mean Cr concentration of 0.004 mg/L with a standard deviation of 0.002 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been developed for Cr. A maximum acceptable concentration of 0.05 mg/L has been established for domestic water use. A maximum concentration value of 0.0089 mg/L has been established for the protection of freshwater aquatic life. The maximum concentration in water to be used for irrigation purposes is 0.0049 mg/L. The maximum concentration in water to be used for livestock purposes is 0.050 mg/L. One of the mixed coal-sandstone aquifer water samples (sample 27) exceeds the guideline values for the protection of freshwater aquatic life. Three of the coal or mixed coal-sandstone aquifer water samples (samples 9, 27, 35) exceed the guideline value for irrigation purposes.

The summary statistics for water samples collected during this study are presented in Table 125. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 125. Belly River Group: Chromium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.005	0.005	11	0.021	0.001
Belly River wells (Upper Cretaceous) this study -sandstone	0.004	0.002	5	0.0063	0.0019
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	21	-	<0.001
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	0.0009*	0.0002*	13	0.001	<0.001
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.122 Belly River Group – Cobalt

Eight of the 11 Belly River Group coal or mixed coal-sandstone aquifer water samples have Co concentrations above the analytical detection limit of 0.0001 mg/L. The mean concentration for these water samples is 0.0002 mg/L with a standard deviation of 0.0002 mg/L (N=11). Four of the five wells completed in Belly River Group sandstone aquifers have a Co concentration above the analytical detection limit. A mean of 0.0006 mg/L with a standard deviation of 0.0004 mg/L (N=5) was calculated for the sandstone aquifer samples. The complete chemistry dataset is found in Appendix A, Table 183.

The maximum concentration of cobalt in water to be used for irrigation purposes is 0.050 mg/L. The maximum concentration in water to be used for livestock purposes is 1.00 mg/L. None of the water samples exceed the guideline values.

The summary statistics for water samples collected during this study are presented in Table 126. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 126. Belly River Group: Cobalt.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.0002*	0.0002*	11	0.0004	<0.0001
Belly River wells (Upper Cretaceous) this study -sandstone	0.0005*	0.0004*	5	0.0010	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	0.0002	<0.0001
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.123 Belly River Group – Copper

Six of the 11 coal or mixed coal-sandstone aquifer water samples have Cu concentrations above the analytical detection limit of 0.001 mg/L. The mean Cu concentration in these samples is 0.001 mg/L with a standard deviation of 0.001 mg/L (N=11). Two of the five wells completed in Belly River Group sandstone aquifers have Cu concentrations above the analytical detection limit of 0.001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective concentration of less than or equal to 1.00 mg/L has been established for domestic water use. The range of maximum acceptable concentrations of Cu for the protection of aquatic life is between 0.002 and 0.004 mg/L. The range of maximum concentrations in water to be used for irrigation purposes is between 0.200 and 1.00 mg/L. The range of maximum concentrations in water to be used for livestock purposes is between 0.500 and 5.00 mg/L. None of the coal or mixed coal-sandstone aquifer water samples have Cu concentrations that exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 127. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 127. Belly River Group: Copper.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max (mg/L)**	**Min (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.001*	0.001*	11	0.003	<0.001
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	0.002	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.009*	0.0042*	21	0.148	<0.002
Belly River – Alberta Basin[b] (Upper Cretaceous)	0.143	0.107	3	0.26	0.05
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	5.36	4.26	47	28.6	1.5
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.124 Belly River Group – Lead

Four of the 11 Belly River Group coal or mixed coal-sandstone aquifer water samples (samples 6, 9, 37, 40) have Pb concentrations above the analytical detection limit of 0.0001 mg/L. Lead concentrations in these water samples are 0.0003, 0.0001, 0.0003 and 0.0004 mg/L respectively. One of the five wells (sample 38) completed in a Belly River Group sandstone aquifer has a Pb concentration of greater than the detection limit of 0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.010 mg/L has been established for domestic water use. The range of maximum acceptable concentrations of Pb for the protection of aquatic life is between 0.001 and 0.007 mg/L. The maximum Pb concentration in water to be used for irrigation purposes is 0.200 mg/L. The maximum Pb concentration in water to be used for livestock purposes is 0.100 mg/L. None of the water samples exceeds these guideline values.

The summary statistics for water samples collected during this study are presented in Table 128. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 128. Belly River Group: Lead.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	0.0004	<0.0001
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	0.0006	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.00043*	0.00060*	21	0.0057	<0.00001
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	0.00043	<0.0001
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	0.00028*	0.00031*	13	0.100	<0.001
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O’Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.125 Belly River Group – Lithium

The mean Li concentration in the coal or mixed coal-sandstone aquifer water samples from the Belly River Group is 0.063 mg/L with a standard deviation of 0.043 mg/L (N=11). Wells completed in Belly River Group sandstone aquifers have a mean Li concentration of 0.077 mg/L with a standard deviation of 0.050 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

The maximum Li concentration in water to be used for irrigation purposes is 2.50 mg/L. None of the water sample Li concentrations exceeds this value.

The summary statistics for water samples collected during this study are presented in Table 129. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 129. Belly River Group: Lithium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.063	0.043	11	0.162	0.026
Belly River wells (Upper Cretaceous) this study -sandstone	0.077	0.050	5	0.147	0.015
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	0.357	0.17	3	0.52	0.18
Belly River – Alberta Basin[c] (Upper Cretaceous)	1	0	4	1	1
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.052	0.036	47	0.208	0.018
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.126 Belly River Group – Molybdenum

Seven of the 11 (samples 5, 6, 7, 15, 17, 26, 37) Belly River coal or mixed coal-sandstone aquifer water samples have Mo concentration above the analytical detection limit of 0.001 mg/L. The mean Mo concentration of these water samples is 0.002 mg/L with a standard deviation of 0.004 mg/L (N=11). Two of the five wells completed in Belly River Group sandstone aquifers have a Mo concentration above the analytical detection limit of 0.001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The maximum acceptable concentration for the protection of freshwater aquatic life is 0.073 mg/L. The range of maximum Mo concentrations in water to be used for irrigation purposes is between 0.010 and 0.050 mg/L. The maximum Mo concentration in water to be used for livestock purposes is 0.500 mg/L. One of the coal aquifer water sample (sample 15) Mo concentrations falls within the maximum concentration range for water to be used for irrigation purposes.

The summary statistics for water samples collected during this study are presented in Table 130. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the Unites States are presented for comparison purposes.

Table 130. Belly River Group: Molybdenum.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.002*	0.004*	11	0.013	<0.001
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	0.007	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.0013*	0.0013*	21	0.0043	<0.00005
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.127 Belly River Group – Nickel

None of the Belly River coal or mixed coal-sandstone aquifer water samples have Ni concentrations above the analytical detection limit of 0.0005 mg/L. Water wells completed in Belly River Group sandstone aquifers have Ni concentrations less than 0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The range of maximum acceptable concentrations of Ni for the protection of freshwater aquatic life is between 0.025 and 0.150 mg/L. The maximum Ni concentration in water to be used for irrigation purposes is 0.200 mg/L. The maximum Ni concentration in water to be used for livestock purposes is 1.00 mg/L. None of the water samples exceeds these guideline values.

The summary statistics for water samples collected during this study are presented in Table 131. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 131. Belly River Group: Nickel.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	-	<0.0005
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	-	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.00037*	0.00055*	21	0.0021	<0.0002
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.0065*	0.0068*	47	0.0354	<0.0005
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.128 Belly River Group – Selenium

One of the Belly River coal aquifer water samples (sample 15) has a Se concentration above the analytical detection limit of 0.0002 mg/L. The Se concentration in this water sample is 0.0004 mg/L. Wells completed in Belly River Group sandstone aquifers have Se concentrations less than 0.0002 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of 0.010 mg/L has been established for domestic water use. The maximum acceptable concentration for the protection of freshwater aquatic life is 0.001 mg/L. The range of maximum Se concentrations in water to be used for irrigation purposes is between 0.020 and 0.050 mg/L. The maximum Se concentration in water to be used for livestock purposes is 0.050 mg/L. None of the water samples exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 132. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 132. Belly River Group: Selenium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	0.0004	<0.0002
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	-	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.002
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O’Neil et al. (1989)					

3.6.129 Belly River Group – Silver

All of the Belly River coal or mixed coal-sandstone aquifer water samples have Ag concentrations below the analytical detection limit of 0.0001 mg/L. Wells completed in Belly River Group sandstone aquifers also have Ag concentrations less than 0.0005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

The maximum acceptable concentration of Ag in water for the protection of freshwater aquatic life is 0.0001 mg/L. None of the water samples exceed this guideline value.

The summary statistics for water samples collected during this study are presented in Table 133. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 133. Belly River Group: Silver.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	-	<0.0001
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	-	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.001
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.130 Belly River Group – Strontium

The mean concentration of Sr within Belly River Group coal or mixed coal-sandstone aquifer water samples is 0.442 mg/L with a standard deviation of 0.501 mg/L (N=11). Wells completed in Belly River Group sandstone aquifers have a mean Sr concentration of 0.338 mg/L with a standard deviation of 0.413 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have not been developed for Sr.

The summary statistics for water samples collected during this study are presented in Table 134. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 134. Belly River Group: Strontium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.442	0.501	11	1.69	0.056
Belly River wells (Upper Cretaceous) this study -sandstone	0.338	0.413	5	1.03	0.046
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	9.6	6.4	3	13.3	2.2
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.692	0.412	47	1.9	0.1
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	2.13	1.95	13	7.20	0.27
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.131 Belly River Group – Thallium

None of the water samples collected from Belly River Group coal or mixed coal-sandstone aquifers have Tl concentrations that exceed the analytical detection limit of 0.00005 mg/L. Wells completed in Belly River Group sandstone aquifers have Tl concentrations less than 0.00005 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been developed for maximum Tl concentrations for the protection of freshwater aquatic organisms. The value is 0.0008 mg/L. None of the water samples exceeds these guideline values.

The summary statistics for water samples collected during this study are presented in Table 135. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 135. Belly River Group: Thallium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	-	<0.00005
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	-	<0.00005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	0.00034	<0.0002
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.132 Belly River Group – Titanium

Nine of the 11 coal or mixed coal-sandstone aquifer water samples from the Belly River Group has Ti concentrations above the analytical detection limit of 0.0005 mg/L. A mean of 0.028 mg/L and a standard deviation of 0.061 mg/L (N=11) were determined for the coal or mixed coal-sandstone aquifer water samples. Four of the five sandstone aquifer wells completed in Belly River Group sandstone aquifers have Ti concentrations above the analytical detection limit. These water samples have a mean Ti concentration of 0.046 mg/L with a standard deviation of 0.119 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have not been developed for Ti.

The summary statistics for water samples collected during this study are presented in Table 136. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 136. Belly River Group: Titanium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.028*	0.061*	11	0.13	<0.0005
Belly River wells (Upper Cretaceous) this study -sandstone	0.038*	0.137*	5	0.263	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.050
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.133 Belly River Group – Vanadium

Four of the 11 water samples (samples 6, 9, 37, 40) collected from Belly River Group coal or mixed coal-sandstone aquifers have V concentrations that exceed the analytical detection limit of 0.0001 mg/L. These samples have concentrations of 0.0008, 0.0006, 0.0008 and 0.0015 mg/L respectively. Two of the five wells completed in Belly River Group sandstone aquifers have V concentrations above the analytical detection limit of 0.0001 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

Canadian environmental quality guidelines have been developed for V concentrations in water for irrigation and livestock purposes. The maximum V concentration in water for irrigation and livestock purposes is 0.100 mg/L. None of the observed V concentrations exceeds these guidelines.

The summary statistics for water samples collected during this study are presented in Table 137. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 137. Belly River Group: Vanadium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	0.0015	<0.0001
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	0.0021	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.0002
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.134 Belly River Group – Zinc

The Belly River Group coal or mixed coal-sandstone aquifer water sample mean Zn concentration is 0.069 mg/L with a standard deviation of 0.193 mg/L (N=11). Three of the five wells completed in Belly River Group sandstone aquifers have a Zn concentration above the analytical detection limit of 0.001 mg/L. The mean Zn concentration of these water samples is 0.002 mg/L with a standard deviation of 0.026 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

An aesthetic objective concentration of less than or equal to 5.00 mg/L has been established for Zn concentrations in water for domestic use. A maximum concentration of 0.030 mg/L has been established for the protection of freshwater aquatic life. The range of maximum concentrations in water for irrigation purposes is between 1.00 and 5.00 mg/L. The maximum concentration in water for livestock purposes is 50 mg/L. Two of mixed coal-sandstone aquifer water samples (samples 17, 27) have Zn concentrations that exceed the maximum concentration of Zn in water for the protection of aquatic life.

The summary statistics for water samples collected during this study are presented in Table 138. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 138. Belly River Group: Zinc.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.069	0.193	11	0.645	0.001
Belly River wells (Upper Cretaceous) this study -sandstone	0.002*	0.026*	5	0.041	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.065	0.113	21	0.470	0.0007
Belly River – Alberta Basin[b] (Upper Cretaceous)	1.07	1.71	3	3.05	0.08
Belly River – Alberta Basin[c] (Upper Cretaceous)	0.35	0.48	2	0.69	0.01
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	0.0804	<0.001
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	0.032*	0.063*	13	0.240	<0.005
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.135 Belly River Group – Fluorine

The Belly River Group coal or mixed coal-sandstone aquifer water sample mean fluorine concentration is 2.1 ppm with a standard deviation of 1.5 ppm (N=11). The mean fluorine concentration of the sandstone aquifer water samples is 1.7 ppm with a standard deviation of 1.4 ppm (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

A maximum allowable concentration of 1.5 mg/L has been established for fluoride concentrations in water for domestic use. Samples 6, 7, 9, 15, 18, 26, 27, 37, 38 and 40 may have observed fluorine concentrations that could exceed this guideline. The maximum recommended concentration of fluoride in water for use for irrigation purposes is 1.0 mg/L. The maximum recommended concentration of fluoride in water for use for livestock purposes is between 1.0 and 2.0 mg/L. Samples 6, 7, 9, 15, 18, 26, 27, 35, 37, 38, 39 and 40 may have observed fluorine concentrations that could exceed these agricultural guidelines.

The summary statistics for water samples collected during this study are presented in Table 139. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 139. Belly River Group: Fluorine.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	2.1*	1.5*	11	6.1	<0.5
Belly River wells (Upper Cretaceous) this study -sandstone	1.7*	1.4*	5	3.9	<0.5
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.92	0.32	47	1.7	0.42
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.136 Belly River Group – Bromine

Nine of the 11 water samples collected from Belly River Group coal or mixed coal-sandstone aquifers have measurable Br concentrations. A mean of 1.5 mg/L with a standard deviation of 4.3 mg/L (N=11) was determined for these samples. Three of five wells completed in Belly River Group sandstone aquifers have measurable Br concentrations. The mean Br concentration in the sandstone aquifer water samples is 0.15 mg/L with a standard deviation of 1.75 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Br.

The summary statistics for water samples collected during this study are presented in Table 140. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 140. Belly River Group: Bromine

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	1.5*	4.3*	11	14.6	<0.045
Belly River wells (Upper Cretaceous) this study -sandstone	0.15*	1.75*	5	2.7	<0.048
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.11*	0.18*	47	0.85	<0.02
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.137 Belly River Group – Iodine

Five of the 11 water samples collected from Belly River Group coal or mixed coal-sandstone aquifers have measurable I concentrations. Two of the five wells completed in Belly River Group sandstone aquifers have measurable I concentrations. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for I.

The summary statistics for water samples collected during this study are presented in Table 141. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 141. Belly River Group: Iodine.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	6.3	<0.0069
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	0.7	<0.016
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.138 Belly River Group – Scandium

The mean Sc concentration in water samples collected from coal or mixed coal-sandstone aquifers in the Belly River Group is 0.0001 mg/L with a standard deviation of 0.00006 mg/L (N=11). Wells completed in Belly River Group sandstone aquifers have a mean Sc concentration of 0.0001 mg/L with a standard deviation of 0.00004 mg/L (N=5). The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Sc.

The summary statistics for water samples collected during this study are presented in Table 142. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 142. Belly River Group: Scandium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.0001	0.00006	11	0.0003	0.0001
Belly River wells (Upper Cretaceous) this study -sandstone	0.0001	0.00004	5	0.0002	0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)					
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.00120*	0.00079*	47	0.003	<0.0001
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.139 Belly River Group – Rubidium

None of the Belly River Group coal or mixed coal-sandstone aquifer water samples have measurable Rb concentrations. None of the wells completed in Belly River Group sandstone aquifers have measurable Rb concentrations. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for Rb.

The summary statistics for water samples collected during this study are presented in Table 143. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 143. Belly River Group: Rubidium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	-	<0.0052
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	-	<0.0052
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	0.12	0.05	3	0.18	0.08
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	0.0118	0.0061	47	0.0382	0.0041
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.140 Belly River Group – Gross Alpha and Gross Beta Radiation

Three of the 11 Belly River Group coal or mixed coal-sandstone aquifer water samples (samples 5, 9, 17) have measurable gross alpha radioactivity of 0.5, 0.6 and 0.1 Bq/L respectively. Seven of the 11 Belly River coal or mixed coal-sandstone aquifer water samples (samples 5, 6, 7, 9, 15, 17, 35) have measurable gross beta radioactivity. The mean gross beta radioactivity value for these water samples is 0.11 Bq/L with a standard deviation of 0.099 Bq/L (N=11). Three of the wells completed in Belly River Group sandstone aquifers have measurable gross alpha (samples 16, 38, 39) and gross beta (samples 10, 16, 39) radioactivity levels. The mean gross alpha and beta radioactivities for the sandstone aquifer water samples are 0.12 Bq/L with standard deviations of 0.08 Bq/L (N= 5). The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for gross alpha and gross beta radioactivity levels in water.

The summary statistics for water samples collected during this study are presented in Table 144 and Table 145. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 144. Belly River Group: Gross Alpha Radiation.

Water samples – Gross alpha					
Location	**Mean (Bq/L)**	**Std. dev. (Bq/L)**	**N**	**Max. (Bq/L)**	**Min. (Bq/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	0.6	<0.1
Belly River wells (Upper Cretaceous) this study -sandstone	0.12*	0.08*	5	0.2	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

Table 145. Belly River Group: Gross Beta Radiation.

Water samples –Gross beta					
Location	**Mean (Bq/L)**	**Std. dev. (Bq/L)**	**N**	**Max. (Bq/L)**	**Min. (Bq/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.11*	0.099*	11	0.3	<0.1
Belly River wells (Upper Cretaceous) this study -sandstone	0.12*	0.08*	5	0.2	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.141 Belly River Group – Thorium

Five of the 11 Belly River Group coal or mixed coal-sandstone aquifer water samples (samples 9, 17, 35, 37, 40) have measurable Th concentrations of 0.0004, 0.0002, 0.0003, 0.001 and 0.0006 mg/L respectively. Two of the five wells completed in Belly River Group sandstone aquifers have measurable Th concentrations. The complete chemistry dataset is found in Appendix A, Table 183.

No Canadian environmental quality guidelines have been established for total concentration of Th in water. A maximum acceptable level of radioactivity of 0.1 Bq/L has been established in water for domestic use. None of the radioactivity levels for Th are above this value.

The summary statistics for water samples collected during this study are presented in Table 146. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 146. Belly River Group: Thorium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	0.001	<0.00014
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	0.0007	<0.00015
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.020
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.142 Belly River Group – Uranium

None of the Belly River coal or mixed coal-sandstone aquifer water samples has a measurable U concentration. A well completed in a Belly River Group sandstone aquifer has a U concentration of 0.003 mg/L. The complete chemistry dataset is found in Appendix A, Table 183.

A maximum acceptable concentration of U of 0.100 mg/L has been established for water for domestic purposes. A maximum concentration of 0.010 mg/L has been established for water used for irrigation purposes. A maximum concentration of 0.200 mg/L has been established for water used for livestock purposes. None of the observed U concentrations are above these guideline values. Maximum acceptable levels of radioactivity of 4 Bq/L for ^{234}U, ^{235}U and ^{238}U have been established for U in water for domestic use. None of the observed radioactivity levels exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 147. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 147. Belly River Group: Uranium.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	0.002	<0.001
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	0.004	<0.003
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.0014*	0.0023*	21	0.0078	<0.000005
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	-	<0.020
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)					

3.6.143 Belly River Group – Phenols

Three of the 11 coal or mixed coal-sandstone aquifer water samples (samples 26, 27, 40) from the Belly River Group have phenols concentrations above the analytical detection limit of 0.001 mg/L. The samples have concentrations of 0.001, 0.002 and 0.011 mg/L respectively. None of the five water samples from sandstone aquifers within the Belly River Group has a phenols concentration above the detection limit of 0.001 mg/L. The entire chemistry dataset is found in Appendix A, Table 183.

Canadian environmental water quality guideline maximum concentrations for the protection of freshwater aquatic life and for the use of water for livestock purposes of 0.004 mg/L and 0.002 mg/L respectively have been established. One of the mixed coal-sandstone aquifer water samples has a phenols concentration that exceeds the maximum concentration for the use of water for livestock purposes.

The summary statistics for water samples collected during this study are presented in the table below (Table 148). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 148. Belly River Group: Phenols.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	-	-	11	0.011	<0.001
Belly River wells (Upper Cretaceous) this study -sandstone	-	-	5	-	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.144 Belly River Group – Non-Halogenated Aromatic Hydrocarbons (BTEX)

None of the coal or mixed coal-sandstone aquifer water samples from the Belly River Group have BTEX concentrations above the analytical detection limits of 0.001 mg/L. Water samples from sandstone aquifers within the Belly River Group have BTEX concentrations less than 0.001 mg/L. The entire chemistry dataset is found in Appendix A, Table 183.

The table below (Table 149) lists the Canadian environmental water quality guideline maximum concentrations for benzene, toluene, ethylbenzene and xylene. None of the measured concentrations of BTEX exceeds these values.

Table 149. Canadian environmental water-quality guideline values for BTEX.

Parameter	Domestic water use		Aquatic life – freshwater (mg/L)	Agriculture	
	MAC,IMAC (mg/L)	AO (mg/L)		Irrigation (mg/L	Livestock (mg/L)
Benzene	0.005	-	0.370	-	-
Toluene	-	≤ 0.024	0.002	-	0.024
Ethylbenzene	-	≤ 0.0024	0.090	-	0.0024
Xylene	-	≤ 0.300	-	-	-

The summary statistics for water samples collected during this study are presented in Table 150. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 150. Belly River Group: BTEX.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.666	0.574	11	1.97	0.061
Belly River wells (Upper Cretaceous) this study -sandstone	0.706	0.553	5	1.45	0.021
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	4	-	2	5	3
Belly River – Alberta Basin [c] (Upper Cretaceous)	8.5	8.4	4	21	3
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	47	0.217	<0.100
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.145 Belly River Group – Purgeable and Extractable Hydrocarbons

Five of the 11 coal or mixed coal-sandstone aquifer water samples (samples 6, 7, 17, 26, 37) from the Belly River Group have a purgeable hydrocarbon concentration at or above the analytical detection limits of 0.01 mg/L. The purgeable hydrocarbon concentrations in these water samples are 0.01, 0.03, 0.16, 0.02 and 0.02 mg/L respectively. One of the five water samples from sandstone aquifers within the Belly River Group has a purgeable hydrocarbons concentration of above the analytical detection limit of 0.01 mg/L. The concentration in this water sample is 0.01 mg/L. See Appendix A, Table 183 for dataset.

One of the 11 coal aquifer water samples (sample 35) has an extractable hydrocarbons concentration at or above the analytical detection limit of 0.1 mg/L. The concentration of extractable hydrocarbons in this water sample is 0.4 mg/L. All of the water samples from sandstone aquifers within the Belly River Group have an extractable hydrocarbons concentration less than 0.1 mg/L. See Appendix A, Table 183 for dataset.

The summary statistics for water samples collected during this study are presented in the table below (Table 151). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 151. Belly River Group: Purgeable and extractable hydrocarbons.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max (mg/L)**	**Min (mg/L)**
Belly River wells (Tertiary-Cretaceous) this study – purgeable hydrocarbons – coal and mixed coal-sandstone aquifers	-	-	11	0.16	<0.01
Belly River wells (Tertiary-Cretaceous) this study – purgeable hydrocarbons – sandstone aquifers	-	-	5	0.01	<0.01
Belly River wells (Tertiary-Cretaceous) this study – extractable hydrocarbons – coal and mixed coal-sandstone aquifers	-	-	11	0.4	<0.1
Belly River wells (Tertiary-Cretaceous) this study – extractable hydrocarbons – sandstone aquifers	-	-	5	-	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.6.146 Belly River Group – Polycyclic Aromatic Hydrocarbons (PAH)

None of the 11 coal or mixed coal-sandstone aquifer water samples from the Belly River Group have PAH concentrations above the analytical detection limits. Water samples from sandstone aquifers within the Belly River Group also have PAH concentrations below the analytical detection limits. The complete dataset is found in Appendix A, Table 183.

The table below (Table 152) lists the Canadian environmental water quality guideline maximum concentrations for PAHs in water. None of the measured concentrations of PAHs exceeds these values.

Table 152. Canadian environmental water-quality guideline values for PAHs.

Parameter	Domestic water use		Aquatic life – freshwater (mg/L)	Agriculture	
	MAC,IMAC (mg/L)	AO (mg/L)		Irrigation (mg/L	Livestock (mg/L)
Naphthalene	-	-	0.0011	-	-
Acenaphthylene	-	-	-	-	-
Acenaphthene	-	-	0.0058	-	-
Fluorene	-	-	0.003	-	-
Phenanthrene	-	-	0.0004	-	-
Anthracene	-	-	0.00012	-	-
Acridine	-	-	0.0044	-	-
Fluoranthene	-	-	0.00004	-	-
Pyrene	-	-	0.000025	-	-
Benzo(a)anthracene	-	-	0.000018	-	-
Chrysene	-	-	-	-	-
Benzo(b)fluoranthene	-	-	-	-	-
Benzo(k)fluoranthene	0.005	-	0.370	-	-
Benzo(a)pyrene	0.00001	-	0.000015	-	-
Indeno(1,2,3-c,d)pyrene	-	≤ 0.0024	0.090	-	0.0024
Dibenzo(a,h)anthracene	-	-	-	-	-
Benzo(g,h,I)perylene	-	-	-	-	-

The summary statistics for water samples collected during this study are presented in (Table 153). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 153. Belly River Group: PAHs.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal and mixed coal-sandstone aquifers					
Naphthalene	-	-	11	-	<0.0001
Acenaphthylene	-	-	11	-	<0.0001
Acenaphthene	-	-	11	-	<0.0001
Fluorene	-	-	11	-	<0.0001
Phenanthrene	-	-	11	-	<0.0001
Anthracene	-	-	11	-	<0.0001
Acridine	-	-	11	-	<0.00005
Fluoranthene	-	-	11	-	<0.0001
Pyrene	-	-	11	-	<0.00002
Benzo(a)anthracene	-	-	11	-	<0.00001
Chrysene	-	-	11	-	<0.0001
Benzo(b)fluoranthene	-	-	11	-	<0.00001
Benzo(k)fluoranthene	-	-	11	-	<0.00001
Benzo(a)pyrene	-	-	11	-	<0.00001
Indeno(1,2,3-c,d)pyrene	-	-	11	-	<0.0001
Dibenzo(a,h)anthracene	-	-	11	-	<0.00001
Benzo(g,h,I)perylene	-	-	11	-	<0.0001
Belly River wells[a] (Tertiary-Cretaceous)					
Pyrene	-	-	21	-	<0.0001
Benzo(b,j,k)fluoranthene	-	-	21	-	<0.0001
Benzo(a)pyrene	-	-	21	-	<0.0001
Indeno(1,2,3-cd)pyrene	-	-	21	-	<0.0001
Dibenz(ah,ai,aj)pyrene	-	-	21	-	<0.0001
U.S.A. – Black Warrior Basin[d] (Pennsylvanian)					
Naphthalene	-	-	1	-	<0.30
Acenaphthylene	-	-	1	-	<0.50
Acenaphthene	-	-	1	-	<1.00
Fluorene	-	-	1	-	<0.07
Phenanthrene	-	-	1	-	<0.03
Anthracene	-	-	1	-	<0.02
Fluoranthene	-	-	1	-	<0.10
Pyrene	-	-	1	-	<0.10
Benzo(a)anthracene	-	-	1	-	<0.05
Benzo(k)fluoranthene	-	-	1	-	<0.20
Benzo(a)pyrene	-	-	1	-	<0.07
Dibenzo(a,h)anthracene	-	-	1	-	<0.20
Benzo(g,h,I)perylene	-	-	1	-	<0.20
Indeno(1,2,3-c,d)pyrene	-	-	1	-	<0.20
Chrysene	-	-	1	-	<0.03
Benzo(b)fluoranthene	-	-	1	-	<0.20
Data sources:					
[a] Goodarzi (2002)					
[d] O’Neil et al. (1989)					

3.6.147 Belly River Group – Adsorbable Organic Halides

The mean concentration of adsorbable organic halides from water samples taken from coal or mixed coal-sandstone aquifers within the Belly River Group is 0.024 mg/L with a standard deviation of 0.040 mg/L (N=11). Water samples from sandstone aquifers within the Belly River Group have a mean adsorbable organic halides concentration of 0.005 mg/L with a standard deviation of 0.002 mg/L (N=5). The entire chemistry dataset can be found in Appendix A, Table 183.

Canadian environmental quality guidelines have not been defined specifically for total adsorbable organic halides.

The summary statistics for water samples collected during this study are presented in the table below (Table 154). In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 154. Belly River Group: Adsorbable organic halides.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Belly River wells (Upper Cretaceous) this study – coal or mixed coal-sandstone aquifers	0.024	0.040	11	0.11	0.0027
Belly River wells (Upper Cretaceous) this study -sandstone	0.005	0.002	5	0.009	0.0038
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [b] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [c] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [d] (Upper Cretaceous)	-	-	-	-	-
Belly River – Alberta Basin [e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[f] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[g] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[h] (Pennsylvanian)	-	-	-	-	-
Data sources:					
[a] Goodarzi (2002)					
[b] Hitchon et al. (1971)					
[c] Connolly et al. (1990a)					
[d] Michael (2002)					
[e] Bachu and Michael (2002)					
[f] Rice et al. (2000)					
[g] Decker et al. (1987)					
[h] O'Neil et al. (1989)					

3.7 Stable Isotopes

3.7.1 Oxygen and Hydrogen

Oxygen has three stable isotopes, with abundances as follows (Firestone, 2000): ^{16}O (abundance 99.76215%), ^{17}O (abundance 0.0383%) and ^{18}O (abundance 0.20012%). Hydrogen has two stable isotopes (Firestone, 2000): ^{2}H (Abundance 0.015%) and ^{1}H (Abundance 99.985%). Research into the abundance and variation of oxygen isotopes in the hydrosphere has found that a change in ^{18}O versus ^{16}O in precipitation is accompanied by a change in ^{2}H versus ^{1}H (Friedman, 1953). Craig (1961) discovered that these two isotopes are partitioned by meteorological processes in a predictable manner. The effect of these processes provides a characteristic fingerprint of their origin, which is fundamental to investigating the provenance of groundwater (Clark and Fritz, 1997, p. 36).

The measured values of $\delta^{18}O$ and $\delta^{2}H$ are usually compared to a meteoric water line in order to assess the similarities between the water samples and global or local precipitation, and then infer the reasons for any differences. Samples collected during this project are compared to two such meteoric water lines, a Global Meteoric Water Line (GMWL) and an Approximate Edmonton Meteoric Water Line (AEMWL). The Rozanski et al. (1993) GMWL was chosen over the Craig (1961) GMWL because it is a more recent interpretation of the data. The equation for the line is as follows:

$\delta^{2}H = 8.17\delta^{18}O + 11.27$

The AEMWL was constructed using data collected between 1960 and 1969 from a sample site in Edmonton and compiled into the Global Network for Isotopes in Precipitation Database (International Atomic Energy Agency-World Meteorological Organization, 2001). Linear regression of the data results in a line with the following equation:

$\delta^{2}H = 7.66\delta^{18}O - 1.00$

This equation differs slightly from the meteoric water line equation established by Maulé et al. (1994) for the period 1985 to 1987. Regression analysis of these data results in a line with the following equation:

$\delta^{2}H = 7.32\delta^{18}O - 6.35$

In addition, the sample results are compared to data reported by Connolly et al. (1990b) and Hitchon and Friedman (1969). From these data, formation water line equations were determined using regression of the data from each investigation and are designated as the Connolly Formation Water Line (CFWL) and the Hitchon-Friedman Formation Water Line (HFFWL). The equations are as follows:

$\delta^{2}H = 3.57\delta^{18}O - 62.1$ CWFL

$\delta^{2}H = 3.81\delta^{18}O - 72.8$ HFFWL

3.7.1.1 Observations – Paskapoo-Scollard Formation

The mean $\delta^{18}O$ value in water samples from Paskapoo-Scollard Formation mixed coal-sandstone aquifers is –16.3‰ VSMOW, with a standard deviation of 2.0‰ VSMOW (N=6). For comparison purposes, a water sample from a Paskapoo-Scollard sandstone aquifer has a $\delta^{18}O$ value of –17.6‰ VSMOW. The complete chemistry dataset is provided in Appendix A (Table 184).

The mean $\delta^{2}H$ value in water samples from Paskapoo-Scollard mixed coal-sandstone aquifers is –138‰ VSMOW, with a standard deviation of 12‰ VSMOW (N=6). For comparison purposes, a water sample from a Paskapoo-Scollard sandstone aquifer has a $\delta^{2}H$ value of –146‰ VSMOW. The complete chemistry dataset is provided in Appendix A (Table 184).

The summary statistics for water samples collected during this study are presented in Table 155.

Table 155. Paskapoo-Scollard Formation: $\delta^{18}O$ and $\delta^{2}H$.

Location	Mean (‰ VSMOW)	Std. dev. (‰ VSMOW)	N	Max. (‰ VSMOW)	Min. (‰ VSMOW)
Water samples: $\delta^{18}O$					
Paskapoo-Scollard wells (Tertiary-Cretaceous): this study	-16.9	2.0	6	-13.0	-17.9
Water samples: $\delta^{2}H$					
Paskapoo-Scollard wells (Tertiary-Cretaceous): this study	-138	12	6	-117	-151

All of the water samples fall below the GMWL, the AEMWL and the CFWL (Figure 26): samples 23, 29, 42, 44 and 45 fall below the HFFWL; sample 46 falls on the HFFWL; and sample 22 falls above the HFFWL. Samples 22, 45 and 46 have more enriched $\delta^{18}O$ values than the mean annual precipitation value reported for Edmonton, samples 22 and 46 have more enriched $\delta^{2}H$ values than the mean annual precipitation value reported for Edmonton (Figure 26).

The samples fall along a line with the following equation:

$\delta^{2}H = 6.12\delta^{18}O – 38.03$ ($R^2 = 0.9527$)

An increase of depth corresponds to an enrichment in $\delta^{18}O$ and $\delta^{2}H$ (Figure 27, Figure 28). The equations of the lines are as follows:

$\delta^{18}O = 0.0445\text{Depth} – 18.87$ ($R^2 = 0.8026$)

$\delta^{2}H = 0.2653\text{Depth} – 153.09$ ($R^2 = 0.7257$)

No obvious trends appear to exist between either $\delta^{2}H$ or $\delta^{18}O$ and well elevation, water temperature and TDS.

3.7.1.2 Observations – Horseshoe Canyon Formation

The mean $\delta^{18}O$ value in water samples from Horseshoe Canyon Formation coal aquifers is -17.4 ‰ VSMOW, with a standard deviation of 2.4 ‰ VSMOW (N=6). The mean $\delta^{18}O$ value in water samples from Horseshoe Canyon mixed coal-sandstone aquifers is –17.7 ‰ VSMOW, with a standard deviation of 1.4 ‰ VSMOW (N=13). For comparison purposes, a water sample from a Horseshoe Canyon Formation sandstone aquifer has a $\delta^{18}O$ value of –17.2 ‰ VSMOW. The complete chemistry dataset is found in Appendix A (Table 184).

The mean $\delta^{2}H$ value in water samples from Horseshoe Canyon Formation coal aquifers is -147 ‰ VSMOW, with a standard deviation of 14 ‰ VSMOW (N=6). The mean $\delta^{2}H$ value in water samples from Horseshoe Canyon Formation mixed coal-sandstone aquifers is –146 ‰ VSMOW, with a standard deviation of 9 ‰ VSMOW (N=13).For comparison purposes, a water sample from a Horseshoe Canyon Formation sandstone aquifer has a $\delta^{2}H$ value of –143 ‰ VSMOW. The complete chemistry dataset is found in Appendix A (Table 184).

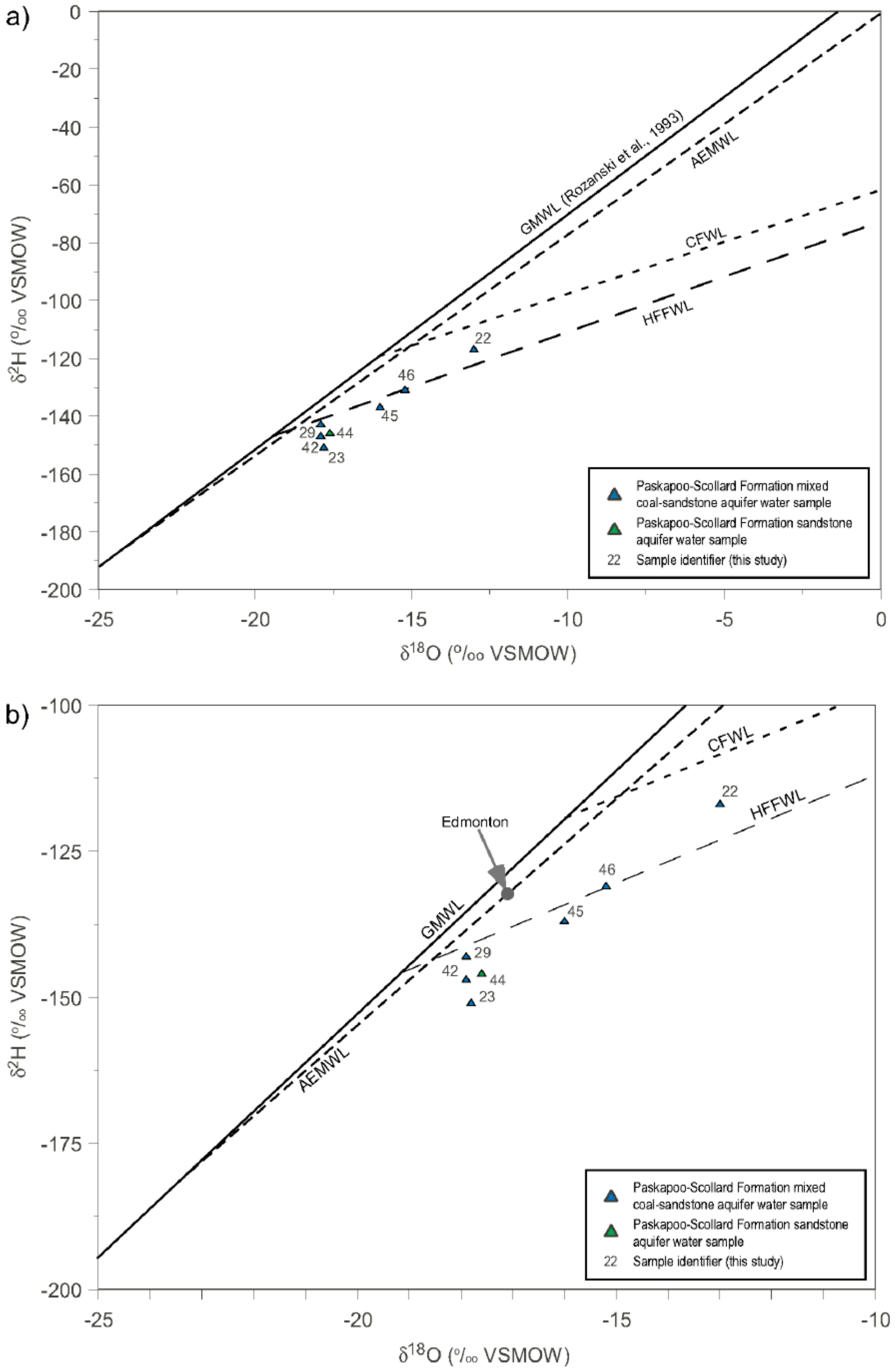


Figure 26. Paskapoo-Scollard Formation: a) δ^2H vs. δ^{18}O; and b) δ^2H vs. δ^{18}O (more detailed view). Abbreviations: AEMWL, Appropriate Edmonton Meteoric Water Line; CFWL, Connolly Formation Water Line; GMWL, Global Meteoric Water Line; HFFWL, Hitchon Friedman Formation Water Line; VSMOW, Vienna Standard Mean Ocean Water.

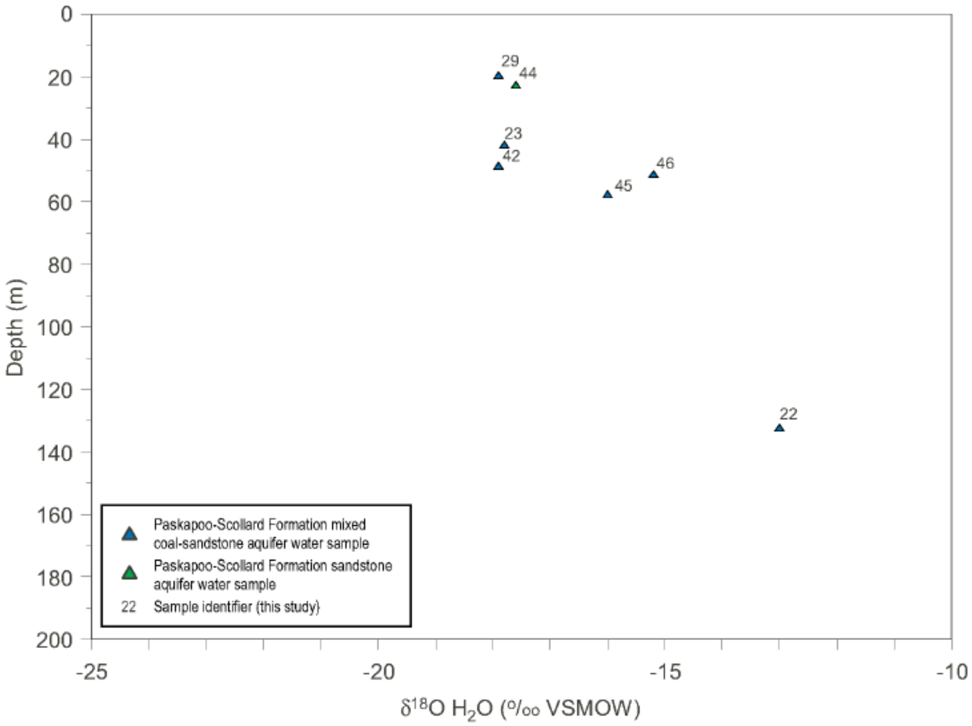


Figure 27. Paskapoo-Scollard Formation: δ^{18}O vs. depth. Abbreviation: VSMOW, Vienna Standard Mean Ocean Water.

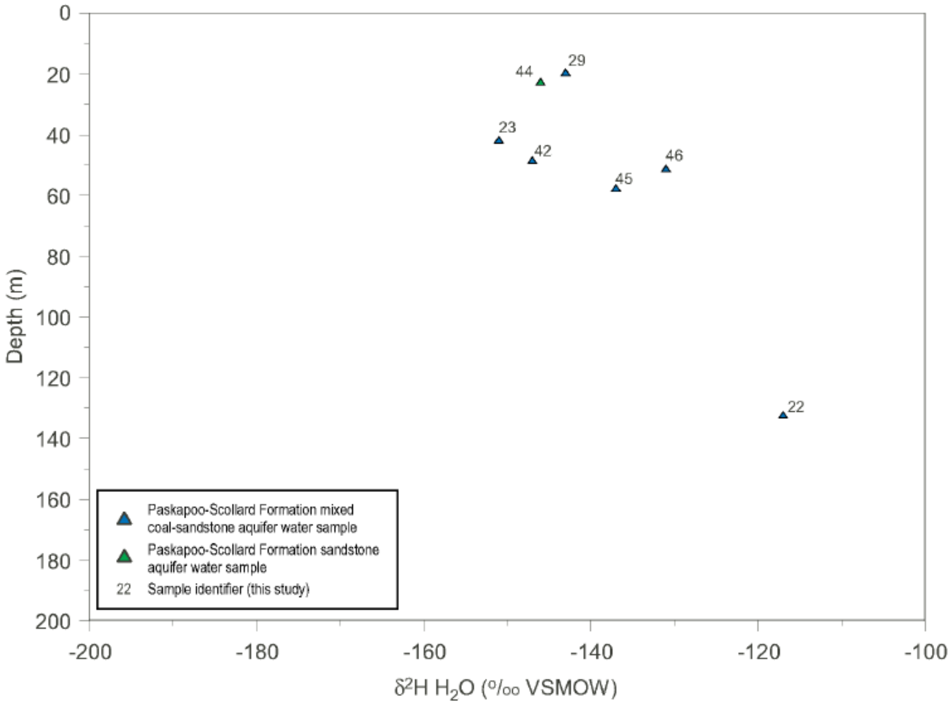


Figure 28. Paskapoo-Scollard Formation: δ^2 H vs. depth. Abbreviation: VSMOW, Vienna Standard Mean Ocean Water.

The summary statistics for water samples collected during this study are presented in Table 156 below.

Table 156. Horseshoe Canyon Formation: $\delta^{18}O$ and $\delta^{2}H$.

Location	Mean (‰ VSMOW)	Std. dev. (‰ VSMOW)	N	Max. (‰ VSMOW)	Min. (‰ VSMOW)
Water samples: $\delta^{18}O$					
Horseshoe Canyon wells (Upper Cretaceous): this study (coal aquifers)	-17.4	2.4	6	-13.7	-19.9
Horseshoe Canyon wells (Upper Cretaceous): this study (mixed coal-sandstone aquifers)	-17.7	1.4	13	-15.8	-19.5
Water samples: $\delta^{2}H$					
Horseshoe Canyon wells (Upper Cretaceous): this study (coal aquifers)	-147	14	6	-129	-164
Horseshoe Canyon wells (Upper Cretaceous): this study (mixed coal-sandstone aquifers)	-146	9	13	-132	-160

Samples 30 and 34 plot above the HFFWL (Figure 29). Sample 24 falls on the HFFWL. All of the samples fall below the GMWL, the AEMWL and the CFWL. Samples 21, 24, 25, 30, 32, 33, 34 and 36 have more enriched $\delta^{18}O$ values than the mean annual precipitation value reported for Edmonton. Samples 25 and 30 have more enriched $\delta^{2}H$ values than the mean annual precipitation value reported for Edmonton.

The samples fall along a line with the following equation:

$\delta^{2}H = 5.99\delta^{18}O - 41.33$ $\quad$ ($R^2 = 0.9072$)

No obvious trends appear to exist between $\delta^{2}H$ or $\delta^{18}O$ and well elevation, water temperature and TDS.

3.7.1.3 Observations – Belly River Group

The mean $\delta^{18}O$ value in water samples from Belly River Group coal aquifers is –18.6 ‰ VSMOW, with a standard deviation of 2.9 ‰ VSMOW (N=3). The mean $\delta^{18}O$ value in water samples from Belly River Group mixed coal-sandstone aquifers water samples is –17.3 ‰ VSMOW, with a standard deviation of 2.0 ‰ VSMOW (N=7). For comparison purposes, water samples from Belly River Group sandstone aquifers have a mean $\delta^{18}O$ value of –17.7 ‰ VSMOW, with a standard deviation of 1.6 ‰ VSMOW (N=5). The complete chemistry dataset is found in Appendix A, Table 184.

The mean $\delta^{2}H$ value in water samples from Belly River Group coal aquifers is –150 ‰ VSMOW, with a standard deviation of 14 ‰ VSMOW (N=3). The mean $\delta^{2}H$ value in water samples from Belly River Group mixed coal-sandstone aquifers is –143 ‰ VSMOW, with a standard deviation of 15 ‰ VSMOW (N=7). For comparison purposes, water samples from Belly River Group sandstone aquifers have a mean $\delta^{2}H$ value of –147 ‰ VSMOW, with a standard deviation of 9 ‰ VSMOW (N=5). The complete chemistry dataset is found in Appendix A, Table 184.

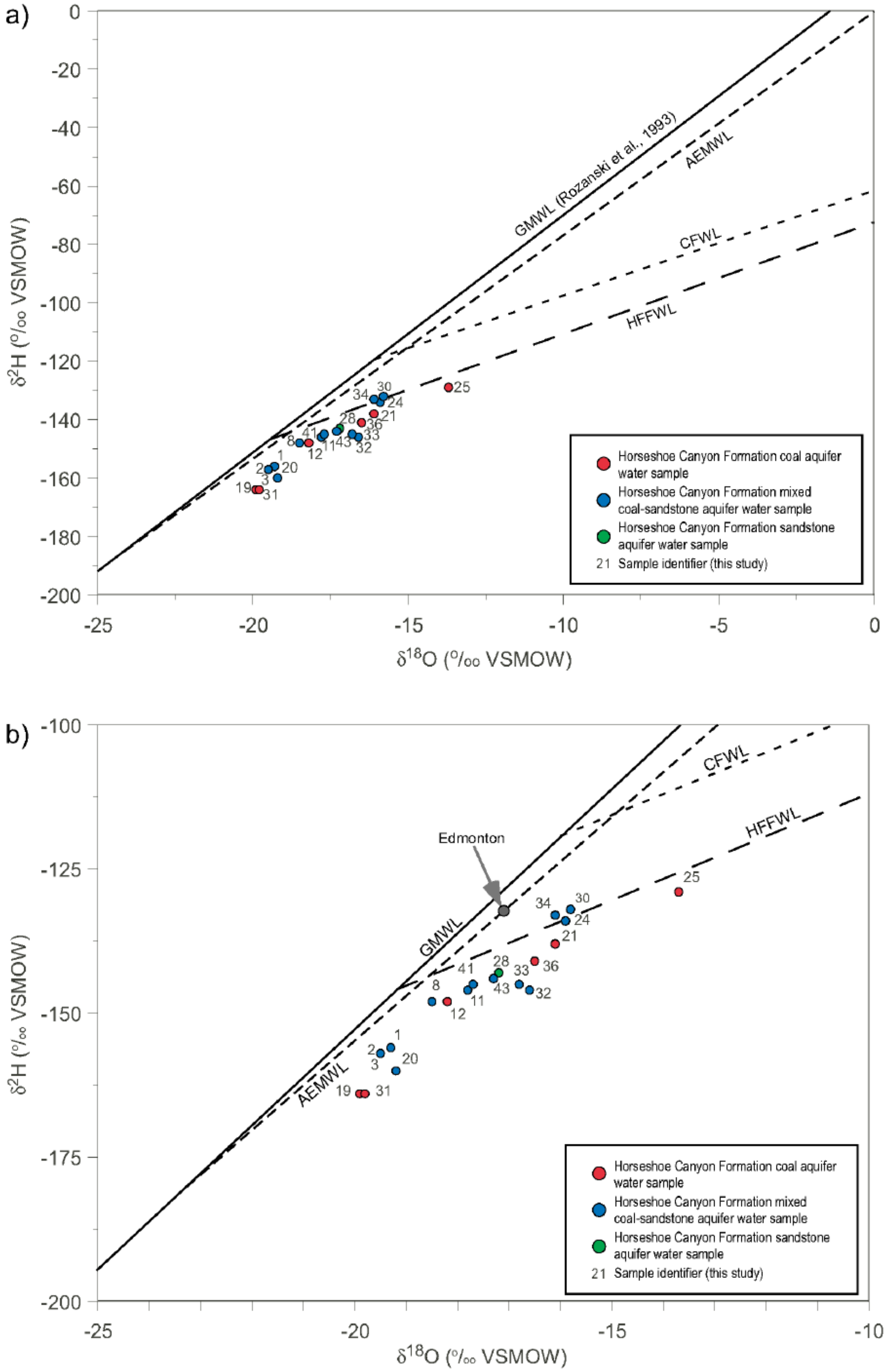


Figure 29. Horseshoe Canyon Formation: a) δ² H vs. δ¹⁸ O; and b) δ² H vs. δ¹⁸ O (more detailed view). Abbreviations: AEMWL, Approximate Edmonton Meteoric Water Line; CFWL, Connolly Formation Water Line; GMWL, Global Meteoric Water Line; HFFWL, Hitchon Friedman Formation Water Line; VSMOW, Vienna Standard Mean Ocean Water.

The summary statistics for water samples collected during this study are presented in Table 157 below.

Table 157. Belly River Group: $\delta^{18}O$ and $\delta^{2}H$.

Location	Mean (‰ VSMOW)	Std. dev. (‰ VSMOW)	N	Max. (‰ VSMOW)	Min. (‰ VSMOW)
Water samples $\delta^{18}O$					
Belly River Group wells (Upper Cretaceous) this study – coal aquifers	-18.6	2.9	3	-15.9	-21.6
Belly River Group wells (Upper Cretaceous) this study – mixed coal-sandstone aquifers	-17.3	1.9	8	-13.8	-19.0
Belly River Group wells (Upper Cretaceous) this study – sandstone aquifers	-17.7	1.6	5	-15.9	-19.3
Belly River Group (Upper Cretaceous) from Connolly et al. (1990b)	-10.2	0.2	3	-10.0	-10.4
Belly River Group (Upper Cretaceous) from Hitchon and Friedman (1969)	-9.5	0.4	3	-9.2	-10.0
Water samples $\delta^{2}H$					
Belly River Group wells (Upper Cretaceous) this study – coal aquifers	-150	14	3	-137	-164
Belly River Group wells (Upper Cretaceous) this study – mixed coal-sandstone aquifers	-143	14	8	-118	-154
Belly River Group wells (Upper Cretaceous) this study – sandstone aquifers	-147	9	5	-137	-155
Belly River Group (Upper Cretaceous) from Connolly et al. (1990b)	-100	1	3	-99	-101
Belly River Group (Upper Cretaceous) from Hitchon and Friedman (1969)	-113	9	3	-104	-121

Sample 15 plots slightly above the GMWL and above the AEMWL (Figure 30). The $\delta^{18}O$ and $\delta^{2}H$ values of sample 15 (-21.6 ‰ and –164 ‰) fall within the range of isotopic values reported for precipitation that fell between the months of November and May, 1961 to 1969 (International Atomic Energy Agency, 2001). Samples 17 and 27 plot above the HFFWL. The remaining samples plot below the GMWL, the AEMWL, the CFWL and the HFFWL. Samples 16, 17, 18, 27 and 35 have more enriched $\delta^{18}O$ values than the mean annual precipitation value reported for Edmonton. Samples 17 and 27 have more enriched $\delta^{2}H$ values than the mean annual precipitation value reported for Edmonton.

The samples fall along a line with the following equation:

$\delta^{2}H = 6.00\delta^{18}O - 39.44$ $(R^2 = 0.9447)$

Connolly et al. (1990b) and Hitchon and Friedman (1969) reported the following values for $\delta^{18}O$ and $\delta^{2}H$ for formation water samples from the Belly River Group (Table 158). Calculated values using the equation above and the $\delta^{18}O$ values reported by Connolly et al. (1990b) and Hitchon and Friedman (1969) are also included in (Table 158).

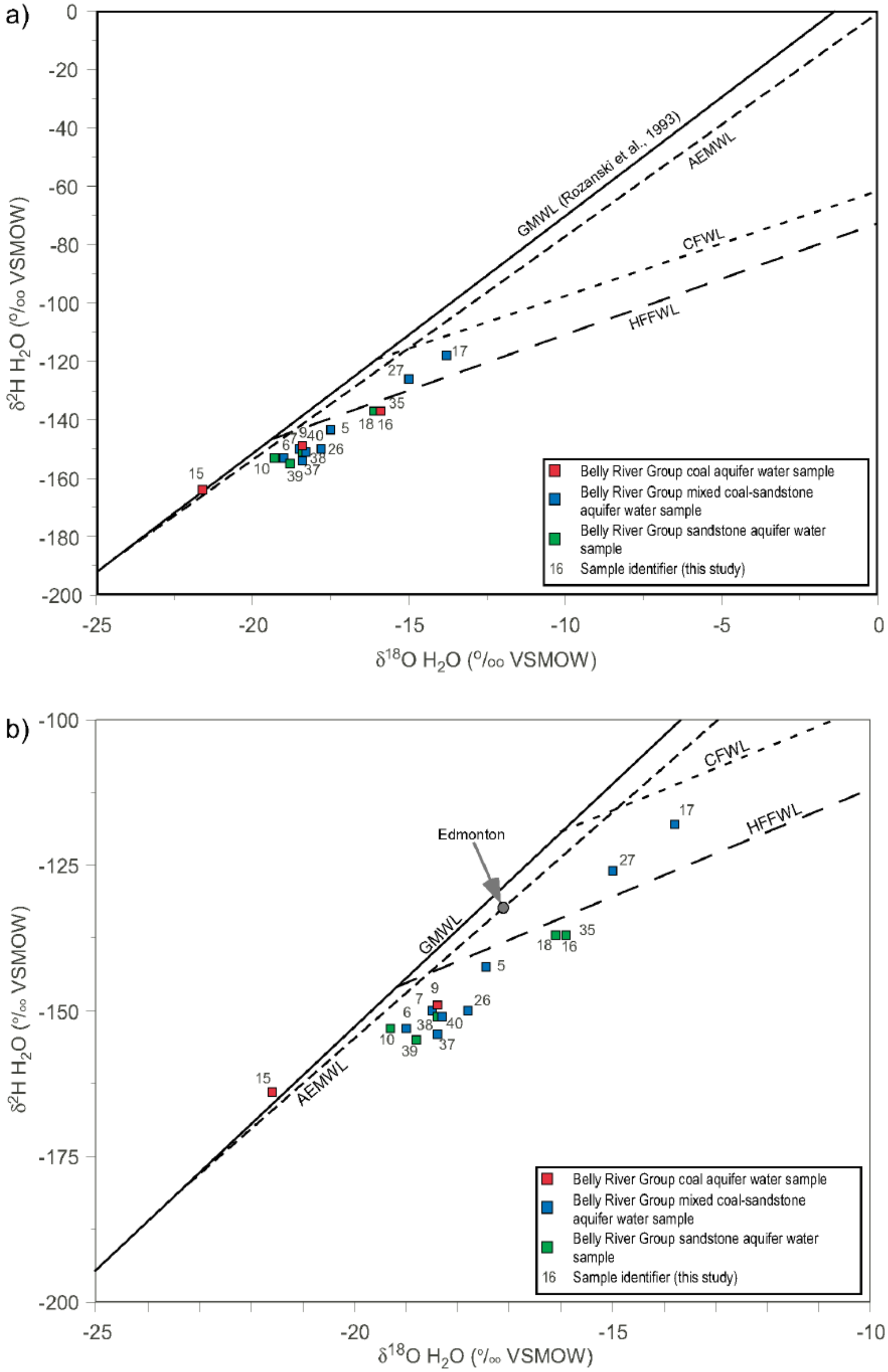


Figure 30. Belly River Formation: a) δ^2H vs. $\delta^{18}O$; and b) δ^2H vs. $\delta^{18}O$ (more detailed view). Abbreviations: AEMWL, Appropriate Edmonton Meteoric Water Line; CFWL, Connolly Formation Water Line; GMWL, Global Meteoric Water Line; HFFWL, Hitchon Friedman Formation Water Line; VSMOW, Vienna Standard Mean Ocean Water.

Table 158. Belly River Group: Summary (Hitchon and Friedman, 1969; Connolly et al., 1990b).

Formation	$\delta^{18}O$ (‰ SMOW)	$\delta^{2}H$ (‰ SMOW)	$\delta^{2}H$ Calculated (‰ VSMOW)
Belly River[a]	-10.3	-99	-101
Belly River[a]	-10.4	-100	-102
Belly River[a]	-10.0	-101	-99
Belly River[b]	-9.4	-114	-96
Belly River[b]	-9.2	-104	-95
Belly River[b]	-10.0	-121	-99
Sources:			
[a]Connolly et al. (1990b)			
[b]Hitchon and Friedman (1969)			

The calculated values correspond closely to those reported by Connolly et al. (1990b).

A relationship appears to exist between TDS and O and H for the water samples collected from coal aquifers (Figure 31 and Figure 32). Linear regression yields the following equations:

$\delta^{18}O = -0.0091TDS - 9.12$ $(R^2 = 0.8677)$

$\delta^{2}H = -0.0425TDS - 105.31$ $(R^2 = 0.8463)$

A relationship also appears to exist between temperature and O and H for the water samples collected from coal aquifers (Figure 33 and Figure 34). Linear regression yields the following equations.

$\delta^{18}O = -1.5\text{Temperature} - 7.31$ $(R^2 = 0.8873)$

$\delta^{2}H = -7.1\text{Temperature} - 96.76$ $(R^2 = 0.8663)$

These relationships are based on three data points.

No obvious trends appear to exist between $\delta^{2}H$ or $\delta^{18}O$ and water temperature and TDS for wells completed in mixed coal-sandstone or sandstone aquifer water samples.

3.7.1.4 Preliminary Interpretation – General

Linear regression of the data from all three coal-bearing intervals yields equations with very similar slopes and intercepts. Correlation coefficients are all greater than 0.90. This suggests that a similar process is controlling the isotopic composition of the aquifer water samples regardless of which formation the aquifer belongs to.

The line generated from the equations intercepts the AEMWL at a point that coincides with the $\delta^{18}O$ and $\delta^{2}H$ values of precipitation samples collected in Edmonton between the months of November and May, 1961 to 1969, as part of the Global Network of Isotopes in Precipitation initiative (Figure 35). The line intercepts the CFWL at a point that closely approximates the measured $\delta^{18}O$ and $\delta^{2}H$ values of formation-water samples collected by Connolly et al. (1990b) from the Belly River Group (Table 158, Figure 35). This suggests that a two-component mixing system could be responsible for the observed isotopic values. Because of the intercept position along the AEMWL, the meteoric-water end member is likely snow. Because of the intercept position along the CFWL, the formation-water end member is likely Upper

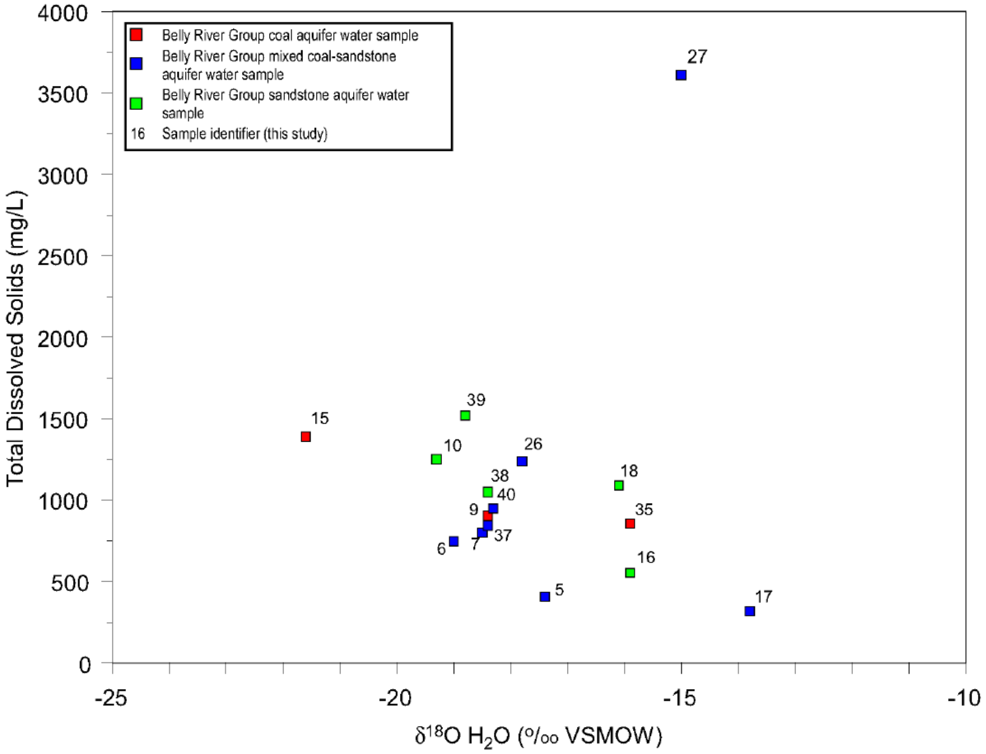


Figure 31. Belly River Group: $\delta^{18}O$ vs. Total Dissolved Solids. Abbreviation: VSMOW, Vienna Standard Mean Ocean Water.

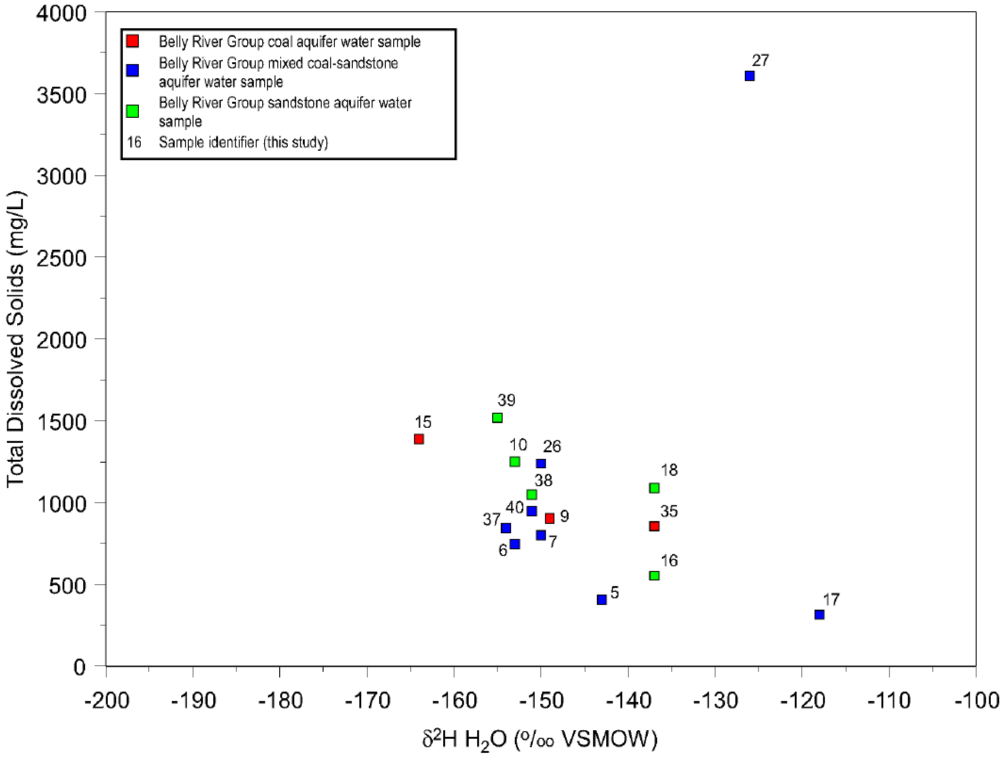


Figure 32. Belly River Group: $\delta^{2}H$ vs. Total Dissolved Solids. Abbreviation: VSMOW, Vienna Standard Mean Ocean Water

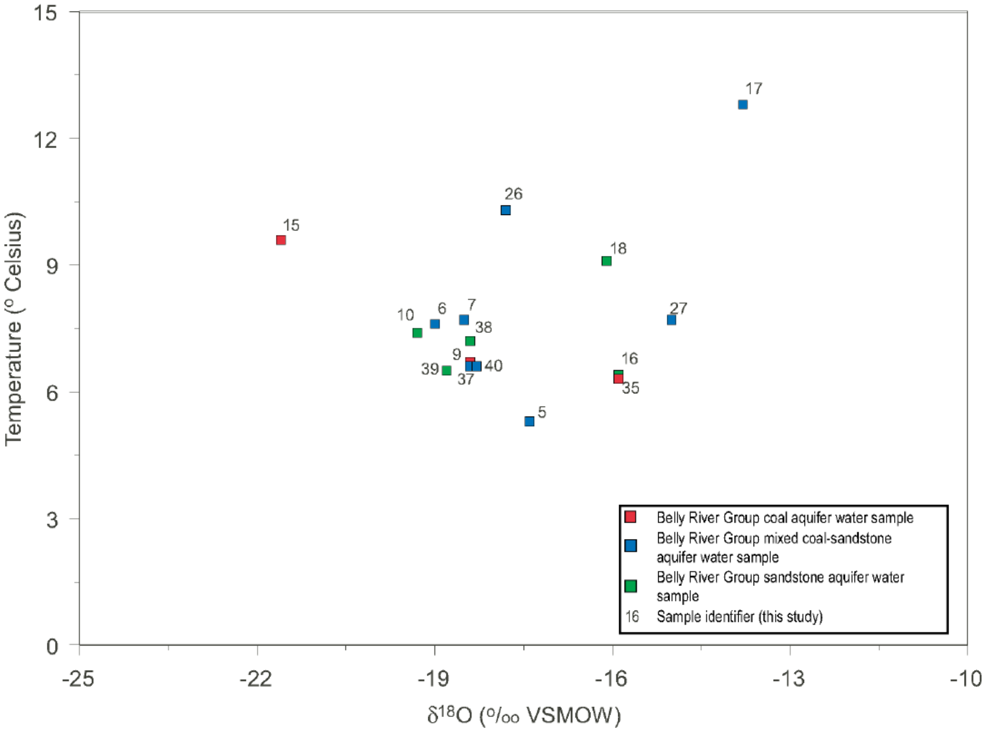


Figure 33. Belly River Group. Temperature vs. δ^{18}O. Abbreviation: VSMOW, Vienna Standard Mean Ocean Water.

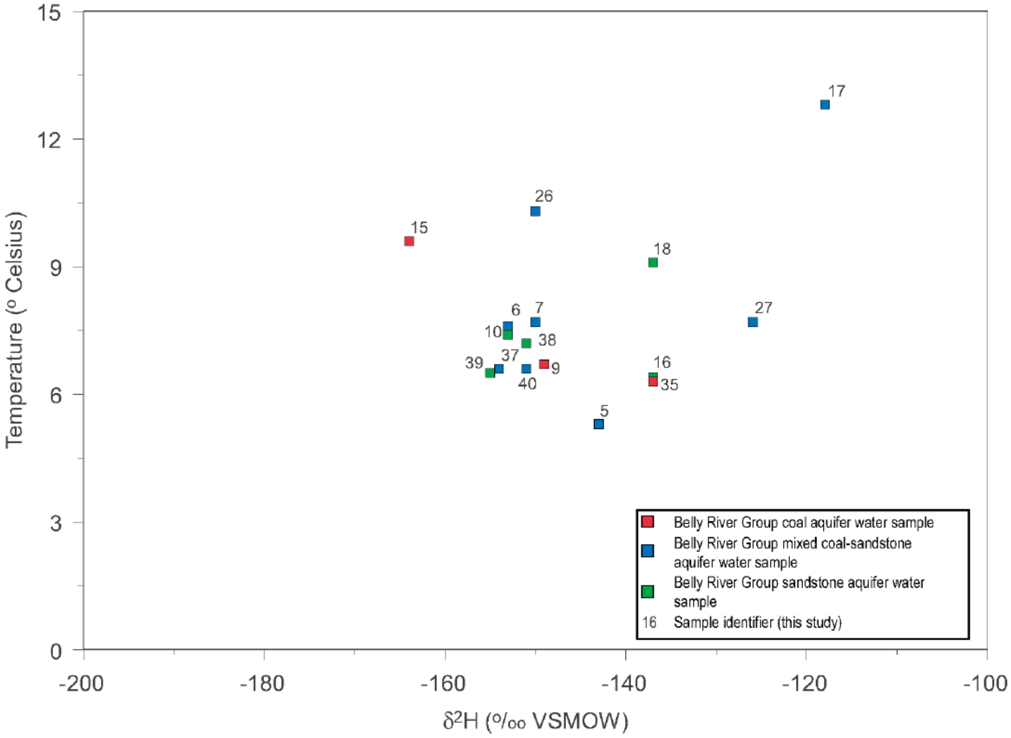


Figure 34. Belly River Group. Temperature vs. δ^{2}H. Abbreviation: VSMOW, Vienna Standard Mean Ocean Water.

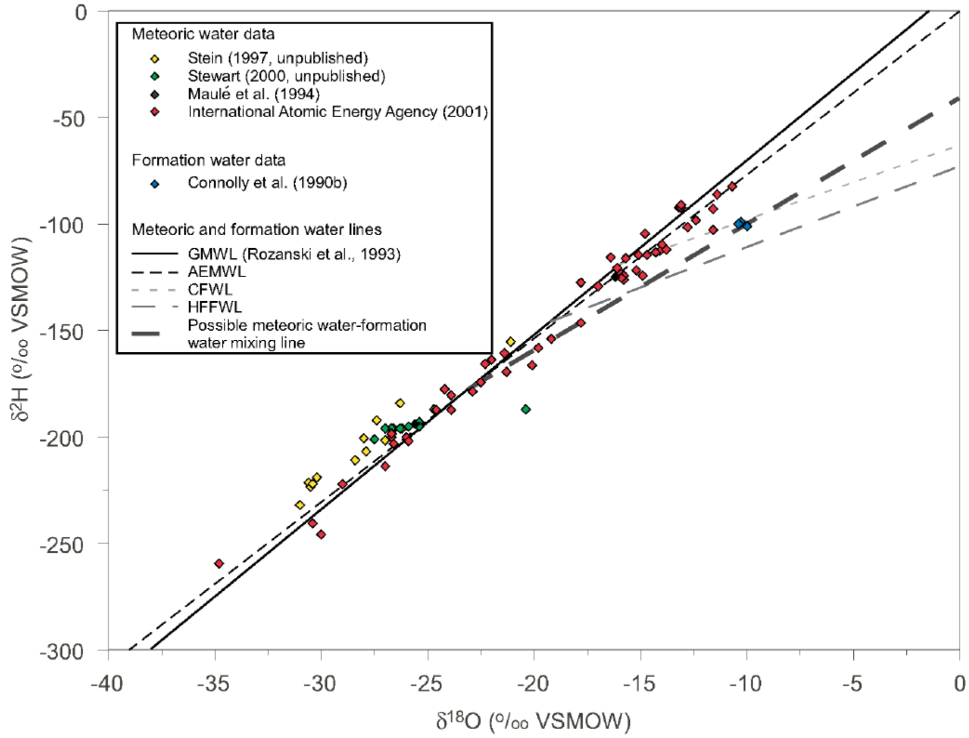


Figure 35. End-member compositions of coal-aquifer water. Abbreviations: AEMWL, Approximate Edmonton Meteoric Water Line; CFWL, Connolly Formation Water Line; GMWL, Global Meteoric Water Line; HFFWL, Hitchon Friedman Formation Water Line; VSMOW, Vienna Standard Mean Ocean Water.

Cretaceous formation water. In fact, linear regression of $\delta^{18}O$ and $\delta^{2}H$ values determined from snow samples collected by the Alberta Geological Survey (unpublished data) from northeastern Alberta, along with the $\delta^{18}O$ and $\delta^{2}H$ values of Upper Cretaceous formation-water samples collected by Connolly et al. (1990b) from the Belly River Group, yields an equation that is very similar to those determined for the water samples collected from the various aquifers:

$$\delta^{2}H = 5.90\delta^{18}O - 40.86 \qquad (R^2 = 0.9643)$$

This strongly suggests that the observed $\delta^{18}O$ and $\delta^{2}H$ values are arrived at through mixing of meteoric water with Tertiary–Upper Cretaceous formation water. This indicates that similar processes are occurring to modify the isotopic composition of the water within the shallow Tertiary–Upper Cretaceous coal, mixed coal-sandstone and sandstone aquifers throughout the Alberta Basin.

3.7.1.5 Preliminary Interpretation – Paskapoo-Scollard Formation

The isotopic composition of the water samples from Paskapoo-Scollard Formation aquifers is likely controlled by mixing of formation water with meteoric water. Sample 22 has the highest TDS and plots closest to the CFWL. It is therefore most like the original formation water in terms of its isotopic composition. Samples 45 and 46 have the lowest TDS values and therefore should be most like meteoric water, but they plot between sample 22 and samples 23, 29, 42 and 44, which have higher TDS values. Samples 45 and 46 are from wells that are used as depressurization wells. The wells are completed across sandstone, shale and coal units. The high pumping rates necessary to ensure sufficient drawdown are likely removing water from more than the aquifer units. The isotopic composition may therefore be influenced by the total water isotopic composition rather than just the aquifer water composition.

Samples 23, 29, 42 and 44 have intermediate TDS values. These samples likely represent the effects of the heterogeneities in the aquifer and the different locations along the flow paths and within the aquifers on the isotopic composition.

3.7.1.6 Preliminary Interpretation – Horseshoe Canyon Formation

The linear regression analysis of the isotope values yielded an equation similar to those of the other formations. The control on the isotopic composition is therefore likely controlled by the same mechanism. The samples do not show any obvious trend between TDS and $\delta^{18}O$ and $\delta^{2}H$. This suggests that the isotopic values reflect the effects of aquifer heterogeneities and the locations along the flow paths and within the various aquifers on the isotopic composition.

3.7.1.7 Preliminary Interpretation – Belly River Group

As with samples from other aquifers, the isotopic composition of those from the Belly River Group aquifers appears to be controlled by mixing of meteoric water with formation water. There appear, however, to be some discrepancies. Sample 17 plots closest to the CFWL but has the lowest TDS value. Samples plotting closest to the CFWL should most closely represent the original formation-water composition. The explanation for the observed isotopic composition of sample 17 may relate to its temperature. Sample 17 has the highest observed water temperature, with a median value of 12.8°C. This may indicate that the water has undergone evaporation before or during recharge, thereby shifting its isotopic composition. Sample 27 is the sample that has the highest TDS value and, after sample 17, plots closest to the intersection of the mixing line with the CFWL. It therefore most closely approximates the original formation-water isotopic composition. The remaining samples likely reflect the effects of aquifer heterogeneities and the locations along the flow paths and within the various aquifers on the isotopic composition.

3.7.2 Carbon

Carbon possesses two stable isotopes, with abundances as follows (Firestone, 2000): ^{12}C (abundance 98.90%) and ^{13}C (abundance 1.10%). Carbon enters the hydrosphere through a number of organic and inorganic reactions, including dissolution of CO_2, weathering of carbonate and silicate minerals and dissolution of organic material. Bacteria mediate many of these reactions. This bacterial involvement is important for two reasons: 1) they derive their energy from redox reactions and so act as catalysts speeding up reactions that are otherwise kinetically impeded; and 2) bacteria are isotopically selective, preferring to break the weaker (^{12}C) bonds producing a large isotope fractionation between the electron donor and the reaction products (Clark and Fritz, 1997, p. 112).

These reactions impart a different isotopic composition to the products. This fractionation is generally predictable if the temperature and original $\delta^{13}C$ composition is known. The fractionation factors are governed by the following equation:

$$10^3 \ln\alpha = a(10^6/T_K^2) + b(10^3/T_K) + c$$

where α is the fractionation factor

T_K is the temperature (in °Kelvin)

a, b and c are experimentally determined constants

Based on the determination of the α values, enrichment factors can be calculated, and the effect on the isotopic values can be evaluated. The enrichment factor ε is calculated using the following equation:

$\varepsilon = (\alpha - 1) \times 1000$

The chemistry and isotopes of carbon species provide insights into carbonate evolution and carbon cycling in groundwater that are required for an understanding of groundwater quality, fate of contaminants and for a correct interpretation of groundwater age (Clark and Fritz, 1997, p. 112).

3.7.2.1 Observations – Paskapoo-Scollard Formation

The mean $\delta^{13}C$ value in water samples from Paskapoo-Scollard mixed coal-sandstone aquifers is –5.7 ‰ VPDB, with a standard deviation of 11.7 ‰ VPDB (N=6). For comparison purposes, water samples from a Paskapoo-Scollard Formation sandstone aquifer has a $\delta^{13}C$ value of –12.4 ‰ VPDB. The complete chemistry dataset is found in Appendix A, Table 184.

The summary statistics for water samples collected during this study are presented in Table 159 below.

Table 159. Paskapoo-Scollard Formation: $\delta^{13}C$.

Water samples $\delta^{13}C$					
Location	**Mean (‰ VPDB)**	**Std. dev. (‰ VPDB)**	**N**	**Max. (‰ VPDB)**	**Min. (‰ VPDB)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-5.7	11.7	6	17	-14.0

The summary statistics for calcite cements found in the Paskapoo-Scollard Formation are presented in Table 160 below.

Table 160. Paskapoo-Scollard Formation: $\delta^{13}C$ for calcite cement.

Calcite cement samples $\delta^{13}C$					
Location	**Mean (‰ VPDB)**	**Std. dev. (‰ VPDB)**	**N**	**Max. (‰ VPDB)**	**Min. (‰ VPDB)**
Paskapoo-Scollard wells (Tertiary-Cretaceous) Beaton (pers. comm., 2002)	-15.6	4.9	27	6.3	-19.4

The mixed coal-sandstone aquifer water sample $\delta^{13}C$ values determined fall within the range of values reported for plants, soil CO_2, groundwater dissolved inorganic carbon (DIC), freshwater carbonate, atmospheric CO_2 and mantle CO_2, as reported by Clark and Fritz (1997, p. 113).

The sandstone aquifer water sample $\delta^{13}C$ value determined falls within the range of values reported for plants, soil CO_2, groundwater DIC and freshwater carbonate, as reported by Clark and Fritz (1997, p. 113).

There appears to be a relationship between depth and $\delta^{13}C$ values (Figure 36). As depth increases, so does $\delta^{13}C$. The equation of the line generated through linear regression is:

$\delta^{13}C = 0.2669\text{depth} - 20.9490 \qquad R^2 = 0.8353$

No other obvious trends appear to exist between $\delta^{13}C$ and any other parameters.

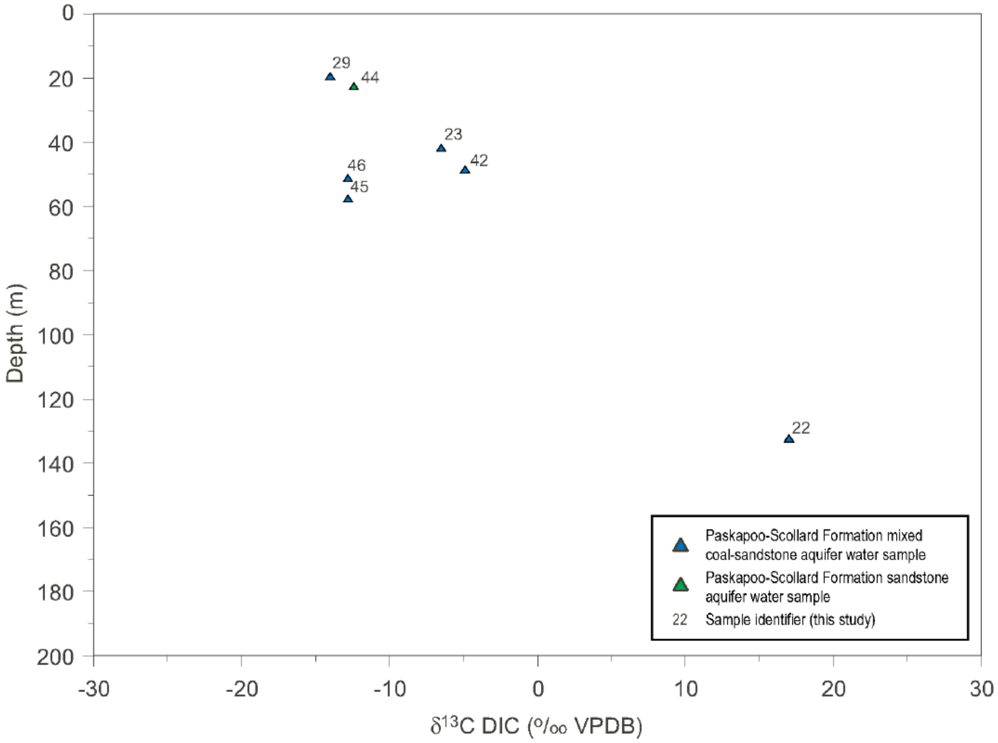


Figure 36. Paskapoo/Scollard Formation: $\delta^{13}C$ vs. depth. Abbreviation: VPDB, Vienna Pee Dee Belemnite.

3.7.2.2 Observations – Horseshoe Canyon Formation

The mean $\delta^{13}C$ value in water samples from Horseshoe Canyon Formation coal aquifers is –11.2 ‰ VPDB, with a standard deviation of 9.3 ‰ VPDB (N=6). The mean $\delta^{13}C$ value in water samples from Horseshoe Canyon Formation mixed coal-sandstone aquifers is –12.7 ‰ VPDB, with a standard deviation of 6.1 ‰ VPDB (N=13). For comparison purposes, a water sample from a Horseshoe Canyon Formation sandstone aquifer has a $\delta^{18}O$ value of –18.4 ‰ VPDB. The complete chemistry dataset is found in Appendix A, Table 184.

The summary statistics for water samples collected during this study are presented in Table 161 below.

Table 161. Horseshoe Canyon Formation: $\delta^{13}C$.

Location	Mean (‰ VPDB)	Std. dev. (‰ VPDB)	N	Max. (‰ VPDB)	Min. (‰ VPDB)
Water samples $\delta^{13}C$					
Horseshoe Canyon Formation wells (Upper Cretaceous) this study – coal aquifers	-11.2	9.3	6	6.8	-18.8
Horseshoe Canyon Formation wells (Upper Cretaceous) this study – mixed aquifers	-12.7	6.1	13	0.6	-24.9

The coal aquifer water sample $\delta^{13}C$ values determined fall within the range of values reported for plants, soil CO_2, groundwater DIC, freshwater carbonate and metamorphic CO_2, as reported by Clark and Fritz, (1997, p. 113).

The mixed coal-sandstone aquifer water sample $\delta^{13}C$ values determined fall within the range of values reported for plants, soil CO_2, coal, petroleum, thermogenic CH_4, groundwater DIC, freshwater carbonate, mantle CO_2, ocean DIC and marine limestone, as reported by Clark and Fritz, (1997, p. 113).

The sandstone aquifer water sample $\delta^{13}C$ value determined falls within the range of values reported for plants, soil CO_2, groundwater DIC and freshwater carbonate, as reported by Clark and Fritz, (1997, p. 113).

No obvious trends exist between $\delta^{13}C$ and other measured or recorded parameters.

3.7.2.3 Observations – Belly River Group

The mean $\delta^{13}C$ value in water samples from Belly River Group coal aquifers is –13.2 ‰ VPDB, with a standard deviation of 3.9 ‰ VPDB (N=3). The mean $\delta^{13}C$ value in water samples from Belly River Group mixed coal-sandstone aquifers is –14.0 ‰ VPDB, with a standard deviation of 2.3 ‰ VPDB (N=8). For comparison purposes, water samples from Belly River Group sandstone aquifers have a mean $\delta^{13}C$ value of -15.7 ‰ VPDB, with a standard deviation of 6.8 ‰ VPDB (N=5). The complete chemistry dataset is found in Appendix A, Table 184.

The summary statistics for water samples collected during this study are presented in Table 162 below.

Table 162. Belly River Group: $\delta^{13}C$.

Water samples $\delta^{13}C$					
Location	**Mean (‰ VPDB)**	**Std. dev. (‰ VPDB)**	**N**	**Max. (‰ VPDB)**	**Min. (‰ VPDB)**
Belly River Group wells (Upper Cretaceous) this study – coal aquifers	-13.2	3.9	3	-9.9	-17
Belly River Group wells (Upper Cretaceous) this study – mixed coal-sandstone aquifers	-14.0	2.3	8	-10.1	-17.4
Belly River Group wells (Upper Cretaceous) this study – sandstone aquifers	-15.7	6.8	5	-12.0	-27.9

The summary statistics for calcite cements found in the Belly River Group are presented in Table 163 below. It should be noted that these samples were collected from the same well, but from multiple depths (Connolly et al., 1990b).

Table 163. Belly River Group: $\delta^{13}C$ for calcite cement.

Calcite cement samples $\delta^{13}C$					
Location	**Mean (‰ VPDB)**	**Std. dev. (‰ VPDB)**	**N**	**Max. (‰ VPDB)**	**Min. (‰ VPDB)**
Belly River Group wells (Upper Cretaceous; Connolly et al., 1990b)	-2.9	2.8	5	0.5	-5.2

The coal aquifer water sample $\delta^{13}C$ values determined fall within the range of values reported for plants, soil CO_2, groundwater DIC, freshwater carbonate and mantle CO_2, as reported by Clark and Fritz, (1997, p. 113).

The mixed coal-sandstone aquifer water sample $\delta^{13}C$ values determined fall within the range of values reported for plants, soil CO_2, groundwater DIC and freshwater carbonate, as reported by Clark and Fritz, (1997, p. 113).

The sandstone aquifer water sample $\delta^{13}C$ values determined fall within the range of values reported for plants, soil CO_2, groundwater DIC, freshwater carbonate, coal, petroleum and thermogenic methane, as reported by Clark and Fritz, (1997, p. 113).

No obvious trends exist between $\delta^{13}C$ and any of the measured or recorded parameters.

3.7.2.4 Preliminary Interpretations – Paskapoo-Scollard Formation

The water samples collected from the Paskapoo-Scollard Formation have $\delta^{13}C$ values that could correspond to a number of possible sources. Possible mechanisms that could explain the observed $\delta^{13}C$ values include: 1) incorporation of C from plant material, coal, or dissolution of soil CO_2; 2) dissolution of carbonate minerals; 3) contamination by atmospheric CO_2; and 4) incorporation of biogenically affected carbon.

The range of $\delta^{13}C$ values does intersect the values reported from C_4 plants, or those plants that utilize the Hatch-Slack photosynthetic cycle. However, it is the C_3 plants, or those plants that utilize the Calvin photosynthetic cycle that almost exclusively form the natural vegetation in temperate regions (Clark and Fritz, 1997, p. 119). The $\delta^{13}C$ values from C_3 plants are lower than those determined for the water samples. Therefore direct incorporation of C from plants is unlikely.

Two possible mechanisms of deriving the measured $\delta^{13}C$ values are through the incorporation of C from coal, and through the dissolution of soil CO_2 generated from root respiration and organic decay of C_3 plants. Calculation of the enrichment that occurs as soil $CO_2(g)$ or coal derived C is transformed into carbonate species can test the potential of these mechanisms to generate the observed $\delta^{13}C_{DIC}$ values.

Under the pH conditions present within the aquifers (pH between 7.1 and 8.59), the dominant carbonate species will be bicarbonate, with $CO_2(aq)$ and carbonate present in lower concentrations (Figure 37). Both soil CO_2 and aquifer-derived organic carbon have $\delta^{13}C$ values of approximately -23‰ (Clark and Fritz, 1997, p. 120, 125). The table below contains the results of the calculations of the expected affect on $\delta^{13}C$ values of soil CO_2 dissolution and coal-derived C transformation into bicarbonate and carbonate (Table 164).

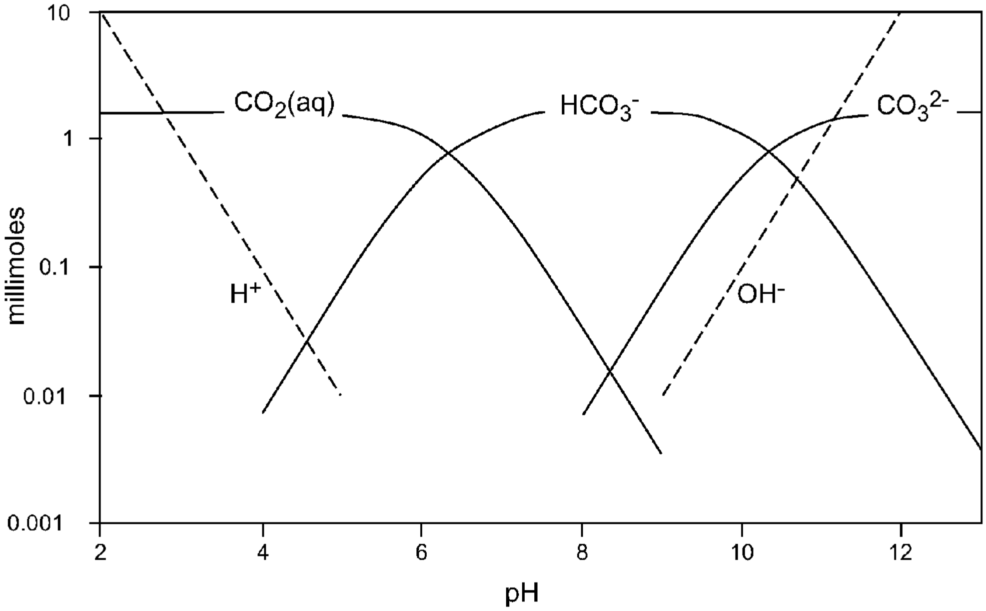


Figure 37. Dominant carbonate species at various pH values.

Table 164. Paskapoo-Scollard Formation: calculated $\delta^{13}C$ values for CO_2 dissolution at sample temperatures vs. measured $\delta^{13}C$.

Sample ID	Temp. (°C)	Temp. (°K)	$\delta^{13}C$ CO_2(gas)	$\delta^{13}C$ $CO_2(g)$ – $CO_2(aq)$	$\delta^{13}C$ $CO_2(aq)$ – HCO_3^-	$\delta^{13}C$ HCO_3^- – CO_3^{2-}	Measured $\delta^{13}C$ (‰ VPDB)
22	9.8	282.8	-23	-24.1	-13.3	-13.9	17.0
23	7.2	280.2	-23	-24.1	-13.0	-13.6	-6.5
29	6.9	279.9	-23	-24.1	-13.0	-13.5	-14.0
42	6.1	279.1	-23	-24.1	-12.9	-13.4	-4.9
44	5.7	278.7	-23	-24.1	-12.8	-13.4	-12.4
45	5.7	278.7	-23	-24.1	-12.8	-13.4	-12.8
46	5.7	278.7	-23	-24.1	-12.8	-13.4	-12.8

The calculated $\delta^{13}C$ values for samples 44, 45 and 46 are similar to the $\delta^{13}C$ values determined for these samples. This suggests that in these samples, possible mechanisms of generating the observed $\delta^{13}C$ values are through the dissolution of soil CO_2, or through the incorporation of coal-derived C. Sample 29 has a measured $\delta^{13}C$ value less than that expected for dissolution of soil CO_2 or for incorporation of coal-derived C and the subsequent formation of carbonate species. This variation is explainable through natural variation of the $\delta^{13}C_{CO2(g)}$. Another possibility exists however. The pH of this sample is 7.20 which indicates that although bicarbonate is the dominant carbonate species, CO_2(aq) is also present , whereas carbonate is present only in very low concentrations (Figure 37). This suggests the possibility that this observed $\delta^{13}C_{DIC}$ value is generated by mixing between the higher $\delta^{13}C_{HCO3}$ value and the lower $\delta^{13}C_{CO2(aq)}$ value.

Samples 22, 23 and 44 do not appear related to the soil CO_2 dissolution process or to the incorporation of coal-derived C.

A second possibility that might explain the observed aquifer water sample $\delta^{13}C$ values is carbonate mineral dissolution. Calcite cement has been identified and $\delta^{13}C$ values have been determined for samples from Tertiary–Upper Cretaceous coal zones. The summary statistics of the cement $\delta^{13}C$ values are presented in Table 159. Calculations of the expected effects of dissolving calcite cement on the $\delta^{13}C$ values of carbonate and bicarbonate are presented in Table 165 below.

Table 165. Paskapoo-Scollard Formation: calculated $\delta^{13}C$ values for calcite dissolution at sample temperatures vs. measured $\delta^{13}C$.

Sample ID	Temp. (°C)	Temp. (°K)	Av. calcite cement $\delta^{13}C$	$\delta^{13}C$ calcite – CO_3^{2-}	$\delta^{13}C$ CO_3^{2-} – HCO_3^-	Measured $\delta^{13}C_{DIC}$ (‰ VPDB)
22	9.8	282.8	-15.6	-15.7	-15.1	17.0
23	7.2	280.2	-15.6	-15.6	-15.0	-6.5
29	6.9	279.9	-15.6	-15.6	-15.0	-14.0
42	6.1	279.1	-15.6	-15.5	-15.0	-4.9
44	5.7	278.7	-15.6	-15.5	-15.0	-12.4
45	5.7	278.7	-15.6	-15.5	-15.0	-12.8
46	5.7	278.7	-15.6	-15.5	-15.0	-12.8

Direct incorporation of carbon from the dissolution of calcite cement does not appear to explain the observed $\delta^{13}C_{DIC}$ values.

The Paskapoo-Scollard Formation is composed predominantly of quartz, with small amounts of feldspar as well as shale, limestone, chert and quartzite (Allan and Sanderson, 1945). Dissolution of this limestone component may therefore explain some of the observed $\delta^{13}C$ values. Clark and Fritz (1997, p. 123) predict that dissolution of carbonate minerals with a $\delta^{13}C$ value of approximately 0‰ VPDB should result in a $\delta^{13}C_{DIC}$ value of between –15 and –12.5‰ VPDB given the pH of the water samples. Samples 29, 44, 45 and 46 have $\delta^{13}C$ values that fall within this range. The $\delta^{13}C$ values for samples 29, 44 and 45 are consistent given the pH of the water samples. DIC values however are greater than the values used by Clark and Fritz (1997, p. 123). Limestone makes up approximately 13.3 percent of the Paskapoo-Scollard Formation rock mass (Allan and Sanderson, 1945). The question therefore becomes, is there a sufficient limestone component present in the formation to effect this sort of mixing result.

Samples 23 and 42 have values similar to those reported for atmospheric CO_2 (Clark and Fritz, 1997, p. 113). This suggests the possibility of contamination of the samples. Agrawal and O'Donoghue (2002) report the $\delta^{13}C$ values for atmospheric CO_2 for different latitudes and show that atmospheric CO_2 values for latitudes greater than 45°N are less than –7.9‰ but not less than –8.0‰. Although similar, the values of the $\delta^{13}C_{DIC}$ is significantly different from that of atmospheric CO_2. It therefore appears unlikely that contamination has occurred.

Samples 22, 23 and 42 have $\delta^{13}C$ values above those predicted for soil CO_2 dissolution, incorporation of coal-derived C, and carbonate mineral dissolution and mixing with original aquifer water. Atmospheric contamination also appears unlikely, as do sources such as mantle CO_2, and extraterrestrial carbon sources (Clark and Fritz, 1997, p. 113). A possible mechanism of generating the observed $\delta^{13}C$ values is the incorporation of biogenically derived CO_2 mixing with the already present $\delta^{13}C_{DIC}$. The biogenic production of methane in the subsurface follows this simplified reaction pathway:

$$2CH_2O \rightarrow CO_2 + CH_4$$

The resulting fractionation enriches the $\delta^{13}C_{CO2}$ over the $\delta^{13}C_{CH4}$ by between 50 and 80‰ (Clark and Fritz, 1997, p. 128).

The generation of methane by bacteria requires a fully saturated environment that excludes atmospheric O_2 and requires an organic carbon substrate. The aquifers these samples were collected from are confined. Dissolved oxygen measurements were all below 0.4 mg/L. The aquifer rock types consist of alternating coal shale and sandstone units. The criteria for biogenesis of methane therefore appear satisfied. In addition, gas was detected in all three of these samples. It is therefore likely that the $\delta^{13}C$ values determined from samples 22, 23 and 44 have been affected by biogenesis of methane.

A relationship between depth and $\delta^{13}C$ was observed. This trend is likely caused by the change in redox conditions with depth allowing for the biogenesis of methane and subsequent enrichment of the $\delta^{13}C$ in the deeper samples. Samples 45 and 46 have $\delta^{13}C$ values similar to those of the shallowest wells. The two wells these samples were collected from are used as depressurization wells for a coal mining operation. They are therefore unlikely to follow the observed trend with depth.

3.7.2.5 Preliminary Interpretations – Horseshoe Canyon Formation

Similar reactions are likely occurring within the Horseshoe Canyon as were detailed above in the Paskapoo-Scollard Formation. The effect of incorporation of soil CO_2 or coal-derived C on the carbonate species is calculated in the table below (Table 166).

Table 166. Horseshoe Canyon Formation: calculated $\delta^{13}C$ values for CO_2 dissolution at sample temperatures vs. measured $\delta^{13}C$.

Sample ID	Temp. (°C)	Temp. (°K)	$\delta^{13}C$ $CO_2(g)$	$\delta^{13}C$ $CO_2(g) – CO_2(aq)$	$\delta^{13}C$ $CO_2(aq) – HCO_3^-$	$\delta^{13}C$ $HCO_3^- – CO_3^{2-}$	Measured $\delta^{13}C$ (‰ VPDB)
1	7.6	280.6	-23	-24.1	-13.0	-13.6	-15.1
2	7.2	280.2	-23	-24.1	-13.0	-13.6	-13.3
3	7.2	280.2	-23	-24.1	-13.0	-13.6	-13.8
8	8.5	281.5	-23	-24.1	-13.0	-13.6	-15.1
11	7.3	280.3	-23	-24.1	-13.1	-13.7	-24.9
12	7.9	280.9	-23	-24.1	-13.0	-13.6	-13.0
19	7.2	280.2	-23	-24.1	-13.1	-13.6	-10.8
20	5.5	278.5	-23	-24.1	-13.0	-13.6	-13.7
21	7.5	280.5	-23	-24.1	-12.8	-13.4	6.8
24	7.1	280.1	-23	-24.1	-13.0	-13.6	-13.9
25	6.9	279.9	-23	-24.1	-13.0	-13.6	-16.6
28	7.5	280.5	-23	-24.1	-13.0	-13.5	-18.4
30	6.3	279.3	-23	-24.1	-13.0	-13.6	-3.3
31	6.4	279.4	-23	-24.1	-12.9	-13.5	-18.8
32	6.2	279.2	-23	-24.1	-12.9	-13.5	-14.2
33	13.0	285.0	-23	-24.1	-12.9	-13.5	-15.8
34	6.1	279.1	-23	-24.1	-13.7	-14.2	0.6
36	6.6	279.6	-23	-24.1	-12.9	-13.4	-15.0
41	8.2	281.2	-23	-24.1	-12.9	-13.5	-9.5
43	8.8	281.8	-23	-24.1	-13.1	-13.7	-13.4

Samples 2, 3, 12, 20, 24, 32 and 43 have measured $\delta^{13}C$ values similar to those calculated for carbonate species derived from either dissolved soil CO_2 or coal-derived C. Ranges in the original composition of $\delta^{13}C$ $CO_2(g)$ for soil CO_2 and for organically derived CO_2 vary between –26 and -20‰ VPDB and –28 and -22‰ VPDB respectively. This implies that samples 1, 8, 28, 31, 33, 36 and 41 can be explained by this process.

No $\delta^{13}C$ information on calcite cement or carbonate minerals from the Horseshoe Canyon Formation was available to directly assess the possibility of carbonate mineral dissolution. However, Allan and Sanderson (1945) describe the presence of arenaceous limestone and calcareous sandstone in the Edmonton Group. Carbonate minerals are therefore present within this formation. Given the range of pH values determined for the Horseshoe Canyon Formation, the expected $\delta^{13}C$ values that would result from the dissolution of carbonate minerals would likely fall within a range between –14 and -12‰ VPDB (Clark and Fritz, 1997, p. 123). Samples 2, 3, 12, 20, 24, 32 and 43 fall within this range of values. However, only samples 2, 3, 12 and 20 have $\delta^{13}C$ values that approximate those predicted by Clark and Fritz (1997, p.123) at the sample pH values. DIC values are greater than those used by Clark and Fritz (1997, p. 123). The question then becomes, is there sufficient carbonate material present within the Horseshoe Canyon Formation to affect this transformation in $\delta^{13}C$ values.

None of the samples have values similar to atmospheric CO_2, suggesting none of the samples were contaminated during sampling.

Samples 11, 21, 30 and 34 have $\delta^{13}C$ values that cannot be explained through dissolution of soil CO_2, incorporation of coal-derived C or through the dissolution of carbonate minerals. Dissolved gas was noted during water sampling of these samples. The relatively enriched $\delta^{13}C$ values in samples 21, 30 and 34 suggest that biogenesis of methane along with mixing have combined to produce the observed $\delta^{13}C$ values. Biogenesis of methane results in the depletion of the $\delta^{13}C_{CH4}$ and the enrichment of the $\delta^{13}C_{DIC}$. In sample 11 however the $\delta^{13}C_{DIC}$ value is highly depleted. In addition, a sulphur odour was noted during sampling. This suggests that a process such as bacterial oxidation of methane has occurred. This process results in a positive shift in the $\delta^{13}C_{CH4}$, a depletion in the $\delta^{13}C_{DIC}$ and the production of H_2S through sulphate reduction. Although explainable through the process of soil CO_2 dissolution or incorporation of coal-derived C, a similar process may have occurred at sample locations 1 and 31. Depletion in the $\delta^{13}C_{DIC}$ was also observed in these samples. Gas was detected in these samples, accompanied by a sulphur odour.

3.7.2.6 Preliminary Interpretation – Belly River Group

It is likely that $\delta^{13}C$ values within the Belly River Group are controlled by reactions similar to those occurring in the Paskapoo-Scollard and Horseshoe Canyon formations. The effect of incorporation of soil CO_2 or coal-derived C on the carbonate species is calculated in the table below (Table 167).

Table 167. Belly River Group: calculated $\delta^{13}C$ values for CO_2 dissolution at sample temperatures vs. measured $\delta^{13}C$.

Sample ID	Temp. (°C)	Temp. (°K)	$\delta^{13}C$ $CO_2(g)$	$\delta^{13}C$ $CO_2(g)$ – $CO_2(aq)$	$\delta^{13}C$ $CO_2(aq)$ – HCO_3^-	$\delta^{13}C$ HCO_3^- – CO_3^{2-}	Measured $\delta^{13}C$ (‰ VPDB)
5	5.3	278.3	-23	-24.2	-12.8	-13.4	-13.9
6	7.6	280.6	-23	-24.1	-13.0	-13.6	-12.8
7	7.7	280.7	-23	-24.1	-13.1	-13.6	-13.9
9	6.7	279.7	-23	-24.1	-12.9	-13.5	-9.9
10	7.4	280.4	-23	-24.1	-13.0	-13.6	-12.8
15	9.6	282.6	-23	-24.1	-13.3	-13.8	-17.0
16	6.4	279.4	-23	-24.1	-12.9	-13.5	-13.5
17	12.8	285.8	-23	-24.1	-13.7	-14.2	-12.3
18	9.1	282.1	-23	-24.1	-13.2	-13.8	-27.9
26	10.3	283.3	-23	-24.1	-13.4	-13.9	-16.6
27	7.7	280.7	-23	-24.1	-13.1	-13.6	-17.4
35	6.3	279.3	-23	-24.1	-12.9	-13.5	-12.6
37	6.0	279.0	-23	-24.1	-12.8	-13.4	-14.7
38	7.2	280.2	-23	-24.1	-13.0	-13.6	-12.0
39	6.5	279.5	-23	-24.1	-12.9	-13.5	-12.3
40	6.6	279.6	-23	-24.1	-12.9	-13.5	-10.1

Given the pH of the water samples (between 6.91 and 8.95), the dominant carbonate species will be bicarbonate, with dissolved CO_2 and carbonate present but at lesser concentrations (Figure 37). Samples 6, 7, 10, 16 and 35 have measured values that closely compare to the calculated carbonate species values. Given the possible range in soil CO_2 and coal $\delta^{13}C$ values (soil CO_2 between –26 and -20‰ VPDB; coal-derived CO_2 between –28 and -22‰ VPDB), it is possible that the $\delta^{13}C$ values of samples 5, 9, 15, 17, 26, 27, 37, 38, 39 and 40 could also be accounted for by processes that incorporate the soil CO_2 or coal derived C into the groundwater DIC.

Calcite cement $\delta^{13}C$ values reported by Connolly et al. (1990b) vary between –5.2 and 0.5‰ PDB. These values were determined from five samples collected at one location at depths between 981 and 995 metres. The samples are likely not representative of the Belly River Group calcite cement $\delta^{13}C$ values throughout the Alberta Basin, however since information on Belly River Groups calcite cement $\delta^{13}C$ values is scarce, the values do allow for a comparison between the deeper portions of the basin and the shallower portions of the basin. It is unlikely that dissolution of calcite cement within the Belly River Group is responsible for the measured groundwater $\delta^{13}C_{DIC}$ values. The table below (Table 168) shows the expected carbonate and bicarbonate values associated with dissolution of calcite cement with a composition similar to that reported by Connolly et al. (1990b).

Table 168. Belly River Group: calculated $\delta^{13}C$ values for calcite dissolution at sample temperatures vs. measured $\delta^{13}C$.

Sample ID	Temp. (°C)	Temp. (°K)	Ave. calcite cement $\delta^{13}C$	$\delta^{13}C$ Calcite – CO_3^{2-}	$\delta^{13}C$ CO_3^{2-} – HCO_3^-	Measured $\delta^{13}C$ (‰ VPDB)
5	5.3	278.3	-2.9	-2.8	-2.2	-13.9
6	7.6	280.6	-2.9	-2.9	-2.3	-12.8
7	7.7	280.7	-2.9	-2.9	-2.4	-13.9
9	6.7	279.7	-2.9	-2.9	-2.3	-9.9
10	7.4	280.4	-2.9	-2.9	-2.3	-12.8
15	9.6	282.6	-2.9	-3.0	-2.5	-17.0
16	6.4	279.4	-2.9	-2.9	-2.3	-13.5
17	12.8	285.8	-2.9	-3.2	-2.7	-12.3
18	9.1	282.1	-2.9	-3.0	-2.4	-27.9
26	10.3	283.3	-2.9	-3.1	-2.5	-16.6
27	7.7	280.7	-2.9	-2.9	-2.4	-17.4
35	6.3	279.3	-2.9	-2.8	-2.3	-12.6
37	6.0	279.0	-2.9	-2.8	-2.2	-14.7
38	7.2	280.2	-2.9	-2.9	-2.3	-12.0
39	6.5	279.5	-2.9	-2.9	-2.3	-12.3
40	6.6	279.6	-2.9	-2.9	-2.3	-10.1

Based on the results above, it does not appear likely that dissolution of calcite cement with a composition similar to that reported by Connolly et al. (1990b) is directly responsible for the observed $\delta^{13}C$ values.

Mack and Jerzykiewicz (1989) indicate that the Belly River Group in the southern Foothills contains carbonate rock fragments with a mean percentage of 1.1%. In the central Foothills this value varies between 0 and 1.3%. Dissolution of carbonate minerals might explain some of the observed $\delta^{13}C$ values. However, none of the water sample $\delta^{13}C$ values approximate those predicted by Clark and Fritz (1997, p.123) for dissolution of carbonate minerals, given the pH values of the water samples. It therefore appears unlikely that carbonate mineral dissolution is responsible for the observed $\delta^{13}C$ values.

Sample 18 has the lowest observed $\delta^{13}C$ value. Dissolved gas was observed during sampling. This suggests that a process such as microbial oxidation of methane may be occurring. This process results in a positive shift in the $\delta^{13}C_{CH4}$ and a depletion in the $\delta^{13}C_{DIC}$. The reaction is likely occurring according to the following reaction:

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$$

3.7.3 Sulphur

Sulphur possesses four stable isotopes, ^{32}S (Abundance 95.03%), ^{33}S (Abundance 0.75%), ^{34}S (Abundance 4.22%) and ^{36}S (Abundance 0.02%) (Firestone, 2000). Major forms of sulphur in the subsurface include sulphate and sulphide minerals, dissolved sulphate (SO_4^{2-}), dissolved sulphide (HS^-), hydrogen sulphide gas (H_2S) and organic sulphur associated with humic substances, kerogen and hydrocarbons (Clark and Fritz, 1997, p. 138). Seawater contains dissolved sulphate (SO_4^{2-}), sulphide (HS^-), hydrogen sulphide gas (H_2S) and organic sulphur. Atmospheric sources include natural or industrial SO_2, particulate sulphur and aerosols of marine sulphate (Clark and Fritz, 1997, p. 138). The movement of sulphur through the geosphere and hydrosphere constitute the sulphur cycle. Sulphur isotopes and the fractionation of the isotopes have been used to determine the cycling of sulphur in agricultural watersheds, the origin of salinity in aquifers, groundwater contamination by landfills, acid mine drainage and dating of groundwater (Clark and Fritz, 1997, p. 138). The study of sulphur isotopes can be complicated by the fact that fractionation between sulphur compounds is affected by biological cycling. The $^{18}O/^{16}O$ content of sulphate can be used in concert with the $^{34}S/^{32}S$ content of sulphate to further assess the reactions occurring during the sulphur cycle.

3.7.3.1 Observations – Paskapoo-Scollard Formation

The mean $\delta^{34}S$ SO_4 value in water samples from Paskapoo-Scollard mixed coal-sandstone aquifer is 11.2 ‰ CDT, with a standard deviation of 13.4 ‰ CDT (N=6). For comparison purposes, a water sample from a Paskapoo-Scollard Formation sandstone aquifer has a $\delta^{34}S$ SO_4 value of 6.4 ‰ CDT. The complete chemistry dataset is found in Appendix A, Table 184.

The mean $\delta^{34}S$ S^2 value in water samples from Paskapoo-Scollard mixed coal-sandstone aquifer is –0.5 ‰ CDT, with a standard deviation of 6.2 ‰ CDT (N=6). For comparison purposes, a water sample from a Paskapoo-Scollard Formation sandstone aquifer has a $\delta^{34}S$ S^2 value of 1.9 ‰ CDT. The complete chemistry dataset is found in Appendix A, Table 184.

The summary statistics for water samples collected during this study are presented in Table 169 below.

Table 169. Paskapoo-Scollard Formation: $\delta^{34}S$.

Location	Mean (‰ CDT)	Std. dev. (‰ CDT)	N	Max. (‰ CDT)	Min. (‰ CDT)
Water samples $\delta^{34}S$ SO_4					
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	12.0	13.4	5	34.8	3.1
Water samples $\delta^{34}S$ S^2					
Paskapoo-Scollard wells (Tertiary-Cretaceous) this study	-0.5	6.2	6	6.8	-11.8

The mixed coal-sandstone aquifer water sample $\delta^{34}S$ SO_4 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, Devonian to Cenozoic $CaSO_4$, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The sandstone aquifer water sample $\delta^{34}S$ SO_4 value determined falls within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The mixed coal-sandstone aquifer water sample $\delta^{34}S$ S^2 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The sandstone aquifer water sample $\delta^{34}S$ S^2 value determined falls within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

A general trend appears to exist between $\delta^{34}S$ SO_4 and sulphate concentration as well as between $\delta^{34}S$ S_2 and sulphate concentration (Figure 38 and Figure 39). As sulphate concentration increases, so does the value of $\delta^{34}S$ SO_4 and $\delta^{34}S$ S_2. There also appear to be a correlation between $\delta^{34}S$ SO_4 and $\delta^{34}S$ S_2. As $\delta^{34}S$ SO_4 increases, so does $\delta^{34}S$ S_2 (Figure 40).

No obvious trends are observed between the stable isotopic composition of sulphur and any other parameter.

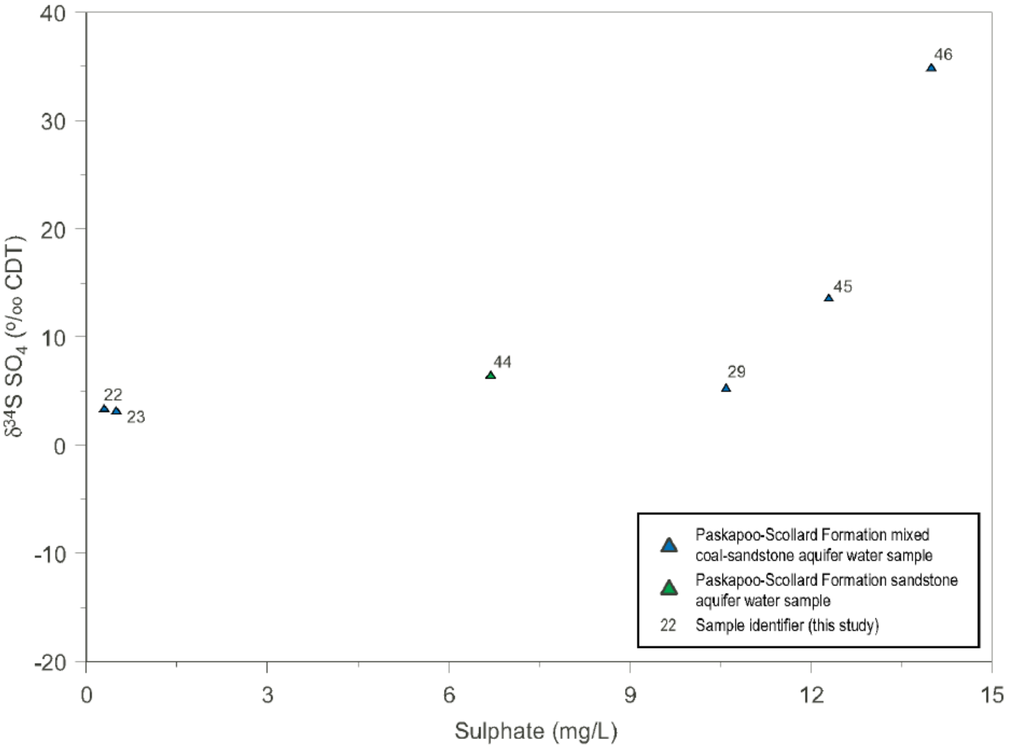


Figure 38. Paskapoo-Scollard Formation: δ^{34}S SO_4 vs. SO_4. Abbreviation: CDT, Cañon Diablo Troilite.

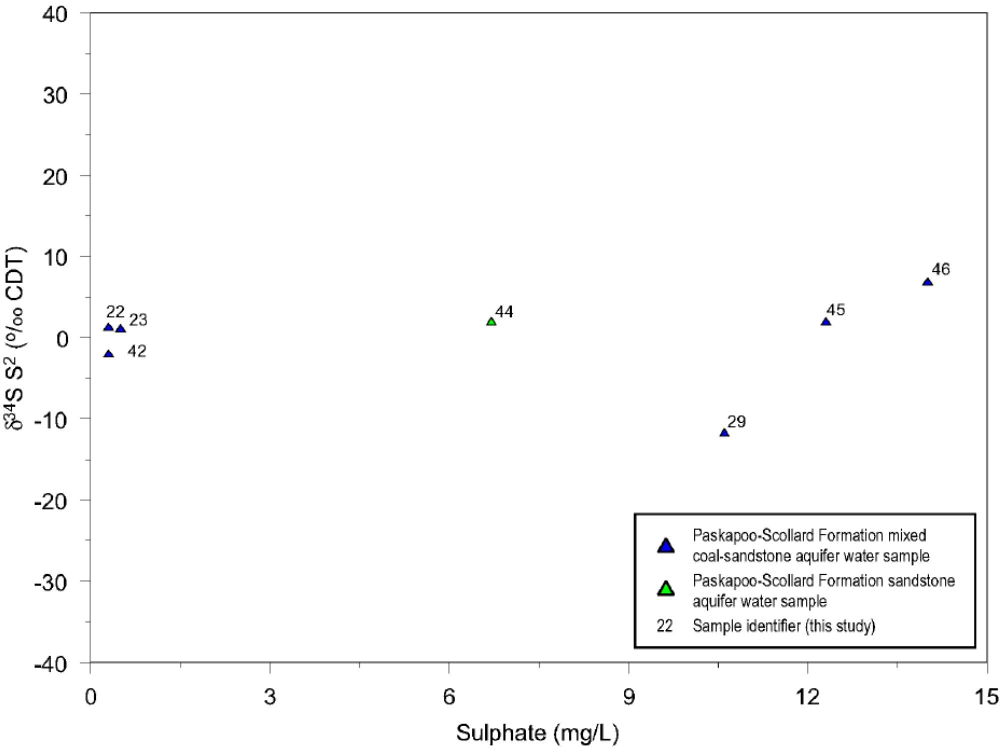


Figure 39. Paskapoo-Scollard Formation: δ^{34}S S^2 vs. SO_4. Abbreviation: CDT, Cañon Diablo Troilite.

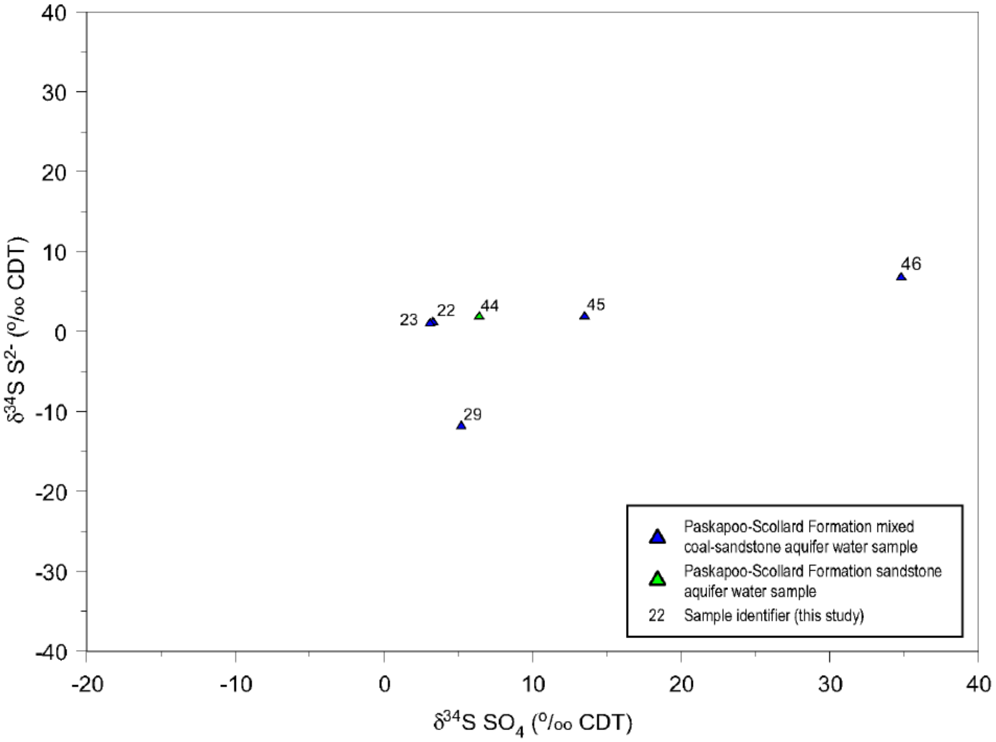


Figure 40. Paskapoo-Scollard Formation: δ^{34}S S^{2-} vs. SO$_4$

It should be noted that the peak sizes used to determine the δ^{34}S S^2 values were only 1/10 of the optimal peak size (Taylor, pers. comm.). Therefore, the values are suspect although not necessarily incorrect. They are presented for completeness and in an effort to understand the sulphur cycle in these various aquifers.

3.7.3.2 Observations – Horseshoe Canyon Formation

The mean δ^{34}S SO$_4$ value in water samples from Horseshoe Canyon Formation coal aquifers is 0.0 ‰ CDT, with a standard deviation of 10.5 ‰ CDT (N=6). The mean δ^{34}S SO$_4$ value in water samples from Horseshoe Canyon Formation mixed coal-sandstone aquifers is 0.7 ‰ CDT, with a standard deviation of 6.8 ‰ CDT (N=12) For comparison purposes, a water sample from a Horseshoe Canyon Formation sandstone aquifer has a δ^{34}S SO$_4$ value of 2.5 ‰ CDT. The complete chemistry dataset is found in Appendix A, Table 184.

The mean δ^{34}S S^2 value in water samples from Horseshoe Canyon Formation coal aquifer water samples is –0.3 ‰ CDT, with a standard deviation of 4.7 ‰ CDT (N=5). The mean δ^{34}S S^2 value in water samples from Horseshoe Canyon Formation mixed coal-sandstone aquifers is 2.2 ‰ CDT, with a standard deviation of 4.7 ‰ CDT (N=12). For comparison purposes, a water sample from a Horseshoe Canyon Formation sandstone aquifer has a δ^{34}S S^2 value of 4.4 ‰ CDT. The complete chemistry dataset is found in Appendix A, Table 184.

The summary statistics for water samples collected during this study are presented in Table 170 below.

Table 170. Horseshoe Canyon Formation: $\delta^{34}S$.

Location	Mean (‰ CDT)	Std. dev. (‰ CDT)	N	Max. (‰ CDT)	Min. (‰ CDT)
Water samples $\delta^{34}S$ SO_4					
Horseshoe Canyon wells (Upper Cretaceous) this study – coal aquifers	0.0	10.5	6	16.5	-10.5
Horseshoe Canyon wells (Upper Cretaceous) this study – mixed aquifers	0.7	6.8	12	10.0	-13.1
Water samples $\delta^{34}S$ S^2					
Horseshoe Canyon wells (Upper Cretaceous) this study – coal aquifers	-0.3	4.7	5	5.0	-6.4
Horseshoe Canyon wells (Upper Cretaceous) this study – mixed aquifers	2.2	14.1	12	34.0	-25.8

The coal aquifer water sampled $\delta^{34}S$ SO_4 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, Devonian to Cenozoic $CaSO_4$, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The mixed coal-sandstone aquifer water sample $\delta^{34}S$ SO_4 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The sandstone aquifer water sample $\delta^{34}S$ SO_4 value determined falls within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The coal aquifer water sampled $\delta^{34}S$ S^2 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The mixed coal-sandstone aquifer water sample $\delta^{34}S$ S^2 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The sandstone aquifer water sample $\delta^{34}S$ S^2 value determined falls within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

Correlations appear to exist between δ^{34}S SO_4, depth, elevation, sulphate concentrations and δ^{34}S S^2 values (Figure 41, Figure 42, Figure 43 and Figure 44). These trends are observed more particularly in those samples collected from coal aquifers. An increase in depth corresponds to an increase in the δ^{34}S SO_4 values for the coal aquifer water samples, with the exception of sample 25. A decrease in elevation corresponds to an increase in the δ^{34}S SO_4 values for the coal aquifer water samples, with the exception of samples 12 and 36. A decrease in the sulphate concentration corresponds to an increase in the δ^{34}S SO_4 values. An increase in the δ^{34}S SO_4 values for the various aquifer water samples corresponds to an increase in the δ^{34}S S^2 values, with the exception of samples 32 and 33.

In addition, correlations appear to exist between δ^{34}S S^2, depth and sulphate concentrations (Figure 45 and Figure 46), particularly for those samples collected from coal aquifers. Coal aquifer water sample δ^{34}S S^2 values appear to increase as depth increases. Coal aquifer water samples δ^{34}S S^2 values appear to increase as sulphate concentration values decrease.

No other obvious trends were observed. It should be noted that the peak sizes used to determine the δ^{34}S S^{2-} values were only 1/10 of the optimal peak size. Therefore, the values are suspect although not necessarily incorrect. They are presented for completeness and in an effort to understand the sulphur cycle in these various aquifers.

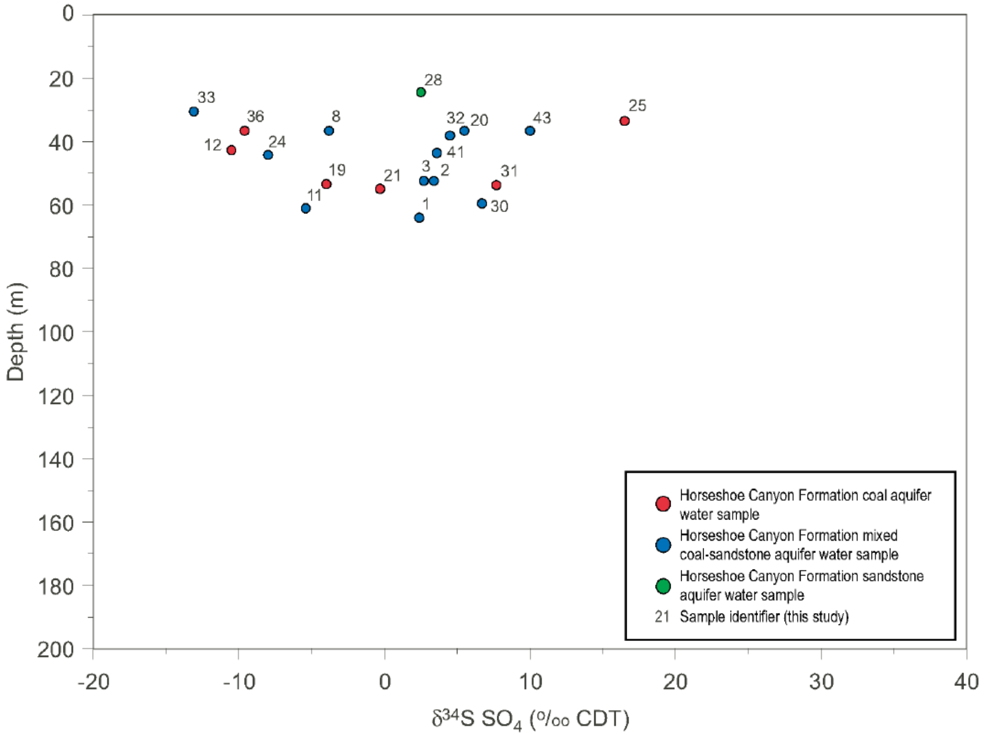


Figure 41. Horseshoe Canyon Formation: ^{34}S SO_4 vs. depth. Abbreviation: CDT, Cañon Diablo Troilite.

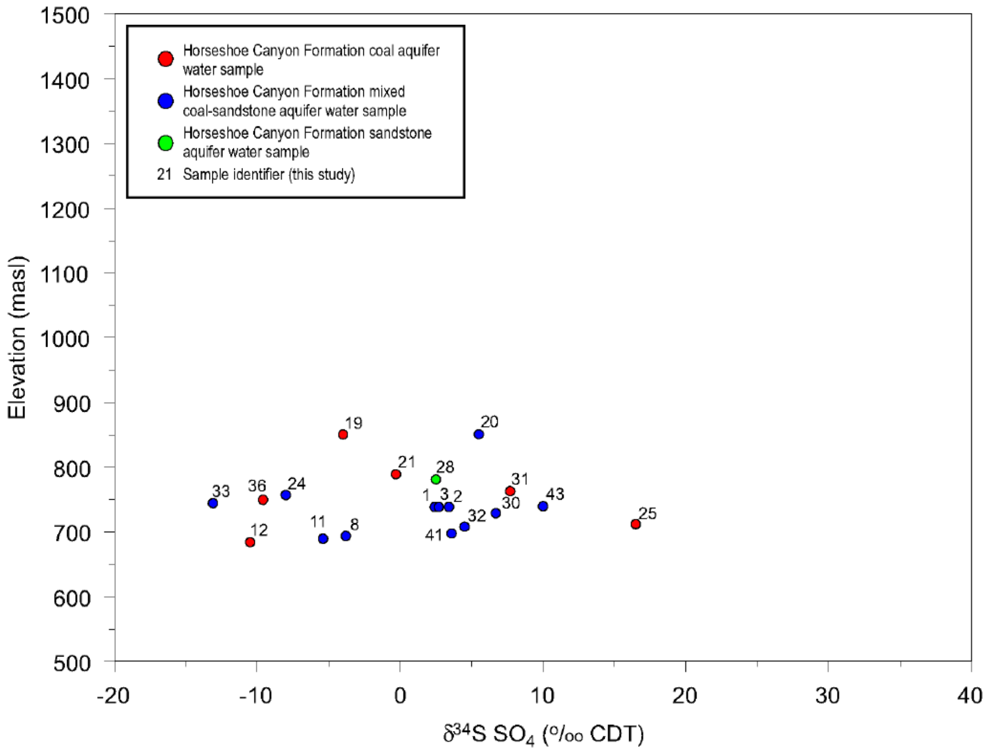


Figure 42. Horseshoe Canyon Formation: ^{34}S SO$_4$ vs. elevation. Abbreviation: CDT, Cañon Diablo Troilite; masl, metres above sea level.

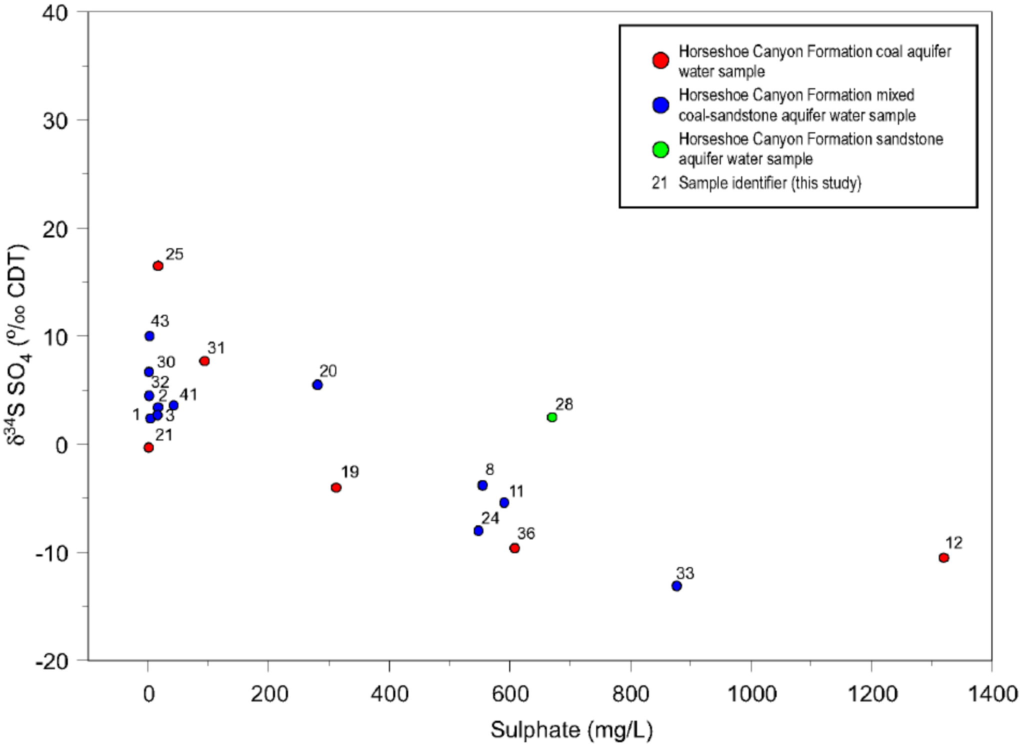


Figure 43. Horseshoe Canyon Formation: ^{34}S SO$_4$ vs. SO$_4$. Abbreviation: CDT, Cañon Diablo Troilite.

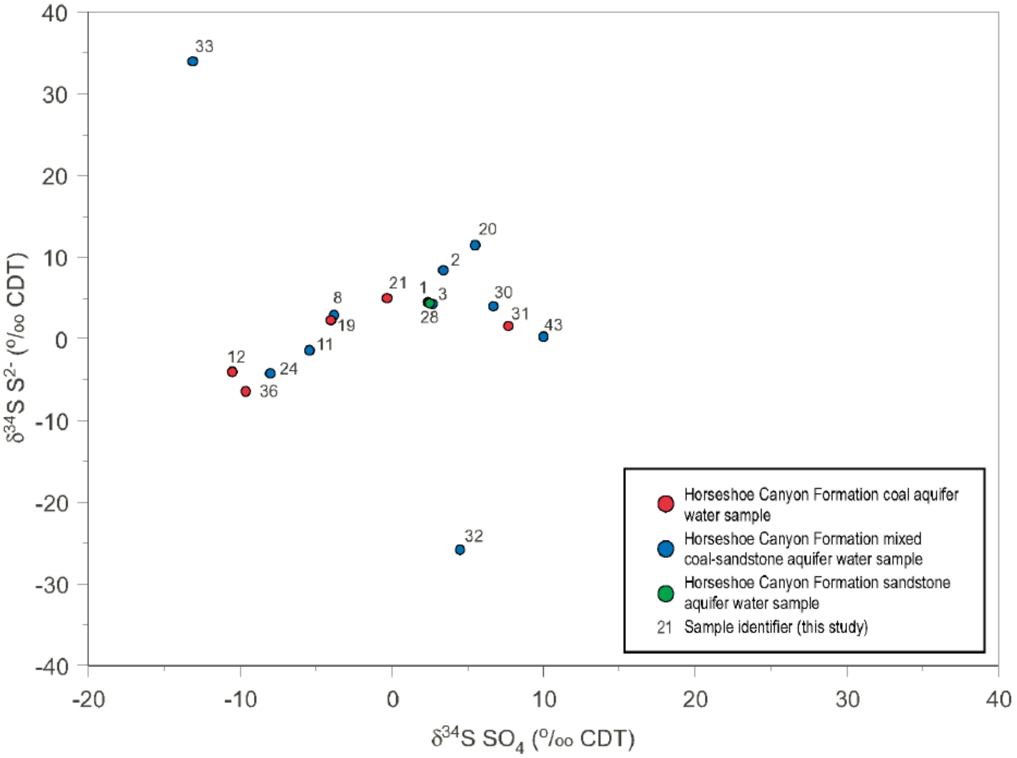


Figure 44. Horseshoe Canyon Formation: $^{34}S\ SO_4$ vs. $\delta^{34}S\ S^{2}$. Abbreviation: CDT, Cañon Diablo Troilite.

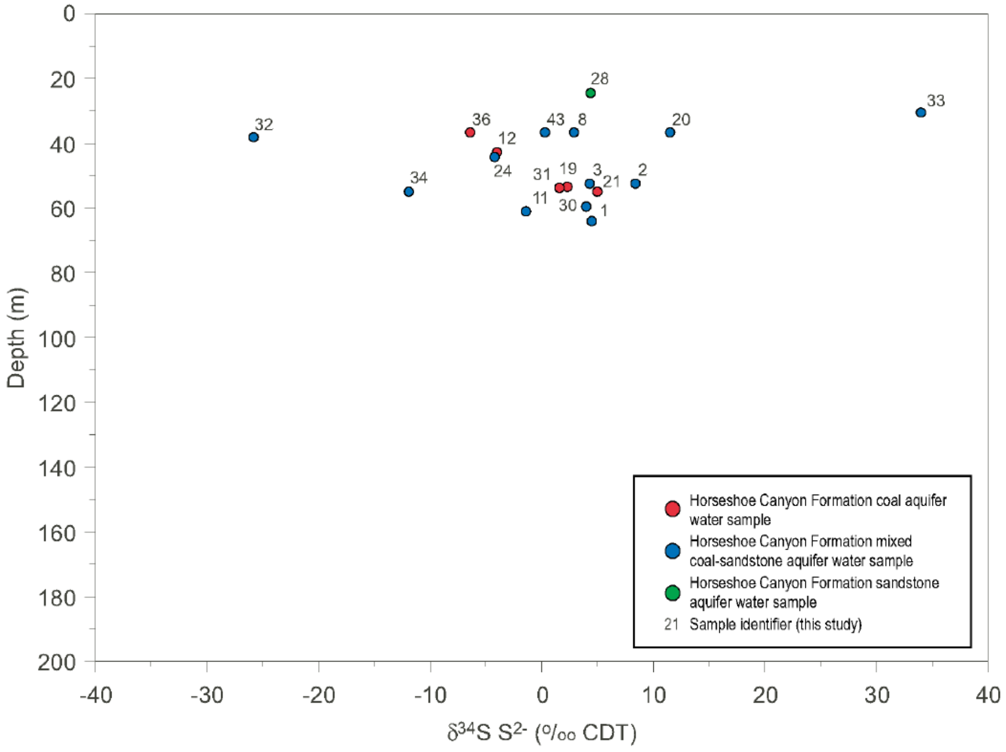


Figure 45. Horseshoe Canyon Formation: $^{34}S\ S^{2-}$ vs. depth. Abbreviation: CDT, Cañon Diablo Troilite.

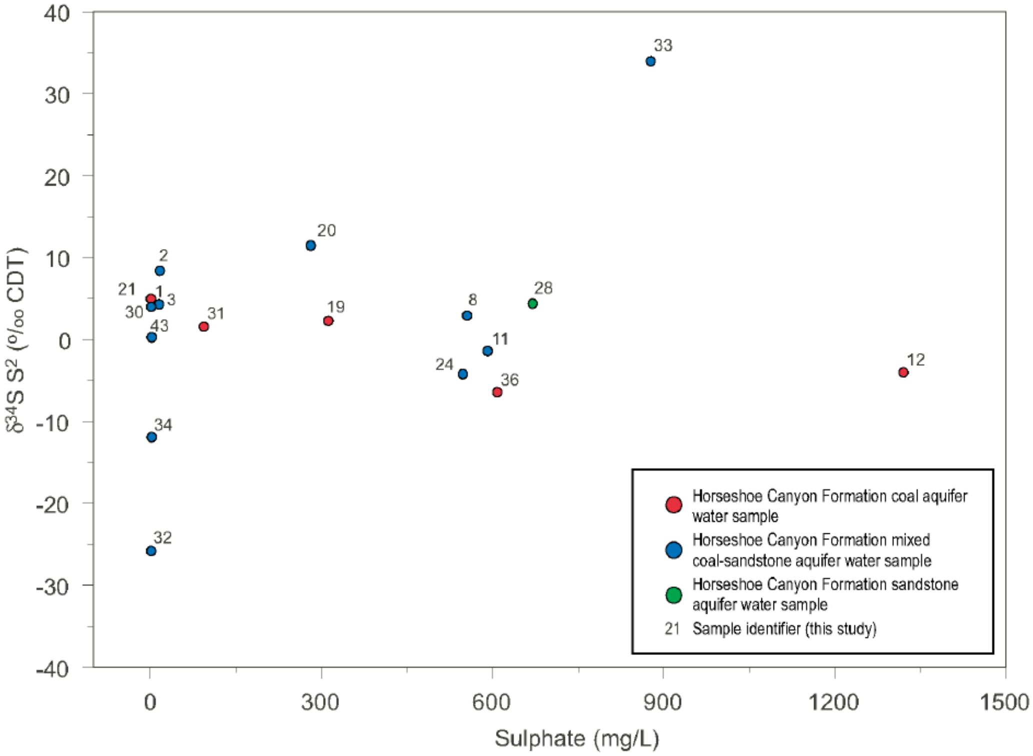


Figure 46. Horseshoe Canyon Formation: ^{34}S S^2 vs. SO_4. Abbreviation: CDT, Cañon Diablo Troilite.

3.7.3.3 Observations – Belly River Group

The mean $\delta^{34}S$ SO_4 value in water samples from Belly River Group coal aquifers is 0.4 ‰ CDT, with a standard deviation of 5.6 ‰ CDT (N=3). The mean $\delta^{34}S$ SO_4 value in water samples from Belly River Group mixed coal-sandstone aquifers is 0.6 ‰ CDT, with a standard deviation of 9.0 ‰ CDT (N=8). The mean $\delta^{34}S$ SO_4 value in water samples from Belly River Group sandstone aquifers is –0.1 ‰ CDT, with a standard deviation of 8.1 ‰ CDT (N=5). The complete chemistry dataset is found in Appendix A, Table 184.

The mean $\delta^{34}S$ S^2 value in water samples from Belly River Group coal aquifers is –0.3 ‰ CDT, with a standard deviation of 8.1 ‰ CDT (N=3). The mean $\delta^{34}S$ S^2 value in water samples from Belly River Group mixed coal-sandstone aquifers is 0.3 ‰ CDT, with a standard deviation of 6.5 ‰ CDT (N=7). The mean $\delta^{34}S$ S^2 value in water samples from Belly River Group sandstone aquifers is 2.2 ‰ CDT, with a standard deviation of 7.1 ‰ CDT (N=4). The complete chemistry dataset is found in Appendix A, Table 184.

The summary statistics for water samples collected during this study are presented in Table 171 below.

Table 171. Belly River Group: $\delta^{34}S$.

Location	Mean (‰ CDT)	Std. dev. (‰ CDT)	N	Max. (‰ CDT)	Min. (‰ CDT)
Water samples $\delta^{34}S$ SO_4					
Belly River Group wells (Upper Cretaceous) this study – coal aquifers	0.4	5.6	3	5.1	-5.8
Belly River Group wells (Upper Cretaceous) this study – mixed aquifers	0.6	9.0	8	12.4	-13.5
Belly River Group wells (Upper Cretaceous) this study – sandstone Aquifers	-0.1	8.1	5	7.6	-10.4
Water samples $\delta^{34}S$ S^2					
Belly River Group wells (Upper Cretaceous) this study – coal aquifers	-0.3	8.1	3	7.3	-8.8
Belly River Group wells (Upper Cretaceous) this study – mixed aquifers	0.3	6.5	7	7.1	-8.8
Belly River Group wells (Upper Cretaceous) this study – sandstone aquifers	2.2	7.1	4	9.0	-7.8

The coal aquifer water sampled $\delta^{34}S$ SO_4 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The mixed coal-sandstone aquifer water sample $\delta^{34}S$ SO_4 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, Devonian to Cenozoic $CaSO_4$, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The sandstone aquifer water sample $\delta^{34}S$ SO_4 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The coal aquifer water sampled $\delta^{34}S$ S^2 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The mixed coal-sandstone aquifer water sample $\delta^{34}S$ S^2 values determined fall within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

The sandstone aquifer water sample $\delta^{34}S$ S^2 value determined falls within the range of values reported for igneous rocks, volcanic sulphur, combustion of petroleum and coal, shale and limestone, as reported by Clark and Fritz (1997, p. 139).

Correlations appear to exist between $\delta^{34}S$ SO_4 and elevation, sulphate concentration and $\delta^{34}S$ S^2, particularly for those samples collected from sandstone aquifers (Figure 47, Figure 48 and Figure 49). An increase in elevation appears to correspond to an increase in $\delta^{34}S$ SO_4. A decrease in sulphate concentration appears to correspond to an increase in $\delta^{34}S$ SO_4. A decrease in $\delta^{34}S$ S^2 appears to correspond to an increase in $\delta^{34}S$ SO_4.

No other obvious trends were observed between $\delta^{34}S$ SO_4 or $\delta^{34}S$ S^2 and other parameters.

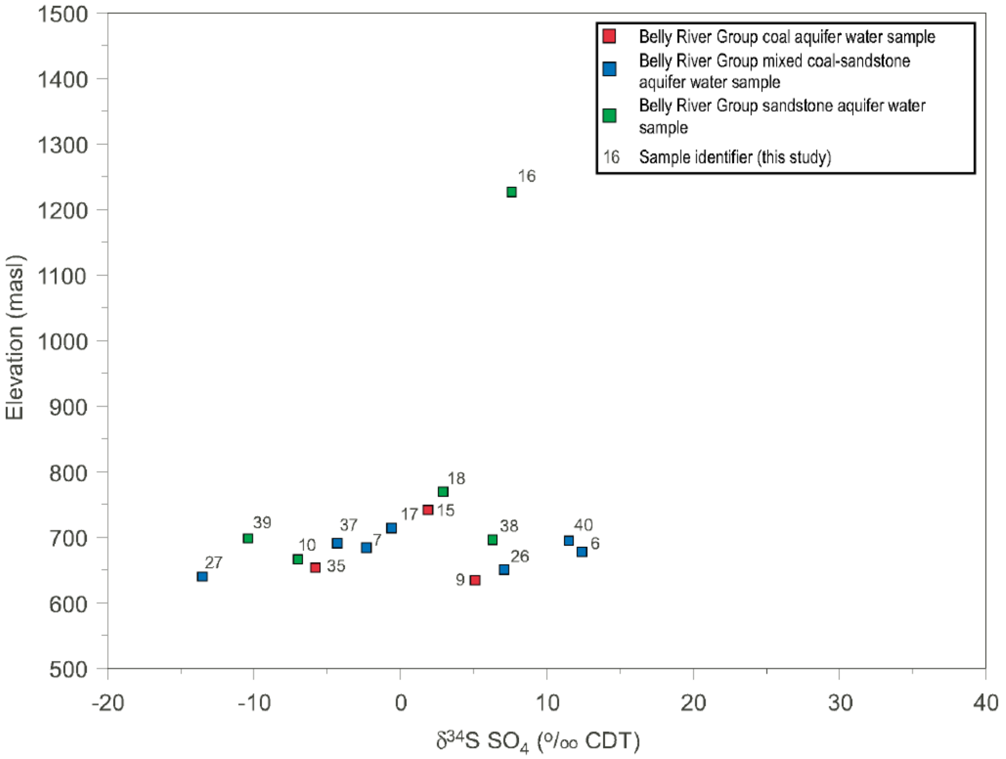


Figure 47. Belly River Group: $^{34}S\ SO_4$ vs. elevation. Abbreviation: CDT, Cañon Diablo Troilite; masl, metres above sea level.

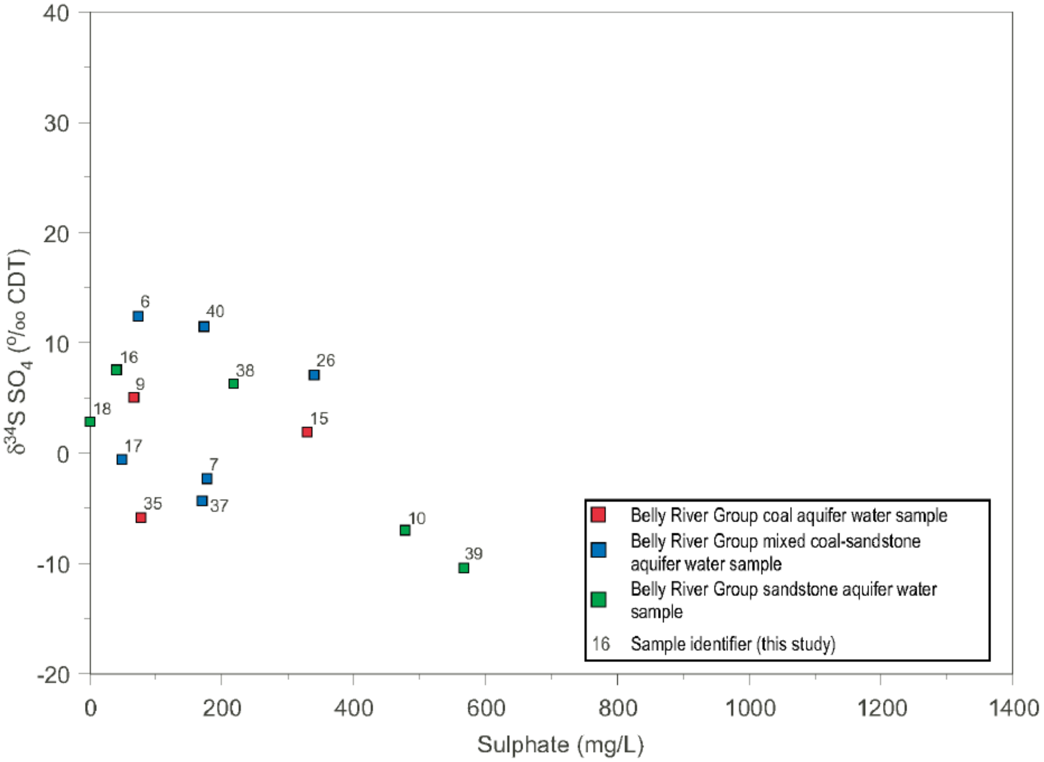


Figure 48. Belly River Group: $^{34}S\ SO_4$ vs. SO_4. Abbreviation: CDT, Cañon Diablo Troilite

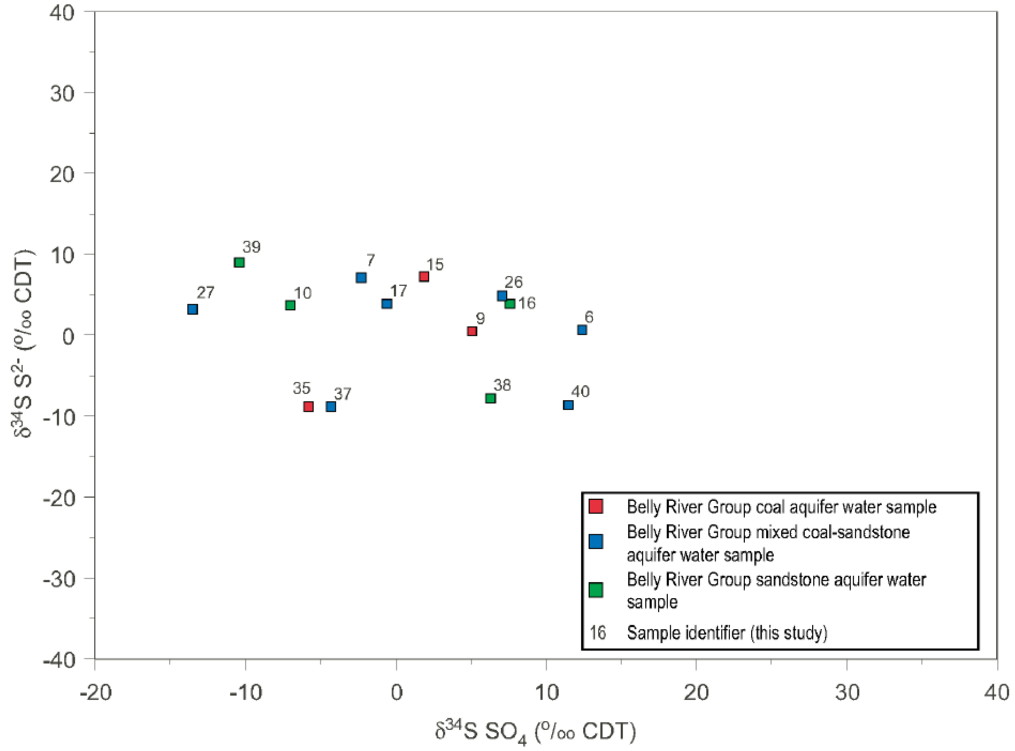


Figure 49. Belly River Group: ^{34}S S^{2-} vs. ^{34}S SO$_4$. Abbreviation: CDT, Cañon Diablo Troilite

It should be noted that the peak sizes used to determine the δ^{34}S S^2 values were only 1/10 of the optimal peak size. Therefore, the values are somewhat suspect. They are presented for completeness and in an effort to understand the sulphur cycle in these various aquifers.

3.7.3.4 Preliminary Interpretations – Paskapoo-Scollard Formation

There are a number of possible sources of sulphate in groundwater, including dissolution of sulphate minerals such as gypsum and anhydrite, chemical or biological oxidation of sulphide minerals, and atmospheric inputs, such as precipitation and dry fallout. Each of these sulphate introduction mechanisms has a generally distinct isotopic signature that can be used to evaluate it as a sulphate source. Sulphate reduction either through biological or inorganic mechanisms also affects the isotopic composition of sulphur in both the remaining sulphate fraction, and in the produced sulphide fraction.

Based on the work of Claypool et al. (1980), marine sulphate δ^{34}S values during the Tertiary and Cretaceous periods have mean values of 19.4 and 15.6‰ CDT respectively with standard deviations of 3.1 and 1.6‰ CDT respectively (N = 22 and 49 respectively). Terrestrial sulphates have δ^{34}S SO$_4$ values between –15 and 10‰ CDT respectively (Clark and Fritz, 1997, p. 143). The dissolution of gypsum or anhydrite occurs without measurable isotope effects, and so the isotope content of SO$_4^{2-}$ can be used as a tracer for sulphate origin (Clark and Fritz, 1997, p. 141). Samples collected from mixed coal-sandstone aquifers in the Paskapoo-Scollard Formation Appendix A, Table 183 have δ^{34}S SO$_4$ values of 3.3, 3.1, 5.2, 6.4, 13.5 and 34.8‰ CDT. The confining beds within the Paskapoo-Scollard Formation are terrestrial in origin (Beaton, pers. comm., 2003). Based on this, as well as the isotopic composition, the direct incorporation of SO$_4$ from marine sulphate minerals does not appear likely. Samples 22, 23, 29 and 44 have δ^{34}S SO$_4$ values that fall within the range of values defined by Clark and Fritz (1997, p. 143) for terrestrial sulphate and therefore, the δ^{34}S SO$_4$ in these samples may be a reflection of the dissolution of terrestrial sulphate minerals. Pollock et al. (2000) report between 1 and 2 wt % gypsum in mudstone and shale within the Paskapoo-Scollard Formation and 3 wt % gypsum within a coal zone. They also report an instance of barite within a shaly coal. In the mineralogical description of the Paskapoo Formation, by Allan and Sanderson (1945), they make no mention of sulphate minerals within the sandstone. The dissolution of gypsum or anhydrite should result in equal concentrations of calcium and sulphate in solution. Examination of these concentrations in solution (Table 172) shows that the molar ratio of calcium to sulphate does not approach one for any of the samples. In all of the water samples, calcium concentration exceeds the sulphate concentration. The conflicting information makes it difficult to assess the possibility of a terrestrial sulphate source as the source of sulphate within these aquifers. Information provided by the $\delta^{18}O$ SO_4 should help clarify this point.

Table 172. Paskapoo-Scollard Formation: evaporite mineral dissolution.

Sample ID	Ca (mg/L)	SO_4 (mg/L)	Ca (mmol/L)	SO_4 (mmol/L)	Ca/SO_4	$\delta^{34}S$ SO_4 (‰ CDT)	$\delta^{34}S$ S^2 (‰ CDT)	$\delta^{34}S$ SO_4 – $\delta^{34}S$ S^2 (‰ CDT)
22	4.5	0.3	0.112	0.003	36.0	3.3	1.2	-2.1
23	4.0	0.5	0.100	0.005	19.2	3.1	1.0	-2.1
29	96.3	10.6	2.40	0.110	21.8	5.2	-11.8	-17.0
42	3.6	0.3	0.090	0.003	28.8	-	-2.1	-
44	5.1	6.7	0.127	0.070	1.80	6.4	1.9	-4.5
45	70.9	12.3	1.77	0.128	13.8	13.5	1.9	-11.6
46	92.0	14.0	2.30	0.146	15.8	34.8	6.8	-28.0

Pollock et al. (2000) identified sulphide minerals in a shaly coal sample. These included pyrite and sphalerite. Chemical oxidation of sulphide minerals by O_2 imparts an approximate 5‰ CDT depletion on the produced sulphate (Fry et al., 1988). Anaerobic oxidation of sulphide minerals could also produce sulphate. The fractionation that could occur as a result of anaerobic oxidation is uncertain, although Toran and Harris (1989) report values similar to the one reported by Fry et al. (1986). Aerobic oxidation of sulphide by bacteria can result in a depletion of approximately 20‰ CDT in the produced sulphate (Clark and Fritz, 1997, p. 142; Canfield, 2001). Eh conditions are similar to those expected for iron reduction, suggesting that chemical oxidation is unlikely, although anaerobic oxidation might still be a possibility. However, a comparison between the $\delta^{34}S$ S^2 and the $\delta^{34}S$ SO_4 shows that the sulphide is in fact more depleted than the sulphate. In addition, none of the values approaches those expected for sulphide oxidation. Sulphide oxidation therefore appears to be an unlikely source of the observed sulphate.

Atmospheric input of sulphate plays a role in the sulphur cycle particularly in shallow groundwater and soil (Clark and Fritz, 1997, p. 144). Sulphate from combustion of fossil fuels and coal typically has $\delta^{34}S$ SO_4 values between approximately –8 and 10‰ CDT (Clark and Fritz, 1997, p. 144). Atmospherically derived sulphate has a $\delta^{34}S$ SO_4 value of between –5 and 10‰ CDT (Clark and Fritz, 1997, p. 143). As previously mentioned, samples 22, 23, 29 and 44 have $\delta^{34}S$ SO_4 values that fall within the range of values reported for combustion of petroleum and coal and for atmospherically derived sulphate. This may indicate that the sulphate in these samples is derived from an atmospheric source. The average sulphate concentration in Alberta precipitation collected from 11 meteorological stations, between 1992 and 1999 is 1.2 mg/L. Sulphate concentrations in samples 22, 23 and 42 are less than the average precipitation sulphate concentration, whereas samples 29, 44, 45 and 46 have values that exceed the average precipitation value. If recharge of the aquifers with water affected by atmospheric sources of sulphate is occurring, processes appear to be removing sulphate from groundwater at certain locations while introducing sulphate into groundwater at other locations. Are recharge rates to these aquifers sufficient to introduce atmospheric sulphate into the aquifers and if so, is the signature of the atmospherically derived sulphate preserved given the fact that additional sulphate is introduced? The oxygen and hydrogen isotopes of water suggest that mixing is occurring between meteoric water and original formation water producing the observed $\delta^{18}O$ and $\delta^{2}H$ values. It therefore appears likely that such mixing could also affect the $\delta^{34}S$ values.

A final mechanism that affects stable sulphur isotopic values is sulphate reduction. Reduction of sulphate to sulphide, especially in the presence of bacteria, is generally at the root of the variations of isotopic composition of sulphate in solution (Clark and Fritz, 1997, p. 145). The reduction of sulphate results in an enrichment in the remaining sulphate and a depletion in the produced sulphide. Under closed system conditions, sulphate reduction will also result in a decrease in sulphate in solution. Bacterial sulphate reduction leads to an enrichment in the $\delta^{34}S$ SO_4 value of approximately 25‰ CDT while inorganic sulphate reduction results in an enrichment of approximately 70‰ CDT (Clark and Fritz, 1997, p. 146). Inorganic sulphate reduction is considered insignificant in most groundwater systems however (Clark and Fritz, 1997, p. 146). Canfield (2001) states that with abundant sulphate present (> 1 mmol/L), fractionations range between 3 and 46‰ CDT with an average around 18‰ CDT. Canfield (2001) goes on to state that fractionations become significantly suppressed when sulphate concentrations drop below around 1 mmol/L, although the database is small.

Water samples collected from the Paskapoo-Scollard Formation are enriched in $\delta^{34}S$ SO_4 in comparison to $\delta^{34}S$ S^2 (Table 172). However, only samples 29 and 46 show enrichment of approximately 25‰ CDT (Table 172), whereas samples 29, 44, 45 and 46 fall within the range of values for fractionations listed by Canfield (2001). Samples 22 and 23 fall below this range of values. Sulphate concentrations measured in the six water samples are < 1 mmol/L. As previously mentioned, Canfield (2001) states that fractionations become significantly suppressed when sulphate concentrations drop below around 1 mmol/L. A concentration of ≤1 mmol/L therefore may limit the magnitude of fractionation that occurs during the sulphate reduction reaction in these aquifers. A second possibility is proposed in Drever (1997). Drever (1997, p. 171-172) states that much of the organic matter in sedimentary rocks, such as coal, is refractory and is not easily utilized by bacteria and therefore, the process of sulphate reduction is generally slow. Therefore, the degree of fractionation is likely related not only to sulphate concentrations, but also to the ability of the bacteria to use the organic carbon substrate.

A relationship exists between the difference in the $\delta^{34}S$ values and the sulphate concentration (Figure 50). Linear regression of the data results in the following relationship:

$$\delta^{34}S\ S^2 - \delta^{34}S\ SO_4 = -1.4944SO_4\ (mg/L) + 0.1751 \qquad R^2 = 0.7487$$

This relationship appears to support the link between fractionation and dissolved sulphate concentrations proposed by Canfield (2001).

Samples 29, 44, 45 and 46 have sulphate concentrations in excess of precipitation values. Addition of sulphate to groundwater is generally thought to occur through the dissolution of sulphate minerals. As stated above, the similarities of the sulphur isotopes to atmospheric sources of sulphate, the molar ratios of Ca and SO_4, as well as the mineralogical description of the Paskapoo-Scollard Formation support and dispute the presence of sulphate minerals in the aquifers. These wells are completed in mixed coal-sandstone aquifers with shale units present separating individual aquifer units. Chapelle (2001, p. 277-279) discussed an example from a clastic coastal plain aquifer that may apply to this case and help explain the source of the sulphate in the mixed coal-sandstone aquifers. The coastal plain aquifer water contained between 20 and 30 mg/L sulphate, similar to some of the samples collected during this study. Confining beds of marine origin in the coastal plain aquifer case contained between 200 and 600 mg/L, whereas confining beds of nonmarine origin contained <50 mg/L, suggesting that diffusion of sulphate from the confining beds into the aquifers could occur, especially between the confining beds of marine origin and the aquifers in question. Viable sulphate reducing bacteria were collected from the aquifer material, but not from the confining units. This lead to a conclusion that diffusion of sulphate from the confining beds was occurring and that sulphate reduction in the aquifers maintained the sulphate concentration at low values. The origin of the sulphate in the confining beds was believed to be the oxidation of sulphide minerals by iron-bearing minerals. As stated previously, Pollock et al. (2000) reported the presence of pyrite and sphalerite in a shaly coal unit within the Paskapoo-Scollard Formation. In addition, Beaton (pers. comm.) indicated that sulphide minerals are present within confining beds in the Paskapoo-Scollard Formation. These confining beds are terrestrial in origin (Beaton, pers. comm.) and likely will have lower sulphate concentrations, resulting in lower concentration gradients and therefore lower concentrations of sulphate in the aquifers. The components of the coastal plain model detailed by Chapelle (2001) appear to be present within the mixed coal-sandstone aquifers of the Paskapoo-Scollard Formation. This diffusion-controlled mechanism might therefore explain the observed sulphate and sulphide sulphur isotopic compositions.

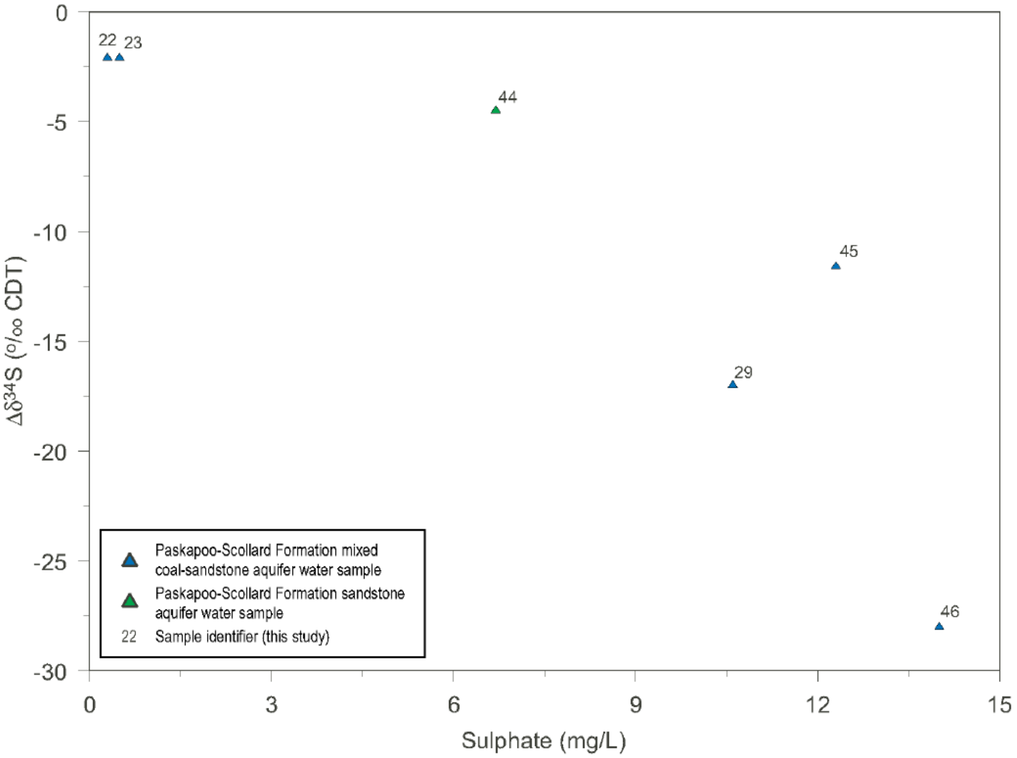


Figure 50. Paskapoo-Scollard Formation: Δ^{34}S vs. SO$_4$. Abbreviation: CDT, Cañon Diablo Troilite

3.7.3.5 Preliminary Interpretations – Horseshoe Canyon Formation

Claypool et al. (1980) report that Cretaceous marine sulphates have an average δ^{34}S SO$_4$ value of 15.6‰ CDT with a standard deviation of 1.6‰ CDT (N = 49). Sample 25 (Table 173) has a value similar to the Claypool et al. (1980) average value. This sample may have a marine sulphate source. The Ca/SO$_4$ ratio exceeds three indicating that simple dissolution of sulphate minerals of marine origin is an unlikely source of the sulphate in this sample. Terrestrial sulphates have δ^{34}S SO$_4$ values between –15 and 10‰ CDT respectively (Clark and Fritz, 1997, p. 143). Samples 1, 2, 8, 11, 12, 19, 20, 21, 24, 28, 30, 31, 32, 33, 34, 36, 41 and 43 have δ^{34}S SO$_4$ values that fall within this range of values (Table 173). Except in the case of sample 28 (Ca/SO$_4$ = 0.79), the Ca/SO$_4$ ratios for these samples do not approach 1. As with sample 25, this suggests that simple dissolution of sulphate, in this case sulphate of terrestrial origin, is an unlikely source of sulphate. The δ^{18}O SO$_4$ values should help clarify the origin of the sulphate.

Table 173. Horseshoe Canyon Formation: evaporite mineral dissolution.

Sample ID	Ca (mg/L)	SO_4 (mg/L)	Ca (mmol/ L)	SO_4 (mmol/L)	Ca/SO_4	$\delta^{34}S$ SO_4(‰ CDT)	$\delta^{34}S$ S^2 (‰ CDT)	$\delta^{34}S$ SO_4 – $\delta^{34}S$ S^2 (‰CDT)
1	7.00	4.10	0.175	0.0430	4.09	2.4	4.5	2.1
2	21.5	16.5	0.536	0.172	3.12	3.4	8.4	5.0
8	9.80	555	0.245	5.78	0.0400	-3.8	2.9	6.7
11	10.4	591	0.259	6.15	0.0400	-5.4	-1.4	4.0
12	21.1	1320	0.526	13.7	0.0400	-10.5	-4	6.5
19	17.4	312	0.434	3.25	0.130	-4.0	2.3	6.3
20	15.0	281	0.374	2.92	0.130	5.5	11.5	6.0
21	3.40	1.00	0.085	0.0100	8.15	-0.3	5	5.3
24	128	548	3.19	5.70	0.560	-8.0	-4.2	3.8
25	21.8	16.6	0.544	0.173	3.15	16.5	-	-
28	222	670	5.54	6.97	0.790	2.5	4.4	1.9
30	7.30	1.40	0.182	0.0150	12.5	6.7	4.0	-2.7
31	5.60	93.8	0.140	0.976	0.140	7.7	1.6	-6.1
32	11.4	1.60	0.284	0.0170	17.1	4.5	-25.8	-30.3
33	27.0	877	0.674	9.13	0.0700	-13.1	34	47.1
34	3.30	2.50	0.0820	0.0260	3.16	-	-11.9	-
36	13.8	608	0.344	6.33	0.0500	-9.6	-6.4	3.2
41	8.00	42.2	0.200	0.439	0.450	3.6	-	-
43	2.70	2.50	0.0670	0.0260	2.59	10.0	0.3	-9.7

Allan and Sanderson (1945) described the mineralogy of the Edmonton Group sandstone between Edmonton and Calgary and indicate that sulphide minerals such as pyrite and marcasite are present within the sandstone. Beaton (pers. comm., 2003) also indicated that sulphide minerals are present within both aquifers and confining units within this formation. Aerobic oxidation of sulphide by bacteria can result in a depletion of between 0 to 20‰ CDT in the produced sulphate (Clark and Fritz, 1997, p. 142; Canfield, 2001). Chemical oxidation of sulphide minerals by O_2 imparts an approximate 5‰ CDT depletion on the produced sulphate (Fry et al., 1988). Anaerobic oxidation of sulphide minerals also occurs, but the fractionations involved in this process are not well documented. Toran and Harris (1989) reported values similar to those reported by Fry et al. (1988). Chemical oxidation appears unlikely since the measured Eh values indicate that the dominant redox processes occurring in the various aquifers is either iron or sulphate reduction. Samples 1, 2, 8, 11, 12, 19, 20, 21, 24, 28, 33 and 36 have $\delta^{34}S$ values that suggest that bacterial or abiological oxidation of sulphide minerals is possibly responsible for the observed values. The $\delta^{34}S$ values for sample 33 have the largest difference in the $\delta^{34}S$ values. The value is twice as large as the maximum expected fractionation value reported for bacterial oxidation of sulphide. This may indicate that additional processes are occurring, affecting the isotope values. Such processes might include disproportionation reactions or perhaps repeated instances of oxidation and reduction of sulphur.

Atmospheric input of sulphate plays a role in the sulphur cycle particularly in shallow groundwater and soil (Clark and Fritz, 1997, p. 144). Sulphate from combustion of fossil fuels and coal typically has $\delta^{34}S$ SO_4 values between approximately –8 and 10‰ CDT (Clark and Fritz, 1997, p. 144). Atmospherically derived sulphate has a $\delta^{34}S$ SO_4 value of between –5 and 10‰ CDT (Clark and Fritz, 1997, p. 143). As previously mentioned, samples 1, 2, 8, 11, 19, 20, 21, 24, 28, 30, 31, 32, 36, 41 and 43 have $\delta^{34}S$ SO_4 values that fall within the range of values reported for combustion of petroleum and coal as well as for atmospherically derived sulphate. This may indicate that the sulphate in these samples is derived from an atmospheric source. The average sulphate concentration in Alberta precipitation collected from 11 meteorological stations, between 1992 and 1999 is 1.2 mg/L. Only in sample 21 has a sulphate concentration less than the average precipitation sulphate concentration. All other samples have values that exceed the average precipitation value. If recharge of the aquifers with water affected by atmospheric sources of sulphate is occurring, processes appear to be introducing additional sulphate into groundwater. Are recharge rates to these aquifers sufficient to introduce atmospheric sulphate into the aquifers and if so, is the signature of the atmospherically derived sulphate preserved given the fact that additional sulphate is introduced? The oxygen and hydrogen isotopes of water suggest that mixing is occurring between meteoric water and original formation water producing the observed $\delta^{18}O$ and $\delta^{2}H$ values. It therefore appears likely that such mixing could also affect the $\delta^{34}S$ values.

Samples 30, 31, 32 and 43 have $\Delta\ \delta^{34}S$ values inconsistent with processes such as sulphide oxidation. Another process must therefore be responsible for the observed $\delta^{34}S$ values. Sulphate reduction results in a depletion of the produced sulphide $\delta^{34}S\ S^{2}$ values and an enrichment in the remaining sulphate $\delta^{34}S$ SO_4 values. Bacterial sulphate reduction leads to an enrichment in the $\delta^{34}S\ SO_4$ value of approximately 25‰ CDT, whereas inorganic sulphate reduction can lead to enrichment of approximately 70 (Clark and Fritz, 1997, p. 146). Inorganic sulphate reduction is considered insignificant in most groundwater systems (Clark and Fritz, 1997, p. 146). Canfield (2001) stated that with abundant sulphate present (> 1 mmol/L), fractionations range between 3 and 46‰ CDT with an average around 18‰ CDT. Canfield (2001) went on to state that fractionations become significantly suppressed when sulphate concentrations drop below around 1 mmol/L. Samples 30, 31, 32 and 43 have $\delta^{34}S$ values that suggest that sulphate reduction may be occurring. Fractionations of between –2.7 and 30.3‰ CDT are observed and are consistent with the values reported by Clark and Fritz (1997, p. 146) and Canfield (2001) for fractionation resulting from sulphate reduction. These samples all have sulphate concentrations < 1 mmol/L perhaps explaining the large range of observed fractionations within the sample set. Drever (1997, p. 171–172) stated that the organic matter in coal is refractory and therefore is not easily utilized by bacteria. This implies that sulphate reduction in coal aquifers is slow. The fractionation of sulphur between sulphate and sulphide is likely controlled not only by the dissolved sulphate concentration, but also by the ability of the bacteria to utilize the organic carbon substrate.

3.7.3.6 Preliminary Interpretations – Belly River Group

As mentioned previously, the average $\delta^{34}S\ SO_4$ value for Cretaceous seawater is 15.6‰ CDT with a standard deviation of 1.6‰ CDT (Claypool et al., 1980). Only sample 7 approaches this value (Table 174). The Belly River Group is overlain and underlain by marine shale units of the Bearpaw and Lea Park formations. A source of marine sulphate could therefore exist for the Belly River Group sandstone. The Ca/SO_4 molar ratio is almost one, further indicating the possibility of a sulphate mineral source for the observed $\delta^{34}S\ SO_4$. Terrestrial sulphates have $\delta^{34}S\ SO_4$ values between –15 and +10‰ CDT respectively (Clark and Fritz, 1997, p. 143). All of the samples with the exception of sample 7 fall within this range of values. Only samples 38 and 39 however have Ca/SO_4 ratio values that approach one. This suggests that a terrestrial source of sulphate may be the sulphate source in samples 38 and 39. The $\delta^{18}O\ SO_4$ values should help confirm the sources of dissolved sulphate.

Table 174. Belly River Group: evaporite mineral dissolution.

Sample ID	Ca (mg/L)	SO_4 (mg/L)	Ca (mmol/L)	SO_4 (mmol/L)	Ca /SO_4	$\delta^{34}S$ SO_4 (‰ CDT)	$\delta^{34}S$ S^2 (‰ CDT)	$\delta^{34}S$ SO_4 – $\delta^{34}S$ S^2 (‰CDT)
5	85.9	27.8	2.14	0.289	7.4	11.5	-8.6	-20.1
6	2.2	13.0	0.055	0.135	0.41	-5.4	-	-
7	1.8	4.0	0.045	0.042	1.08	12.4	0.7	-11.7
9	2.0	12.0	0.050	0.125	0.40	-2.3	7.1	9.4
10	74.0	9.0	1.85	0.094	19.7	5.1	0.5	-4.6
15	18.6	6.0	0.464	0.062	7.4	-7	3.7	10.7
16	150.0	8.0	3.74	0.083	44.9	1.9	7.3	5.4
17	48.8	10.0	1.22	0.104	11.7	7.6	3.9	-3.7
18	2.8	1.0	0.070	0.010	6.7	-0.6	3.9	4.5
26	25.6	7.0	0.639	0.073	8.8	2.9	-	-
27	44.4	15.0	1.11	0.156	7.1	7.1	4.9	-2.2
35	70.6	14.0	1.76	0.146	12.1	-13.5	3.2	16.7
37	4.2	2.0	0.105	0.021	5.0	-5.8	-8.8	-3
38	3.2	5.0	0.080	0.052	1.53	-4.3	-8.8	-4.5
39	5.1	11.0	0.127	0.115	1.1	6.3	-7.8	-14.1
40	3.0	3.0	0.075	0.031	2.4	-10.4	9	19.4

Beaton (pers. comm., 2003) indicated that sulphide minerals are present within both aquifers and confining units within this formation. Oxidation of sulphide by bacteria can result in a depletion of between 0 to 20‰ CDT in the produced sulphate (Clark and Fritz, 1997, p. 142; Canfield, 2001), whereas chemical oxidation of sulphide minerals by O_2 imparts an approximate 5‰ CDT depletion on the produced sulphate (Fry et al., 1988). Toran and Harris (1989) reported fractionation values for abiological and anaerobic sulphide oxidation similar to those reported by Fry et al. (1988) for chemical oxidation of sulphide minerals. Chemical oxidation appears unlikely since the measured Eh values indicate that the dominant redox process occurring in the various aquifers is iron reduction. Samples 9, 15, 16, 18, 35 and 40 have $\delta^{34}S$ values that suggest that bacterial or abiological oxidation of sulphide minerals is possibly responsible for the observed values.

Sulphate from combustion of fossil fuels and coal typically has $\delta^{34}S$ SO_4 values between approximately –8 and 10‰ CDT (Clark and Fritz, 1997, p. 144). Atmospherically derived sulphate has a $\delta^{34}S$ SO_4 value of between –5 and 10‰ CDT (Clark and Fritz, 1997, p. 143). As previously mentioned, samples 6, 9, 10, 15, 16, 17, 18, 26, 27, 37, 38 and 39 have $\delta^{34}S$ SO_4 values that fall within the range of values reported for combustion of petroleum and coal as well as for atmospherically derived sulphate. This may indicate that the sulphate in these samples is derived from an atmospheric source. The average sulphate concentration in Alberta precipitation collected from 11 meteorological stations, between 1992 and 1999 is 1.2 mg/L. Only in sample 18 is the sulphate concentration less than the average precipitation sulphate concentration. All other samples have values that exceed the average precipitation value. If recharge of the aquifers with water affected by atmospheric sources of sulphate is occurring, processes appear to be introducing additional sulphate into groundwater. Are recharge rates to these aquifers sufficient to introduce atmospheric sulphate into the aquifers and if so, is the signature of the atmospherically derived sulphate preserved given the fact that additional sulphate is introduced? The oxygen and hydrogen isotopes of water suggest that mixing is occurring between meteoric water and original formation water producing the observed $\delta^{18}O$ and $\delta^{2}H$ values. It therefore appears likely that such mixing could also affect the $\delta^{34}S$ values.

Samples 5, 7, 10, 17, 27, 37, 38 and 39 have Δ $\delta^{34}S$ values that are inconsistent with sulphide oxidation, but rather indicate the possibility that sulphate reduction is occurring. As mentioned previously, sulphate reduction results in a depletion of the produced sulphide $\delta^{34}S$ S^2 values and an enrichment in the remaining sulphate $\delta^{34}S$ SO_4 values. Bacterial sulphate reduction leads to an enrichment in the $\delta^{34}S$ SO_4 value of approximately 25‰ CDT (Clark and Fritz, 1997, p. 146). Inorganic sulphate reduction is considered insignificant in most groundwater systems (Clark and Fritz, 1997, p. 146) but where it occurs, enrichments on the order of 70‰ CDT are observed. Canfield (2001) states that with abundant sulphate present (> 1 mmol/L), fractionations range between 3 and 46‰ CDT with an average around 18‰ CDT. Canfield (2001) goes on to state that fractionations become significantly suppressed when sulphate concentrations drop below around 1 mmol/L. Sulphate concentrations in samples 5, 7, 10, 17, 27, 37, 38 and 39 are all < 1 mmol/L. The fractionation values all fall within the range of values listed by Canfield (2001). Sample 5 approaches the fractionation value listed by Clark and Fritz (1997, p. 146). Sulphate reduction rates in coal aquifers are generally slow (Drever, 1997, p. 172). This occurs because the organic matter in coal is generally difficult for bacteria to utilize. The fractionation of sulphur isotopes is likely related not only to sulphate concentration, but also to the ability of the bacteria to make use of the organic matter present in the aquifers.

3.7.4 Boron

Boron possesses two stable isotopes, ^{10}B (Abundance 19.9%) and ^{11}B (Abundance 80.1%). Boron is bonded to oxygen in rocks and water in either a tetrahedral complex, such as $B(OH)_4^-$, or a trigonal complex, such as $B(OH)_3$ (Palmer and Swihart, 1996). Fractionation between the two isotopes is almost entirely controlled by their relative partitioning between the trigonal and tetrahedral species with the heavier isotope (^{11}B) concentrated in the trigonal complexes and the lighter isotope (^{10}B) concentrated in the tetragonal complexes (Palmer and Swihart, 1996). The isotope systematics are sensitive to pH and possibly temperature changes. Boron isotopes have been used to trace the origin of water masses, track the evolution of brines, examine hydrothermal flow systems (Kendall et al., 1998), and provide insight into the sources and water-sediment interactions of fossil water in aquitards (Vengosh and Hendry, 2001). Groundwater will contain boron derived from such processes as weathering, diagenesis and mineral dissolution along the flow path, contamination by anthropogenic sources and perhaps even contribution from organic material (Bassett, 1990).

3.7.4.1 Observations – Paskapoo-Scollard Formation

All seven samples have been analyzed; however, four of the sample results are undergoing confirmation. The three mixed coal-sandstone aquifer water samples have a mean $\delta^{11}B$ value of 23 ‰ NIST SRM 951, with a standard deviation of 15 ‰ NIST SRM 951 (N=3). The complete chemistry dataset is found in Appendix A, Table 184. A summary of the data is provided in Table 175 below.

Table 175. Paskapoo-Scollard Formation: $\delta^{11}B$.

Location	Mean (‰ NIST SRM 951)	Std. dev. (‰ NIST SRM 951)	N	Max. (‰ NIST SRM 951)	Min. (‰ NIST SRM 951)
Paskapoo-Scollard Formation wells (Tertiary-Upper Cretaceous) this study	23	15	3	32	5

All three samples have $\delta^{11}B$ values within the range of values for groundwater reported by Palmer and Swihart (1996). The values also fall within the range of values reported by Lemay (2002c) and Cold Lake Operations - Imperial Oil Resources (1998) for Quaternary and Lower Cretaceous water samples collected from northeast Alberta.

There appears to be a relationship between δ^{11}B values and pH. As the pH increases, so do the δ^{11}B values (Figure 51). A relationship between δ^{11}B and boron concentration also appears to exist, as does a linear relationship between δ^{11}B and 1/boron (Figure 52). Note: These relationships are based on only three points.

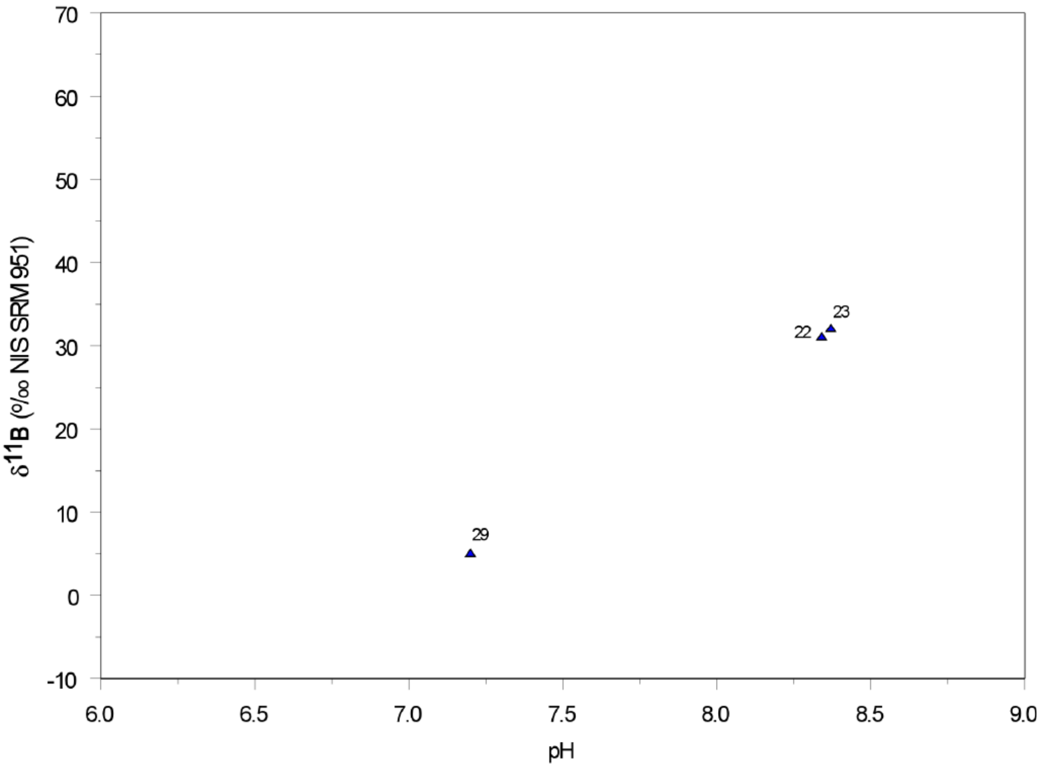


Figure 51. Paskapoo-Scollard Formation: δ^{11}B vs. pH.

3.7.4.2 Observations – Horseshoe Canyon Formation

The mean δ^{11}B value in water samples from Horseshoe Canyon Formation coal aquifers is 16 ‰ NIST SRM 951, with a standard deviation of 11 ‰ NIST SRM 951 (N=6). The mean δ^{11}B value in water samples from Horseshoe Canyon Formation mixed coal-sandstone aquifers is 25 ‰ NIST SRM 951, with a standard deviation of 10 ‰ NIST SRM 951 (N=12). A Horseshoe Canyon Formation sandstone aquifer water sample has a δ^{11}B value of 17 ‰. The complete chemistry dataset is found in Appendix A, Table 184. A summary of the data is provided in Table 176 below.

Table 176. Horseshoe Canyon Formation: δ^{11}B.

Location	Mean (‰ NIST SRM 951)	Std. dev. (‰ NIST SRM 951)	N	Max. (‰ NIST SRM 951)	Min. (‰ NIST SRM 951)
Horseshoe Canyon Formation wells (Upper Cretaceous) this study – coal aquifers	16	11	6	24	0
Horseshoe Canyon Formation wells (Upper Cretaceous) this study – mixed coal-sandstone aquifers	25	10	12	43	11

The δ^{11}B vs. boron and δ^{11}B vs. 1/boron plots (Figure 53) indicate a relationship exists between the concentration of boron and the δ^{11}B values of the water samples. A curvilinear trend is observed in the δ^{11}B vs. boron plot, whereas two linear trends are observed on the δ^{11}B vs. 1/boron plot.

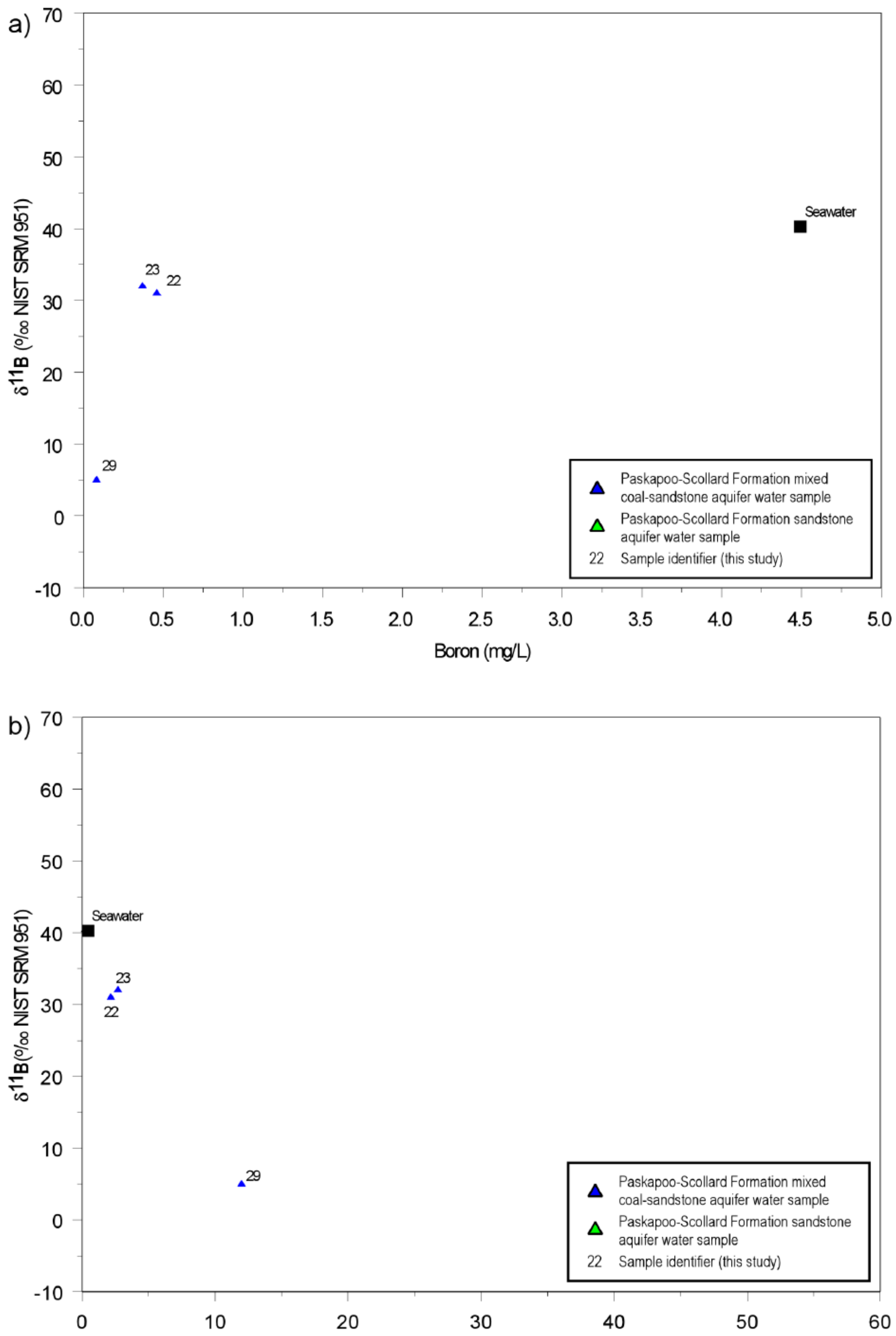


Figure 52. Paskapoo-Scollard Formation: a) δ^{11}B vs. Boron; and b) δ^{11}B vs. 1/Boron.

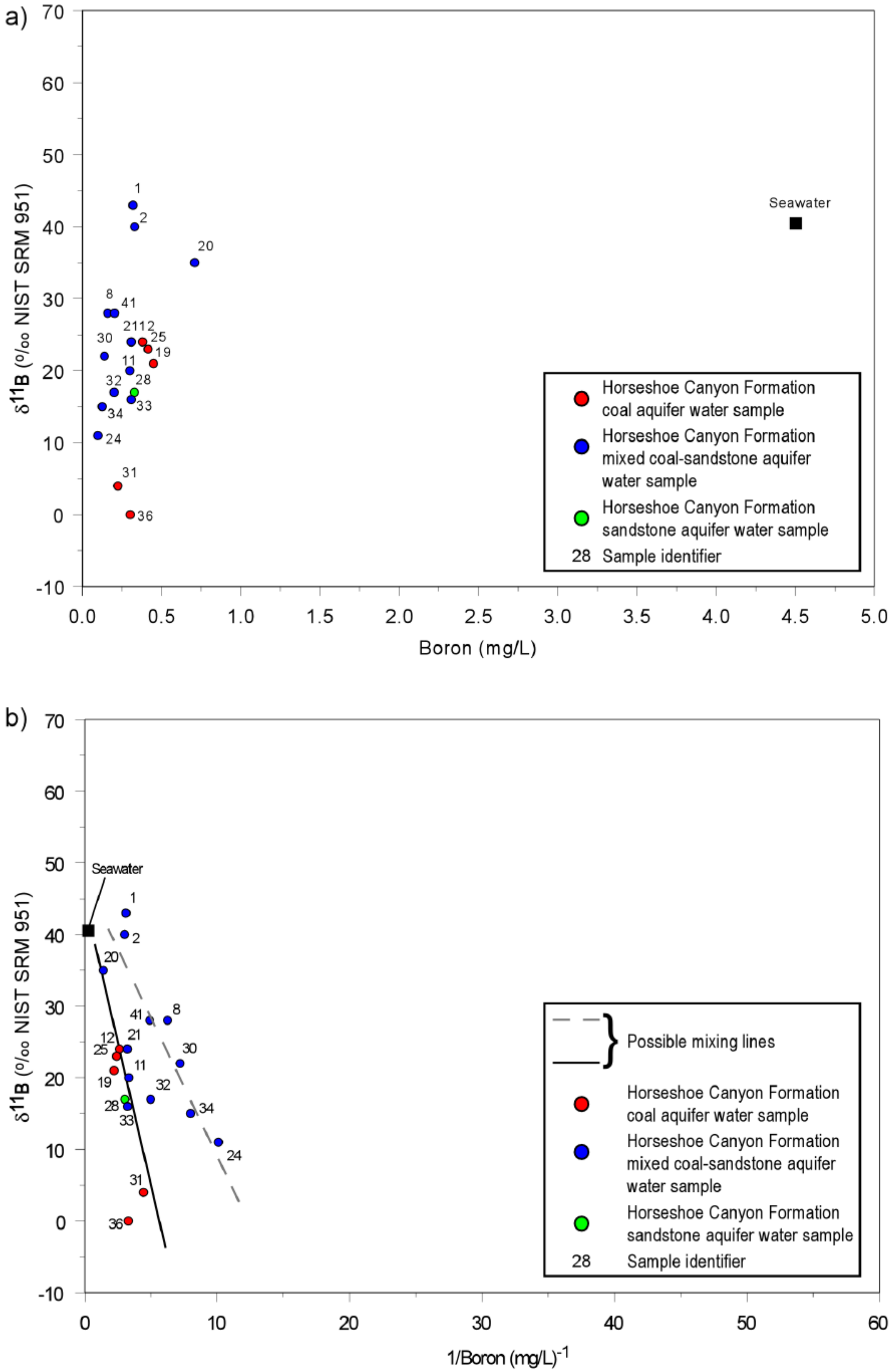


Figure 53. Horseshoe Canyon Formation: a) δ^{11}B vs. Boron; and b) δ^{11}B vs. 1/Boron.

The coal aquifer δ^{11}Bwater samples fall within the range of values reported for precipitation (Vengosh and Hendry, 2001), groundwater (Palmer and Swihart, 1996; Lemay 2002c and Cold Lake Operations - Imperial Oil Resources, 1998) and Cretaceous formation water in northeast Alberta (Lemay, 2002c; and Cold Lake Operations - Imperial Oil Resources Oil, 1998). The mixed coal-sandstone aquifers δ^{11}B values fall within the range reported for precipitation (Vengosh and Hendry, 2001), groundwater (Palmer and Swihart, 1996; Lemay, 2002c; and Cold Lake Operations - Imperial Oil Resources Oil, 1998), seawater (Bassett, 1990) and Cretaceous formation water in northeast Alberta (Lemay 2002c; and Cold Lake Operations - Imperial Oil Resources, 1998).

3.7.4.3 Observations – Belly River Group

The mean δ^{11}B value in water samples from Belly River Group coal aquifer water samples is 38 ‰ NIST SRM 951, with a standard deviation of 3 ‰ NIST SRM 951 (N=3). The mean δ^{11}B value in water samples from Belly River Group mixed coal-sandstone aquifer water samples is 31 ‰ NIST SRM 951, with a standard deviation of 18 ‰ NIST SRM 951 (N=8). The mean δ^{11}B value in water samples from Belly River Group sandstone aquifer water samples is 28 ‰ NIST SRM 951, with a standard deviation of 19 ‰ NIST SRM 951 (N=5). The complete chemistry dataset is found in Appendix A, Table 184. A summary of the data is provided in Table 177 below.

Table 177. Belly River Group: δ^{11}B.

Location	Mean (‰ NIST SRM 951)	Std. dev. (‰ NIST SRM 951)	N	Max. (‰ NIST SRM 951)	Min. (‰ NIST SRM 951)
Belly River Group wells (Upper Cretaceous) this study – coal aquifers	38	3	3	40	35
Belly River Group wells (Upper Cretaceous) this study – mixed coal-sandstone aquifers	31	18	8	59	2
Belly River Group wells (Upper Cretaceous) this study – sandstone aquifers	33	10	5	44	18

A general trend appears to exist between δ^{11}B and pH (Figure 54). An increase in pH results in an increase in δ^{11}B.

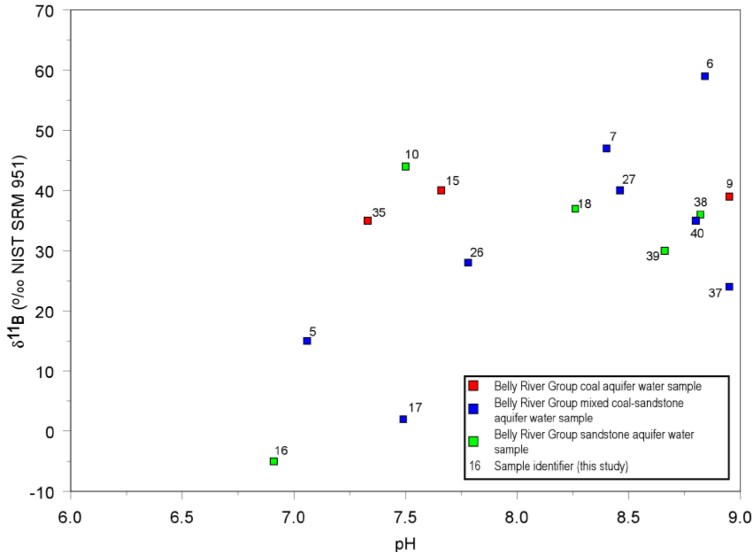


Figure 54. Belly River Group: δ^{11}B vs. pH.

The $\delta^{11}B$ vs. boron and $\delta^{11}B$ vs. 1/boron plots (Figure 55) indicate a relationship exists between the concentration of boron and the $\delta^{11}B$ values of the water samples. One or more curvilinear trends are observed in the $\delta^{11}B$ vs. boron plot, whereas two linear trends are observed on the $\delta^{11}B$ vs. 1/boron plot.

The coal aquifer water samples fall within the range of values reported for groundwater (Palmer and Swihart, 1996; Lemay 2002c and Cold Lake Operations - Imperial Oil Resources, 1998) and Cretaceous formation water in northeast Alberta (Lemay, 2002c; and Cold Lake Operations - Imperial Oil Resources, 1998). The mixed coal-sandstone aquifer water samples fall within the range of values reported for precipitation (Vengosh and Hendry, 2001), groundwater (Palmer and Swihart, 1996; Lemay, 2002c; and Cold Lake Operations - Imperial Oil Resources , 1998), seawater (Bassett, 1990) and Cretaceous formation water in northeast Alberta (Lemay 2002c; and Cold Lake Operations - Imperial Oil Resources, 1998). The sandstone aquifer water samples fall within the range of values reported for precipitation (Vengosh and Hendry, 2001), groundwater (Palmer and Swihart, 1996; Lemay, 2002c; and Cold Lake Operations - Imperial Oil Resources , 1998), seawater (Bassett, 1990) and Cretaceous formation water in northeast Alberta (Lemay 2002c; and Cold Lake Operations - Imperial Oil Resources, 1998).

3.7.4.4 Preliminary Interpretations – Paskapoo-Scollard Formation

Palmer, Spivack and Edmond (1987) found that adsorption of boron on marine clays and fractionation during adsorption is partially controlled by pH. During adsorption, the light isotope is preferentially incorporated into the adsorbed phase, with less fractionation occurring at higher pH values (Palmer, Spivack and Edmond, 1987). Sample 29 is the shallowest of the three wells and has the lowest $\delta^{11}B$ and pH value, whereas samples 22 and 23 are deeper and have higher $\delta^{11}B$ and pH values. These wells are completed in mixed coal-sandstone aquifers that usually have shale intervals between aquifer units. Clays are, therefore, present and available to participate in the adsorption processes. The greatest difference in $\delta^{11}B$ values is noted between sample 29 and sample 22. Despite the fact that samples 22 and 23 have similar $\delta^{11}B$ values, the depth difference is greatest between these two samples. The pH measured at these two sample locations was much greater than at sample site 29. This suggests the possibility that adsorption of boron onto clay mineral surfaces may be affecting the $\delta^{11}B$ value with pH playing an important role in controlling the fractionation of the boron isotopes in these aquifers. Boron concentrations in samples 22 and 23 are similar despite a difference in depth of almost 90 m. However, boron concentrations increase with depth, indicating another source of boron is being introduced into the aquifer system. The relationships between $\delta^{11}B$ and boron concentrations might help explain the addition of boron into the system.

The plots of $\delta^{11}B$ vs. boron and $\delta^{11}B$ vs. 1/boron (Figure 52) indicate the possibility that mixing is occurring between two end member water compositions. One end member is likely meteoric recharge represented by a composition similar to that of sample 29, whereas the other end member is likely formation water represented by a composition similar to that of seawater. The formation water would introduce greater concentrations of boron with a higher $\delta^{11}B$ isotopic composition. Mixing reactions and subsequent interaction with the aquifer and aquitard materials would buffer the boron concentrations and lower the $\delta^{11}B$ values.

3.7.4.5 Preliminary Interpretations – Horseshoe Canyon Formation

The plots of $\delta^{11}B$ vs. boron and $\delta^{11}B$ vs. 1/boron (Figure 53) indicate the possibility that mixing is occurring between two end member water compositions. The first possible mixing system includes samples 1, 2, 8, 24, 30, 34 and 41. One end member is likely meteoric recharge represented by a composition similar to that of sample 24, whereas the other end member is likely formation water represented by a composition similar to that of seawater. These samples are situated close to one another

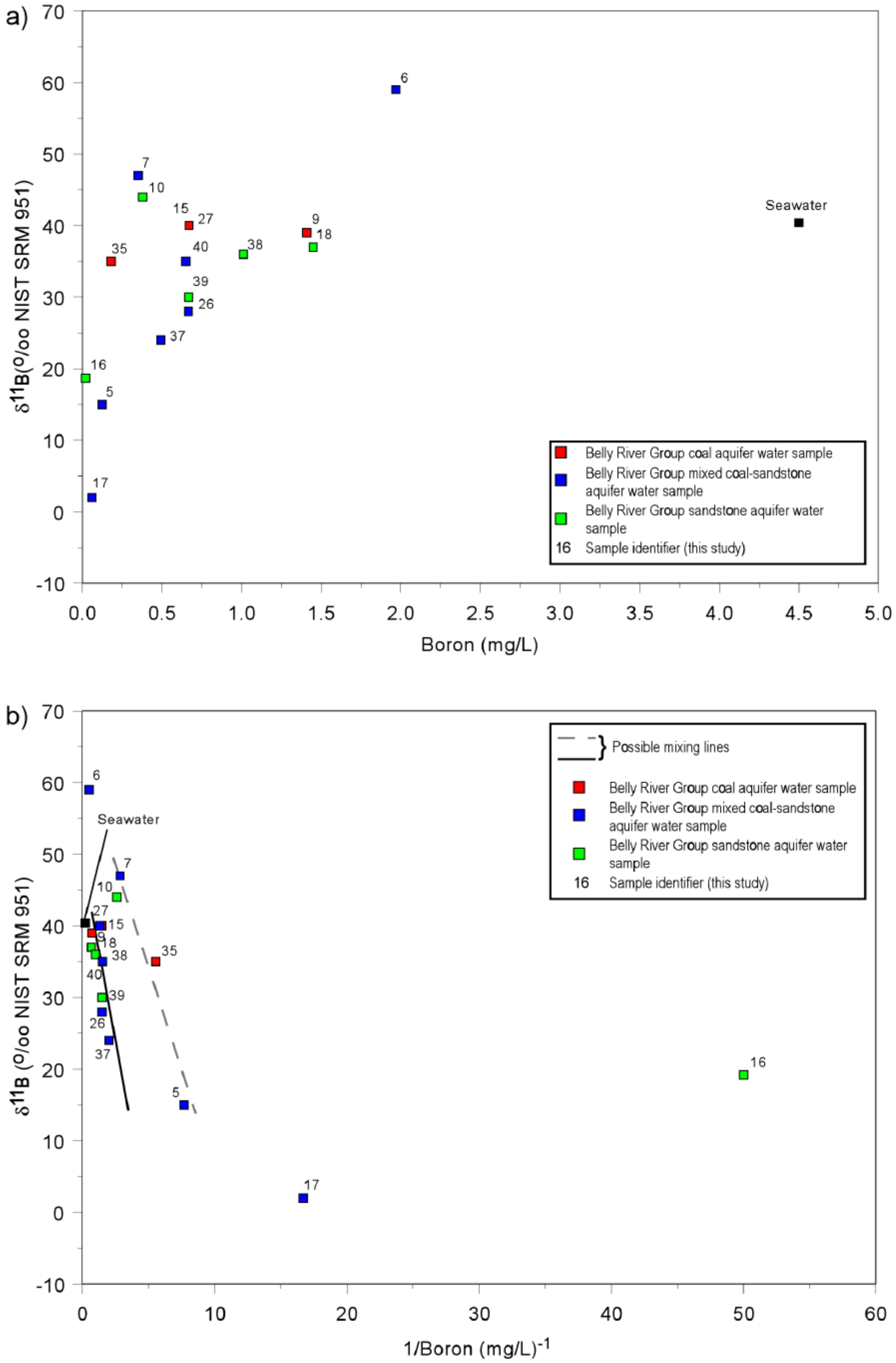


Figure 55. Belly River Group: a) δ^{11}B vs. Boron; and b) δ^{11}B vs. 1/Boron.

surrounding the city of Edmonton (Figure 17). The second possible mixing system includes samples 11, 12, 19, 20, 21, 25, 28, 31, 32, 33, 36 and 43. The second system likely has a formation water end member composition similar to that of seawater. The other end member composition is more difficult to define. Although similar $\delta^{11}B$ values for groundwater have been documented that match the low values represented by samples 31 and 36, none have been documented in Alberta. The source of these low values might reflect differences in the $\delta^{11}B$ of precipitation, or could indicate that water-rock interactions are affecting initial $\delta^{11}B$ values. The samples within this group are spread out across the study area, whereas the samples from the first group are clustered (Figure 17). The lithology of the Horseshoe Canyon Formation does vary. This lithologic variation and the subsequent water-rock reactions might explain the difference in initial $\delta^{11}B$ end member composition.

The formation water would introduce greater concentrations of boron with a higher $\delta^{11}B$ isotopic composition. Mixing reactions would alter both the boron concentration and the $\delta^{11}B$ values of the water. Concentrations of boron in solution are generally quite similar. This may indicate that subsequent interactions between the aquifer water and the aquifer-aquitard materials could be buffering the boron concentrations.

3.7.4.6 Preliminary Interpretations – Belly River Group

The Belly River Group aquifer water sample $\delta^{11}B$ values appear to be related to pH as well as to boron concentrations. If a relationship exists, it is very general in nature. The pH does vary with depth, but the data generally appear to form clusters (Figure 56), whereas samples 15, 16 and 18 form a separate, somewhat linear, trend. The pH may be affecting $\delta^{11}B$ values, but that conclusion is difficult to substantiate.

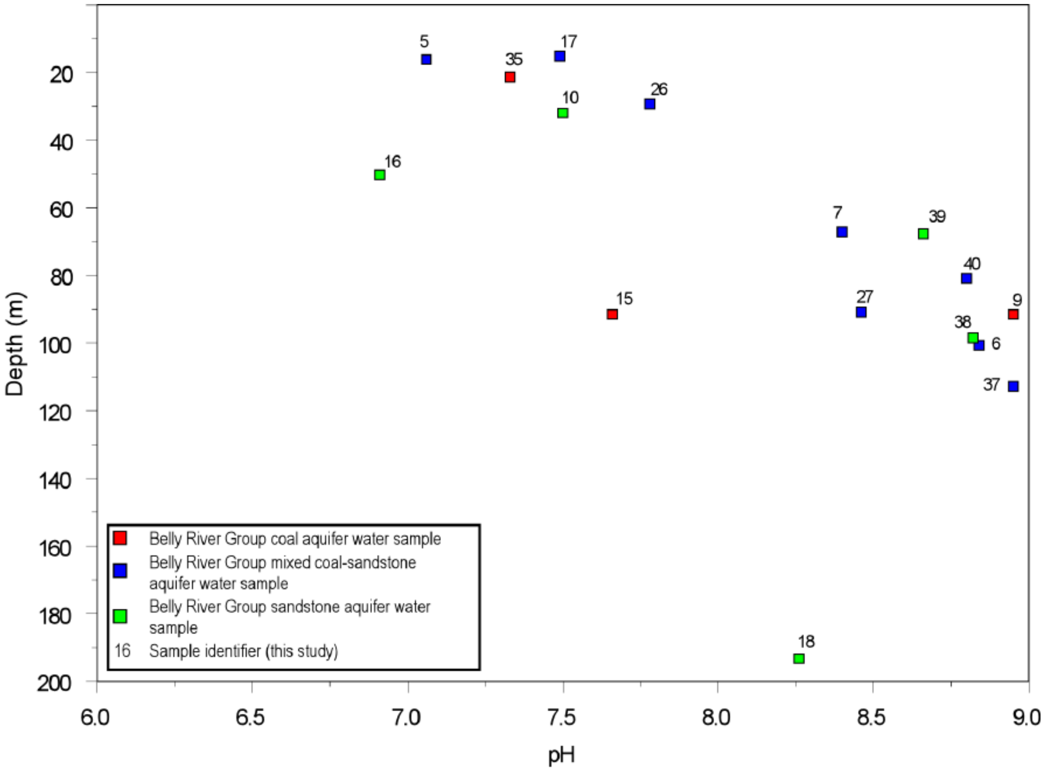


Figure 56. Belly River Group: pH vs. Depth.

The relationship between $\delta^{11}B$ and boron concentration is somewhat more straightforward. Samples 5, 6, 7, 10 and 35 appear to indicate a mixing relationship between an end member with a $\delta^{11}B$ composition consistent with meteoric water and an end member with a $\delta^{11}B$ composition consistent with marine brines. These samples form a linear trend (Figure 21). Samples 9, 15, 18, 26, 27, 37, 38, 39 and 40 appear to belong to a second mixing process. The likely end members are meteoric water and formation water with a $\delta^{11}B$ composition similar to seawater. Samples 16 and 17 do not appear related to the other samples. They are both located in the southern portion of the study area, however, and may indicate that this portion of the study area is not well connected to central or northern portions of the study area.

The highest boron concentrations were observed in the Belly River Group samples. Concentrations vary between 0.021 and 1.97 mg/L. This may indicate that boron-buffering processes are not as effective in Belly River Group aquifers and aquitards.

3.8 Radiogenic Isotopes

3.8.1 Strontium

Strontium isotopes ($^{87}Sr/^{86}Sr$) have proven to be a useful indicator of water-rock interaction, and as a tracer for groundwater movement and the origin of salinity (Clark and Fritz, 1997, p. 260). Strontium is a divalent cation with similar characteristics to Ca, and can substitute for Ca in a number of minerals, as well as form minerals with similar structures. Strontium can therefore be found in feldspar, clay, sulphate and carbonate minerals in place of Ca. Independently, Sr will form minerals such as strontianite ($SrCO_3$) and celestite ($SrSO_4$). Strontium geochemistry is also linked to the geochemistry of K. The decay of ^{87}Rb produces ^{87}Sr. Rubidium has similar chemical characteristics to K. Therefore K-rich rocks are likely to have high ^{87}Rb and ^{87}Sr concentrations. Strontium isotope ratios in water are linked to water-rock interactions and the chemical characteristics of the rocks themselves. Residence times and Sr leaching rates can be estimated knowing the rock Sr isotope ratios and the water Sr isotope ratios. The mixing of water from different sources can be determined if the original Sr isotope compositions of the different water sources are known.

3.8.1.1 Observations – Paskapoo-Scollard Formation

The $^{87}Sr/^{86}Sr$ values appear to fall into three groups. Mixed coal-sandstone aquifer water samples 22, 23 and 42 have $^{87}Sr/^{86}Sr$ values of 0.705513, 0.705375 and 0.705353 and fall within Group 1 (Figure 57). The second group includes samples 29 and 46. The isotopic values of these samples are 0.706325 and 0.706020 respectively (Figure 57). The third group contains sample 45. This sample has a $^{87}Sr/^{86}Sr$ value of 0.707659. The sandstone aquifer water sample $^{87}Sr/^{86}Sr$ value is 0.705694 and appears to fall within Group 1 (Figure 57). The strontium isotope data can be found in Appendix A, Table 184.

Group 1 samples have $^{87}Sr/^{86}Sr$ values similar to those reported for geothermal brines, igneous rocks, clastic sedimentary rocks and Proterozoic marine carbonate rocks (Figure 58). Group 2 samples have $^{87}Sr/^{86}Sr$ values within the range of values reported for Cretaceous, Precambrian and geothermal brines, continental volcanic and plutonic rocks, clastic sedimentary rocks, groundwater and marine carbonate rocks deposited during the Cretaceous, Jurassic, Permian and Proterozoic (Figure 58). The Group 3 sample has a $^{87}Sr/^{86}Sr$ value within the range reported for Cretaceous, Precambrian and geothermal brines, continental plutonic rocks, clastic sedimentary rocks, groundwater and marine carbonate rocks deposited during the Tertiary, Triassic, Permian, Carboniferous and Proterozoic (Figure 58).

Frost et al. (2002) reported $^{87}Sr/^{86}Sr$ values of between 0.7127 and 0.7151 for coal seams from the Tertiary Powder River Basin of Wyoming. Sandstone aquifer water samples had $^{87}Sr/^{86}Sr$ values of between 0.7126 and 0.7127. These values are significantly different from those reported during this study.

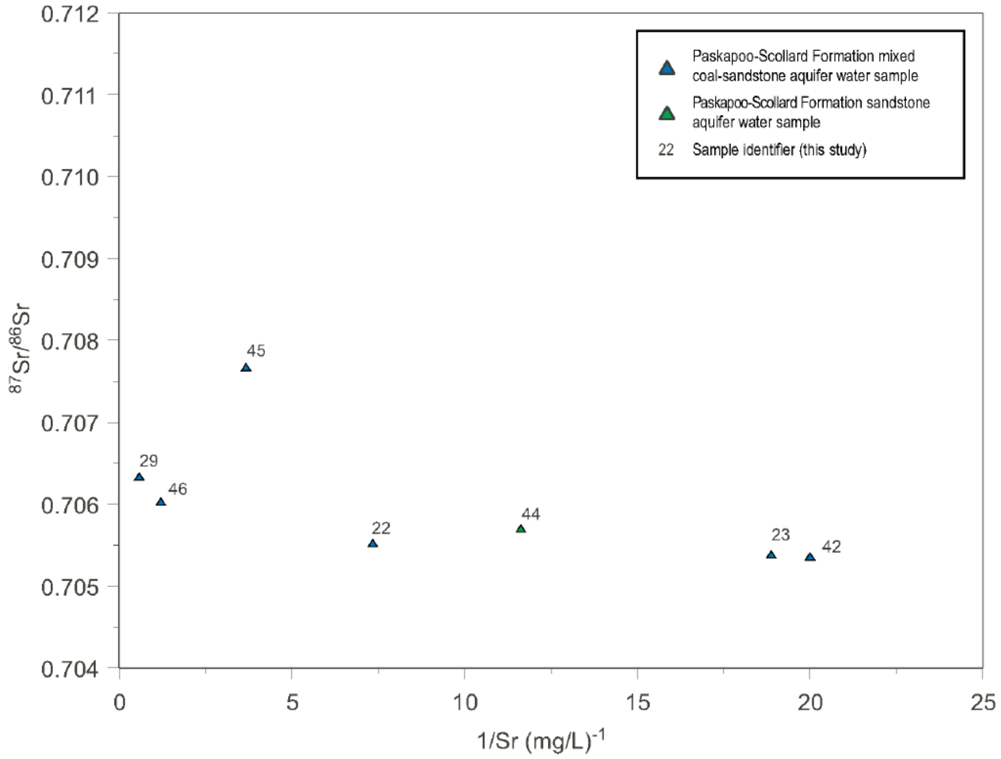


Figure 57. Paskapoo-Scollard Formation: $^{87}Sr/^{86}Sr$ vs 1/Sr.

Certain geochemical relationships can be inferred from cross-plots of elemental concentrations. The geochemistry of Sr is closely related to the geochemistry of Ca and K and therefore cross-plots involving these elements can be useful in determining the origin of Sr in the water sample. Cross-plots and correlation coefficient calculations based on the cross plots for the water samples are in and of themselves deceptive. Different relationships appear to exist between the concentrations for samples 29, 45 and 46 (Group A) inferred to be located in recharge areas, and between samples 22, 23, 42 and 44 (Group B) inferred to be located farther along groundwater flow paths. Plots of Ca vs. Sr and Mg vs. Sr, for the mixed coal-sandstone and sandstone aquifers show a positive correlation between both groups of samples (Figure 59 and Figure 60). Plots of Ca vs. HCO_3 and Sr vs. HCO_3 show positive correlations for Group A, but slightly negative correlations for Group B (Figure 61 and Figure 62). Plots of Ca vs. K and Sr vs. K show no correlation to a weakly negative correlation for the Group A samples and positive correlations for the Group B samples (Figure 63 and Figure 64).

Plots of Ca vs. Sr and K vs. Sr for mixed coal-sandstone aquifer water samples from the Paskapoo-Scollard Formation show negative correlations between the elements. The correlation coefficient between Ca and Sr is 0.95 , whereas the correlation coefficient between K and Sr is 0.54 (Figure 59 and Figure 64).

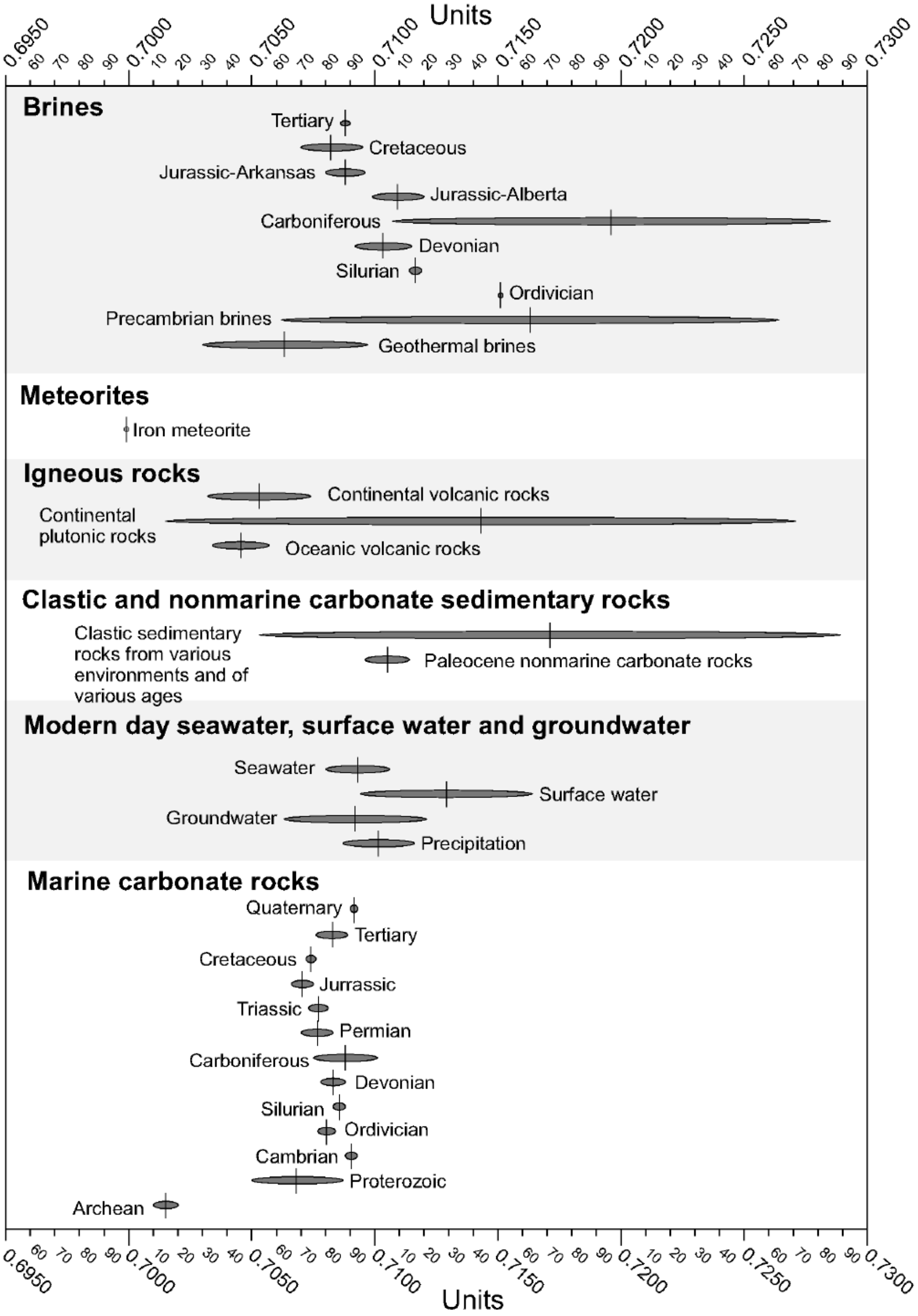


Figure 58. Range of $^{87}Sr/^{86}Sr$ values in geological materials. Compiled from: Brookins et al. (1969), Chaudhuri (1978), Connolly et al. (1990a), Dasch (1969), Denison et al. (1997), Demaiffe and Fieremans (1981), Elderfield and Greaves (1981), Ewart and Stipp (1968), Faure and Hurley (1963), Faure et al. (1965, 1967, 1978), Fisher and Stueber (1976), Hogan et al. (2000), Hurley et al. (1965), Johnson and DePaolo (1997), Jones and Faure (1978), Kistler and Peterman (1973), Leeman (1970, 1974), Lyons et al. (1995), McNutt (1987), McNutt et al. (1990), Mukhopadhyay and Brookins (1976), Neat et al. (1979), Peterman et al. (1970), Pushkar and Condie (1973), Sanz et al. (1970), Starinsky et al. (1983), Stueber et al. (1984), Sunwall and Pushkar (1979), Tremba et al. (1975), Veizer and Compston (1974, 1976), Veizer et al. (1983), Whitford (1975) and Woods et al. (2000).

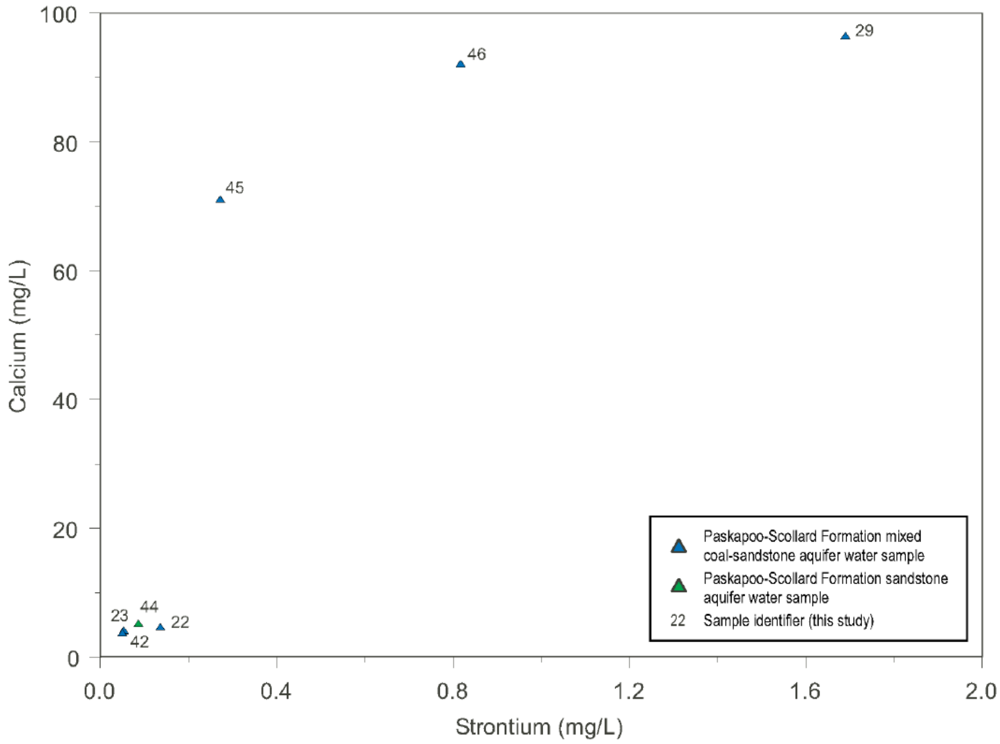


Figure 59. Paskapoo-Scollard Formation: Ca vs. Sr.

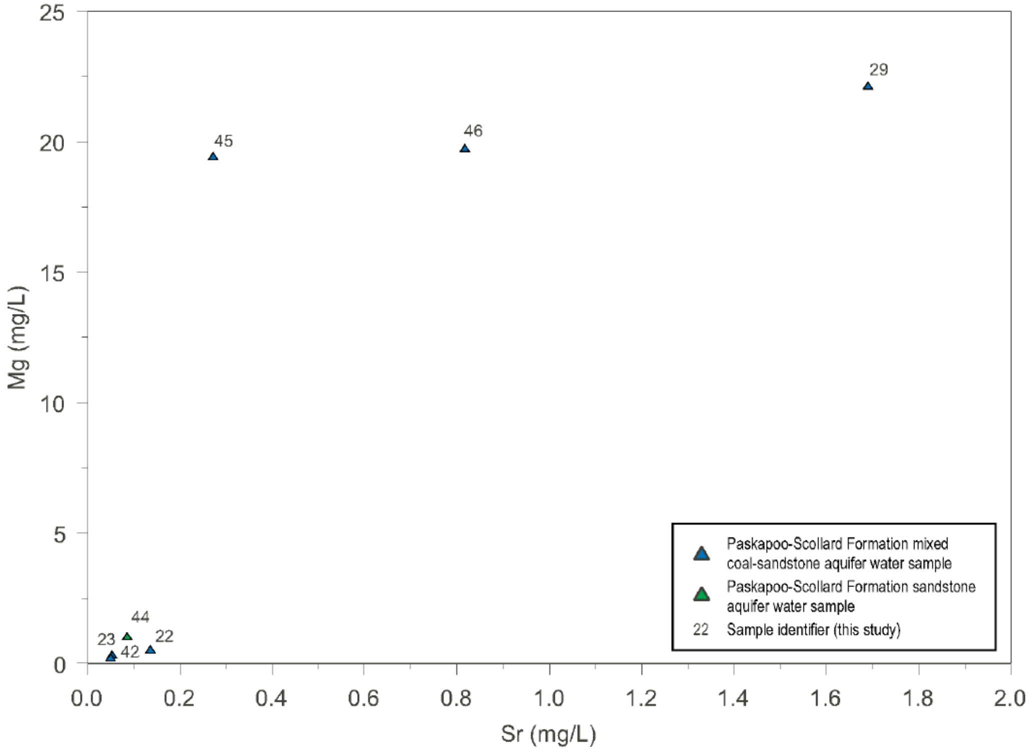


Figure 60. Paskapoo-Scollard Formation: Mg vs. Sr.

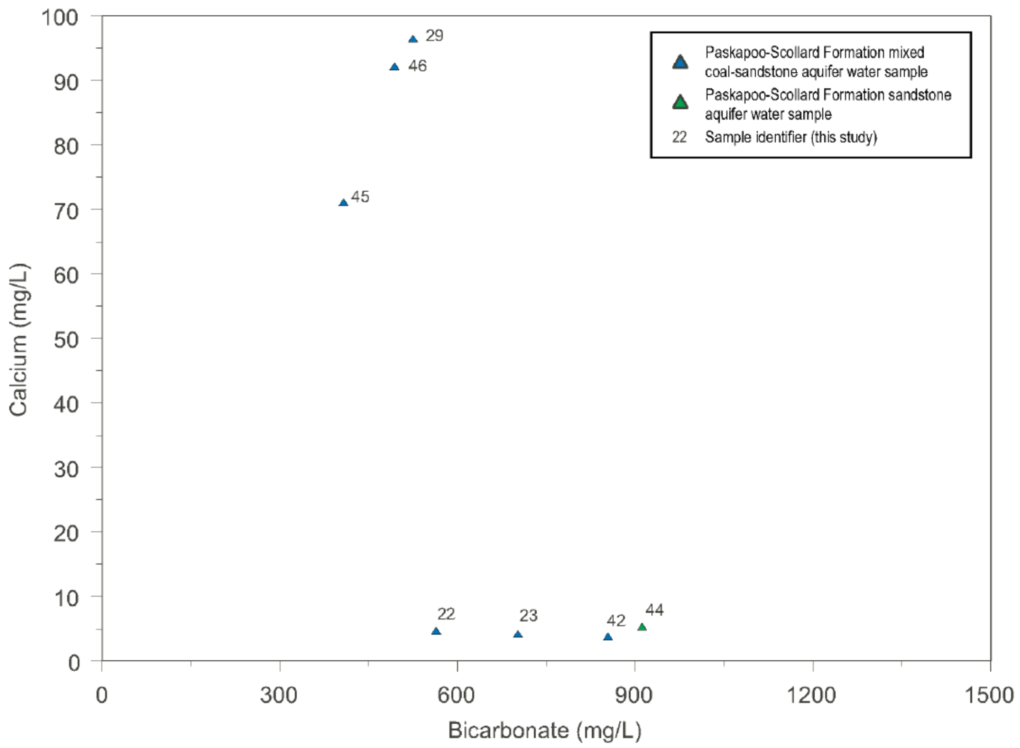


Figure 61. Paskapoo-Scollard Formation: Ca vs. HCO_3.

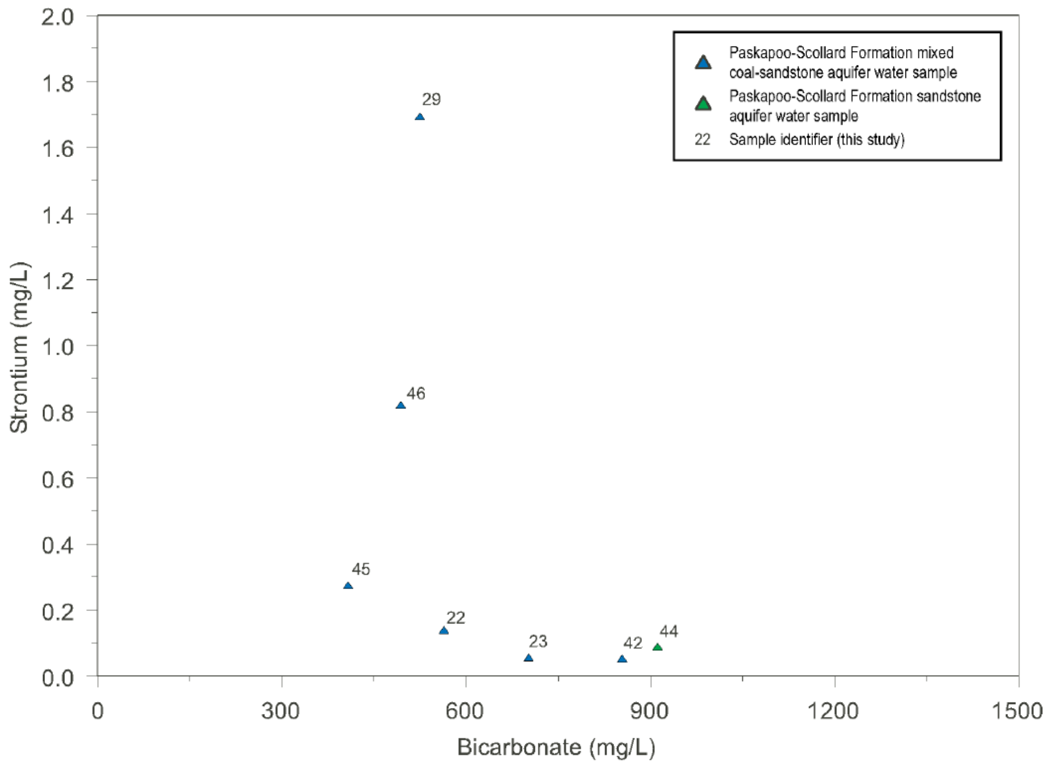


Figure 62. Paskapoo-Scollard Formation: Sr vs. HCO_3.

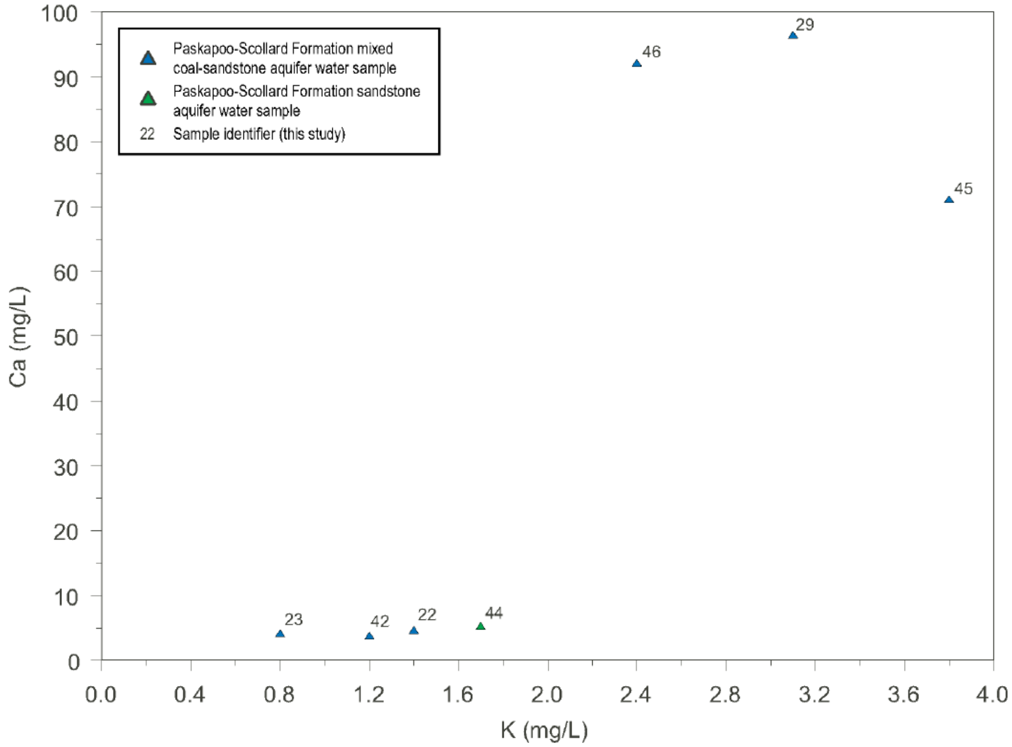


Figure 63. Paskapoo-Scollard Formation: Ca vs. K.

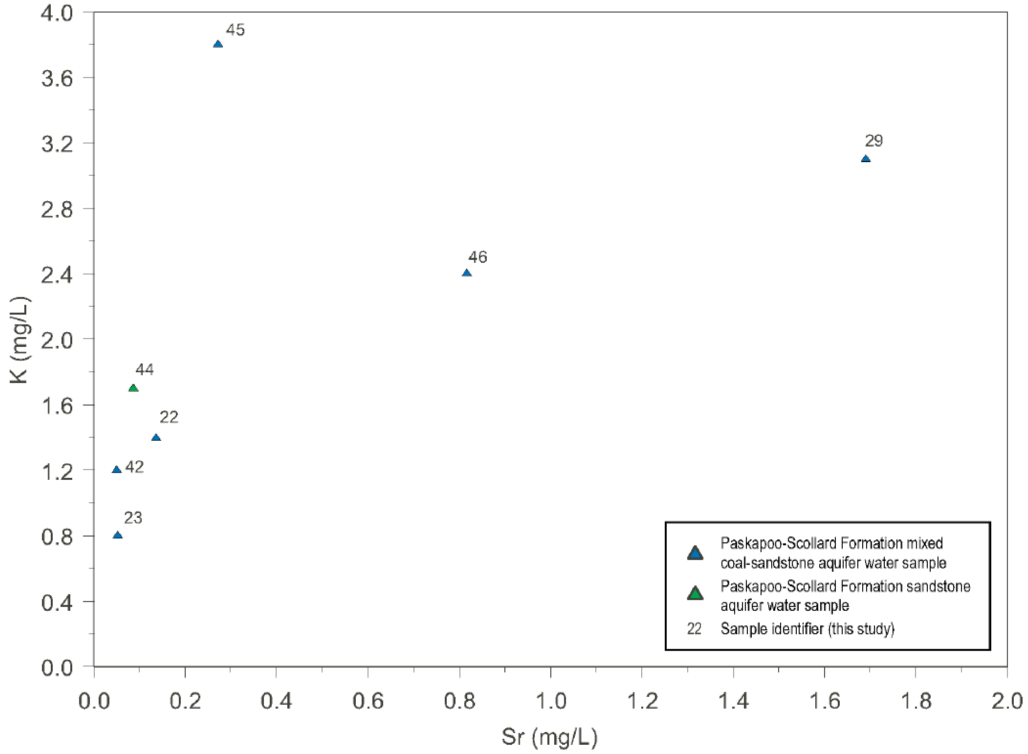


Figure 64. Paskapoo-Scollard Formation: K vs. Sr.

3.8.1.2 Observations – Horseshoe Canyon Formation

The ^{87}Sr/^{86}Sr values appear to fall into one of three groups (Figure 65). Strontium isotope values of the coal aquifer water samples appear to fall within two of the groups. Samples 12, 21, 31 and 36 fall within Group 1 and have ^{87}Sr/^{86}Sr values of 0.705144, 0.705161, 0.705212 and 0.705260 respectively. Group 2 includes samples 19 and 25. These samples have ^{87}Sr/^{86}Sr values of 0.705982 and 0.706015 respectively. The mixed coal-sandstone aquifer water samples primarily appear to belong to one group. Samples 1, 2, 8, 11, 24, 30, 32, 33, 34, 41 and 43 have ^{87}Sr/^{86}Sr values between 0.705129 and 0.705593 and belong to Group 1. Sample 20 has a ^{87}Sr/^{86}Sr value of 0.706115 and belongs to Group 2. Sample 28 was collected from a sandstone aquifer. The sample ^{87}Sr/^{86}Sr value is 0.707849 and belongs to Group 3. The strontium isotope data can be found in Appendix A, Table 184.

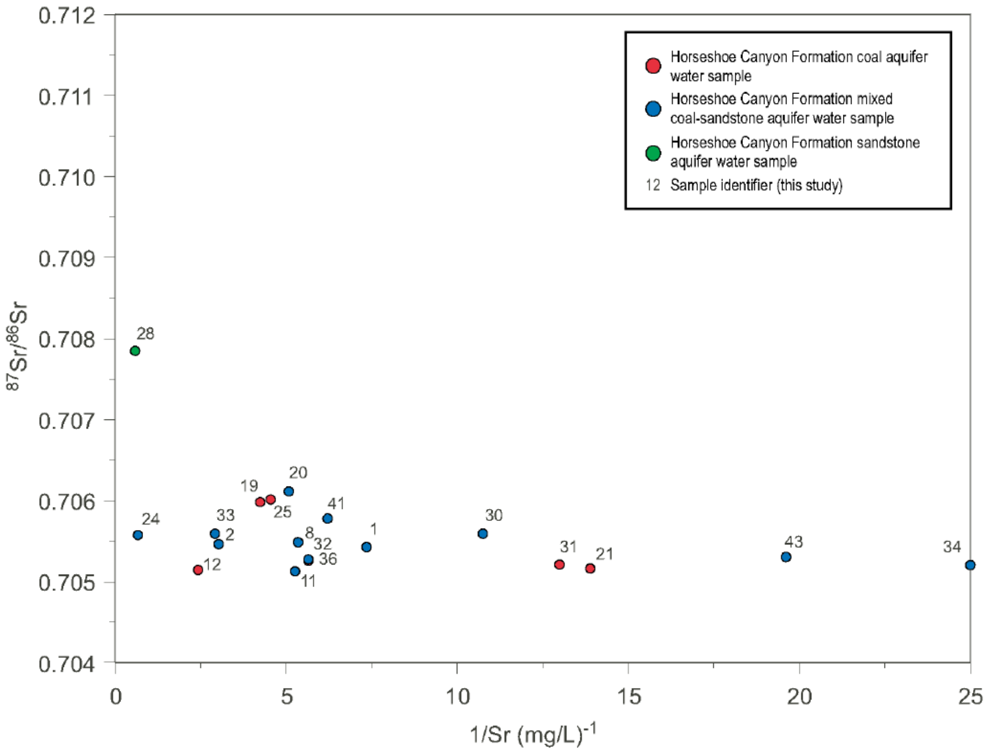


Figure 65. Horseshoe Canyon Formation: ^{87}Sr/^{86}Sr vs. 1/Sr.

Coal aquifer Group 1 samples have ^{87}Sr/^{86}Sr values similar to those reported for geothermal brines, igneous rocks, clastic sedimentary rocks and Proterozoic marine carbonate rocks (Figure 58). Group 2 samples have ^{87}Sr/^{86}Sr values within the range of values reported for Precambrian and geothermal brines, continental volcanic and plutonic rocks, clastic sedimentary rocks and Proterozoic marine carbonate rocks (Figure 58).

Mixed coal-sandstone aquifer samples have ^{87}Sr/^{86}Sr values similar to those of the coal aquifers. Group 1 mixed coal-sandstone aquifer water samples have a range of ^{87}Sr/^{86}Sr values that is similar to those reported for geothermal brines, igneous rocks, clastic sedimentary rocks and Proterozoic marine carbonate rocks (Figure 58). Group 2 member sample 20 has a ^{87}Sr/^{86}Sr value that falls within the range of values reported for Precambrian and geothermal brines, continental volcanic and plutonic rocks, clastic sedimentary rocks, groundwater and Proterozoic marine carbonate rocks (Figure 58).

The sandstone aquifer water sample has a $^{87}Sr/^{86}Sr$ value similar to those reported for Cretaceous, Precambrian and geothermal brines, continental plutonic rocks, groundwater, and marine carbonate rocks deposited during the Tertiary, Cretaceous, Triassic, Permian, Carboniferous, Devonian, Ordovician and Proterozoic (Figure 58).

Certain geochemical relationships can be inferred from cross-plots of elemental concentrations. The geochemistry of Sr is closely related to the geochemistry of Ca and K and therefore cross-plots involving these elements can be useful in determining the origin of Sr in the water sample. Plots of Ca vs. Sr, Ca vs. K, Ca vs. Mg, Sr vs. K, Sr vs. Mg, Sr vs. SO_4 and Sr vs. Si show positive correlations (Figure 66, Figure 67, Figure 68, Figure 69, Figure 70, Figure 71 and Figure 72). Plots of Ca vs. SO_4, Ca vs. Si, Ca vs. Fe and Sr vs. Fe show almost constant Ca and Sr concentrations over a range of SO_4, Si and Fe concentrations (Figure 73, Figure 74, Figure 75 and Figure 76). The concentration of Ca and Sr does appear to increase slightly however. Where Rb was detected, a positive correlation was observed between Rb and K (Figure 77). No obvious correlation exists between Rb and Sr (Figure 78).

Plots of Ca vs. Sr and K vs. Sr for coal samples from the Horseshoe Canyon Formation show negative correlations between the elements (Figure 66 and Figure 69). The correlation coefficient between Ca and Sr is 0.96 , whereas the correlation coefficient between K and Sr is 0.53.

3.8.1.3 Observations – Belly River Group

Coal aquifer water samples appear to fall within two groups, Group 2 and Group 3 (Figure 79). Samples 9 and 35 belong to Group 2 and have $^{87}Sr/^{86}Sr$ values of 0.705955 and 0.706200 respectively. Group 3 would include samples 15. This sample has a $^{87}Sr/^{86}Sr$ value of 0.707393. The mixed coal-sandstone aquifer water samples appear to belong to all four groups (Figure 79). Samples 6, 7, 27 and 40 have $^{87}Sr/^{86}Sr$ values of 0.705240, 0.705330, 0.705310 and 0.705421 respectively and belong to Group 1. Samples 26 and 37 belong to Group 2 and have $^{87}Sr/^{86}Sr$ values of 0.706036 and 0.706257. Sample 5 belongs to Group 3 and has a $^{87}Sr/^{86}Sr$ value of 0.706915. Sample 17 has a $^{87}Sr/^{86}Sr$ value of 0.709042 and belongs to Group 4. The sandstone aquifer water samples belong to two groups (Figure 79). Samples 10, 18, 38 and 39 belong to Group 2 and have $^{87}Sr/^{86}Sr$ values of 0.706307, 0.706289, 0.706229 and 0.705733 respectively. Sample 16 has a $^{87}Sr/^{86}Sr$ value of 0.710181 and belongs to Group 4. Sandstone formation water samples collected by Connolly et al. (1990b) have $^{87}Sr/^{86}Sr$ values that place them within Group 2. The strontium isotope data can be found in Appendix A, Table 184.

Coal aquifer Group 2 samples have $^{87}Sr/^{86}Sr$ values similar to those reported for geothermal brines, continental volcanic and plutonic rocks, clastic sedimentary rocks and Proterozoic marine carbonate rocks (Figure 58). The Group 3 sample has a $^{87}Sr/^{86}Sr$ value within the range of values reported for Cretaceous, Precambrian and geothermal brines, continental volcanic and plutonic rocks, clastic sedimentary rocks, groundwater, and marine carbonate rocks deposited during the Tertiary, Cretaceous, Jurassic, Triassic, Permian and Proterozoic (Figure 58).

Mixed coal-sandstone aquifer samples have $^{87}Sr/^{86}Sr$ values similar to those of the coal aquifers. Group 1 mixed aquifer samples have a range of $^{87}Sr/^{86}Sr$ values that is similar to those reported for geothermal brines, igneous rocks, clastic sedimentary rocks and Proterozoic marine carbonate rocks (Figure 58). Group 2 samples have a range of $^{87}Sr/^{86}Sr$ values that falls within the range of values reported for Precambrian and geothermal brines, continental volcanic and plutonic rocks, clastic sedimentary rocks, groundwater and Proterozoic marine carbonate rocks (Figure 58). The Group 3 sample has a $^{87}Sr/^{86}Sr$ value within the range of values reported for Precambrian and geothermal brines, continental volcanic and plutonic rocks, clastic sedimentary rocks, groundwater, and marine carbonate rocks deposited during the Cretaceous and Proterozoic (Figure 58). The Group 4 sample has a $^{87}Sr/^{86}Sr$ value within the

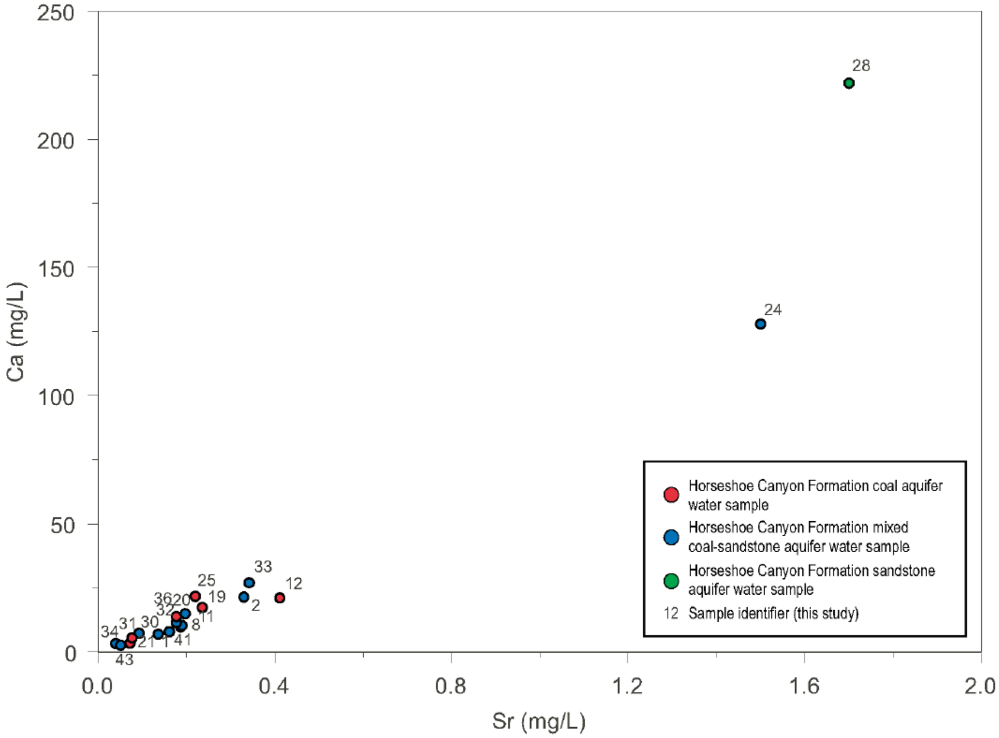


Figure 66. Horseshoe Canyon Formation: Ca vs. Sr.

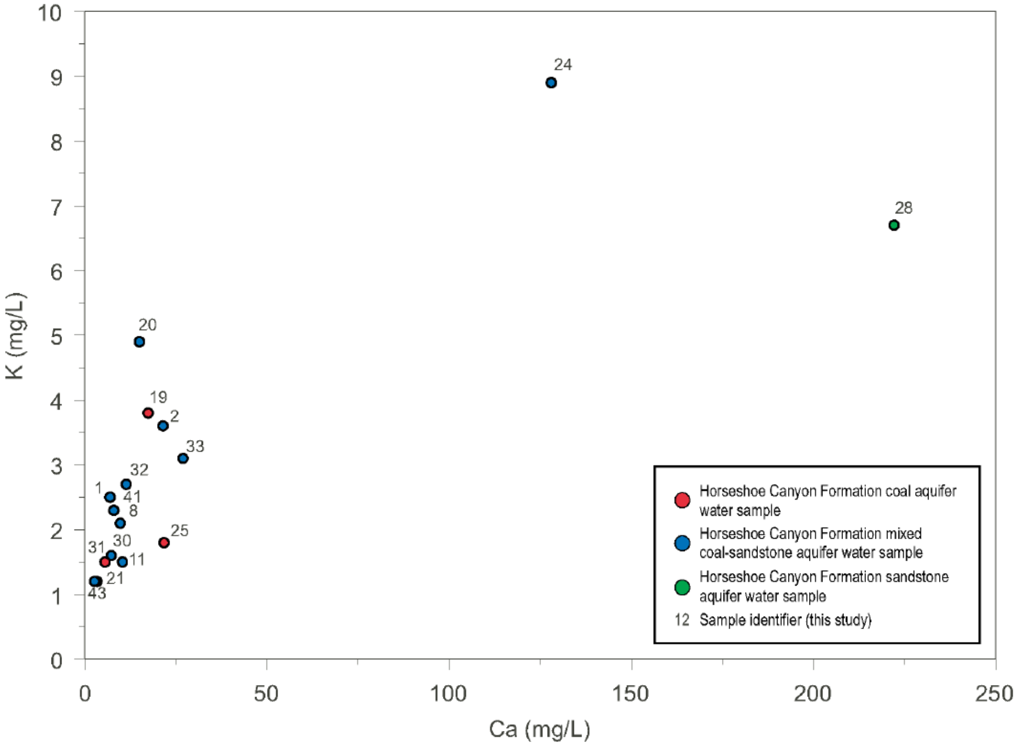


Figure 67. Horseshoe Canyon Formation: Sr vs. K.

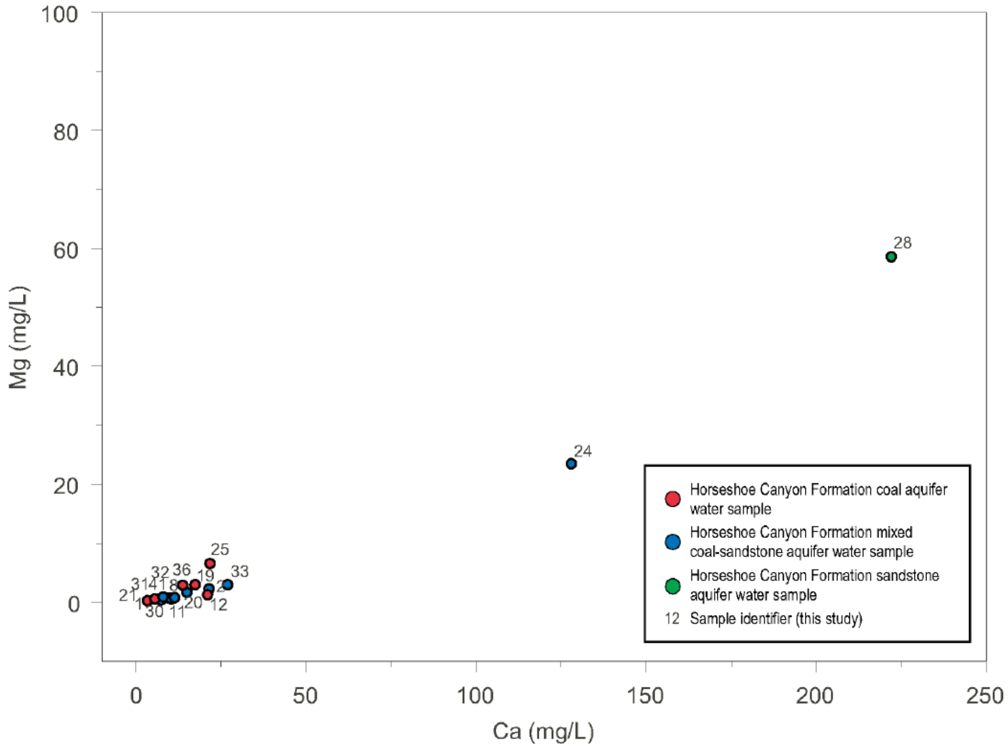


Figure 68. Horseshoe Canyon Formation: Mg vs. Ca.

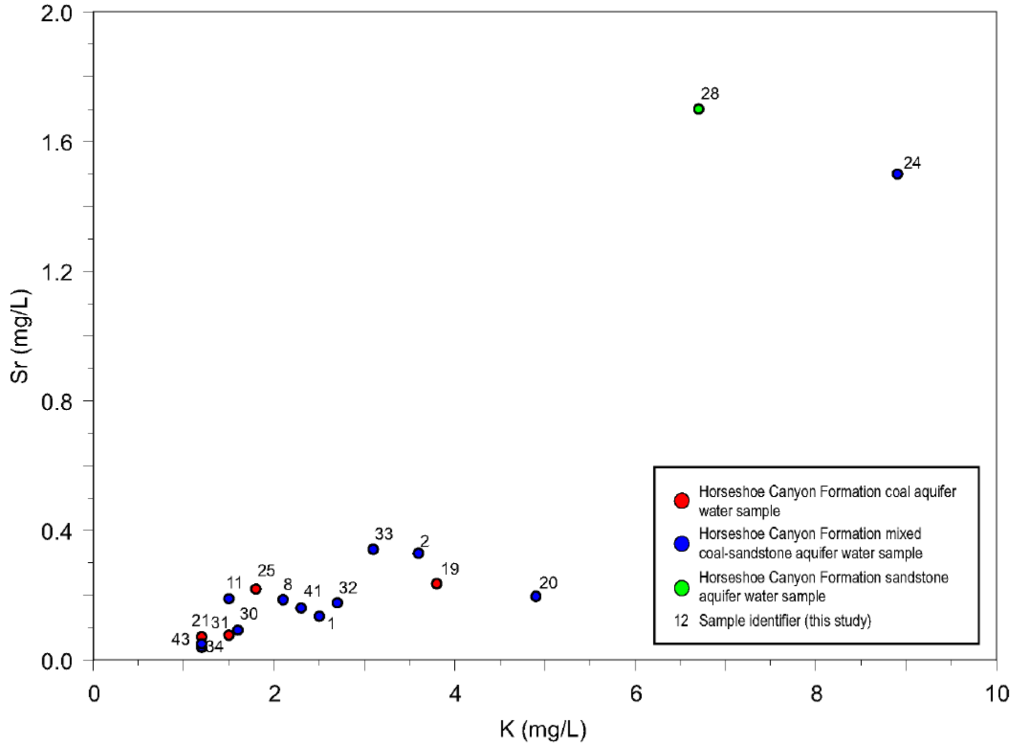


Figure 69. Horseshoe Canyon Formation: Sr vs. K.

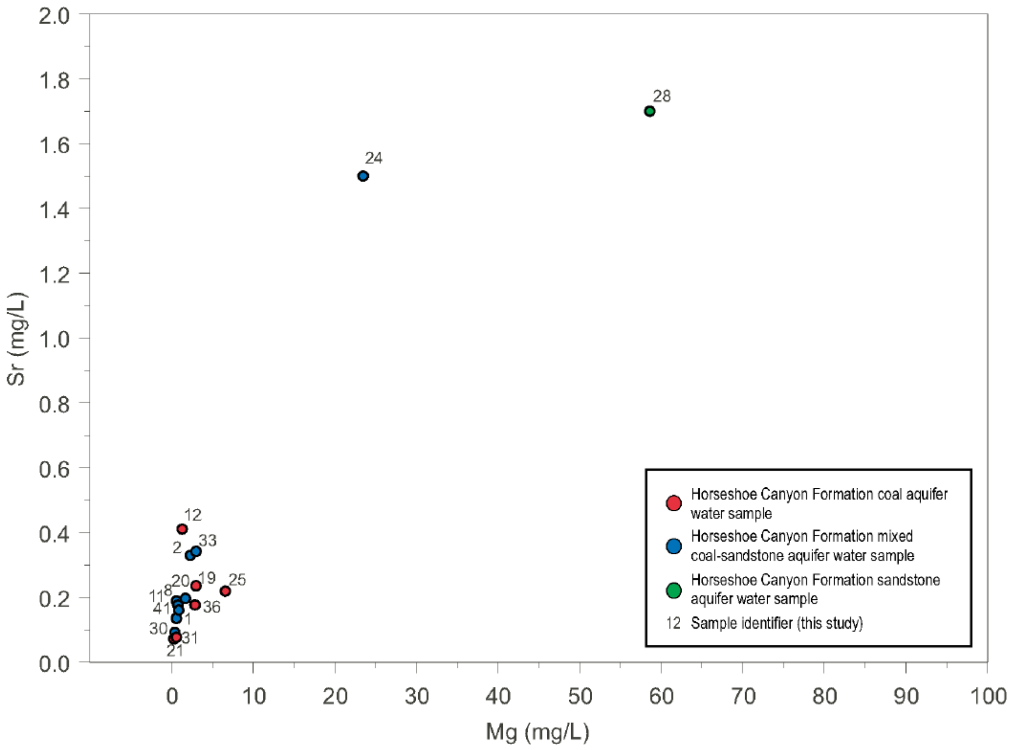


Figure 70. Horseshoe Canyon Formation: Sr vs. Mg.

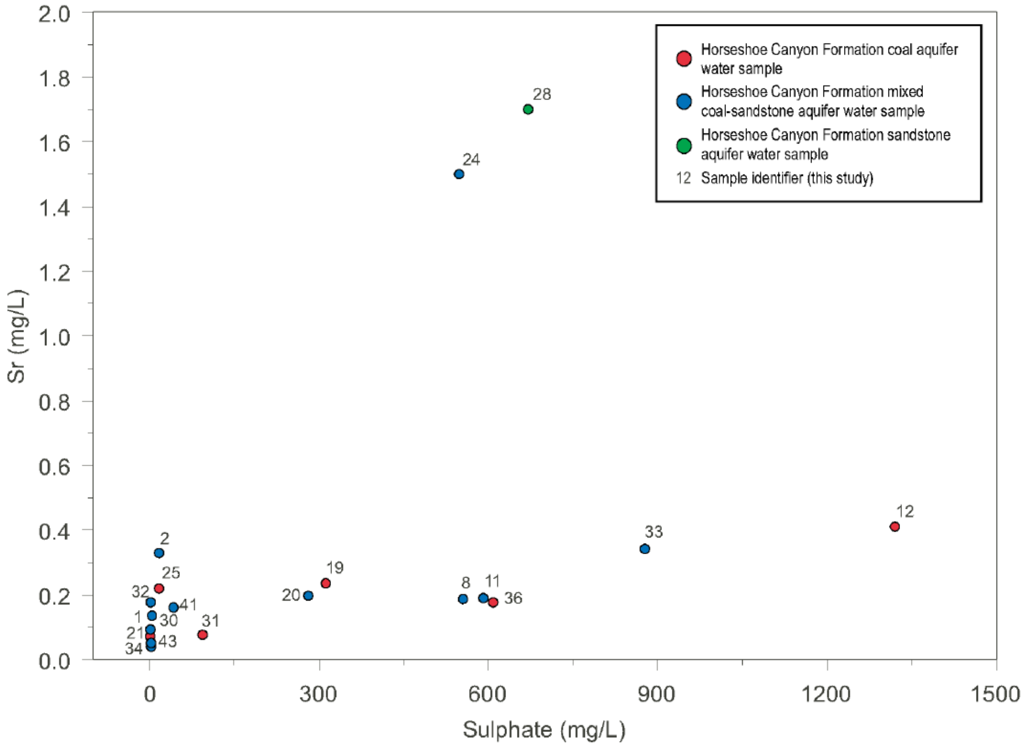


Figure 71. Horseshoe Canyon Formation: Sr vs. SO_4.

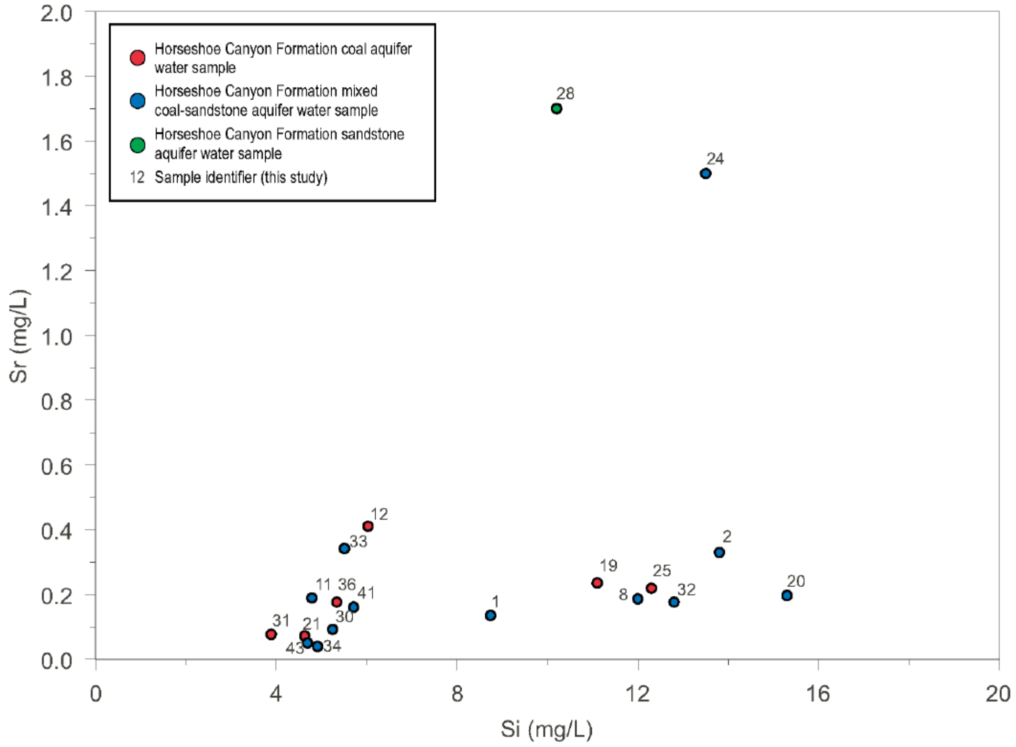


Figure 72. Horseshoe Canyon Formation: Sr vs. Si.

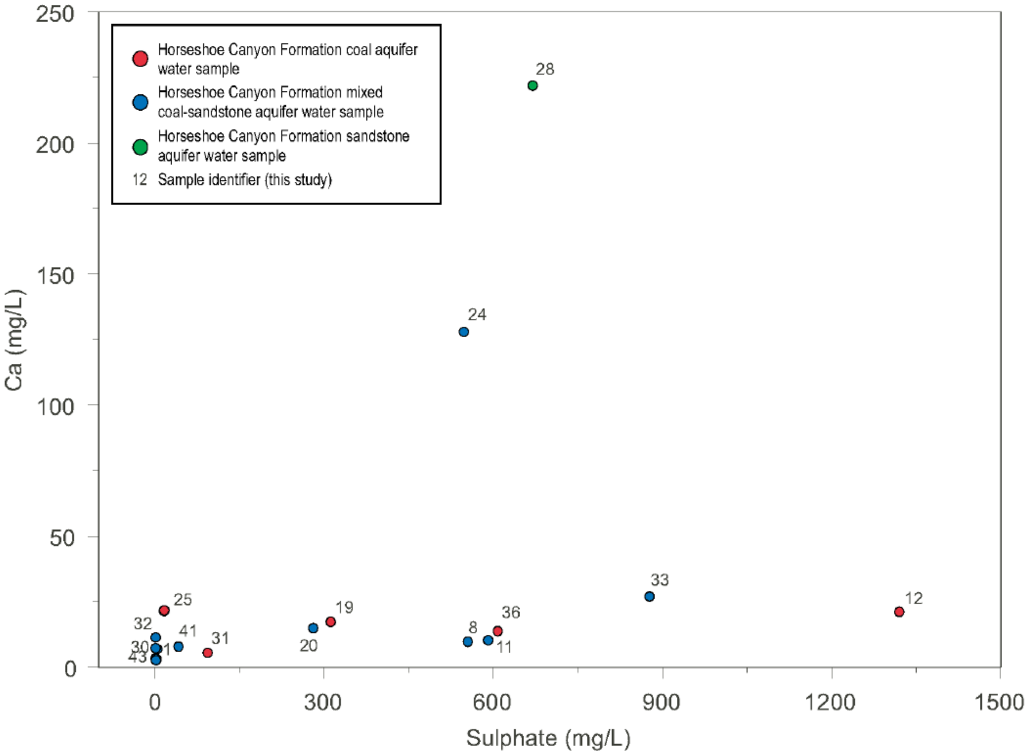


Figure 73. Horseshoe Canyon Formation: Ca vs. SO_4.

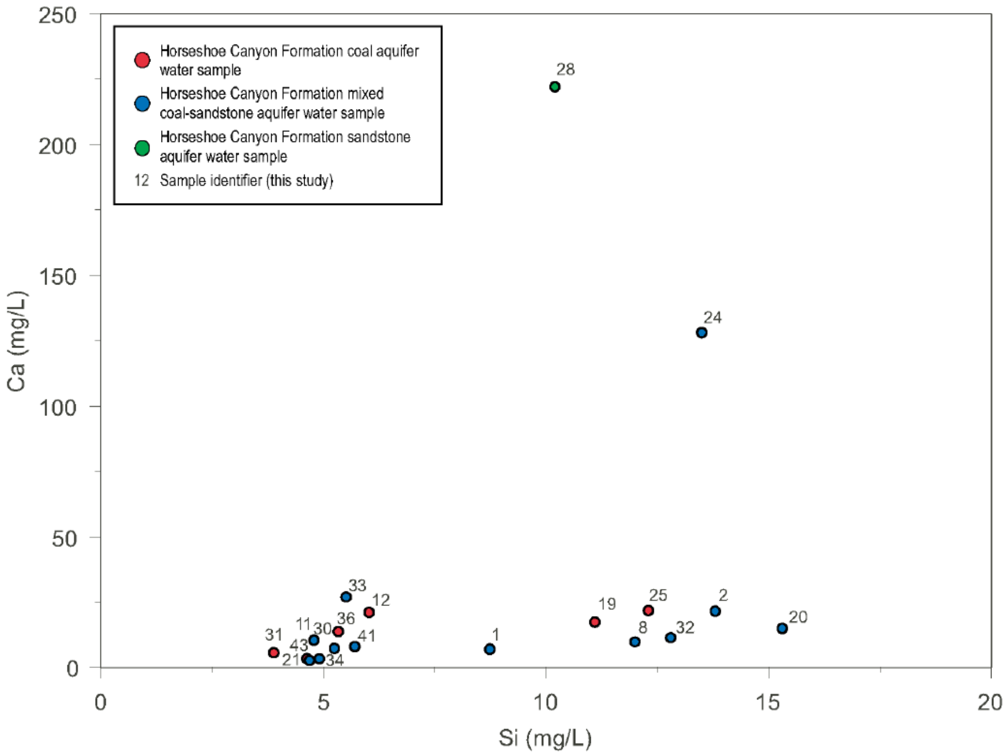


Figure 74. Horseshoe Canyon Formation: Ca vs. Si.

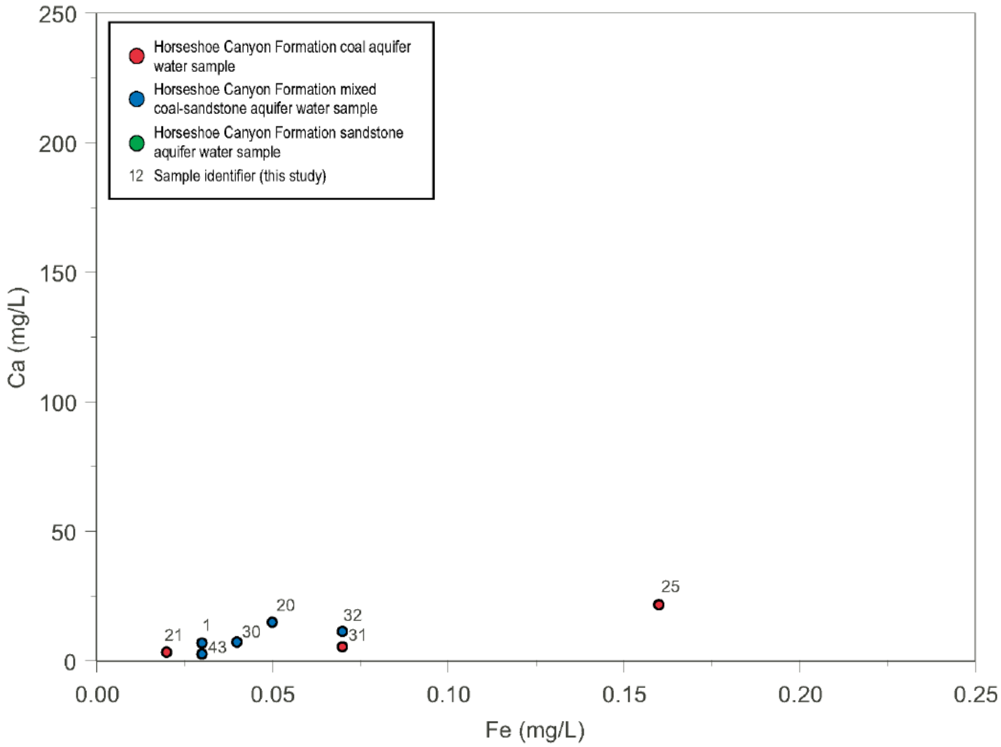


Figure 75. Horseshoe Canyon Formation: Ca vs. Fe.

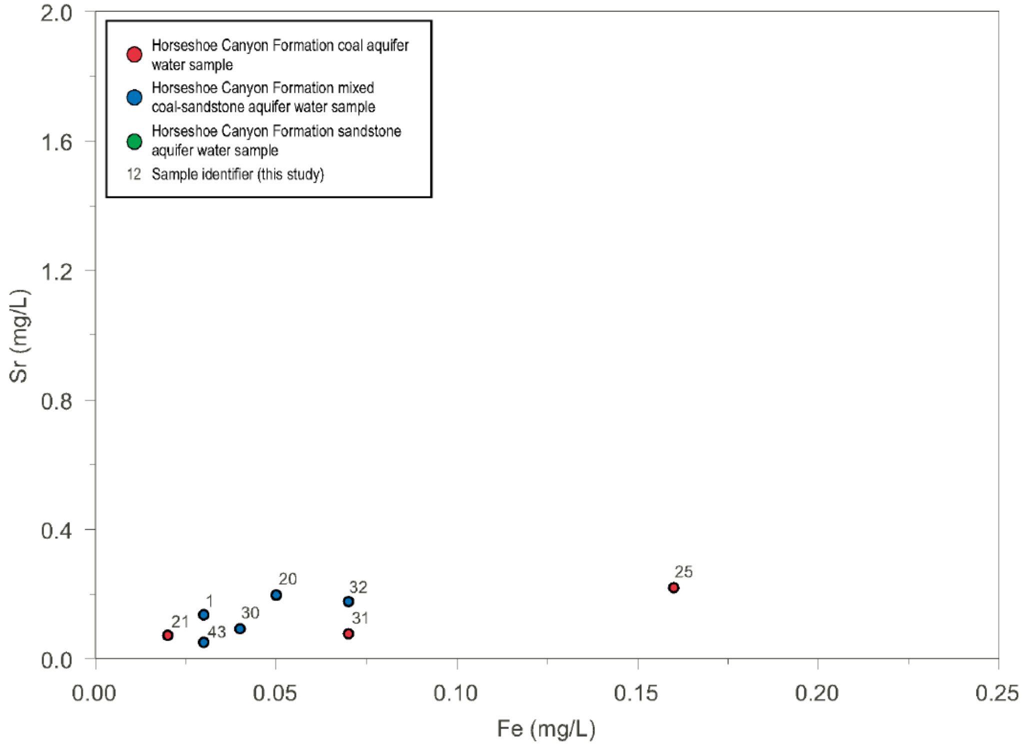


Figure 76. Horseshoe Canyon Formation: Sr vs. Fe.

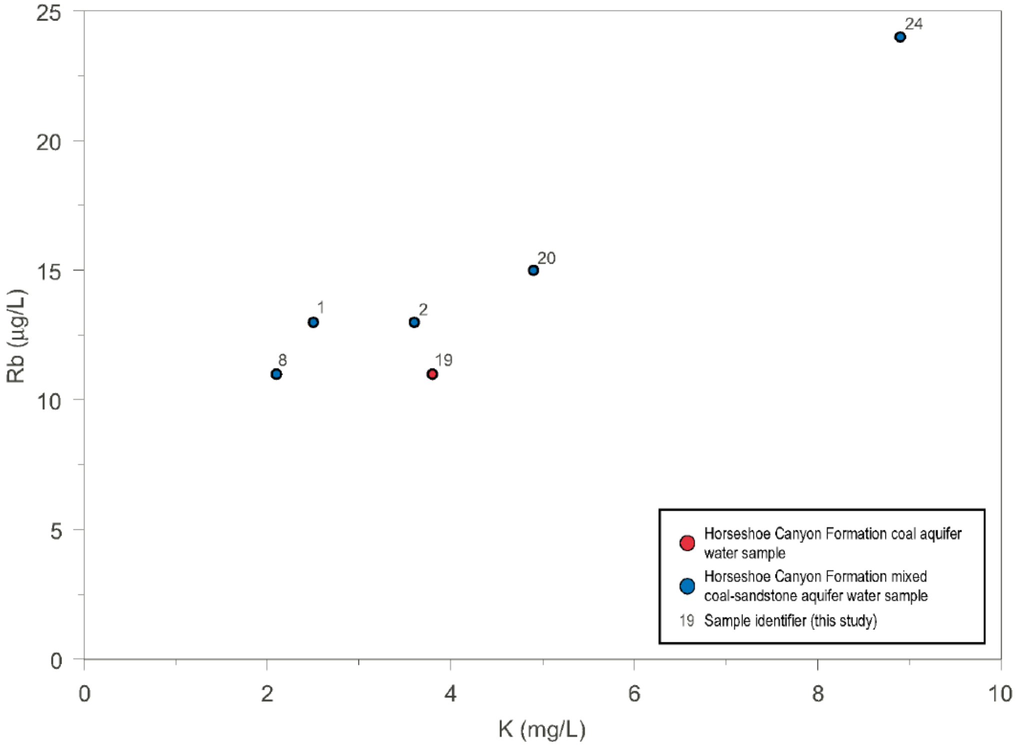


Figure 77. Horseshoe Canyon Formation: Rb vs. K.

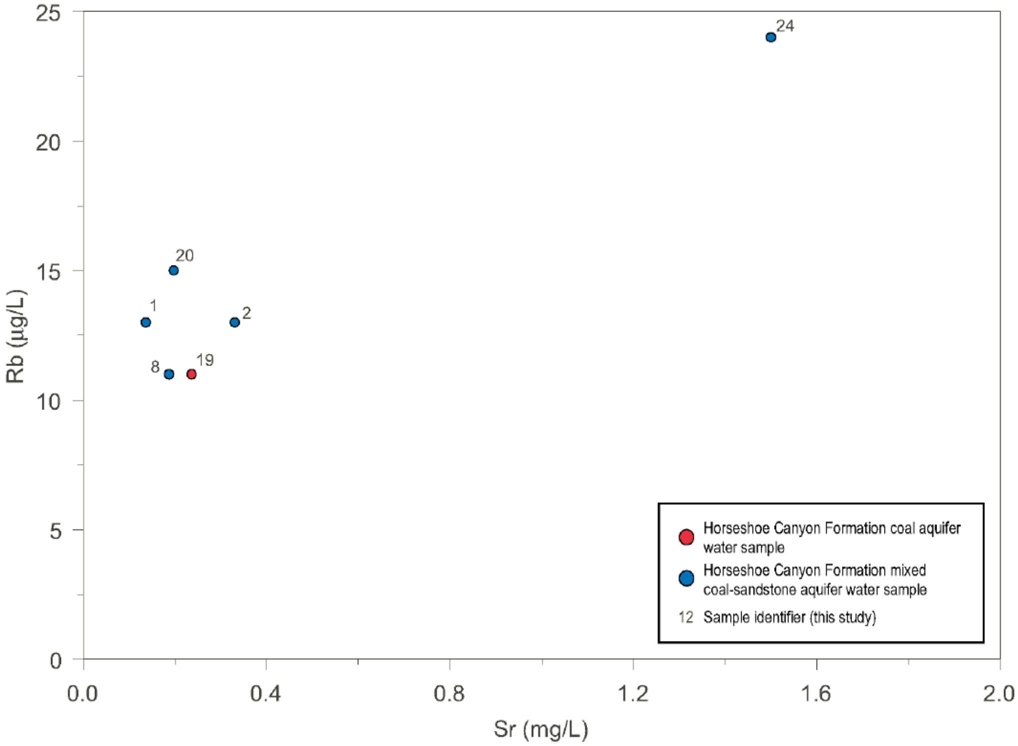


Figure 78. Horseshoe Canyon Formation: Rb vs. Sr.

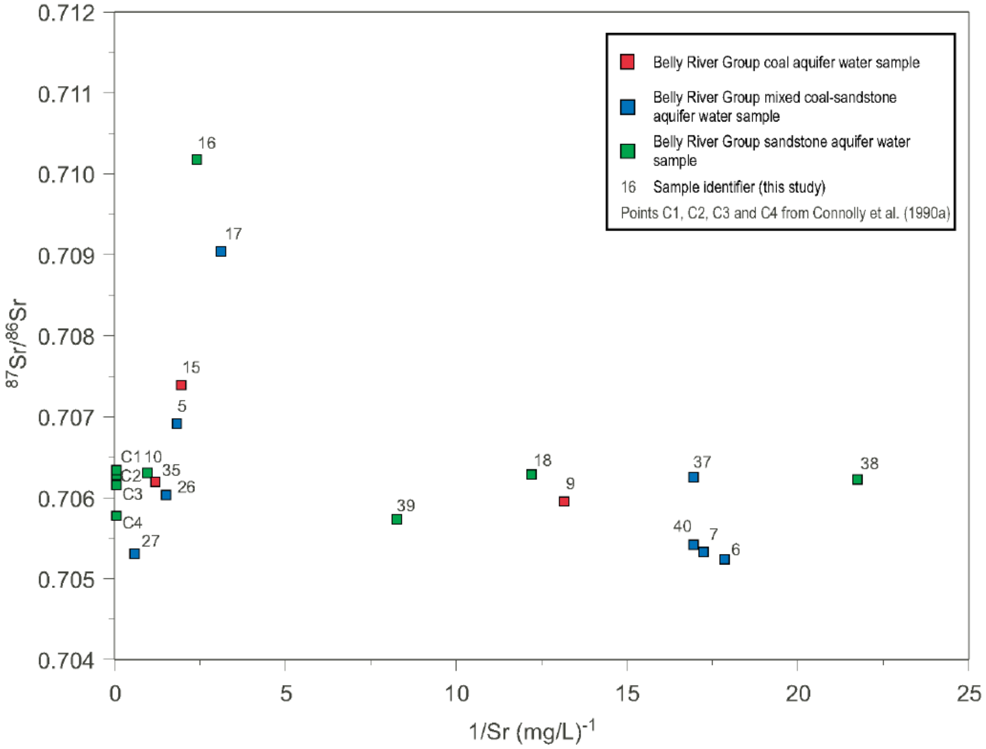


Figure 79. Belly River Group: $^{87}Sr/^{86}Sr$ vs. 1/Sr.

range of values reported for Cretaceous, Precambrian and geothermal brines, continental plutonic rocks, clastic sedimentary rocks, seawater, groundwater, atmospheric precipitation and marine carbonate rocks deposited during the Quaternary, Carboniferous, and Ordovician (Figure 58).

The Group 2 sandstone aquifer water samples have a $^{87}Sr/^{86}Sr$ value similar to those reported for Precambrian and geothermal brines, continental plutonic and volcanic rocks, groundwater, and marine carbonate rocks deposited during the Cretaceous and Proterozoic (Figure 58). The Group 4 sample has a $^{87}Sr/^{86}Sr$ value within the range of values reported for Jurassic and Precambrian brines, continental plutonic rocks, clastic and non-marine carbonate sedimentary rocks, seawater, surface water, groundwater, atmospheric precipitation and marine carbonate rocks deposited during the Carboniferous (Figure 58).

Belly River Group $^{87}Sr/^{86}Sr$ values are similar to those determined for Paskapoo-Scollard Formation and Horseshoe Canyon Formation water samples.

Connolly et al. (1990b) reported $^{87}Sr/^{86}Sr$ values of between 0.70578 and 0.70634 for Belly River Group water samples collected from the Alberta Basin. These values are similar to Group 2 water samples reported in this study.

Certain geochemical relationships can be inferred from cross-plots of elemental concentrations. The geochemistry of Sr is closely related to the geochemistry of Ca and K and therefore cross-plots involving these elements can be useful in determining the origin of Sr in the water sample. Cross-plots and correlation coefficient calculations based on the cross plots for the water samples are in and of themselves deceptive. Correlations between elements from samples inferred to be located in recharge areas are different from correlations observed between elements from samples inferred to be located farther along groundwater flow paths. For samples located within recharge areas, positive correlations were observed between Sr, HCO_3 and SO_4 (Figure 80 and Figure 81). For these same samples, a negative correlation was observed between Sr and Mg (Figure 82). For samples located farther along groundwater flow paths, positive correlations were observed between, Ca and K, Sr, Mg, SO_4 (Figure 83, Figure 84, Figure 85 and Figure 86) and between Sr vs. K (Figure 87).

3.8.1.4 Preliminary Interpretations – Paskapoo-Scollard Formation

Allan and Sanderson (1945) describe the Paskapoo Formation as consisting primarily of soft, grey, clayey sandstone with a coarser more or less uncemented sandstone unit at the base of the formation. Mack and Jerzykiewicz (1989) show that quartz, plagioclase, chert, metamorphic rock fragments and volcanic rock fragments make up roughly equal percentages of the Paskapoo Formation in the Central Foothills. Based on this information, on Figure 58 and consideration of the geological history of the Alberta Basin and of the Paskapoo-Scollard Formation, the most likely sources of strontium in the aquifers of this formation are the interaction of water with clastic sedimentary rocks or with coal deposits.

The strong positive correlation between Sr, Ca, Mg and HCO_3, and weak correlation between Ca, Sr and K, in the water samples inferred to be located in recharge areas and with correlations observed in the available coal analyses, suggests that the source of strontium in these mixed coal-sandstone aquifers is calcium-enriched minerals or their strontium equivalents. The above relationships suggest that either the dissolution of carbonate minerals or weathering reactions of plagioclase feldspars are the likely sources of Sr in these water samples.

Mixed coal-sandstone aquifer sample 45 has a distinctly different $^{87}Sr/^{86}Sr$ ratio value compared to the other water samples. This sample is classed as a $Ca\text{-}Na\text{-}Mg\text{-}HCO_3$ type water. The water type typical of a recharge zone is $Ca\text{-}Mg\text{-}HCO_3$ (Macpherson and Townsend, 1998). Based on the classification of sample 45, as well as on field observations, and criteria such as well depth and TDS, this well is likely located

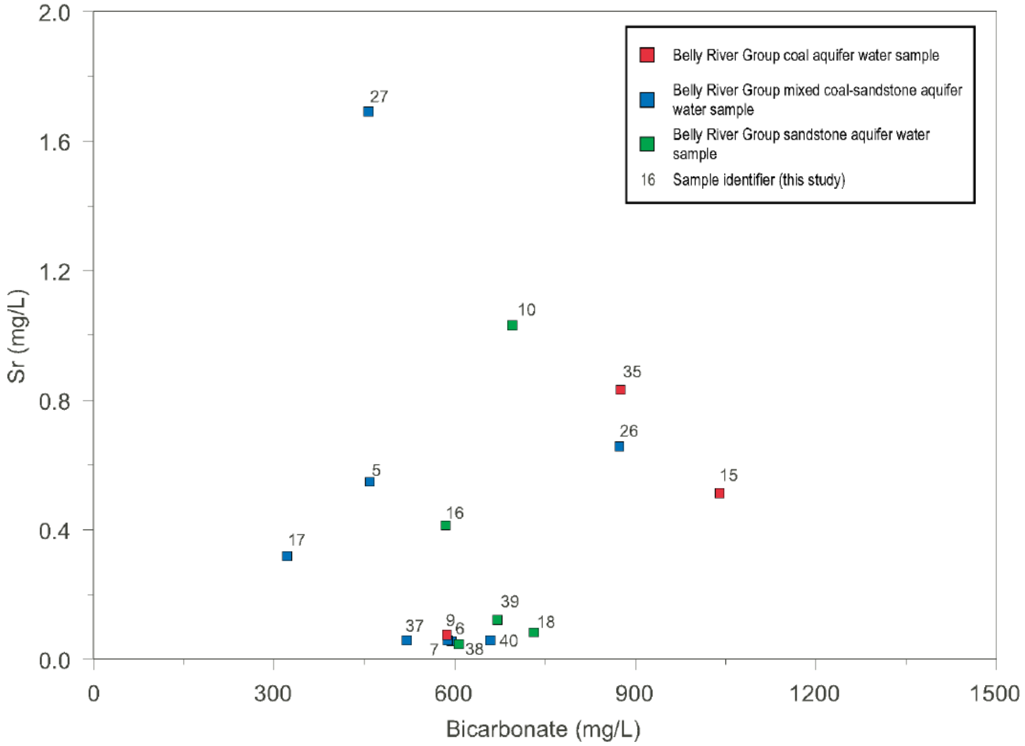


Figure 80. Belly River Group: Sr vs. HCO_3.

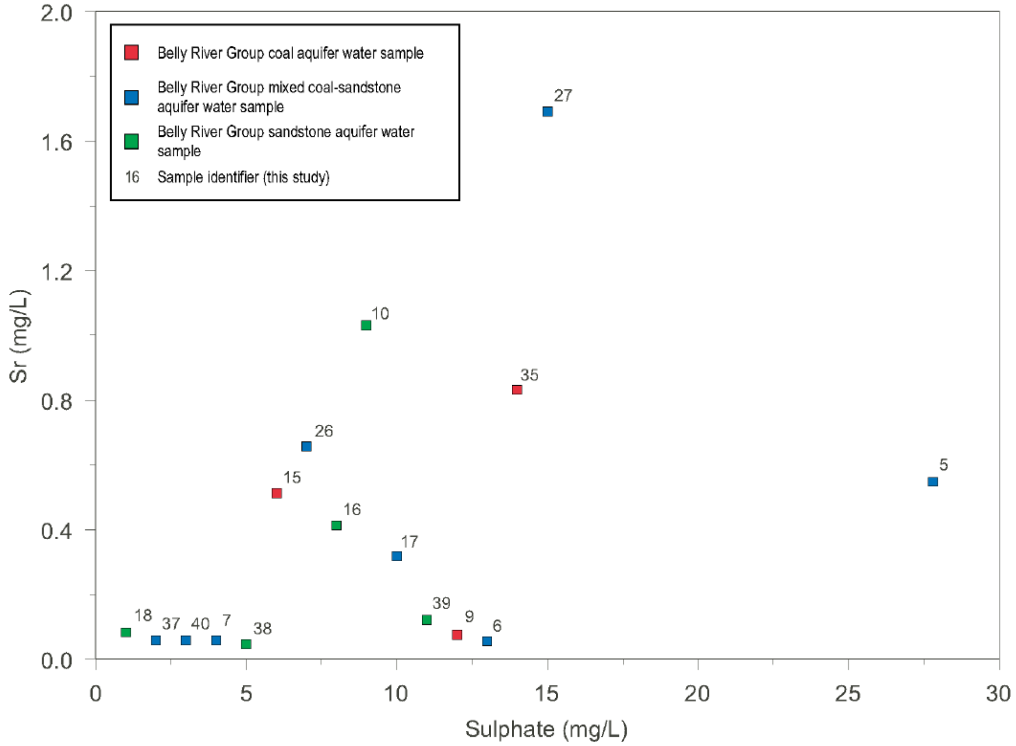


Figure 81. Belly River Group: Sr vs. SO_4.

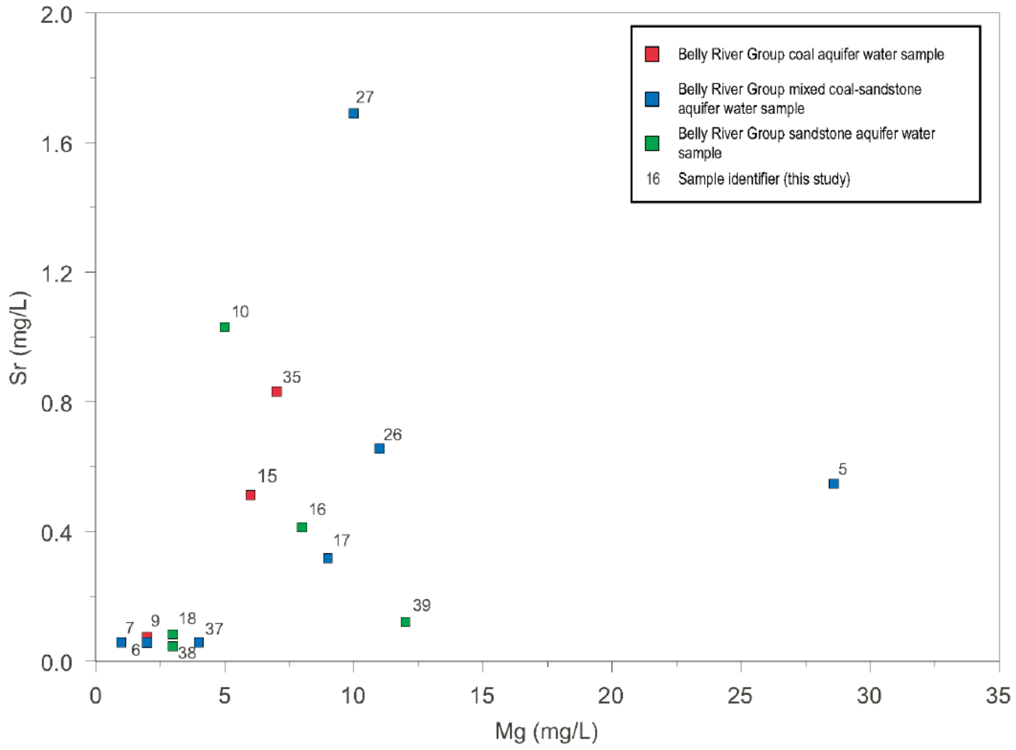


Figure 82. Belly River Group: Sr vs. Mg.

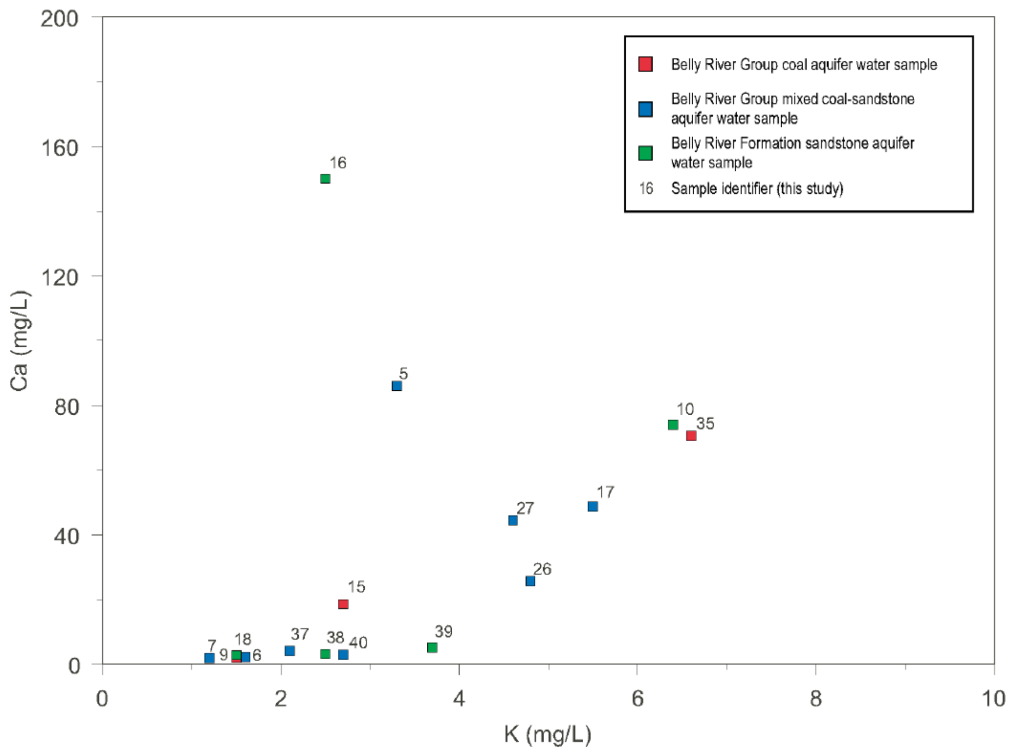


Figure 83. Belly River Group: Ca vs. K.

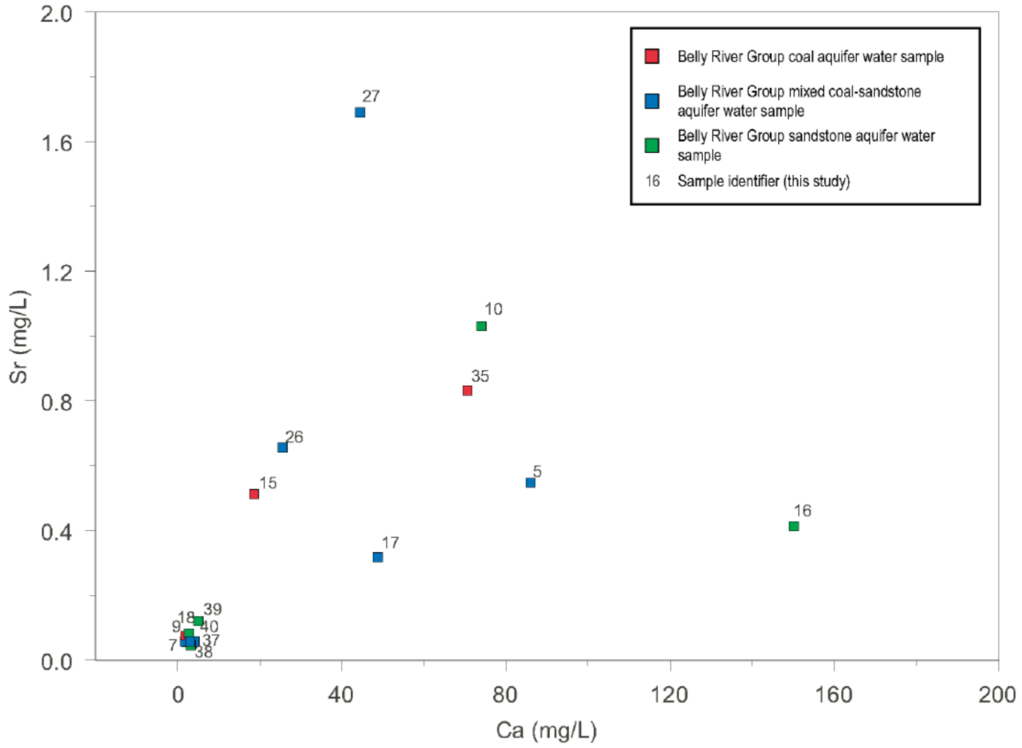


Figure 84. Belly River Group: Sr vs. Ca.

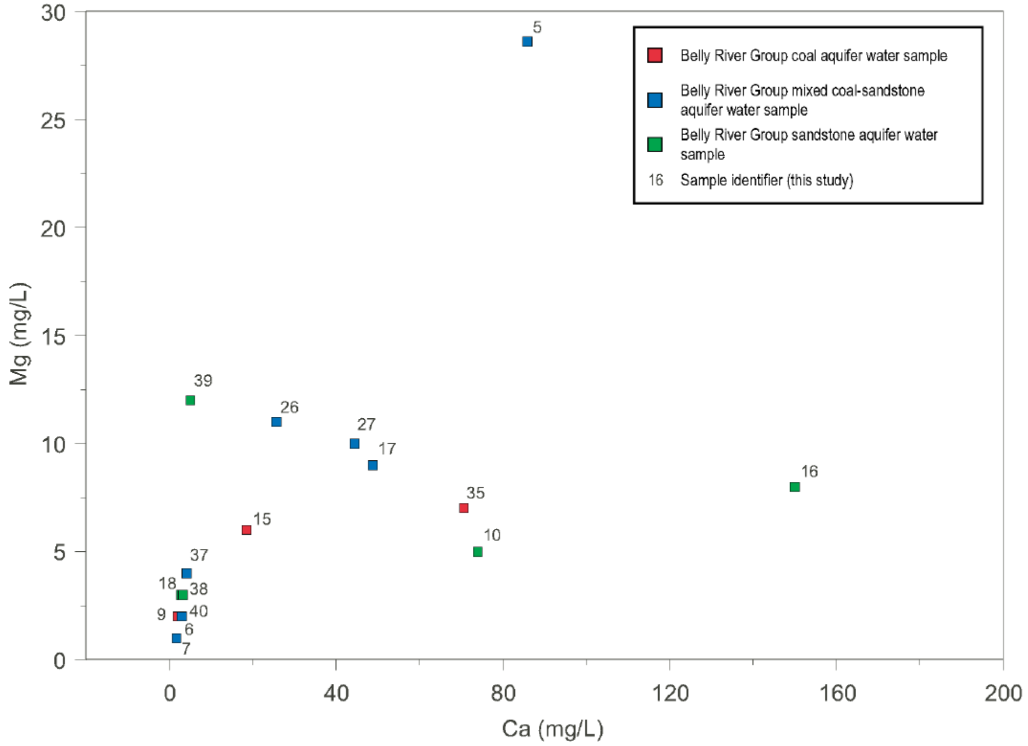


Figure 85. Belly River Group: Mg vs. Ca.

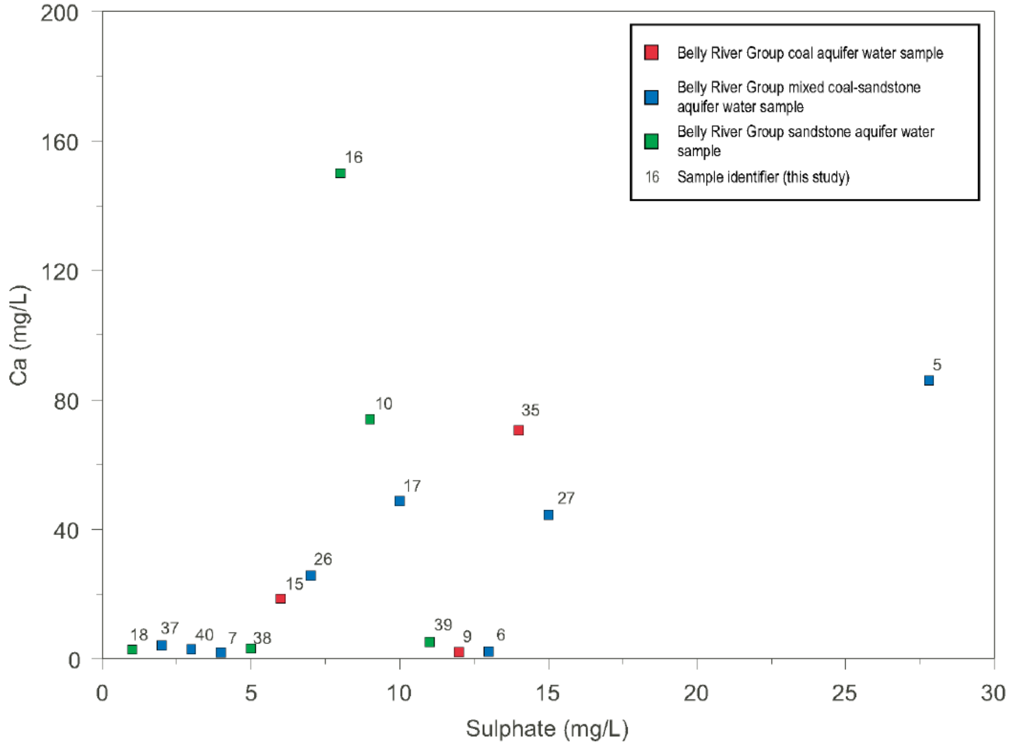


Figure 86. Belly River Group: Ca vs. SO_4.

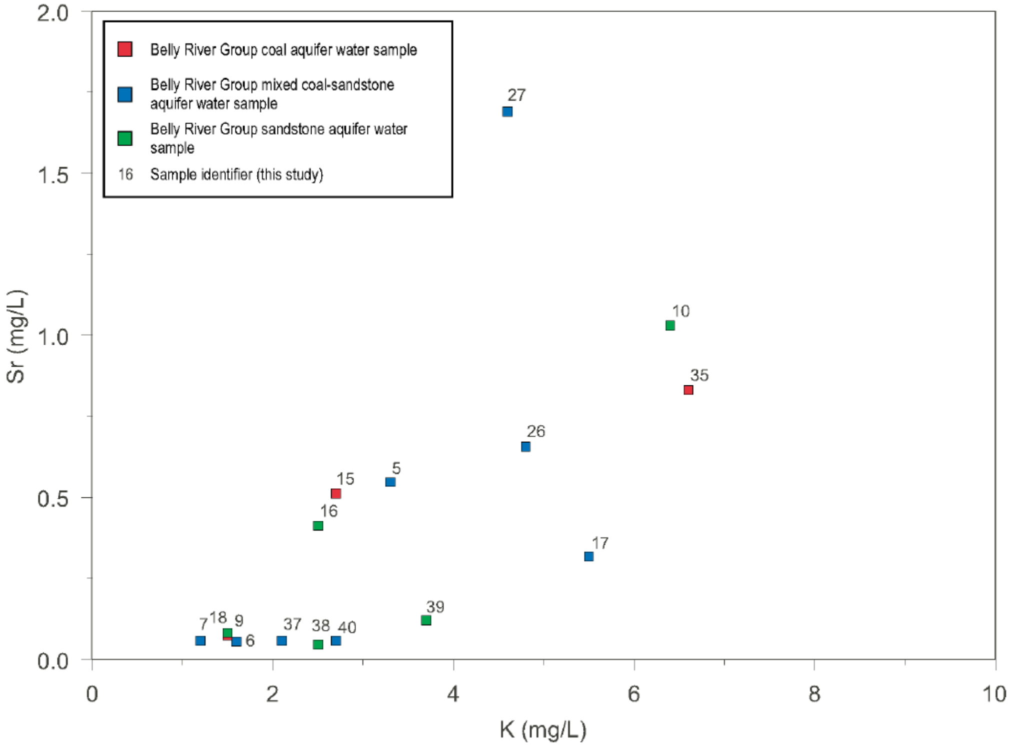


Figure 87. Belly River Group: Sr vs. K.

near the aquifer recharge area. The water type and $^{87}Sr/^{86}Sr$ ratio value of sample 45 suggests that it has undergone less water rock interaction than any other sample. This sample has the highest $^{87}Sr/^{86}Sr$ ratio and is therefore most similar to ratio values for atmospheric precipitation. The $^{87}Sr/^{86}Sr$ ratio value is less than the reported range for atmospheric precipitation however (0.7090 to 0.7120, Figure 58), indicating that it has undergone water-rock interactions that have modified the ratio.

Mixed coal-sandstone aquifer water samples 29 and 45 have similar $^{87}Sr/^{86}Sr$ ratio values. Samples 29 and 46 are classed as Ca-Na-Mg-HCO_3 and Ca-Na-HCO_3 type water respectively. The water type classification of samples 29 and 46 therefore indicates that the samples have undergone geochemical changes from an original recharge composition. These processes have lead to the slight shift in water type, as well as the change in $^{87}Sr/^{86}Sr$ ratio values from those expected of a recharge zone.

The water samples located farther along groundwater flow paths show positive correlations between K, Ca and Sr as well as between Ca, Sr and Mg. Negative correlations were observed between Ca and HCO_3 as well as between Sr and HCO_3. Potassium, calcium, magnesium and strontium are components of feldspar, biotite and clay minerals such as illite and smectite. A source for Sr in these water samples therefore may be dissolution or exchange reactions involving these minerals. These water samples have very similar $^{87}Sr/^{86}Sr$ ratio values, but different strontium concentrations. This indicates a similar source of Sr in these water samples. These samples all belong to the Na-HCO_3 water type (Figure 11). This suggests that the water moving through these aquifers has undergone geochemical variation from an original recharge composition. This variation has likely resulted in the overprinting of the original $^{87}Sr/^{86}Sr$ isotopic signature with the aquifer $^{87}Sr/^{86}Sr$ isotopic signature.

Frost et al. (2002) suggest different sources of Sr in the Tertiary coal and sandstone aquifers of the Powder River Basin of Wyoming, U.S.A.. They state that the Sr isotope ratio values in the coal seams of the Powder River Basin are likely caused by increased radiogenic Sr content in organic matter, whereas the Sr source in the sandstone aquifers is from carbonate cement. Conversely, a similar source of Sr appears likely in the Tertiary-Cretaceous coal and sandstone aquifers of the Alberta Basin. It appears that the Sr present in the Paskapoo-Scollard aquifer water samples collected during this study is potentially from of combination of carbonate, clay and silicate minerals. The $^{87}Sr/^{86}Sr$ values suggest that very different Sr compositions are present in the Alberta Basin as compared to the Powder River Basin. This is likely caused by different lithological makeup of the clastic and coal units in the two basins.

3.8.1.5 Preliminary Interpretations – Horseshoe Canyon Formation

Based on Figure 58 and consideration of the geological history of the Alberta Basin and of the Horseshoe Canyon Formation, the most likely sources of strontium in the aquifers of this formation are the interaction of water with clastic sedimentary rocks or with coal deposits. Allan and Sanderson (1945) indicate that the Horseshoe Canyon Formation equivalent in the Red Deer area contains plagioclase, quartz, micas, magnetite, zircon, hornblende, topaz, anatase and garnet held in a matrix of bentonite or calcite. Bentonite is one of the chief constituents in the Horseshoe Canyon Formation equivalent. In addition, they indicate that the Horseshoe Canyon Formation equivalent contains a great deal more of pyroclastic sedimentary rocks than has hitherto been supposed. Shepheard and Hills (1970) show that sedimentary rock fragments and quartz make up the greatest percentages of Horseshoe Canyon Formation in the Badlands of Alberta. Volcanic rock fragments make up > 1% of the material. The dominant rock types observed were sand, silt, shale, coal, arenaceous limestone and bentonite.

The strong correlation between Sr and Ca, Sr and K, Sr and Rb and K and Rb in the water samples is partially reflected in the strong correlation between Sr and Ca in available coal analyses. Only a weak correlation exists between Sr and K in available coal analyses. Strontium is likely introduced through the interaction of water with Ca, Sr and K bearing minerals. The low $^{87}Sr/^{86}Sr$ ratio values of the water samples indicates that whatever ^{87}Sr is contributed from the radiogenic decay of ^{87}Rb (contributed from K-bearing minerals) must be low, since the ratio values of the majority of the samples in which Rb was detected is not significantly higher than those samples where Rb was not detected. That being said, samples 19 and 20 have slightly higher $^{87}Sr/^{86}Sr$ values suggesting that ^{87}Rb decay may have contributed to the ^{87}Sr content of these samples.

The majority of the coal and mixed coal-sandstone aquifer water samples belong to Group 1. Within Group 1, the mixed coal-sandstone aquifer water samples and the coal aquifer water samples belong to various water type categories, including the Na-HCO_3, Na-HCO_3-SO_4, Na-SO_4-HCO_3, Na-HCO_3-Cl, Na-Ca-SO_4-HCO_3 and Na-Ca-HCO_3-SO_4 categories (Figure 15). This indicates a wide range of geochemical processes occurring within the aquifers of the Horseshoe Canyon Formation. The $^{87}Sr/^{86}Sr$ ratio values of these samples vary between 0.705129 and 0.705779, indicating that a similar source of Sr has been introduced into these water samples and that regardless of what geochemical processes the water has undergone, the Sr composition has reached something of an equilibrium. There does not appear to be any link between $^{87}Sr/^{86}Sr$ ratio and depth, or elevation or distance along the groundwater flow path.

The Group 2 coal aquifer water samples belong to the Na-HCO_3 water type, whereas the mixed coal-sandstone aquifer water sample belongs to the Na-HCO_3-SO_4 water type category (Figure 15). Although slightly different geochemical processes are indicated by the chemical composition of the water samples the similar $^{87}Sr/^{86}Sr$ ratios suggest a similar source of Sr for these water samples that is slightly more radiogenic than the Group 1 samples. Rubidium was detected in two of the Group 2 coal aquifer water samples, but concentrations were not significantly different from Group 1 samples. The differences are likely caused by local variations in the Sr-composition of the aquifer materials. There does not appear to any link between $^{87}Sr/^{86}Sr$ ratio and depth, or elevation or distance along the groundwater flow path.

The Group 3 sandstone aquifer water sample belongs to the Na-Ca-SO_4-HCO_3 water type category. Although it has the same water type as a Group 1 water sample, this Group 3 $^{87}Sr/^{86}Sr$ ratio value is much higher indicating a more radiogenic isotopic composition. The Group 3 sandstone aquifer water sample was collected from the shallowest well. This may indicate that the water sampled at this location in the aquifer has undergone less water rock interaction and less water mixing preserving more of the original recharge $^{87}Sr/^{86}Sr$ ratio signature.

3.8.1.6 Preliminary Interpretations – Belly River Group

Based on Figure 58 and consideration of the geological history of the Alberta Basin and of the Belly River Group, the most likely sources of strontium in the aquifers of this formation are the interaction of water with clastic sedimentary rocks or with coal deposits. Mack and Jerzykiewicz (1989) indicate that the Belly River Group in the Southern Foothills is made up primarily of quartz, plagioclase and volcanic rock fragments. Hamblin (1997a) states that the Belly River Group in the central foothills has a high content of volcanic detritus and abundant bentonite.

The moderate correlation between Sr and Ca and weak correlation between Sr and K in the water analyses suggests that strontium is likely introduced through the interaction of water with Ca and Sr bearing minerals. The low $^{87}Sr/^{86}Sr$ ratio values of the majority of the water samples indicates that whatever ^{87}Sr is contributed from the radiogenic decay of ^{87}Rb must be low, since Rb was not detected in any of the Belly River Group water samples.

Group 1 mixed coal-sandstone aquifer water samples belong to the Na-HCO_3, Na-HCO_3-SO_4 and Na-Cl water type categories. This indicates a progressive change in geochemical characteristics of the water samples. What does not appear to change however is the Sr geochemical composition or source within these different water type categories. Samples 6, 7 and 27 are located within the same general geographic location. There does not appear to be a link between depth and water type nor between depth and $^{87}Sr/^{86}Sr$ ratio.

Group 2 coal aquifer water samples belong to the Na-HCO_3 and Na-Ca-HCO_3 water type categories. The Na-Ca-HCO_3 water type is found in the shallower of the two samples and is consistent with established ideas on the geochemical evolution of groundwater with increasing depth. The $^{87}Sr/^{86}Sr$ ratio value decreases slightly as depth increases, suggesting that increased water rock interaction with depth is changing the $^{87}Sr/^{86}Sr$ ratio value. The mixed coal-sandstone aquifer water samples both fall within the Na-HCO_3-SO_4 water type category. The $^{87}Sr/^{86}Sr$ ratio value increases with depth in this case. However, the samples are widely separated geographically (Figure 21). The difference in the $^{87}Sr/^{86}Sr$ ratio values therefore may be caused by local variations in the Sr-composition of the aquifer materials. The sandstone aquifer water samples belong to the Na-HCO_3-SO_4, Na-SO_4-HCO_3 and Na-HCO_3-Cl water type categories. The shallowest well possesses the highest $^{87}Sr/^{86}Sr$ ratio value. No other obvious trends exist between depth, elevation or distance along the groundwater flow path. Despite the fact that the sample locations are widely separated geographically, the similar $^{87}Sr/^{86}Sr$ ratio values suggest that the Sr source could be the same in these water samples. Whatever variations are present are likely caused by local variations in the Sr-composition of the aquifer materials.

Four samples collected by Connolly et al. (1990b) from the Belly River Group fall within the Group 2 samples. This may indicate a similar strontium source for samples located within significantly different areas of the basin both in terms of geographic location as well as depth.

Group 3 water samples include one coal aquifer water sample and one mixed coal-aquifer water sample. The coal aquifer water sample falls within the Ca-Mg-HCO_3 water type. The mixed coal-sandstone aquifer water sample falls within the Na-HCO_3-SO_4 water type category. The coal aquifer water sample is the shallower of the two and possesses a water type signature typical of water located near a recharge zone. The range of reported Sr isotope ratio values for atmospheric precipitation is between 0.7090 and 0.7120 (Figure 58). The $^{87}Sr/^{86}Sr$ ratio of the shallower sample is lower than the values reported for atmospheric precipitation. This indicates that the original recharge water $^{87}Sr/^{86}Sr$ ratio value for the recharging precipitation has been changed by water rock interaction and mixing with the aquifer water already present in the aquifer. The mixed coal-sandstone aquifer water sample has a higher $^{87}Sr/^{86}Sr$ ratio value than the coal aquifer water sample. The two samples are widely separated geographically. Therefore, the variations in $^{87}Sr/^{86}Sr$ ratio values are likely caused by local variations in the Sr-composition of the aquifer materials.

The sole Group 4 sample was collected from a sandstone aquifer. It possesses a Ca-Mg-HCO_3 water type. This sample is located at the highest elevation. Based on the elevation, the water type and the TDS, this sample is interpreted as being located in close proximity to a recharge area. The highest $^{87}Sr/^{86}Sr$ ratio value was observed for this sample. This value falls within the range of values expected for atmospheric precipitation (Figure 58). This water sample is therefore likely to contain relatively unmodified recharge water.

3.8.2 Radium

Radium possesses four naturally occurring radiogenic isotopes, ^{223}Ra (half-life 11.435 d), ^{224}Ra (3.66 d), ^{226}Ra (1600 y) and ^{228}Ra (5.75 y) (Firestone, 2000). Radium-223 is produced as part of the ^{235}U decay chain, whereas ^{224}Ra and ^{228}Ra are part of the ^{232}Th decay chain, and ^{226}Ra is part of the ^{238}U decay chain. The parent isotopes of radium, uranium and thorium, are generally thought to be insoluble in fluids, whereas radium is somewhat soluble in water and therefore mobile and can be produced during well activities (Underhill, 1996, p. 4-5). The concentration of radium in solution will depend on the nature of the rock material, as well as temperature, pressure and pH (Underhill, 1996, p. 5). Radium concentrations in most formation fluids are not of regulatory concern; however, as produced fluids move from the reservoir to production facilities, physical and chemical changes can occur resulting in the precipitation of radium in scale or sludge. Precipitation of radium is generally associated with significant production of reservoir fluids (Underhill, 1996, p. 6). Subsequent exposure to the scale or sludge can pose health risks. Radium isotopes decay through both alpha (^{223}Ra, ^{224}Ra and ^{226}Ra) and beta (^{228}Ra) particle emission. Their daughter products are also radioactive. Radium, calcium, strontium and barium have similar chemical properties. Radium will, therefore, be found to a limited extent in minerals containing these elements.

Samples were selected for analysis of radium content based on the results of the gross alpha and beta radiation analyses as well as on the sample formation. One sample from the Paskapoo-Scollard Formation, three samples from the Horseshoe Canyon Formation, and six samples from the Belly River Formation were submitted for analysis. The radium isotope data are presented in Appendix A, Table 184.

3.8.2.1 Observations – Paskapoo-Scollard Formation

One aquifer water sample was analysed for ^{226}Ra content. Sample 46 has a ^{226}Ra concentration of 0.13 Bq/L. This value is below the Canadian Environmental Water Quality Guidelines ^{226}Ra value of 0.6 Bq/L.

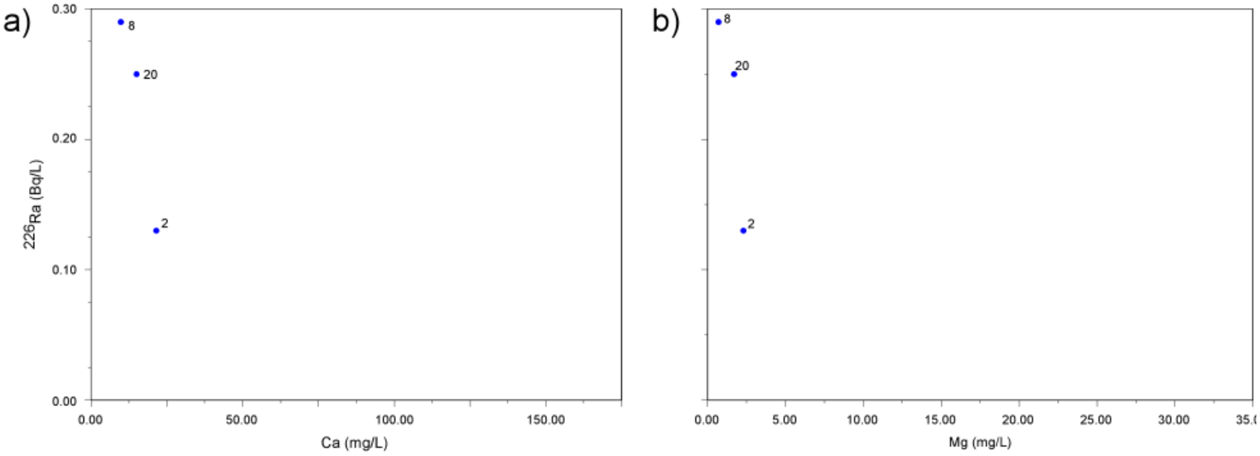
The parent nuclide of ^{226}Ra, uranium has been detected in coal and water from the Paskapoo-Scollard Formation. Uranium mean concentrations of 0.89 ppm (Landheer et al., 1982), 7.3 ppm (Pollock et al, 2000), and 3.5 ppm (Gentzis and Goodarzi, 1995) have been reported from Paskapoo-Scollard Formation coal samples. Uranium concentrations in water samples collected from the Paskapoo-Scollard Formation as part of this study were generally below the analytical detection limit with a maximum concentration of 0.001 mg/L determined. Goodarzi (2002) also reported uranium concentrations from water samples from the Paskapoo-Scollard Formation. The mean concentration for these samples was 0.0014 mg/L.

3.8.2.2 Observations – Horseshoe Canyon Formation

Three samples were analysed for ^{226}Ra content. Sample 2 has a ^{226}Ra concentration of 0.13 Bq/L, sample 8 has a ^{226}Ra concentration of 0.29 Bq/L, whereas sample 20 has a ^{226}Ra concentration of 0.25Bq/L. All of the sample concentrations are below environmental guidelines. The radium isotope data can be found in Appendix A, Table 184.

Uranium is present in coal aquifer material, but was not detected in aquifer water samples at concentrations above analytical detection limits. A mean uranium concentration of 0.89 ppm was determined from Horseshoe Canyon Formation coal samples. None of the Horseshoe Canyon Formation aquifer water samples analysed had uranium concentrations above the analytical detection limits.

Upon inspection of the chemistry data, concentrations of ^{226}Ra decrease as concentrations of Ca, Mg and Sr increase (Figure 88). Linear regression of the data produces R^2 values of 0.9547, 0.8305 and 0.9547, respectively. No apparent trend appears to exist between ^{226}Ra and Ba concentrations. Linear regression analysis of ^{226}Ra and SO_4 concentrations also reveals a trend (Figure 89). Concentrations of ^{226}Ra increase as concentrations of SO_4 increase. The calculated R^2 value is 0.9176. Bicarbonate and ^{226}Ra concentrations also appear to have a correspondence. The calculated R^2 value is 0.9917. Concentrations of ^{226}Ra decrease as bicarbonate concentrations increase (Figure 89). There may also be a correlation between depth and ^{226}Ra concentrations (Figure 89). As depth increases, ^{226}Ra concentrations decrease. Note: These trends are based on only three data points.



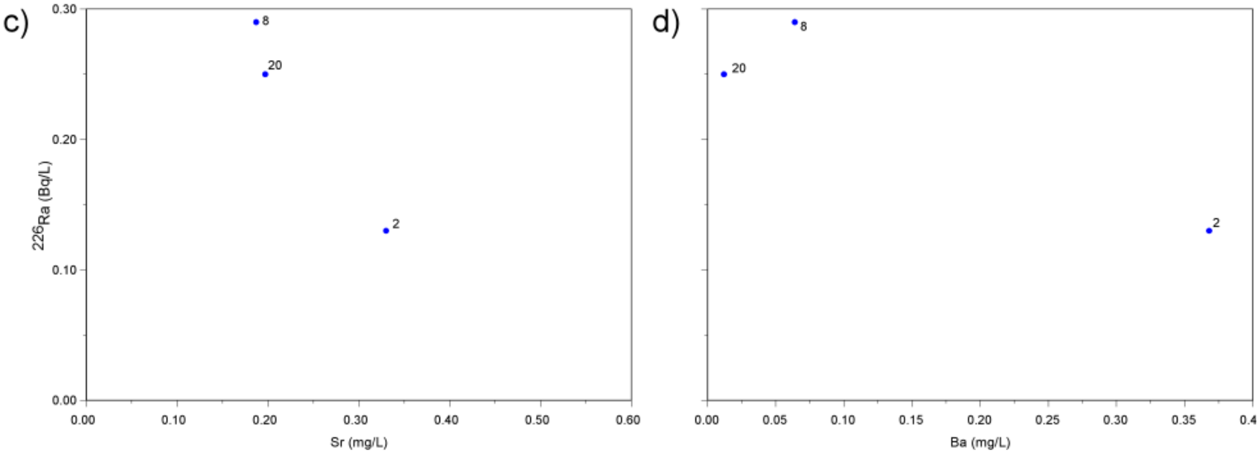


Figure 88. Horseshoe Canyon Formation: a)^{226}Ra vs. Ca; b) ^{226}Ra vs. Mg; c) ^{226}Ra vs. Sr; and d) ^{226}Ra vs. Ba.

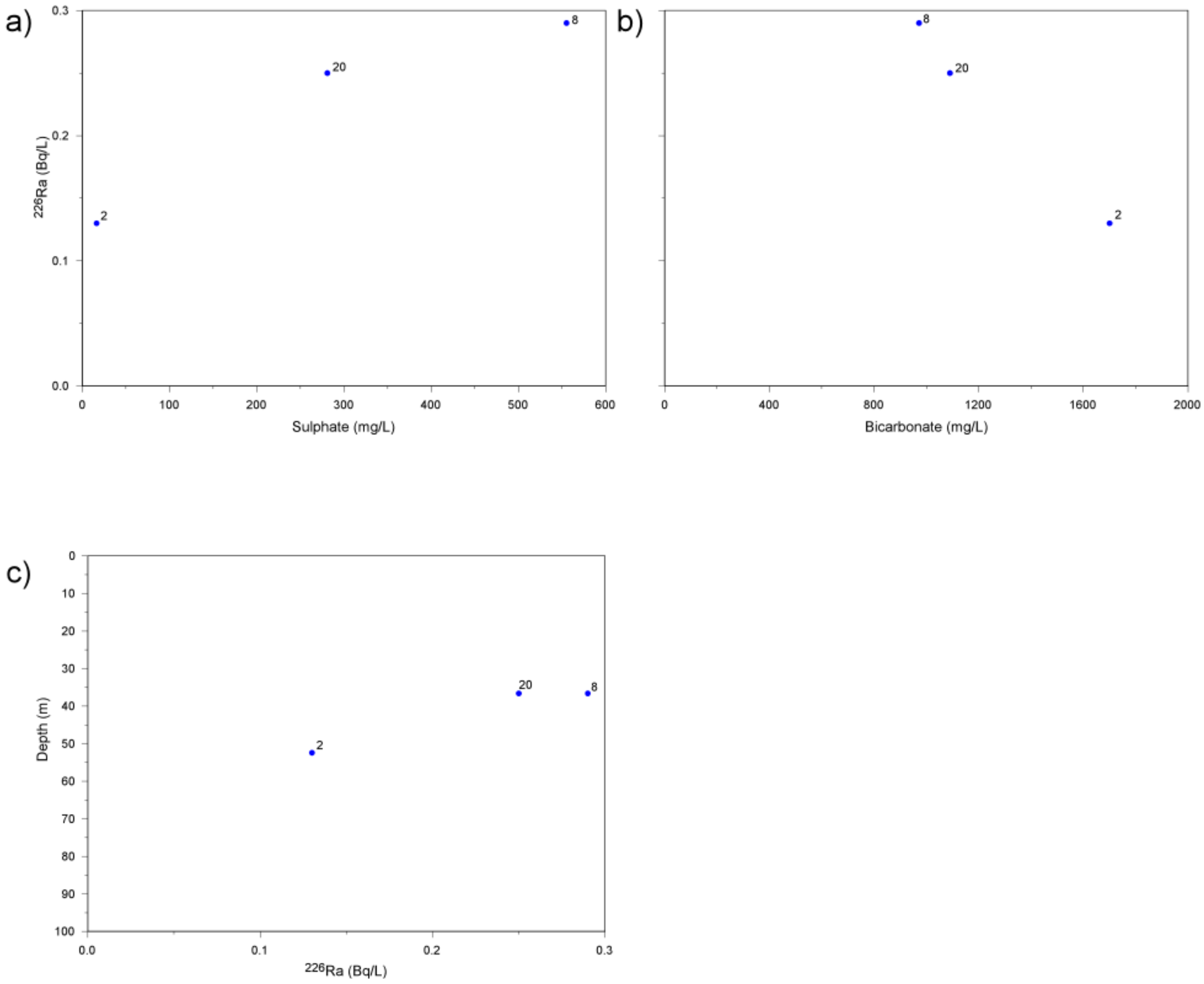


Figure 89. Horseshoe Canyon Formation: a) ^{226}Ra vs. Sulphate; b) ^{226} Ra vs. Bicarbonate; and c) ^{226}Ra vs. Depth.

3.8.2.3 Observations – Belly River Formation

Six aquifer water samples (5, 9, 16, 17, 38 and 39) were analysed for ^{226}Ra content. The average concentration of ^{226}Ra in these samples is 0.12 Bq/L. This value is below environmental guideline values. Uranium was detected in aquifer water samples. The radium isotope data can be found in Appendix A, Table 184.

Uranium concentrations were generally below analytical detection limits. A maximum uranium concentrations of 0.004 mg/L was determined.

No relationships appear to exist between radium concentrations and concentrations of calcium, magnesium, strontium, barium or sulphate in solution (Figure 90 and Figure 91). No relationship appears to exist between radium concentrations and depth (Figure 91).

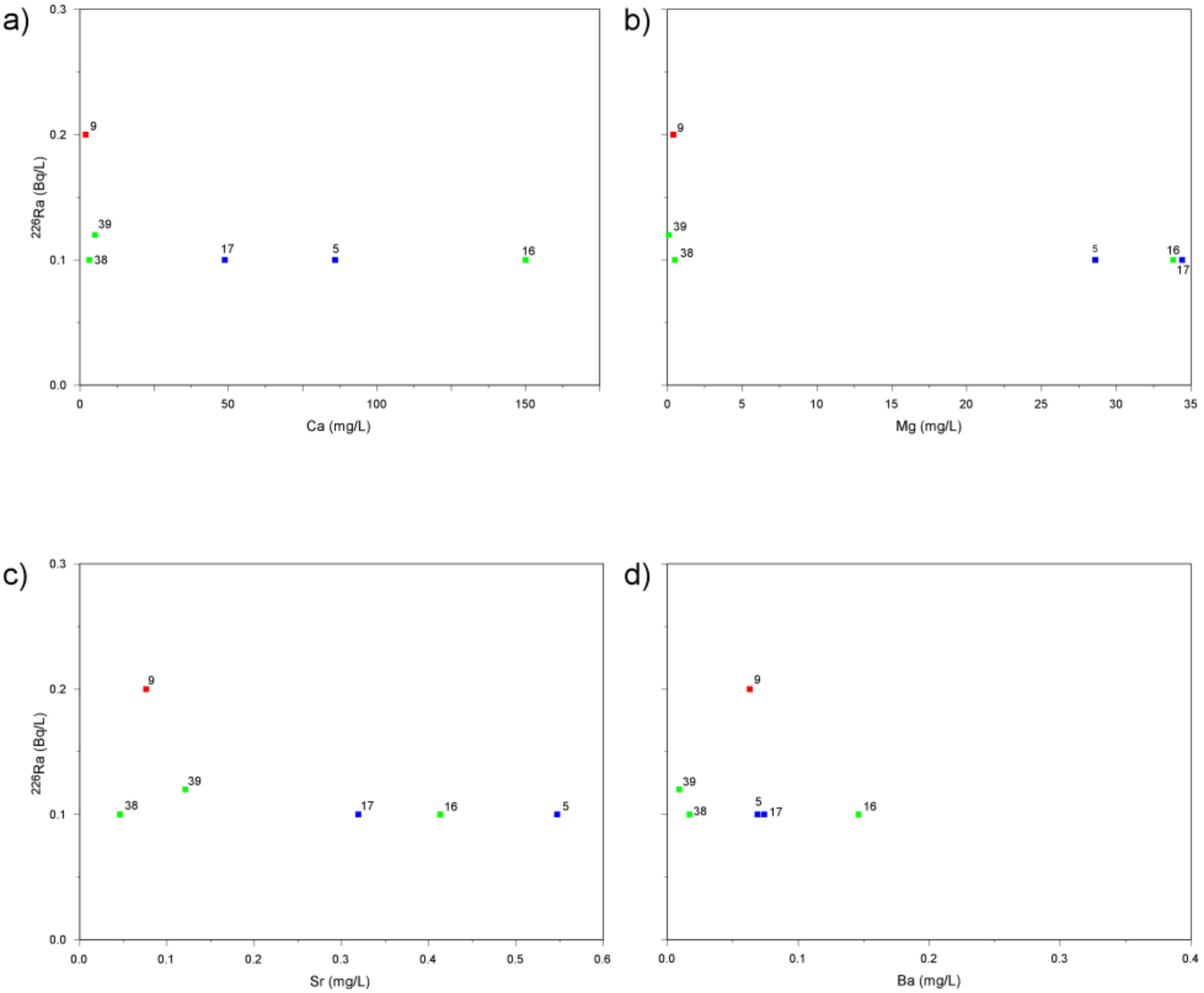


Figure 90. Belly River Group: a) ^{226}Ra vs. Ca; b) ^{226}Ra vs. Mg; c) ^{226} Ra vs. Sr; and d)^{226}Ra vs. Ba.

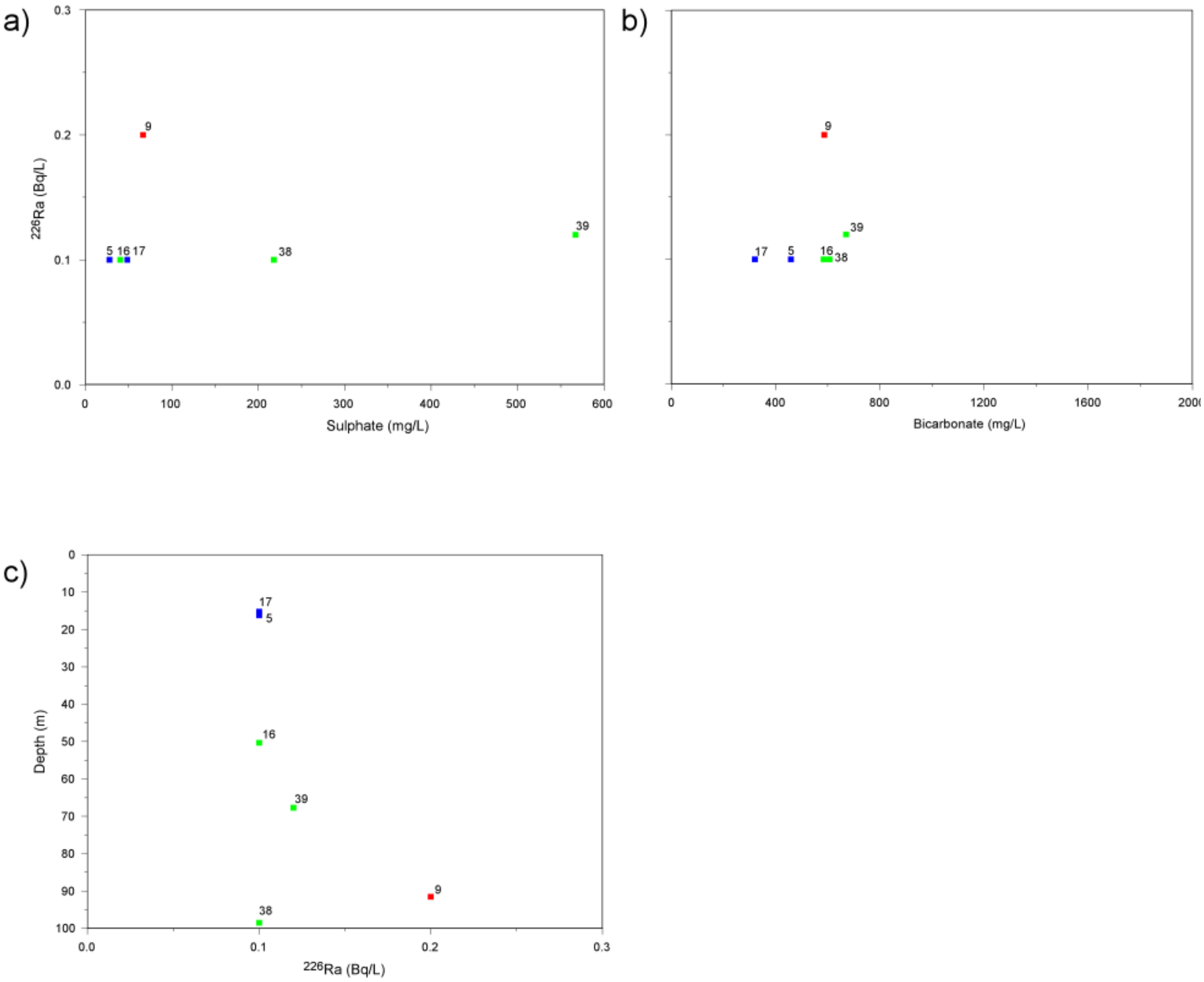


Figure 91. Belly River Group: a) ^{226}Ra vs. Sulphate; b) ^{226}Ra vs. Bicarbonate; and c) ^{226}Ra vs. Depth.

3.8.2.4 Preliminary Interpretations – ^{226}Ra

Focazio et al. (2001) state that, “The occurrence of radionuclides in groundwater depends first on the presence and solubility of the parent element.” Uranium is found in both the rock and water from aquifers within the Paskapoo-Scollard and Horseshoe Canyon formations, and likely from both the rock and water from aquifers within the Belly River Group. The presence of the parent radionuclide of ^{226}Ra can therefore help explain the presence of ^{226}Ra in the groundwater. The parent of ^{226}Ra, ^{238}U, is most mobile in oxygen-rich groundwater and tends to be strongly sorbed to humic substances (Focazio et al., 2001). For the samples in which both ^{238}U and ^{226}Ra were detected, the highest uranium concentrations are associated with the greatest Eh values. In the cases where ^{226}Ra was detected, but ^{238}U was not detected, the Eh values were in general lower than for those cases where ^{238}U was detected. In these cases, ^{238}U may be adsorbed to humic substances or mineral surfaces. The daughter products can still enter into solution through a process known as alpha recoil. As the alpha particle is emitted, the daughter radionuclide is ejected in the opposite direction. If the ejection direction coincides with aquifer pore space, then the daughter product can enter the flow system.

Focazio et al. (2001) state that, "radium tends to be most mobile in oxygen-poor groundwater that is chloride-rich with high concentrations of total dissolved solids." Inspection of the data does not show any obvious links between total dissolved solids or chloride concentrations and ^{226}Ra concentrations. Inspection of the Eh values appears to show a trend opposite to what Focazio et al. (2001) suggest. This may indicate that Cl concentrations, TDS and Eh are not a factor influencing the ^{226}Ra concentration in solution in these aquifers.

Focazio et al. (2001) go on to state that, "radium solubility can be enhanced by the common-ion effect where competing cations [Ca, Sr and Ba] are present in abundance." There appear to be some links between concentrations of Ca, Mg and Sr in solution. As mentioned in the observations section, concentrations of Ca, Mg and Sr decrease as concentrations of ^{226}Ra increase. This indicates competition for adsorption sites may be releasing ^{226}Ra into solution. Another potential source of ^{226}Ra in solution could also be dissolution of sulphate minerals since concentrations of ^{226}Ra increase as concentrations of sulphate concentrations increase. A potential control on the concentration of ^{226}Ra also reveals itself through the inspection of the data. Concentrations of ^{226}Ra decrease as bicarbonate concentrations increase, indicating the possibility that ^{226}Ra concentration is being controlled by carbonate mineral precipitation.

3.8.3 Polonium

Polonium-210 is the last radioactive member of the ^{238}U decay series. The half-life for this isotope is 138.4 days. During decay, ^{210}Po emits an alpha particle to produce the stable isotope of lead, ^{206}Pb. Focazio et al. (2001) indicate that ^{210}Po is not expected to be found in high concentrations in most natural waters. Where it is encountered in high concentrations (> 0.1 Bq/L), the aquifer from which the water was produced is usually enriched in uranium (Mullin, 1982; Kaufmann et al., 1976; and Harada et al., 1989). Control of polonium concentrations in water does not appear to be well understood. Harada et al. (1989) have postulated that high concentrations of ^{210}Po (>17 Bq/L) in an aquifer in Florida are characterized by 1) the presence of sulphide; 2) low pH (<5); and 3) high ^{222}Rn. These characteristics may be controlled by the sulphur cycle and potentially by sulphur reducing bacteria (Harada et al., 1989).

3.8.3.1 Observations – Paskapoo-Scollard Formation

The sample collected from the water well completed in the Paskapoo-Scollard Formation had a ^{210}Po value less than the analytical detection limit. The polonium isotope data can be found in Appendix A, Table 184.

3.8.3.2 Observations – Horseshoe Canyon Formation

Only sample 2 has a ^{210}Po concentration above the analytical detection limit. Samples 8 and 20 have ^{210}Po concentrations below the detection limit. The measured ^{210}Po concentration in sample 2 is 0.05 Bq/L. A sample was obtained for δ^{34}S of sulphide, indicating some sulphide is present in the water. Similar sulphide samples were obtained for the other two Horseshoe Canyon Formation water samples as well. During sampling, no hydrogen sulphide was detected at any of these three sample sites. Sample 2 has the lowest dissolved sulphate concentration and was collected from the deepest of the three wells. A ^{226}Ra concentration was obtained for the sample, indicating parent material is present within the water. However, ^{226}Ra was detected at higher concentrations in the other two Horseshoe Canyon Formation water samples. Values for pH are greater than 5 for all of the samples. The polonium isotope data can be found in Appendix A, Table 184.

3.8.3.3 Observations – Belly River Group

Samples 9 and 16 have measured ^{210}Po concentrations of 0.14 and 0.07 Bq/L, respectively. Water samples from these sites contained sulphide. These samples also contained measurable concentrations of ^{226}Ra. Samples 5, 17, 38 and 39 contain ^{226}Ra and, with the exception of sample 5, also contain sulphide. Samples 9 and 16 have the lowest concentrations of dissolved sulphate, with the exception of sample 17. All measured values for pH are greater than 5. The polonium isotope data can be found in Appendix A, Table 184.

3.8.3.4 Preliminary Interpretations – ^{210}Po

The reasons for the presence or absence of ^{210}Po in aquifer water samples are not clear. Based on the comparison of the chemistry results from the Horseshoe Canyon Formation water samples and, to a lesser extent the Belly River Group water samples, with the work of Harada et al. (1989), a possibility exists that the concentration of ^{210}Po in solution may be linked to the sulphur cycle and perhaps bacterial activity.

3.9 Groundwater Age Calculations in Coal, Mixed Coal-Sandstone and Sandstone Aquifers

The concentrations of three radiogenic isotopes were determined for five groundwater samples from the Paskapoo-Scollard and Horseshoe Canyon Formations, and from the Belly River Group. The sampling program was designed to test sampling methods, assess the feasibility of conducting water sampling for groundwater age determination in coal, mixed coal-sandstone and sandstone aquifers, compare the results of different radiogenic isotope dating techniques, as well as to calculate groundwater ages for water within distinct portions of the various flow regimes. With a limited number of samples, definitive conclusions cannot be drawn regarding flow regimes within the shallow portion of the Alberta Basin. Certain general statements can be made however.

Samples were collected for the determination of the concentrations of ^{14}C, ^{36}Cl and ^{129}I for five samples. One sample was collected from the Paskapoo-Scollard Formation, and two samples were collected from the Horseshoe Canyon Formation and from the Belly River Group. This section begins with a brief description of the concept of groundwater dating and is followed by a discussion of the results of the analyses.

Groundwater Age

Groundwater age is among the most fundamental parameters describing subsurface flow, and is the conceptual link between flow modelling and radiometric dating (Bethke and Johnson, 2002a). With this information, calculations can be performed to determine sustainable yields of aquifers, groundwater flow velocities and, therefore, more accurate representations of groundwater flow. Conceptualizations of groundwater age can be broken down into four separate models: 1) piston flow age; 2) age mass; 3) radiometric dating; and 4) ingrowth from radioactive decay.

Piston Flow Age

The idea behind piston flow age is that groundwater age is the distance to the point of recharge divided by groundwater velocity averaged over the flow path (Bethke and Johnson, 2002a). This implies that a mass of water enters at the recharge point and migrates through the aquifer as a distinct mass. Flow is through advection, and the assumption is made that the exchange of mass between aquifers and aquitards has little or no effect on the age of the water. Several authors have pointed out deficiencies of this concept, including Sudicky and Frind (1981), Walker and Cook (1991), Maloszeski and Zuber (1991), Goode

(1996), Bethke and Johnson (2002a, b) and Park and Bethke (2002). Bethke and Johnson (2002b) state that the piston flow model: 1) provides information only about the rate of advection in one dimension; 2) breaks down when considering any but the simplest flow regimes; 3) produces estimates of age that are unrealistic since water molecules do not move through the subsurface in isolated packets; 4) calculates ages that are inconsistent with dating methods; and 5) does not allow for the analysis of error. However, some successes have been documented using the piston flow age approach. Reilly et al. (1994) used an advective model to show that simulated groundwater age was consistent with the distribution of chlorofluorocarbons and tritium in a shallow sand and gravel aquifer.

Age Mass

Goode (1996) defines groundwater age as the average over its water molecules of the time elapsed since they recharged the subsurface. This suggests that the age of the groundwater is not a measurable physical property, but rather, when different masses of water are mixed, the mean age of the mixture is the mass-weighted average age of the mixed components (Goode, 1996). For example, if 1 kg of 10-year-old water is mixed with 1 kg of 30-year-old water, the result is 2 kg of 20-year-old water (Bethke and Johnson, 2002a). The concept behind the age mass groundwater age is that one water molecule may have migrated from recharge rather directly, whereas another may have been derived from an overlying aquifer, whereas yet another may have entered a confining layer and resided there for a long period of time before returning to the aquifer. All three masses of water combine to give one groundwater age mass. Each component contributes an older or younger age to the entire mass. The most important contributor to the age of the water appears to be the component that flows from the confining units. Bethke and Johnson (2002b) found that the aging of water as it migrates along an aquifer commonly contributes little to its age, but that the mere presence in the subsurface of confining layers and the very old water they contain dominates. In fact, the effect on age does not appear to depend on mixing rate, but rather on the ratio of fluid volume in aquitards in comparison to the fluid volume in aquifers (Bethke and Johnson, 2002a).

This idea appears to contrast completely with the idea of piston flow age, but really it adds to it. Instead of simply accounting for advection, the concept of age mass states that groundwater age is controlled by molecular diffusion, hydrodynamic dispersion, and fluid advection (Bethke and Johnson, 2002a). The distribution of age is, therefore, controlled by the transport of age in three dimensions (Bethke and Johnson, 2002a).

Radiometric Dating

A number of radiogenic isotopes are used for the purposes of calculating groundwater age. These include ^{3}H, ^{14}C, ^{32}Si, ^{36}Cl, ^{37}Ar, ^{39}Ar, ^{81}Kr, ^{85}Kr, ^{129}I, ^{222}Rn, ^{226}Ra, ^{232}Th, ^{235}U and ^{238}U. These radionuclides decay at a constant rate according to the equation

$$a_t = a_0 e^{-\lambda t}$$

where a_t = the activity of the species in question at time t
a_0 = the activity of the species in question at time 0
λ = the decay constant (equal to $\ln 2/t_{1/2}$)
t = time

The half-life ($t_{1/2}$) is the time interval required for the number of atoms or the activity of a radioactive element to fall from any particular value to one half that value (Friedlander et al., 1981, p. 191). With this information, and the determined concentration of the radionuclide in question, dating of materials can be undertaken using the radioactive decay equation.

These ages can be affected by some of the points raised in the previous section. Contribution of a radionuclide by molecular diffusion or hydrodynamic dispersion into the aquifer can cause the age of the water to appear younger than it actually is, whereas molecular diffusion or hydrodynamic dispersion out of the aquifer can cause the age of the water to appear older than it actually is. The decay rate equation is usually modified to try and account for these possibilities.

Ingrowth from Radioactive Decay

Certain radiogenic decay reactions result in the production of decay products that accumulate over time. According to the rates and reactions for subsurface production, estimates of groundwater residence time, or age, can be made. This requires that details of the host aquifer be known so the potential contribution from the aquifer material can be assessed and corrected for.

3.9.1 Groundwater Age – ^{14}C

Carbon-14 differs from regular carbon, carbon-12, in that it has two extra neutrons in its nucleus. It forms in the atmosphere through cosmic-ray bombardment of atmospheric gases and in the earth through either neutron activation of nitrogen, or neutron capture of oxygen caused by spontaneous fission of uranium and other elements. Atmospheric testing of nuclear weapons also created carbon-14. Release of CO_2 by industrial activities, such as burning fossil fuels (which are too old to have significant levels of carbon-14), has resulted in a relative decrease in the concentration of carbon-14 in the Earth's atmosphere, diluting ^{14}C by as much as 25 per cent compared to pre-industrial concentrations (Clark and Fritz, 1997, p. 204).

Carbon-14 is primarily introduced into groundwater in the soil zone through biological processes. Carbon-14 enters groundwater through the soil zone as the CO_2 released by living plants and decaying organic material is dissolved in water and incorporated as dissolved inorganic carbon (DIC). Along the flow path, ^{14}C concentrations begin to decrease according to radioactive decay principles and through any subsequent dilution or geochemical reaction mechanisms. Dilution, loss or addition of ^{14}C through geochemical processes can significantly alter the original ^{14}C concentration. Processes that will affect ^{14}C concentrations include

- carbonate dissolution;
- exchange reactions between the $DI^{14}C$ and the aquifer material;
- oxidation of 'old' organic matter;
- diffusion of ^{14}C into the aquifer;
- sulphate reduction;
- incorporation of geogenic CO_2 from deep crustal or mantle sources; and
- methanogenesis.

Carbon-14 can also enter groundwater directly as a component of precipitation. Table 178 contains a summary of ^{14}C concentrations along the groundwater recharge pathway described above.

Table 178. ^{14}C concentrations along the groundwater recharge pathway (Clark and Fritz, 1997, p. 205).

Component	^{14}C concentration (pmC)
Atmosphere	104.3
Vegetation	100.0
Soil CO_2	100.5
DIC (open system)	102.3
DIC (closed system)	<100.0

Four mixed coal/sandstone aquifer water samples (1, 17, 22 and 27) and a sandstone aquifer water sample (28) were submitted for analysis. The results of the isotopic measurements are presented in Table 179 below. Sample locations can be found in Figure 13, Figure 17 and Figure 21.

Table 179. Summary table of ^{14}C results.

Sample ID	Sample Name	Formation or Group	Aquifer Type	$\delta^{13}C$ DIC (‰ VPDB))	$\delta^{13}C$ CO_2 (‰VPDB)	^{14}C (pmC)	Age (years BP)	Calculation method
1	AERI 02-01	Horseshoe Canyon	Mixed	-15.1	-14.8	na	na	na
17	AERI 02-18	Belly River	Mixed	-12.3	-10.4	93.93±0.46		Uncorrected
22	AERI 02-24	Paskapoo-Scollard	Mixed	17.0	19.4	<0.36	na	na
27	AERI 02-30	Belly River	Mixed	-17.4	0.3	1.09±0.07		Fontes and Garnier (1979)
28	AERI 02-31	Horseshoe Canyon	Sandstone	-18.4	-14.8	55.98±0.30		Fontes and Garnier (1979)

3.9.1.1 Preliminary Interpretation – ^{14}C

Calculated ages range from 503±39 years BP to likely greater than the 45,000 years BP. Percent modern carbon (pmC) values and well completion depths appear to be related. The deepest location sampled, site 22 has the lowest pmC value, whereas the shallowest location sampled, site 17 has the highest pmC value. However, some concerns about the ^{14}C data exist. The original $\delta^{13}C_{DIC}$ samples were collected in vacutainers partially filled with an ammoniacal strontium chloride solution. When sample water mixed with the solution, strontium bicarbonate was precipitated. This precipitate was the material used to determine the $\delta^{13}C_{DIC}$. The ^{14}C measurements were performed on CO_2 samples prepared using water from the same sample locations and collected at the same time. However, differences in the measured $\delta^{13}C$ values are apparent. The $\delta^{13}C_{DIC}$ and $\delta^{13}C_{CO2}$ analyses were performed by different laboratories. Each laboratory has indicated that quality control practices show that the measurements obtained using their equipment are accurate. This suggest either a problem during preparation of the samples or that chemical processes occurring within the samples has changed the isotopic composition. The differences in ages are shown in Table 180 .

Table 180. Groundwater age calculations using ^{14}C.

Sample ID	Sample Name	$\delta^{13}C$ DIC (‰ PDB))	$\delta^{13}C$ CO_2 (‰VPDB)	^{14}C (pmC)	Age using $\delta^{13}C$ DIC (years BP)	Age using $\delta^{13}C$ CO_2 (years BP)	Age calculation method		ΔAge
							$\delta^{13}C$ DIC	$\delta^{13}C$ CO_2	
1	AERI 02-01	-15.1	-14.8	-	-	-	-	-	-
17	AERI 02-18	-12.3	-10.4	93.93±0.46	503	503	1	1	0
22	AERI 02-24	17.0	19.4	<0.36	-	-	-	-	-
27	AERI 02-30	-17.4	0.3	1.09±0.07	42,377	30,833	2	3	11,544
28	AERI 02-31	-18.4	-14.8	55.98±0.30	5375	1887	2	2	3488
Notes:									
1 = Uncorrected									
2 = Correction for matrix exchange of carbonate (Fontes and Garnier, 1979)									
3 = Correction for matrix exchange of carbonate (Fontes and Garnier, 1979) and methanogenesis (Clark and Fritz, 1997, p. 221)									

In addition, the $\delta^{13}C$ values indicate the possibility that some of the DIC, in particular from sample 22 and possibly sample 27 (based on the $\delta^{13}C_{CO2}$ value), was derived from a biogenic process. The most likely source of carbon for the biogenic process would be the geological material, which may older than the ^{14}C method can date. If this carbon is mixed with the original groundwater DIC incorporated during recharge, the possibility exists that the water age could be skewed toward older ages. Although the general conclusion that relative ages increase with depth remains true, the absolute ages are questionable.

3.9.2 Groundwater age – ^{36}Cl

Chlorine-36 has a half-life of 301,000 years and is used as a tool for dating groundwater of Quaternary and latest Tertiary age. Chlorine-36 is also used in studies of groundwater recharge, groundwater infiltration and in the determination of rates of erosion (Clark and Fritz, 1997, p. 231). Groundwater dating using ^{36}Cl is based on two fundamental methods: 1) decay of cosmogenic and epigenic ^{36}Cl over long periods of time in the subsurface; or 2) in growth of hypogenic ^{36}Cl produced radiogenically in the subsurface (Clark and Fritz, 1997, p. 231). An essential parameter is the initial concentration of ^{36}Cl in groundwater recharge. Very old groundwater often gains Cl^- and ^{36}Cl by diffusion from the aquifer matrix of adjacent aquitards and therefore, the ^{36}Cl ages are of the chloride and not of the water (Clark and Fritz, 1997, p. 237). The effect on age of mixing or diffusion does not depend on the mixing rate, but rather on the ratio of fluid volume in aquitards to aquifers (Bethke and Johnson, 2002a). This requires a better understanding of groundwater flow and transport. This idea has been put forward in recent publications by Bethke and Johnson (2002a, 2002b), Park and Bethke (2002) and Goode (1996). In these papers, the authors advocate the use of groundwater flow models and the introduction of reactive transport principles to better explain the age of groundwater. These ideas may signal a new approach to dating, one that focuses less on the results of radiogenic isotope analysis and more on groundwater flow and transport principles.

Four mixed coal/sandstone aquifer water samples (1, 17, 22 and 27) and a sandstone aquifer water sample (28) were submitted for analysis. The results are presented in Table 181 below. Sample locations can be found on Figure 13, Figure 17 and Figure 21.

Table 181. Summary table of ^{36}Cl results.

Sample ID	Sample Name	Formation	Aquifer Type	Cl by NAA (ppm)	Cl by FCM (mg/L)	^{36}Cl/Cl (10^{-15})
1	AERI 02-01	Horseshoe Canyon	Mixed	28	33.6	362±18
17	AERI 02-18	Belly River	Mixed	2.8	3	2160±80
22	AERI 02-24	Paskapoo / Scollard	Mixed	379	425	0±5.3
27	AERI 02-30	Belly River	Mixed	1600	1990	0±3.5
28	AERI 02-31	Horseshoe Canyon	Sandstone	122	135	4.9±5.7
Abbreviations: NAA, Neutron Activation Analysis; FCM, Ferricyanide Method						

3.9.2.1 Preliminary Interpretations – ^{36}Cl

The radioactive decay of ^{36}Cl can be used to estimate the length of time water has been isolated from the atmosphere. In order to determine this groundwater age, the history of the chloride in groundwater must be known along with some of the characteristics of the aquifer. The groundwater age is derived from the equation:

$$t = (1/\lambda^{36}\mathrm{Cl}) \times \ln[A_t(R_t-R_{se})/A_o(R_o-R_{se})]$$

Where: λ^{36}Cl is the ^{36}Cl decay constant of 2.303×10^{-6} in years^{-1}

A_t is the measured Cl concentration in atoms/L

R_t is the measured ^{36}Cl/Cl value

R_{se} is the ^{36}Cl/Cl value at secular equilibrium

A_o is the initial Cl concentration in atoms/L

R_o is the initial ^{36}Cl/Cl value

Values for A_t and R_t are measured and λ^{36}Cl is known. The remaining parameters must be determined through measurement, assumption or calculation. Davis et al. (1998b) propose methods for determining the initial concentration of ^{36}Cl in groundwater. The possible methods appear to be applicable to determining the initial ^{36}Cl/Cl values as well as the A_o values. Davis et al. (1998b) propose that the ^{36}Cl values can be determined by: 1) measuring the values in present-day precipitation and assuming no anthropogenic input; 2) measuring the values of shallow groundwater and assuming that the water retains a record of the initial values; 3) determining the values from desert soil profiles; and 4) measuring the values from ice cores. Davis et al. (1998b) go on to state however that all the methods have serious weaknesses.

A literature search has not turned up any information on ^{36}Cl concentrations in precipitation, desert soil profiles or ice cores in the Alberta Basin. However, some of the samples may be representative of shallow groundwater. Davis et al. (1998b) suggest that groundwater used for the purpose of establishing an initial ^{36}Cl/Cl ratio should be older than 50 years but less than 12,000 years old, should have a chloride concentration less than 10 mg/L and should have a Cl/Br ratio between 80 and 160, which is typical of precipitation. Sample 17 is the only sample that meets all of these criteria. Of concern however is the high ^{36}Cl/Cl ratio. Global fallout ^{36}Cl/Cl values reported by Davis et al. (2000) are 16,200 and 6600.

The secular equilibrium ratio is a function of the physical properties of the aquifer such as porosity and bulk density, as well as epigenic and hypogenic properties of the aquifer such as rate of spallation production and neutron flux. These properties will vary spatially. Such information on aquifers within the Alberta Basin is not available. An additional complicating factor is described by Clark and Fritz (1997, p. 237). They state that, “groundwaters often gain Cl^- and ^{36}Cl by diffusion from the aquifer matrix or adjacent aquitards. In such cases, the ^{36}Cl ages are then of the chloride, and not the water.” Clark and Fritz (1997, p. 237) go on to state that ages can only be calculated, “if decay of an established cosmogenic signal can be measured, and/or subsurface in-growth of ^{36}Cl from the recharge environment can be determined.” Based on this lack of knowledge, estimates of ages will not be calculated. Although absolute ages cannot be calculated based on the available information, certain general statements about relative ages can be made.

In comparison with water associated with coalbed methane collected by G.T. Snyder (pers comm., 2003) from the Fruitland Formation in the United States, the $^{36}Cl/Cl$ and Cl concentration values of samples 1 and 17 fall toward the meteoric end member. Samples 22, 27 and 28 however, fall toward the formation water end member. G.T. Snyder (pers comm., 2003) suggested that based on chloride concentrations and $^{36}Cl/Cl$ values that samples 1 and 17 are likely recent meteoric water samples, whereas samples 22, 27 and 28 could be “recent preanthropogenic water” that can be as old as 2 Ma. However, caution must be exercised since samples with high chloride concentrations can have a mineral source of chloride that will affect the $^{36}Cl/Cl$ ratio by decreasing it, sometimes below detection limits (D. Elmore, pers comm., 2003). Inspection of the Cl/Br ratio, useful in determining the source of Cl, reveals that sample 28 Cl concentrations appear to be affected by water mixing with another Cl source, likely skewing the $^{36}Cl/Cl$ ratio. In this case, the ^{14}C age is likely more accurate.

3.9.3 Groundwater age – ^{129}I

Iodine comes almost exclusively from organic matter in sedimentary basins and has been used as a source indicator for hydrocarbons (Moran, 1996). Iodine has one long-lived naturally occurring isotope, ^{129}I (half life = 15.7 Ma) and one stable isotope ^{127}I. Iodine-129 can be used to study hydrologic and geological processes on time scales up to 100 My (Fabryka-Martin et al., 1985). Iodine-129 is produced by cosmic radiation in the upper atmosphere, as a consequence of weapons testing during the 1950s and 1960s, by activities at nuclear facilities, and through in situ uranium fission. Pre-bomb $^{129}I/I$ ratios should have been constant in time and space and is the starting value in groundwater recharge (Fabryka-Martin et al., 1985). Subsequent ratio changes in groundwater should be determined by isotope contribution from three sources: recharge water, iodine leached from the formation, and in situ uranium fission (Fabryka-Martin et al., 1985).

Four mixed coal/sandstone aquifer water samples (1, 17, 22 and 27) and a sandstone aquifer water sample (28) were submitted for analysis. The results are presented in Table 182 below. Sample locations can be found in Figure 13, Figure 17 and Figure 21.

Table 182. Summary table of ^{129}I results.

Sample ID	Sample Name	Formation	Aquifer Type	^{129}I (10^6 a/L)	I (ppm)	$^{129}I/I$ (10^{-15})
1	AERI 02-01	Horseshoe Canyon	Mixed Coal/Sandstone	na	0.19	na
17	AERI 02-18	Belly River	Mixed Coal/Sandstone	75.5 ± 2	<0.007	na
22	AERI 02-24	Paskapoo-Scollard	Mixed Coal/Sandstone	10.6 ± 0.9	0.82	2724
27	AERI 02-30	Belly River	Mixed Coal/Sandstone	1.8 ± 0.2	6.3	60.2
28	AERI 02-31	Horseshoe Canyon	Sandstone	4.3 ± 0.3	<0.022	na

3.9.3.1 Preliminary Interpretations – ^{129}I

Sample 22 has a Na-Cl-HCO_3 water type. This water type is characteristic of water that has undergone significant geochemical changes and is not indicative of water derived directly from recharge. The TDS value is 1260 mg/L and indicates that the water within the aquifer penetrated by this well is still fresh.

Fabryka-Martin et al., (1985) present the results of a case study where ^{129}I/I values of 7100, 640, 1300 and 920 x 10^{-15} were determined for water samples collected from aquifers within the Jurassic-Cretaceous sequence in the Great Artesian Basin, Australia. Based on these values, Fabryka-Martin et al. (1985) concluded that a subsurface source of iodine was present. The high value of ^{129}I/I in the Paskapoo/Scollard mixed coal/sandstone aquifer water sample may indicate that a subsurface source of iodine is also responsible for this observed value. Fabryka-Martin et al. (1985) proposed two mechanisms for the introduction of ^{129}I into the water. The first possible source is the sediments themselves. The sequence contains interbeds of carbonaceous siltstone and mudstone as well as coal seams, commonly enriched in iodine as well as uranium. The second potential source postulated by Fabryka-Martin et al. (1985) was older water, more highly enriched in uranium and iodine mixing with the Jurassic-Cretaceous aquifer water along identified fault zones. No fault zones have been identified in the area of the Paskapoo-Scollard formation water sampling location. However, Landheer et al. (1982), Gentzis and Goodarzi (1995) and Pollock et al. (2002) have determined uranium concentrations in the Paskapoo/Scollard Formation coal and clastic sediments. The mean concentrations of uranium were 1.55, 3.51 and 7.12 ppm respectively. Uranium fission and iodine release could be possible mechanisms that explain the higher than expected ^{129}I/I values obtained for this water sample. The work of Snyder et al. (in press) indicates that based on the ^{129}I/I values, sample 22 is likely pre-anthropogenic water. The sample could be as old at 2 Ma (Snyder, pers. comm., 2003).

Sample 28 is completed in a sandstone aquifer less than 25 metres below ground surface. The water type determined for this water sample is Na-Ca-SO_4-HCO_3 indicating that it has undergone some geochemical transformations, but appears to retain some characteristics of the original recharge water type.

The very high ^{129}I/I ratio coupled with the below detection limit concentration of I in solution indicates one of the following: 1) this water sample was recharged by water affected by anthropogenic sources of iodine; or 2) this water sample records the fissiogenic production of ^{129}I in the subsurface; or 3) the ^{129}I concentrations are questionable.

Sample 28 is located near Edmonton (Figure 17) and is at the highest elevation of any of the samples in the area. It therefore seems plausible that it is located near a recharge area. Whether or not it is plausible for the recharge water to be enriched with ^{129}I from anthropogenic sources is still debatable, since little is known about the recharge characteristics of the Horseshoe Canyon in this part of the province.

Iodine-129 can be produced by nuclear reactions that occur in conjunction with the spontaneous fission of ^{238}U. Uranium was detected in sample 28 at a concentration of 3 ppb. Gross alpha radiation was below the detection limit of 0.2 Bq/L, but gross beta radiation was measured at 0.2 Bq/L. Fabryka-Martin et al. (1991) used fission of uranium to explain some of the observed ^{129}I/I ratios they observed in the Milk River Formation aquifer in southern Alberta. However, the concentration of uranium present in the Milk River Formation aquifer was 1000 times as great as in the water sample, and 3 times as great as in coal samples from the Horseshoe Canyon Formation (Landheer et al., 1982). Given the range of ^{129}I values presented by Fabryka-Martin of between 1.24 and 5.7 x 10^6 atoms/L and the ^{129}I/I ratio values of between 90 and 790 x 10^{-15}, it is very difficult to draw definite parallels between the Milk River Formation aquifer and the sample collected from the Horseshoe Canyon Formation.

Based on the previous discussion, the most likely source of ^{129}I in the water from the Horseshoe Canyon Formation mixed coal/sandstone aquifer water sample is recharge water enriched in ^{129}I from anthropogenic sources.

Sample 17 is completed to a depth of 15.2 metres and has a $Mg\text{-}Ca\text{-}HCO_3$ water type. This water type is indicative of a groundwater recharge environment. As with sample 28 above, the most likely explanation for the elevated ^{129}I and $^{129}I/I$ values is the recharge of the aquifer with water high in ^{129}I, likely derived from anthropogenic sources.

Sample 27 on the other hand has a Na-Cl water type. This water type is characteristic of water that has undergone the complete range of geochemical changes. The TDS value is 3610 mg/L, the highest TDS observed during water sampling. This sample also has the highest iodine concentration observed.

Values reported by Fabryka-Martin et al. (1991) for $^{129}I/I$ ratios in the Upper Cretaceous Milk River Formation aquifer in southern Alberta indicate that recharge has a $^{129}I/I$ ratio of between $165 \pm 50 \times 10^{-15}$ and $1130 \pm 70 \times 10^{-15}$. The remaining values calculated for water samples collected from locations farther downgradient were between $90 \pm 30 \times 10^{-15}$ and $790 \pm 10 \times 10^{-15}$. The value reported for sample 27 falls within this range of downgradient values reported by Fabryka-Martin et al. (1991). Fabryka-Martin et al. (1985) indicate that older groundwater should gradually take on the isotope characteristics of the formation with which it is associated. The $^{129}I/I$ value of sample 27 therefore likely reflects the $^{129}I/I$ value of the Belly River Group. The Belly River Group was deposited between approximately 83.5 and 80 Ma.

The general formula used to calculate age based on $^{129}I/I$ values is given by Snyder et al. (in press) as:

$$R_{obs} = R_i e^{-\lambda t}$$

Where: R_{obs} is the observed $^{129}I/I$ ratio
R_i is the initial marine $^{129}I/I$ value of 1500×10^{-15}
λ is the decay constant of ^{129}I of 4.41×10^{-8} years^{-1}
t is the time elapsed since the sample was removed from surface reservoirs

Rearranged, the equation becomes:

$$t = -1/\lambda \times \ln(R_{obs}/R_i)$$

The age calculated for sample 27 is 73 Ma and is consistent with the information presented by Snyder et al. (in press). This age differs significantly from the age calculated from the ^{14}C data however. Lending support to the $^{129}I/I$ calculated age is the very low reported value for $^{36}Cl/Cl$. If the water is approximately 73 Ma, then all original ^{36}Cl would have decayed. The reported value of $^{36}Cl/Cl$ for sample 27 is 0. The ^{129}I analysis report indicates that two process blanks were prepared and that the ^{129}I concentrations in these blanks were $1.6 \pm 0.3 \times 10^6$ atoms/L and $2.8 \pm 0.2 \times 10^6$ atoms/L. These values are said to represent an upper limit of the ^{129}I level introduced during the sample preparation procedure. The reported ^{129}I value for sample 27 is $1.8 \pm 0.2 \times 10^6$ atoms/L. The possibility of a contaminated result must therefore be considered.

Once the role of: 1) sample preparation; 2) mixing of recharge with connate water; 3) leaching of I from the rock matrix; and 4) fissiogenic contribution of ^{129}I on the $^{129}I/I$ ratio are better understood, it may be possible to better calculate an apparent age for water moving through the various mixed coal-sandstone and sandstone aquifers within the Alberta Plains.

4 Physical Hydrogeology

Physical hydrogeology is concerned with understanding fluid flow through porous media. This broad goal is reached through the definition of the physical properties of aquifer material and fluids within the aquifer, by defining fluid-flow equations and by constructing conceptual and numerical models of flow systems. The information used to understand these properties, to define these equations and to construct these models is obtained by a combination of field determinations, laboratory analysis and mathematical description.

The flow of fluid through porous media has been mathematically described through the work of many researchers. These equations allow for the construction of conceptual and numerical models that can be used to describe fluid flow. The properties of the aquifer materials can be calculated or determined 1) through the capture of field information such as hydraulic head, 2) the use of these equations during field investigations, or 3) the use of laboratory analysis of aquifer material. Although laboratory analysis of aquifer material is possible, core material can be difficult and expensive to collect. Therefore, one of the most common methods of determining aquifer properties is by conducting aquifer or pumping tests. A pumping test involves withdrawing water from a well at a constant rate and measuring the water level within the well, and/or adjacent observation wells, over a predetermined period of time.

Once the pumping test is complete, the pump-test data can be analyzed to determine aquifer properties. This generally involves plotting the data and using type-curve matching or straight-line techniques to determine the associated aquifer characteristics. Type-curve analysis is not normally used for quantitative analysis of the pumped well, since part of the drawdown or recovery water-level response within the stress well is associated with well and/or formation inefficiencies, or damage induced by the drilling process (Spane and Wurstner, 1993). The straight-line solutions represent an approximation of the general equation describing radial flow to the well, and are valid only after a specified period of time and after infinite-acting, radial-flow conditions have been established (Spane and Wurstner, 1993). These techniques can be insensitive to small changes in water level over the testing time, leading to errors in interpretation and therefore to potential error in the determination of aquifer characteristics.

The reasons for performing well-test analysis are summarized by Bourdet (2002, p. 2):

> Well test analysis provides information on the reservoir and on the well. Geological, geophysical and petrophysical information is used where possible in conjunction with the well test information to build a reservoir model for prediction of the field behaviour and fluid recovery for different operating scenarios. The quality of the communication between the well and the reservoir indicates the possibility to improve the well productivity.
>
> Well test responses characterize the ability of the fluid to flow through the reservoir and to the well. Tests provide a description of the reservoir in dynamic conditions, as opposed to geological and log data.

The recent development of pressure-derivative methods has improved the analysis of pumping tests. The improvement in hydrological-testing analysis through the use of pressure derivatives is attributed to the sensitivity of the derivative response to small variations in the rate of pressure change that occurs during testing, which would otherwise be less obvious with standard pressure change versus time analysis (Spane and Wurstner, 1993). The sensitivity of pressure derivatives to pressure-change responses facilitates their use in identifying the presence of flow regimes within the well. According to Bourdet (2002), typical flow regimes include the

- wellbore storage flow regime;

- radial flow regime;
- heterogeneity influenced flow regime (fissured reservoir, dual porosity, layering);
- linear flow regime (infinite conductivity fractured well);
- bilinear flow regime (finite conductivity fractured well);
- spherical flow regime (well in partial penetration);
- limited-reservoir flow regime (sealing fault or faults);
- closed-reservoir flow regime; and
- constant-pressure-boundary flow regime.

Each flow regime generally has a characteristic pressure-time derivative curve shape that allows for the identification of which flow regimes are present within a given aquifer system. Details on the characteristics of pressure derivative curves, flow regimes, and their interpretation and recognition on plots can be found in Tiab and Kumar (1980), Bourdet et al. (1983a, b, 1989), Ersaghi and Woodbury (1985), Beauheim and Pickens (1986), Ehlig-Economides (1988), Mensch and Benson (1989), Spane and Wurstner (1993) and Bourdet (2002). Once the flow regime has been determined, the data can be replotted in specialized plots that yield information about the aquifer or reservoir behaviour during different portions of the test.

Both Ehlig-Economides (1988) and Ersaghi and Woodbury (1985) indicated that the pressure derivative method can, on occasion, produce results that are not unique. For example, a derivative curve response to reservoir heterogeneity can look similar to the response to a dual porosity system or the response to a fault. These authors have suggested that other sources of data, such as well logs, core data and outcrop information, be used to select the most likely model for the well site.

4.1 Previous Work

Hitchon (1969a, b) formulated the original concepts of regional groundwater flow in the Alberta Basin. He postulated that recharge in the Rocky Mountain Foothills initiated a regional topography-driven flow system that discharged along the basin margin in northeastern Alberta. This model was subsequently refined (Hitchon, 1984; Garven, 1985, 1989). These models have been called into question (Deming and Nunn, 1991; Adams et al., 2000), however, because the topography-driven flow system and model parameters used could not explain the observed water chemistry in various parts of the basin.

Current ideas on groundwater flow in the Alberta Basin suggest that flow mechanisms are different for different portions of the basin and that flow can be generalized into two megahydrostratigraphic units, the pre-Cretaceous and post-Jurassic (Bachu, 1995). In the northern part of the basin, flow within both megahydrostratigraphic units is topographically driven in local- to regional-scale flow systems with recharge originating in the Rocky Mountains and discharge flowing out of the system beneath the Quaternary cover at Great Slave Lake (Bachu, 1995). In the southern and central portions of the basin, flow within the pre-Cretaceous unit is driven by topography in a northward direction, from the recharge area in Montana to the discharge points along the Peace River (Bachu, 1995, 1999; Anfort et al., 2001). The understanding of flow in pre-Cretaceous units in the west-central portions of the basin is still problematic because of conflicting information about groundwater-flow mechanisms (Ge and Garven, 1989, 1994; Hitchon et al., 1990; Bachu, 1995, 1999; Wilkinson, 1995; Machel et al., 1996; Machel and Cavell, 1999; Underschultz and Bartlett, 1999). Michael (2002), in a focused study of the west-central portion of the Alberta Basin, suggested that three hydrostratigraphic units exist, and that each unit is subject to different internal and boundary conditions, with flow being controlled by topography, erosional rebound and tectonic expulsion to varying degrees. Fluid flow in the lower post-Jurassic megahydrostratigraphic unit in the northern portion of the basin is driven by regional- to local-scale topographic systems, whereas flow in the southern portion of the basin is affected by gas accumulations that act as barriers to flow (Thompson, 1989). Recharge of this unit is by meteoric water infiltrating permeable rocks in the Rocky Mountains (Thompson, 1989). In the central and southern portions of the basin, flow within the post-Jurassic megahydrostratigraphic unit is affected by erosional rebound in thick shale successions after the peak of the Laramide orogeny (Corbet and Bethke, 1992; Bachu, 1995; Bachu and Underschultz, 1995; Parks and Tóth, 1995; Bekele et al., 2000).

The Alberta Research Council completed a number of regional groundwater assessments throughout Alberta where coal aquifers were mentioned. These include reports by Tóth (1966), Le Breton (1971), Borneuf (1972, 1973, 1979), Ozoray (1972), Tokarsky (1974, 1977a, b), Ozoray and Lytviak (1974), Bibby (1974), Gabert (1975), Hackbarth (1975), Stevenson and Borneuf (1977), Stein (1976), Ozoray and Barnes (1978), Ceroici (1979) and Ozoray et al. (1980). In these reports, water-well yields were calculated for various areas of the Alberta Basin. These well-yield estimates were usually based on aquifer tests, although some were based on slug or bail tests and others relied on apparent transmissivity estimates. Reports by Tóth (1966), Borneuf (1972), Tokarsky (1974), Ozoray and Lytviak (1974), Gabert (1975), Stein (1976), and Ozoray and Barnes (1978) presented the results of aquifer tests for the various aquifers described in the reports.

An unpublished Alberta Research Council report by Chorley and Vogwill, entitled *Coal aquifers in Alberta – a preliminary assessment of hydraulic characteristics*, contains information on apparent and long-term aquifer tests. The conclusions of the section on hydraulic characteristics were that the hydraulic-conductivity values for coal aquifers determined from aquifer tests were variable, ranging from 0.1 to 800 m/d, with storage values between 10^{-4} and 10^{-5}. The results of the aquifer tests suggested that some coal aquifers behave as homogeneous aquifers, others appear to have barrier boundaries and a final group appears to behave as semiconfined or leaky aquifers.

Bachu and Michael (2002) described the flow systems active in coal-bearing formations of the Alberta Basin. They stated that the Upper Cretaceous–Tertiary strata of the Alberta Basin are in posterosional and postglacial rebound and, as a result, flow is driven by topography and by erosional rebound controlled by permeability barriers created by intervening shaly aquitards and gas-saturated sandstone units, resulting in several flow systems being active in the succession. Flow systems driven by topography occur in the northern, southern and upper portions of the central areas of the basin. The flow system in the deeper portions of the central area of the basin is driven by erosional rebound. Through the use of hydraulic and chemical information, Bachu and Michael (2002) proposed a hydrostratigraphy for the Alberta Basin.

4.2 Coal Aquifer Well Tests

The interpretation of coal-aquifer hydraulic properties, as noted in section 4.1, was attempted by Chorley and Vogwill (unpublished Alberta Research Council report entitled *Coal aquifers in Alberta – a preliminary assessment of hydraulic characteristics*). They utilized well-test information from 405 locations, from which apparent hydraulic conductivities were calculated using the Cooper and Jacob (1946) method. In addition, aquifer properties were determined for 45 locations where long-term aquifer tests were performed, using curve-fitting methods, including the Theis (1935), Cooper and Jacob (1946), Hantush (1956), and Walton (1960) methods. The work of Chorley and Vogwill suggests that many of the flow regimes listed previously are likely present within the coal aquifers of the Alberta Basin. In fact, they suggested that likely flow regimes within these aquifers include the radial, linear, bilinear, limited-reservoir, heterogeneity-influenced and closed-reservoir flow regimes. They did not utilize pressure-derivative methods or detailed well-test analysis, so their conclusions were speculative.

One of the goals of the current project is to better understand the hydraulic properties of Tertiary–Upper Cretaceous coal aquifers in the Alberta Basin. In the absence of deep well-testing information from current NGC development, coal-aquifer hydraulic information is only available from aquifer tests completed for well-yield determinations of domestic or industrial water wells. These records are kept in a database administered by Alberta Environment.

The first step in assessing the hydraulic properties of coal aquifers was the gathering of information. The Alberta Environment database was queried using criteria chosen to select the highest quality aquifer tests available. These criteria included the following:

- Well ≤20 years old
- Presence of a seal and check on the effectiveness of the seal
- Presence of a screened or perforated interval
- Screened or perforated interval with coal as the aquifer material
- Minimum duration of pump test is 6 hours
- Minimum number of water-level measurements is 10
- Information on wellbore, casing and screen or perforation material diameters must be available
- Pumping-rate information must be available

Applying these criteria meant that most aquifer tests conducted in coal or mixed coal-sandstone-shale aquifers were omitted. Twenty-seven aquifer tests were selected, however, including 6 from the Paskapoo-Scollard Formation, 19 from the Horseshoe Canyon Formation and 2 from the Belly River Group.

The preliminary analysis of the aquifer-test plots shows that the speculations of Chorley and Vogwill appear to be substantiated. The pressure-derivative and semilog plots appear to confirm the presence of the wellbore storage (Figure 92), radial (Figure 93), heterogeneity-influenced (Figure 94) and constant-pressure-boundary flow regimes (Figure 95) in coal aquifers of the Alberta Basin. These plots contain a number of features that will require specialized analysis in order to determine aquifer properties. The Alberta Environment well identifiers are provided, along with a formation assignment for the well, for those interested in performing additional analyses (Appendix C).

4.3 Sandstone-Aquifer Well Tests

Bachu and Michael (2002) analyzed 2068 drillstem tests (DST) and determined equivalent freshwater heads in four hydrostratigraphic units. These included the Paskapoo-Scollard unit, the Edmonton–Upper Wapiti unit, the Upper Belly River unit and the Basal Belly River unit. They did not, however, calculate aquifer characteristics from these tests.

In addition to providing information on coal-aquifer characteristics in the Alberta Basin, another goal of this project is to provide information on the various sandstone aquifers in the Tertiary–Upper Cretaceous succession of the Alberta Basin. A similar approach to that taken to define characteristics of the Tertiary–Upper Cretaceous coal aquifers in the Alberta Basin was used to define the characteristics of the Tertiary–Upper Cretaceous sandstone aquifers in the Alberta Basin.

The Alberta Environment database was again queried using criteria chosen to select the highest quality aquifer tests available. These criteria included the following:

- Well ≤20 years old
- Presence of a seal and check on the effectiveness of the seal
- Presence of a screened or perforated interval
- Screened or perforated interval with sandstone as the aquifer material
- Minimum duration of the pump test is 6 hours
- Minimum number of water-level measurements is 10
- Information on wellbore, casing and screen or perforation material diameters must be available
- Pumping-rate information must be available

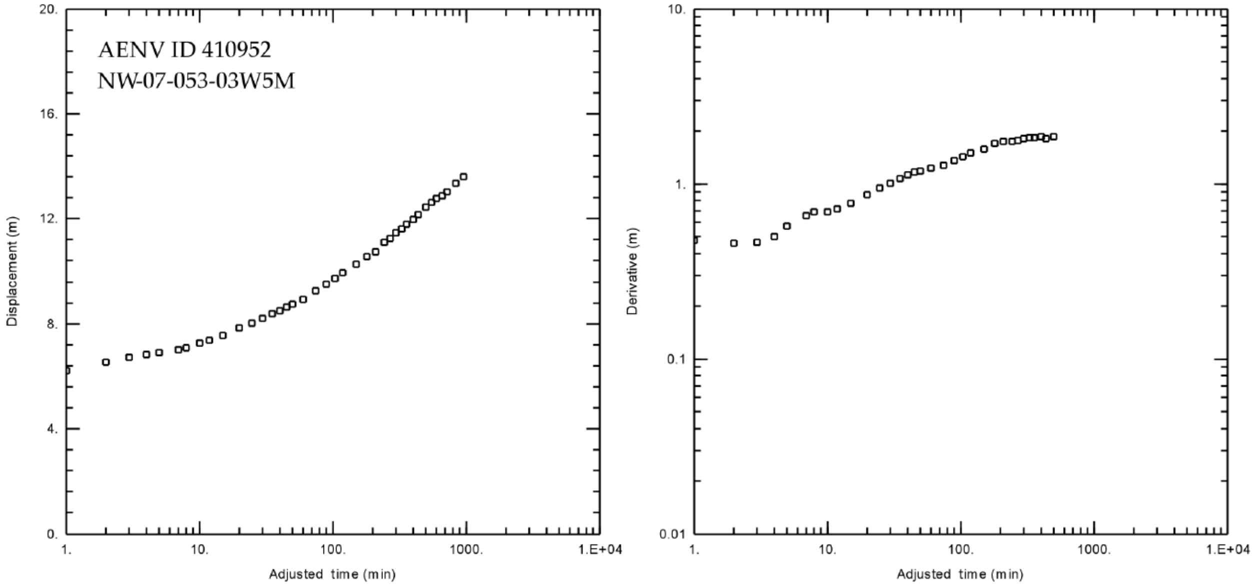


Figure 92. Example of the well storage flow regime in a coal aquifer well test. Abbreviation: AENV, Alberta Environment.

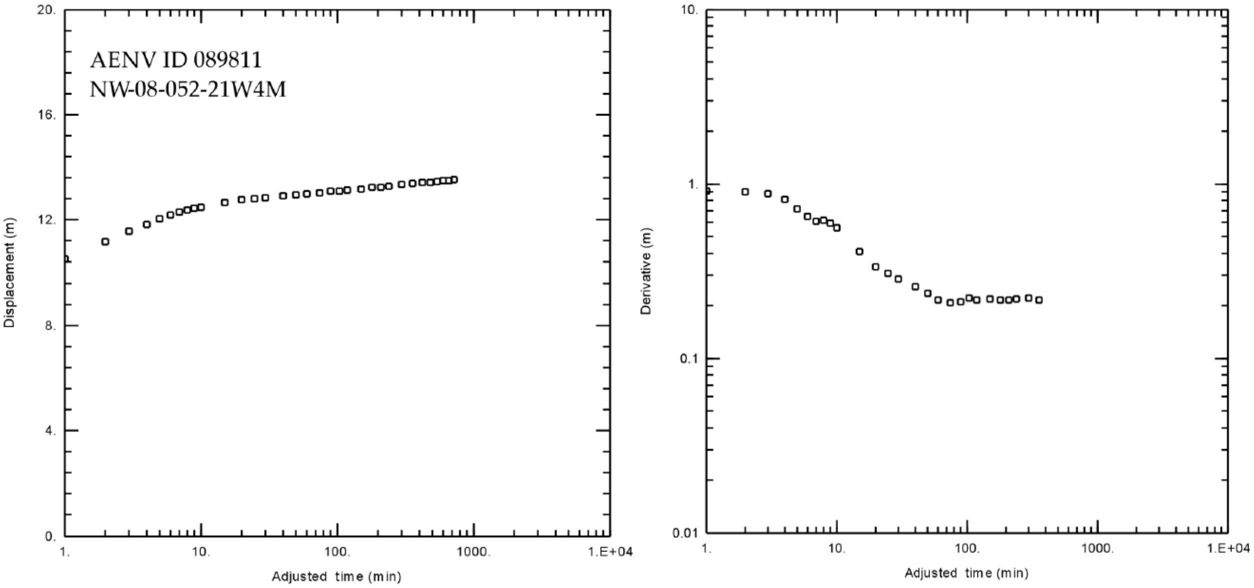


Figure 93. Example of the radial flow regime in a coal aquifer well test. Abbreviation: AENV, Alberta Environment.

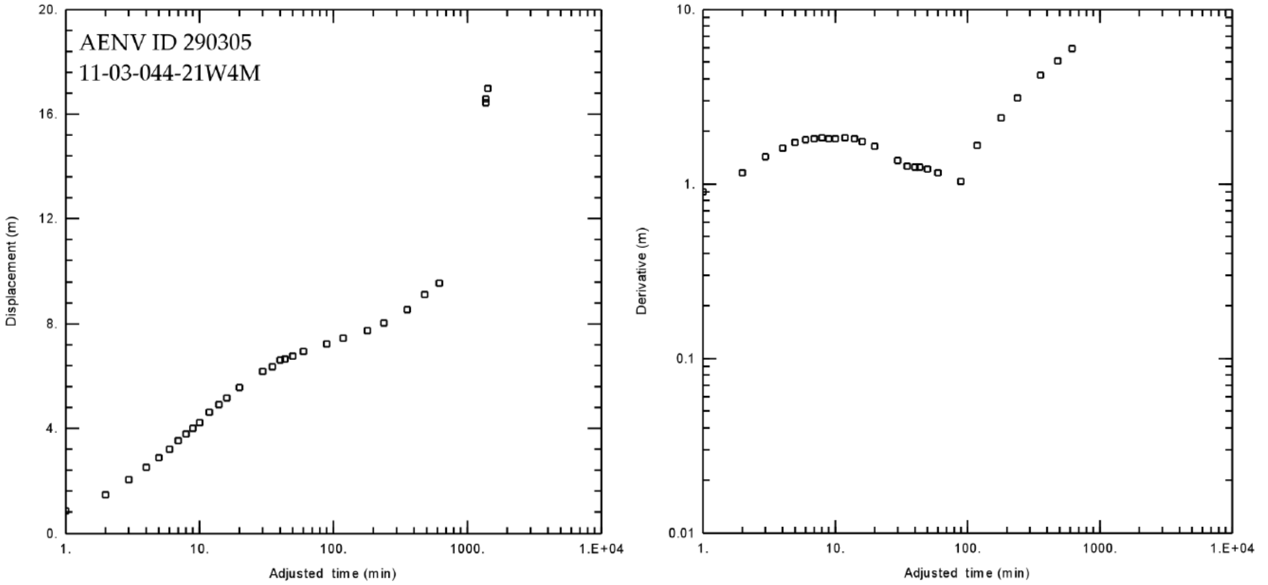


Figure 94. Example of the heterogeneity-influenced flow regime in a coal aquifer well test. Abbreviation: AENV, Alberta Environment.

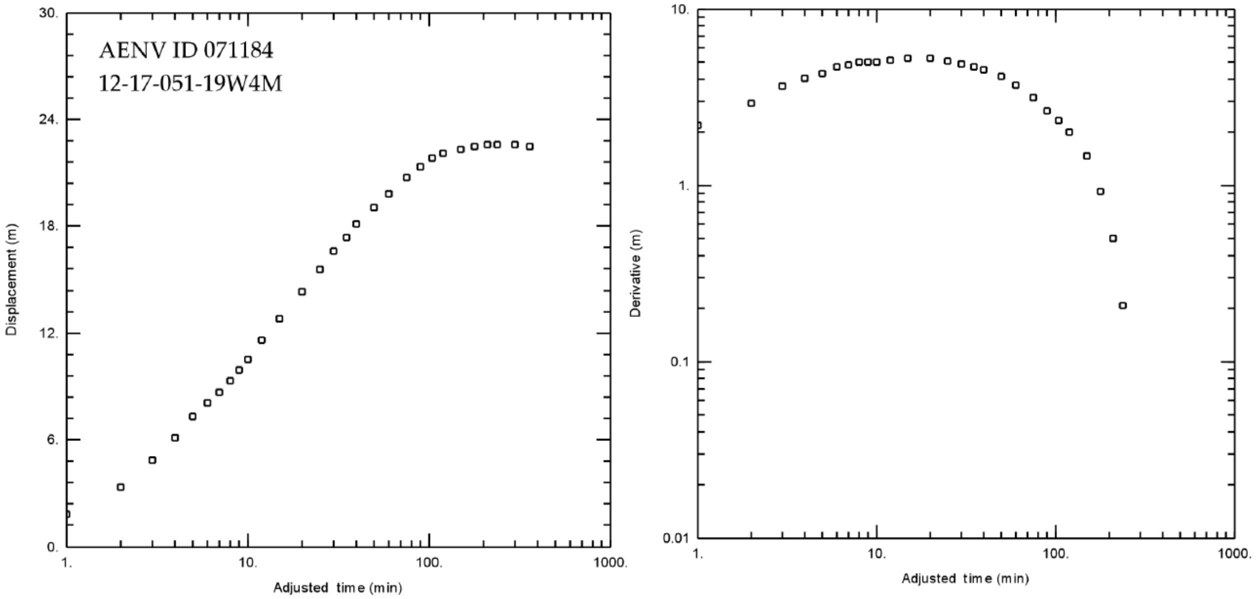


Figure 95. Example of the constant pressbounday flow regime in a coal aquifer well test. Abbreviation: AENV, Alberta Environment.

Five hundred and six aquifer tests appear to have been conducted in the Paskapoo-Scollard unit; 26 test appear to have been conducted in the Edmonton–Upper Wapiti unit; and 31 appear to have been conducted in the Upper Belly River unit.

Most of the tests are conducted across a number of sandstone and shale intervals. As such, the aquifer tests appear to indicate the contribution of groundwater from these multiple intervals. The pressure-derivative and semilog plots of the sandstone aquifer tests appear to indicate the presence of the wellbore storage (Figure 96), radial (Figure 97), heterogeneity-influenced (Figure 98), constant-pressure-boundary (Figure 99) and closed-reservoir flow regimes. Specialized analysis is necessary to determine precise aquifer properties. The Alberta Environment well identifiers are provided, along with a formation assignment for the well, for those interested in performing additional analyses (Appendix C).

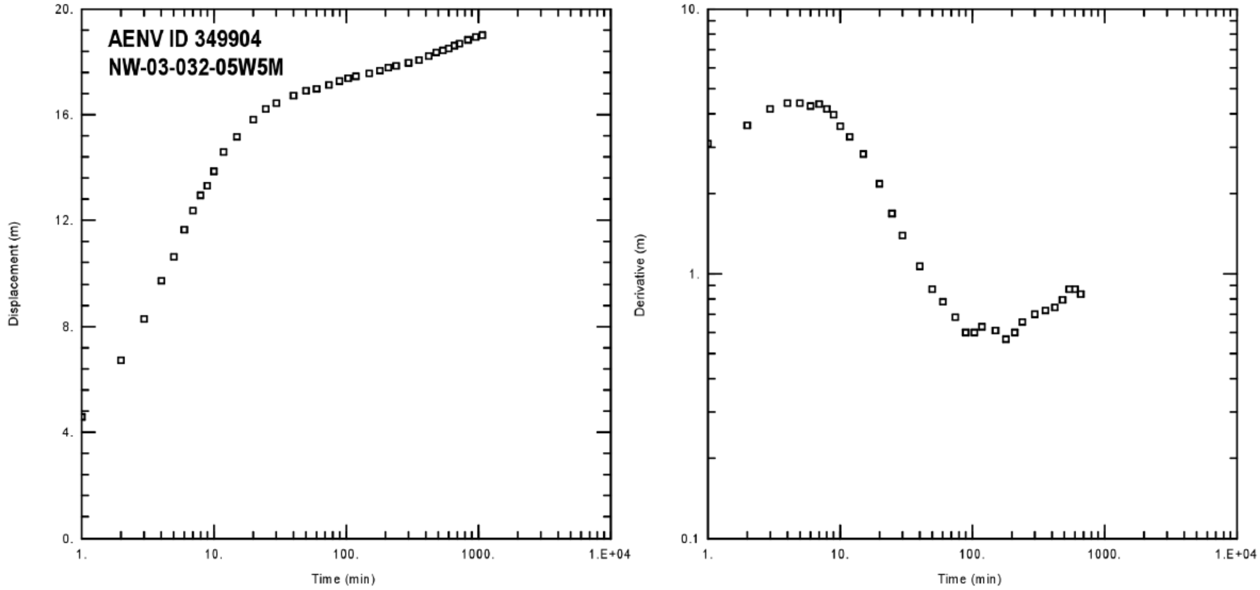


Figure 96. Example of the well storage flow regime in a sandstone aquifer well test. Abbreviation: AENV, Alberta

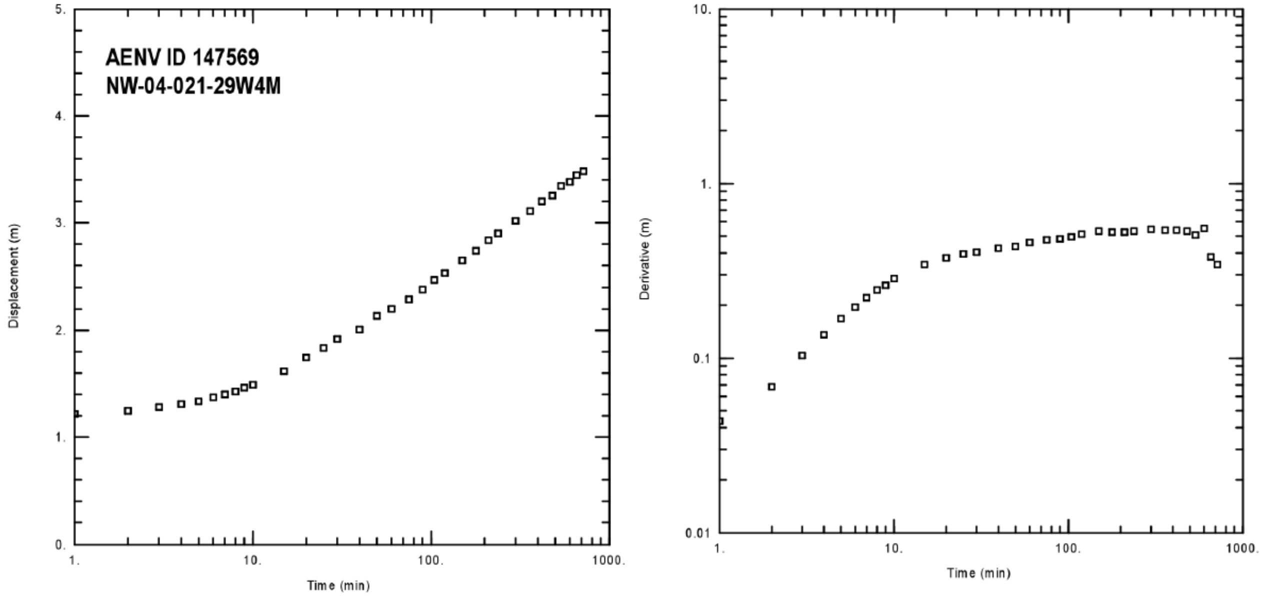


Figure 97. Example of the radial flow regime in a sandstone aquifer well test. Abbreviation: AENV, Alberta Environment.

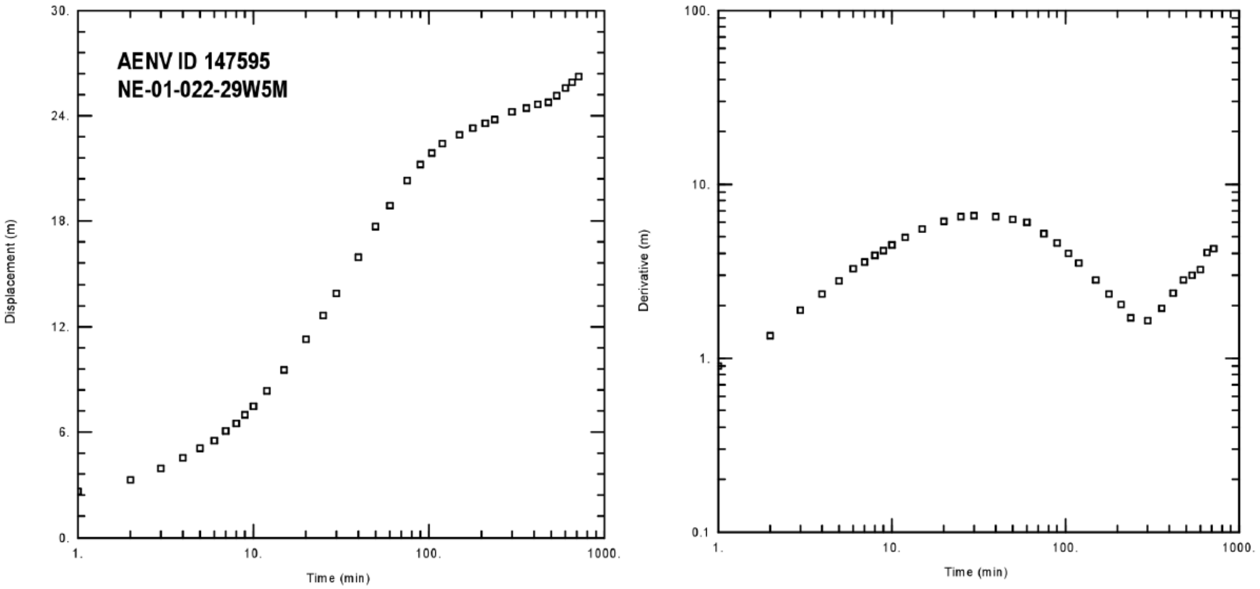


Figure 98. Example of the heterogeneity-influenced flow regime in a sandstone aquifer well test. Abbreviation: AENV, Alberta Environment.

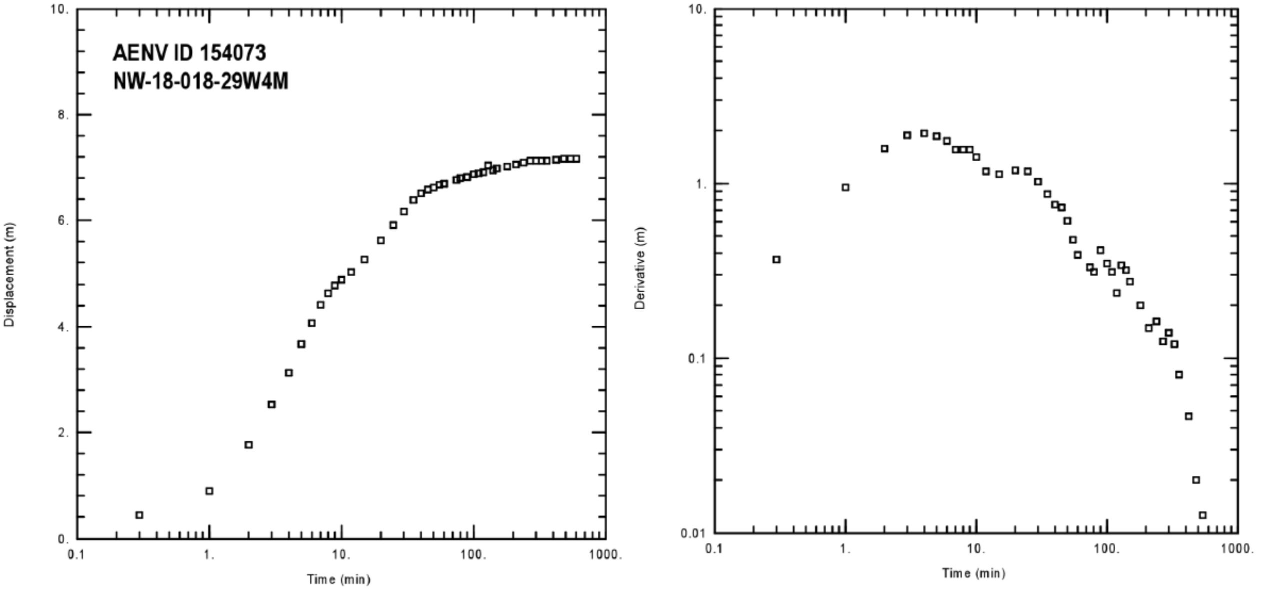


Figure 99. Example of the constant pressure boundary flow regime in a sandstone aquifer well test. Abbreviation: AENV, Alberta Environment.

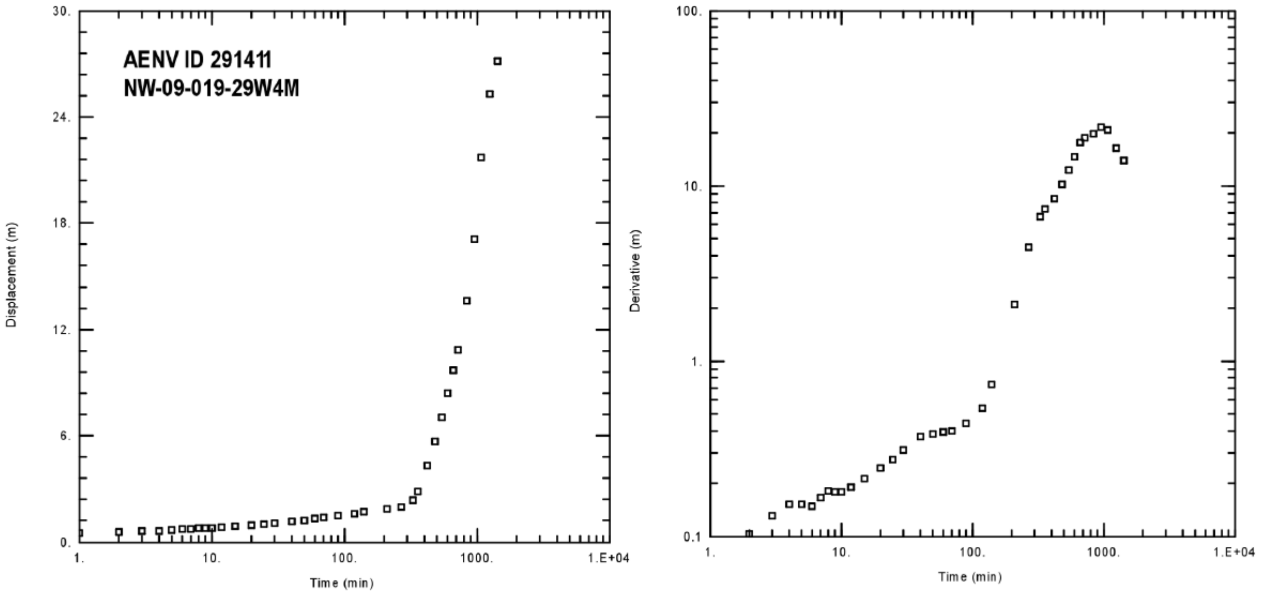


Figure 100. Example of the closed reservoir flow regime in a sandstone aquifer well test. Abbreviation: AENV, Alberta Environment.

5 Conclusions

Water samples were collected from 44 wells completed in coal, mixed coal-sandstone or sandstone aquifers from the Paskapoo-Scollard Formation, the Horseshoe Canyon Formation and the Belly River Group. These samples were analyzed for major-, minor- and trace-element composition, stable-isotope composition, radiogenic-isotope composition, and physical parameters, such as pH, Eh, conductivity, dissolved oxygen, temperature and alkalinity.

The following parameters may exceed Canadian water quality guidelines:.

Paskapoo-Scollard Formation

- Aesthetic objectives for pH (1 of 7 samples), sodium (4 of 7), manganese (3 of 7), chloride (1 of 7) and total dissolved solids (TDS; 4 of 7)
- Irrigation-water quality values for sodium adsorption ratio (SAR; 4 of 7) and chromium (2 of 7)

Horseshoe Canyon Formation

- Aesthetic objectives for pH (2 of 21 samples), sodium (20 of 21), sulphate (7 of 21), chloride (2 of 21), manganese (4 of 21) and TDS (20 of 21)
- Irrigation-water quality values for SAR (18 of 21) and chromium (13 of 21)
- Livestock-water quality values for total phenols and sulphate (1 of 21)

Belly River Group

- Aesthetic objectives for pH (6 of 16 samples), chloride (2 of 16), sulphate (1 of 16), sodium (13 of 16), manganese (5 of 16) and TDS (14 of 16)
- Irrigation-water quality values for SAR (11 of 16), chromium (4 of 16) and boron (9 of 16)

- Livestock-water quality values for arsenic (1 of 16), total phenols (2 of 16) and TDS (1 of 16)
- Interim maximum acceptable concentrations for human consumption for arsenic (1 of 16)

The analyses indicate that the chemical compositions of water samples from these various aquifers are controlled by their position along the recharge-discharge flow path, by water-rock interaction, mineral precipitation and biological processes. Samples collected near recharge zones have a characteristic Ca-Mg-HCO_3 water type, whereas samples collected from farther along the groundwater-flow path have Na-HCO_3, Na-HCO_3-SO_4, Na-SO_4-HCO_3, Na-HCO_3-Cl, Na-Cl-HCO_3 and Na-Cl water types. The evolution in the major cation from Ca to Na is likely related to two processes: ion exchange on mineral surfaces and carbonate mineral precipitation. The dominant anion in solution is bicarbonate. In some instances, however, other anions become more dominant. In the case of SO_4 dominance, processes such as evaporite mineral dissolution or sulphide oxidation are likely introducing the additional sulphate. Where Cl is the dominant anion in solution, sampling of deeper formation water is likely. The presence or absence of the other major, minor and trace elements is controlled by the presence or absence of minerals containing the various elements, the pH and Eh conditions, the adsorption potential of the aquifer matrix, the presence or absence of complexing compounds in solution, and possibly by the presence or absence of micro-organisms capable or mobilizing, or retarding, various elements.

Chloride/bromide ratios, stable-isotope ratios of O and H, and $^{87}Sr/^{86}Sr$ ratios indicate that mixing reactions are occurring within the various aquifers and that perhaps similar mixing reactions with similar end members are occurring within the entire Tertiary–Upper Cretaceous succession. Chloride/bromide ratios are similar for the Paskapoo-Scollard Formation, Horseshoe Canyon Formation and Belly River Group. The deepest Paskapoo-Scollard Formation and Belly River Group wells plot close to the seawater point on Cl/Br vs. Cl plots, whereas the shallower wells plot close to values determined for atmospheric precipitation. Most of the other samples fall on a straight or somewhat curvilinear line between the two potential end members. Oxygen and hydrogen stable-isotope ratios for all three groups of samples plot along regression lines defined by very similar equations. The line is similar to a regression line calculated between oxygen and hydrogen isotope values for Alberta precipitation and those of formation-water samples collected from the Belly River Group in deeper parts of the Alberta Basin. Strontium-isotope ratios for the water samples fall within four groups, with the samples interpreted as being most like recharge or meteoric water having the highest ratios and those interpreted as being most like deeper formation water having lower values. The data appear to support the idea that the composition of the various aquifer water samples are controlled by similar mixing processes between end members of similar compositions, despite the presence of confining layers between the aquifer units.

There is evidence to support the idea that biological processes are affecting water chemistry. Carbon stable-isotope compositions of dissolved inorganic carbon indicate that biological processes have occurred. Enrichment in the $^{13}C_{DIC}$ was noted in a number of samples. This effect was likely produced through a series of bacterially mediated reactions capable of yielding methane and CO_2 as products. Gas evolution was observed during sampling of a number of water wells, lending further support to the idea of biogenic gas generation in some of these wells. The carbon stable-isotope ratios also point to processes such as carbonate dissolution and soil CO_2 dissolution as being important within the aquifers.

Sulphur stable-isotope ratios provide additional evidence of biological processes occurring within the various aquifers. Stable isotopes in the sulphate and sulphide fractions of the water samples indicate the possibility of bacterial processes such as sulphate reduction and sulphide oxidation. The $\delta^{34}S$ and $\Delta\delta^{34}S$ values of some of the samples are consistent with the values obtained by other researchers for processes attributed to bacterial action. Other processes that might be responsible for some of the observed sulphur stable-isotope compositions include evaporite-mineral dissolution, contribution of atmospherically derived sulphate, and sulphide oxidation without bacterial mediation.

Boron isotopes appear to suggest that mixing processes between formation water and meteoric water end members is occurring in all three geological intervals sampled. The samples involved in some of these mixing relationships are located along linear trends or form spatial clusters. There is also evidence to suggest the $\delta^{11}B$ fractionation reactions are controlled by the solution pH. Boron concentration appears to be buffered by adsorption to aquifer and aquitard materials.

Radionuclides were detected in water samples from all three geological intervals. These included ^{238}U and ^{232}Th. Other researchers have also detected these parent radionuclides in coal samples. Daughter radionuclides, such as ^{226}Ra and ^{210}Po, were also detected. Initial examination of the data suggests the possibility that the presence of ^{210}Po in solution may be related to microbial activity.

Analyses of pump-test information also indicate a complex environment. Semilog and derivative plots reveal the presence of radial, heterogeneity-influenced, constant–pressure-boundary and closed-reservoir flow regimes within the coal and sandstone aquifers of the Alberta Plains region. More detailed analyses of the pump tests should provide valuable insight into aquifer and aquitard properties and fluid-flow characteristics of these rock bodies.

Future work should focus on obtaining chemistry and aquifer-property information from coalbed-methane exploration and development wells completed in deeper portions of the Alberta Basin. Integration of the information from these deeper wells with that from shallower wells will enable better exploration and development strategies, better mitigation and water-disposal strategies, and provide information from which a better understanding of gas generation and migration within these unconventional gas reservoirs can be obtained.

6 Recommendations

Water sampling of coal, mixed coal-sandstone and sandstone aquifers during the late summer and fall of 2002 resulted in the compilation of an extensive water-chemistry dataset. These samples were collected from three different coal-bearing geological units throughout the Alberta Plains region of Alberta. The well depths were between 15.2 m and 193.3 m and were generally less than 60 m.

The sampling program has helped characterize the water chemistry of these geological units in the shallow portion of the basin, providing an important dataset that will be used to guide coalbed methane development strategies in the province. However, certain questions still remain about the water chemistry and groundwater flow in these aquifers. Further study is recommended in order to assess the following:

Seasonal variation of water chemistry

Water sampling was conducted in the late summer and fall. In addition, drought conditions had been affecting the province for some time. Since water chemistry can vary seasonally, an assessment of this variation could reveal seasonal trends and potentially the effects of drought conditions on coal, mixed coal-sandstone and sandstone aquifer water chemistry. These variations are significant if they change element concentrations to levels that exceed environmental guideline values, or conversely reduce concentration values that previously exceeded environmental guideline values. These seasonal variations may suggest different strategies for dealing with produced water throughout the production year. The seasonal information also provides a baseline dataset against which future measurements could be compared.

Presence of anomalous concentrations

Some values exceeded environmental guideline values. The confirmation of these exceedences would identify elements and compounds of concern within these aquifer systems.

Presence of dissolved gas in water

Field observations noted the presence of gas in water. Hydrogen sulphide was detected by its characteristic odour whereas other gases were observed at other locations, but no hydrogen sulphide scent was detected. In addition, conversations with well owners revealed the location of other wells where gas had been observed. These observations indicate the existence of gas in shallow coal seams. What these observations do not do is conclusively identify the gas, or the concentration of gas, or the source of the gas in solution. A sampling program designed to collect samples for dissolved gas analysis would identify and quantify the gases in solution, as well as provide information on the nature and origin of the gases. Certain gases are radiogenic and, if present, could potentially reveal information on groundwater age.

Presence of radionuclides in water

There are health risks associated with the accumulation of radionuclides in produced water products, such as scale and sludge. Radionuclides, such as U, Th, Ra and Po, were detected in water samples from the coal, mixed coal-sandstone and sandstone aquifers sampled during this study. However, in order to make the best use of financial resources, the samples submitted were based on measured gross alpha and gross beta radioactivity measurements. Those samples where gross alpha and gross beta radioactivity were detected were submitted for additional radionuclide specific analyses. Once these analyses were received, the widespread presence of ^{226}Ra suggested most samples will contain this radionuclide. The presence of U, Th and Po in some of the same samples indicates some complicated parent-daughter relationships within these aquifer units. Additional sampling would better characterize the concentration of radionuclides in water allowing for a better understanding of issues surrounding water production and potentially issues of mineral dissolution and water-rock interaction.

Presence of micro-organisms

The activity of micro-organisms has been proposed as one possible mechanism for producing methane within coal seams. As mentioned previously, the presence of gas was observed during water sampling. Some of this gas may have been generated by micro-organisms. Isotopes of carbon and sulphur suggest that processes such as methanogenesis, bacterial sulphate reduction and potentially bacterial sulphide oxidation are occurring. Relationships between concentrations of ^{210}Po and sulphate also point to bacterial activity, as do relationships between isotopic compositions and concentrations of bicarbonate and sulphate in solution. Additional research should focus specifically on the determination of the role micro-organisms play in the generation of gases in aquifers by identifying the biological communities present within the aquifers, defining the roles of the various micro-organisms within the communities, calculating rates of gas production, and documenting the limiting factors of biological production of gases in coal seams.

Development of more accurate groundwater age models

Groundwater age is among the most fundamental parameters describing subsurface flow and is the conceptual link between flow modelling and radiometric dating (Bethke and Johnson, 2002a). With this information, calculations can be performed to determine sustainable yields of aquifers, groundwater flow velocities and, therefore, more accurate representations of groundwater flow. The sampling program was designed to test sampling methods, assess the feasibility of conducting water sampling for groundwater age determinations in coal, mixed coal-sandstone and sandstone aquifers, compare the results of different radiogenic isotope dating techniques, as well as to calculate groundwater ages for water within distinct portions of the various flow regimes. With a limited number of samples, definitive conclusions could not be drawn regarding flow regimes within the shallow portion of the Alberta Basin. However, certain general statements were made. Accurate determinations of groundwater age require an understanding of groundwater flow, water-rock interactions, rates of radionuclide production in the subsurface, as well as an understanding of initial concentrations of radionuclides in recharge water. Additional work should be undertaken to develop an understanding of these groundwater age components to understand the characteristics of these aquifers and ensure their sustainability and response to development.

Water-rock interaction

Water chemistry is controlled by the initial composition of the water and its subsequent interaction with other geological materials. Some of the most important reactions occur between the water and the aquifers and aquitards the water comes into contact with. An understanding of the rock chemistry and mineralogy can help to clarify the composition of water within that geological interval, and predict the effects on water chemistry of flow within that interval. A similar baseline sampling-program of aquifer and aquitard material would provide valuable information on the nature and extent of reactions between water and material it has come into contact with.

Water chemistry from deeper portions of the basin

Coalbed methane development will target coal seams at depths greater than 200 m. Water sampling as part of this project targeted the shallower portion of the basin. Analysis of the oxygen, hydrogen and Cl isotopic data suggests that water in these shallower portions is a product of mixing between meteoric water and formation water. Although the composition of the deeper basin water potentially could be extrapolated from the shallower portions of the basin, large errors would be associated with these predictions. A similar, extensive baseline sampling-program of wells completed in deeper portions of the basin would provide fundamental information on the deeper basin water composition. This data would be instrumental in developing produced-water handling strategies.

Recharge water chemistry

Shallow basin water chemistry appears to be a mixture of meteoric water and deeper formation water. In order to fully assess this possibility, end member compositions must be known rather than assumed, as is now required. One of those end members was discussed in the previous point. The other end member is meteoric water. A sampling program to assess the meteoric water composition throughout the Alberta Plains region would provide information on the meteoric water composition and allow area-specific water compositions to be used in groundwater chemistry calculations. The determination of whether mixing is occurring provides insight on groundwater flow within the basin and the nature of connection between aquifers. Both become important in assessing the effect of water production on water volumes within aquifers and the potential area of affect of water production.

Aquifer and aquitard characteristics

A preliminary examination of the hydraulic properties of shallow coal and sandstone aquifers in the Alberta Plains region indicated the presence of complex responses to aquifer tests. These tests suggest producing water from these aquifers initiates flow from the aquifers, flow across aquifer-aquitard boundaries and potentially flow from surface water bodies. These connections became evident under relatively low flow conditions when compared to production rates that would be associated with coalbed methane development. The result of development should be assessed by completing a more detailed analysis of the flow regimes associated with the coal aquifers and extrapolating the aquifer-responses to the increased volumes of water produced under coalbed methane development-scenarios. The possible connection between aquifers and surface water bodies should also be clarified to assess the nature of the connections and the risk to the surface water resources.

Surface water chemistry

Currently, regulations in Alberta forbid the disposal of produced water into surface water bodies. Under very specific circumstances, arrangements can be made between landowners and developers to use produced water. The development of the coalbed methane resource may mean an increase in the number of requests to make use of produced water for agricultural or industrial purposes. Under this scenario, one of the potential receptors of this produced water is surface water, such as rivers and lakes. A comprehensive sampling program of lakes and rivers would provide essential information on the baseline water chemistry of these water bodies and would be instrumental in assessing any future effects to surface water from coalbed methane development.

Organic compounds in groundwater

Some questions were raised about the nature and concentrations of the organic compounds identified and sampled for. Based on an analysis of the results, concerns were raised that some parameters may have been underestimated. Additional sampling and more rigorous chemical analyses would confirm this hypothesis, or would validate the results obtained as part of this study.

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Appendix A – Chemistry Datasets

Appendix A - Chemistry Datasets - Table 183. Aquifer water chemistry.

			Sample	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**
Element or Compound or Measurement	**Units**	**Detection Limit**	**AERI 02-01***	**AERI 02-02***	**AERI 02-05***	**AERI 02-06***	**AERI 02-07***	**AERI 02-08***	**AERI 02-09***	**AERI 02-10***	**AERI 02-11***
Site ID			1	2	5	6	7	8	9	10	11
Sample Date	mm/dd/yyyy		9/30/2002	9/30/2002	10/1/2002	10/1/2002	10/2/2002	10/2/2002	10/3/2002	10/3/2002	10/4/2002
Approximate Location			051-20W4	051-20W4	068-24W4	065-26W4	061-23W4	057-25W5	054-12W4	052-14W4	054-25W4
Well Depth	m		64.0	52.4	16.2	100.6	67.1	36.6	91.5	32.0	61.0
Formation			HC	HC	Belly River	Belly River	Belly River	HC	Belly River	Belly River	HC
Coal Zone			Drumheller	Drumheller	McKay	Taber		Drumheller	McKay	Taber	Drumheller
Water Type			Na-HCO3	Na-HCO3	Ca-Mg-HCO3	Na-HCO3	Na-HCO3-SO4	Na-HCO3-SO4	Na-HCO3	Na-HCO3-SO4	Na-HCO3-SO4
Routine Water Analysis											
Laboratory pH			8.37	7.85	7.31	**8.72**	8.39	8.26	**8.79**	7.74	8.31
Laboratory Conductivity	μS/cm	1	1970	2190	693	1170	1210	2270	1460	1740	2290
Laboratory Temperature	^{o}C	0.1	19.5	19	20.8	21.2	20.8	20.8	20.9	21	21.3
Field measured pH			8.04	7.34	7.06	**8.84**	8.40	8.21	**8.95**	7.50	8.40
Field measured Conductivity	μS/cm	1	1396	1500	438	764	828	1530	969	1200	1500
Field measured Dissolved Oxygen	mg/L	0.01	0.05	0.13	0.11	0.11	0.29	0.25		0.17	0.3
Field measured Temperature	^{o}C	0.1	7.6	7.2	5.3	7.6	7.7	8.5	6.7	7.4	7.3
Field measured Eh	mV	1	-52.6	69.8	174.7	-2.6	219.3	245.5	170.3	214.6	-135.3
Calcium	mg/L	0.2	7	21.5	85.9	2.2	1.8	9.8	2	74	10.4
Magnesium	mg/L	0.2	0.6	2.3	28.6	0.4	0.3	0.7	0.4	19.8	0.6
Sodium	mg/L	0.4	**648**	**683**	36.4	**309**	**310**	**673**	**374**	**325**	**635**
Sodium by NAA	ppm		**524**	**634**	46.6	**432**	**410**	**666**	**518**	**436**	**105**
Potassium	mg/L	0.4	2.5	3.6	3.3	1.6	1.2	2.1	1.5	6.4	1.5
Iron	mg/L	0.01	0.03	<0.01	<0.01	0.06	0.01	<0.01	0.01	<0.01	<0.01
Manganese	mg/L	0.005	<0.005	0.019	**0.209**	<0.005	<0.005	0.007	0.021	**0.194**	0.011
Chloride	mg/L	0.5	33.6	19.4	<0.5	2.5	3.3	<0.5	96.5	3.5	1.9
Nitrate-N	mg/L	0.004	<0.004	<0.02	<0.004	<0.004	<0.004	<0.02	<0.004	<0.004	<0.02
Nitrite-N	mg/L	0.002	<0.002	<0.01	<0.002	<0.002	<0.002	<0.01	<0.002	<0.002	<0.01
Nitrate and Nitrite - N	mg/L	0.006	<0.006	<0.03	<0.006	<0.006	<0.006	<0.03	<0.006	<0.006	<0.03
Sulphate	mg/L	0.2	4.1	16.5	27.8	73	178	**555**	66.6	478	**591**
Hydroxide	mg/L	5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Carbonate	mg/L	6	34	<6	<6	67	17	<6	74	<6	<6
Bicarbonate	mg/L	5	1450	1700	459	595	588	972	587	696	899
P-Alkalinity	mg/L as $CaCO_3$	5	29	<5	<5	56	14	<5	62	<5	<5
T-Alkalinity	mg/L as $CaCO_3$	5	1250	1390	377	600	510	797	605	571	737
Field measured T-Alkalinity	mg/L as $CaCO_3$	2	1102	1154	60		424	572	524	528	520
Total Dissolved Solids	mg/L	1	**1440**	**1580**	408	**749**	**801**	**1720**	**904**	**1250**	**1680**
Hardness	mg/L		20.1	63.3	332	7.1	5.6	27.2	6.6	266	28.3
Ionic Balance	%		110	108	103	100	97	109	101	91	104
Charge Balance Error	%		5%	4%	1%	0%	1%	4%	1%	-5%	2%
Turbidity	NTU		0.9	0.5	**32**	**1.1**	0.2	0.2	0.3	**2.5**	0.3
Sodium adsorption ratio (SAR)	(mmol/L)$^{0.5}$		**63**	**37**	1	**50**	**56**	**56**	**63**	9	**52**
Dissolved Metals											
Silicon	mg/L	0.05	8.74	13.8	9.06	3.64	4.45	12	3.93	5.99	4.79
Sulphur	mg/L	0.05	1.37	5.49	9.27	24.3	59.5	185	22.2	159	197
Mercury	mg/L	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Aluminum	mg/L	0.005	<0.03	<0.03	<0.005	<0.005	<0.005	<0.03	<0.005	<0.005	<0.03
Antimony	mg/L	0.0002	<0.001	<0.001	<0.0002	<0.0002	<0.0002	<0.001	<0.0002	<0.0002	<0.001
Arsenic	mg/L	0.0002	<0.001	<0.001	0.0109	0.0012	<0.0002	<0.001	0.0009	0.004	0.0022
Barium	mg/L	0.001	0.164	0.368	0.069	0.057	0.018	0.064	0.063	0.017	0.035
Beryllium	mg/L	0.0001	<0.0005	<0.0005	<0.0001	<0.0001	<0.0001	<0.0005	<0.0001	<0.0001	<0.0005
Bismuth	mg/L	0.0005	<0.003	<0.003	<0.0005	<0.0005	<0.0005	<0.003	<0.0005	<0.0005	<0.003
Boron	mg/L	0.002	0.32	0.327	0.125	**1.97**	0.347	0.161	**1.41**	0.382	0.302
Cadmium	mg/L	0.00001	<0.00005	<0.00005	<0.00001	<0.00001	<0.00001	<0.00005	<0.00001	<0.00001	0.00011
Chromium	mg/L	0.0005	**0.0075**	**0.0081**	0.0016	0.0032	0.0027	0.0041	**0.0064**	0.0027	0.0041
Cobalt	mg/L	0.0001	<0.0005	<0.0005	0.0004	0.0002	<0.0001	<0.0005	0.0004	0.0002	<0.0005
Copper	mg/L	0.001	<0.005	<0.005	<0.001	<0.001	0.001	0.036	<0.001	0.002	<0.005
Lead	mg/L	0.0001	<0.0005	<0.0005	<0.0001	0.0003	<0.0001	0.0007	0.0001	<0.0001	<0.0005
Lithium	mg/L	0.001	0.142	0.181	0.039	0.027	0.037	0.121	0.033	0.147	0.125

Appendix A - Chemistry Datasets - Table 183. Aquifer water chemistry.

			Sample	Sample	Sample	Sample	Sample	Sample	Sample	Sample	Sample
Element or Compound or Measurement	**Units**	**Detection Limit**	**AERI 02-01***	**AERI 02-02***	**AERI 02-05***	**AERI 02-06***	**AERI 02-07***	**AERI 02-08***	**AERI 02-09***	**AERI 02-10***	**AERI 02-11***
Molybdenum	mg/L	0.001	<0.005	<0.005	0.002	0.004	0.001	<0.005	<0.001	<0.001	<0.005
Nickel	mg/L	0.0005	<0.003	<0.003	<0.0005	<0.0005	<0.0005	<0.003	<0.0005	<0.0005	<0.003
Selenium	mg/L	0.0002	<0.001	<0.001	<0.0002	<0.0002	<0.0002	<0.001	<0.0002	<0.0002	<0.001
Silver	mg/L	0.0001	<0.0005	<0.0005	<0.0001	<0.0001	<0.0001	<0.0005	<0.0001	<0.0001	<0.0005
Strontium	mg/L	0.001	0.136	0.33	0.547	0.056	0.058	0.187	0.076	1.03	0.19
Thalium	mg/L	0.00005	0.0013	0.00038	<0.00005	<0.00005	<0.00005	<0.0003	<0.00005	<0.00005	<0.0003
Thorium	ppb	varied	<0.19	<0.22	<0.14	<0.14	<0.14	<0.19	0.4	<0.15	<0.15
Titanium	mg/L	0.0005	<0.003	<0.003	<0.0005	0.121	0.0059	0.0066	0.0604	0.0051	0.0083
Uranium	ppb	varied	<3	<3	1	<2	<2	<3	<3	<3	<3
Vanadium	mg/L	0.0001	<0.0005	<0.0005	<0.0001	0.0008	<0.0001	<0.0005	0.0006	<0.0001	<0.0005
Zinc	mg/L	0.001	<0.005	<0.005	0.004	0.002	0.011	0.034	0.001	0.005	<0.005
Extractable Metals											
Silicon	mg/L	0.05	7.08	11.3	7.96	3.07	3.82	10.6	3.23	5.37	4.16
Silica	mg/L	0.1	15.1	24.2	17	6.6	8.2	22.6	6.9	11.5	8.9
Agregate organic constituents											
Phenol	mg/L	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Non-halogenated aromatics											
Benzene	mg/L	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	0.001	0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethylbenzene	mg/L	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Total Xylenes	mg/L	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Purgeable hydrocarbons											
Total hydrocarbon (C5-C10)	mg/L	0.01	0.01	<0.01	<0.01	0.01	0.03	0.01	<0.01	0.01	<0.01
Extractable hydrocarbons											
Total (C11-C40+)	mg/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Polycyclic aromatic hydrocarbons											
Naphthalene	ug/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acenaphthylene	ug/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acenaphtene	ug/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Fluorene	ug/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Phenanthrene	ug/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Anthracene	ug/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acridine	ug/L	0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Fluoranthene	ug/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Pyrene	ug/L	0.002	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Benzo(a)anthracene	ug/L	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Chrysene	ug/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Benzo(b)fluoranthene	ug/L	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(k)fluoranthene	ug/L	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(a)pyrene	ug/L	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Indeno(1,2,3-c,d)pyrene	ug/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dibenzo(a,h)anthracene	ug/L	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(g,h,I)perylene	ug/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Adsorbable organic halides in water											
Adsorbable organic halides in water	mg/L	0.003	0.034	0.016	0.0096	0.0035	0.0027	0.005	0.0071	0.0044	0.0034
Anions and Cations by NAA											
F	ppm	varied	2.7	2.2	0.9	2.2	2	1.8	2.2	0.8	2.7
Cl	ppm	varied	28	16	0.6	2.5	3.8	0.7	86	2.2	3.5
Br	ppm	varied	0.41	0.15	0.03	0.05	<0.045	<0.061	0.63	<0.048	0.08
I	ppm	varied	0.19	0.08	<0.0084	<0.019	0.02	<0.025	0.13	<0.019	<0.025
Sc	ppb	varied	0.09	0.14	0.07	0.06	0.07	0.04	0.17	0.05	0.11
Rb	ppb	varied	13	13	<8.6	<6.2	<5.8	11	<6.5	<5.9	<6.2
Notes:											
AO = Aesthetic Objective											
MAC = Maximum Allowable Concentration											
IMAC = Interim Maximum Allowable Concentration											
* Values in bold indicate possible exceedance of water quality guidelines											

Appendix A - Chemistry Datasets - Table 183. Aquifer water chemistry.

	Sample	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**
Element or Compound or Measurement	**AERI 02-12***	**AERI 02-15***	**AERI 02-16AQ***	**AERI 02-18***	**AERI 02-20***	**AERI 02-21***	**AERI 02-22***	**AERI 02-23***	**AERI 02-24***	**AERI 02-25***	**AERI 02-26***
Site ID	12	15	16	17	18	19	20	21	22	23	24
Sample Date	10/4/2002	10/7/2002	10/8/2002	10/8/2002	10/9/2002	10/9/2002	10/10/2002	10/10/2002	10/11/2002	10/11/2002	10/15/2002
Approximate Location	054-25W4	013-06W4	008-02W4	012-06W4	028-06W4	035-17W4	032-14W4	027-21W4	042-25W4	043-23W4	052-21W4
Well Depth	42.7	91.5	50.3	15.2	193.3	53.4	36.6	54.9	132.6	42.1	44.2
Formation	HC	Belly River	Belly River	Belly River	Belly River	HC	HC	HC	Scollard	Paskapoo	HC
Coal Zone	Drumheller			McKay				Daly Weaver	Ardley		Drumheller
Water Type	Na-SO4-HCO3	Na-HCO3-SO4	Ca-Mg-HCO3	Mg-Ca-HCO3	Na-HCO3-Cl	Na-HCO3	Na-HCO3-SO4	Na-HCO3	Na-Cl-HCO3	Na-HCO3	Na-Ca-HCO3-SO4
Routine Water Analysis											
Laboratory pH	8.04	8.22	7.43	8.06	**8.71**	8.18	7.82	8.5	**8.55**	8.48	6.74
Laboratory Conductivity	3440	2030	905	529	1790	2890	2010	1670	2220	1140	2000
Laboratory Temperature	21.6	23.3	23.3	23.3	23.4	23.7	24.2	23.9	23.7	23.7	20.1
Field measured pH	7.97	7.66	6.91	7.49	8.26	7.61	7.18	8.43	8.34	8.37	6.68
Field measured Conductivity	3870	1407	586	396	1238	1970	1320	1161	1530	769	1440
Field measured Dissolved Oxygen	0.08	1.01	0.26	1.6	0.17		0.19	0.14	0.28	0.34	0.16
Field measured Temperature	7.9	9.6	6.4	12.8	9.1	7.2	5.5	7.5	9.8	7.2	7.1
Field measured Eh	93.1	77.4	386.6	419.2	15.9	290.8	249.5	67.5	132.2	78.8	36.9
Calcium	21.1	18.6	150	48.8	2.8	17.4	15	3.4	4.5	4	128
Magnesium	1.3	20.3	33.8	34.4	0.5	3	1.7	0.3	0.5	0.3	23.5
Sodium	**861**	**481**	19.5	19.1	**456**	**778**	**506**	**441**	**503**	**300**	**347**
Sodium by NAA	**935**	**610**	25.6	26.4	**547**	**974**	**682**	**532**	**632**	**372**	**373**
Potassium	<2	2.7	2.5	5.5	1.5	3.8	4.9	1.2	1.4	0.8	8.9
Iron	<0.05	0.03	<0.01	<0.01	0.02	<0.05	0.05	0.02	<0.01	0.04	<0.01
Manganese	<0.02	0.017	**2.02**	0.087	0.007	<0.02	0.017	<0.005	0.006	0.009	**0.295**
Chloride	0.9	28	21.2	3	**209**	28.4	4.2	**120**	**425**	26.9	2.4
Nitrate-N	<0.02	<0.004	<0.004	<0.004	0.541	<0.02	<0.004	0.146	0.617	<0.004	<0.02
Nitrite-N	<0.01	<0.002	<0.002	<0.002	<0.002	<0.01	<0.002	<0.002	<0.01	<0.002	<0.01
Nitrate and Nitrite - N	<0.03	<0.006	<0.006	<0.006	0.541	<0.03	<0.006	0.146	0.617	<0.006	<0.03
Sulphate	**1320**	329	40.2	48.4	0.7	312	281	1	0.3	0.5	**548**
Hydroxide	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Carbonate	<6	<6	<6	<6	59	<6	<6	44	43	35	<6
Bicarbonate	852	1040	585	321	732	1720	1090	864	564	702	848
P-Alkalinity	<5	<5	<5	<5	49	<5	<5	36	36	29	<5
T-Alkalinity	699	852	480	264	699	1410	894	781	535	634	696
Field measured T-Alkalinity	624	798	458	310	716	1330	930	702	550	636	686
Total Dissolved Solids	**2620**	**1390**	**555**	317	**1090**	**1990**	**1350**	**1040**	**1260**	**713**	**1480**
Hardness	58	130	514	264	9.3	56	44.3	9.7	13.3	11.2	416
Ionic Balance	93	96	102	98	101	99	96	102	98	99	93
Charge Balance Error	-4%	-2%	0%	-2%	0%	-1%	-2%	1%	-1%	-1%	-4%
Turbidity	0.2	0.7	0.6	**1.4**	0.4	0.1	0.1	0.2	0.7	0.2	**8.5**
Sodium adsorption ratio (SAR)	**49**	**18**	0	1	**66**	**45**	**33**	**62**	**60**	**39**	7
Dissolved Metals											
Silicon	6.03	5.3	9.12	6.73	4.45	11.1	15.3	4.63	4.57	4.54	13.5
Sulphur	440	110	13.4	16.1	0.22	104	93.6	0.35	0.1	0.17	183
Mercury	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Aluminum	<0.03	<0.005	<0.005	<0.005	<0.005	<0.03	<0.005	<0.005	0.013	<0.005	<0.005
Antimony	<0.001	<0.0002	0.0009	<0.0002	<0.0002	<0.001	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Arsenic	<0.001	0.0009	**0.0353**	0.0005	<0.0002	<0.001	0.0003	0.0005	<0.0002	0.0022	0.0003
Barium	0.018	0.016	0.146	0.074	0.05	0.081	0.012	0.092	0.168	0.065	0.011
Beryllium	<0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Bismuth	<0.003	<0.0005	<0.0005	<0.0005	<0.0005	<0.003	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Boron	0.381	**0.667**	0.021	0.061	**1.45**	0.453	**0.707**	0.311	0.457	0.375	0.099
Cadmium	<0.00005	<0.00001	0.0001	0.00005	<0.00001	<0.00005	0.00092	<0.00001	<0.00001	<0.00001	<0.00001
Chromium	0.0035	0.0036	0.0019	0.001	**0.0063**	**0.0053**	0.0033	**0.0066**	**0.0133**	0.004	0.0027
Cobalt	<0.0005	0.0001	0.001	<0.0001	0.0002	<0.0005	<0.0001	<0.0001	0.0003	0.0003	<0.0001
Copper	<0.005	<0.001	0.002	0.002	<0.001	<0.005	0.001	<0.001	<0.001	<0.001	0.001
Lead	<0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0005	<0.0001	<0.0001	<0.0001	0.0003	<0.0001
Lithium	0.188	0.063	0.015	0.026	0.061	0.383	0.27	0.11	0.11	0.051	0.235

Appendix A - Chemistry Datasets - Table 183. Aquifer water chemistry.

	Sample	Sample	Sample	Sample	Sample	Sample	Sample	Sample	Sample	Sample	Sample
Element or Compound or Measurement	**AERI 02-12***	**AERI 02-15***	**AERI 02-16AQ***	**AERI 02-18***	**AERI 02-20***	**AERI 02-21***	**AERI 02-22***	**AERI 02-23***	**AERI 02-24***	**AERI 02-25***	**AERI 02-26***
Molybdenum	<0.005	**0.013**	0.007	0.002	<0.001	<0.005	<0.001	0.003	<0.001	0.008	<0.001
Nickel	<0.003	<0.0005	<0.0005	<0.0005	<0.0005	0.016	0.0035	<0.0005	<0.0005	0.0007	<0.0005
Selenium	<0.001	0.0004	<0.0002	<0.0002	<0.0002	<0.001	<0.0002	<0.0002	<0.0002	0.0002	<0.0002
Silver	<0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Strontium	0.411	0.513	0.413	0.319	0.082	0.236	0.197	0.072	0.136	0.053	1.5
Thalium	<0.0003	<0.00005	<0.00005	<0.00005	<0.00005	<0.0003	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
Thorium	<0.22	<0.23	0.2	0.2	<0.3	0.3	<0.22	<0.28	<0.32	<0.17	<0.19
Titanium	0.018	0.0028	<0.0005	0.0005	0.0032	0.0038	0.0022	<0.0005	0.0012	0.307	0.0033
Uranium	<3	<3	9	4	<5	<3	<3	<3	<5	<3	<3
Vanadium	<0.0005	<0.0001	0.0002	<0.0001	<0.0001	<0.0005	<0.0001	<0.0001	<0.0001	0.0014	<0.0001
Zinc	<0.005	0.002	0.041	0.645	<0.001	0.011	0.014	<0.001	<0.001	0.002	0.002
Extractable Metals											
Silicon	5.64	5.12	8.46	6.54	11.6	11.6	13.7	4.18	4.49	4.58	12.7
Silica	12.1	11	18.1	14	24.8	24.8	29.4	8.9	9.6	9.8	27.2
Agregate organic constituents											
Phenol	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.001
Non-halogenated aromatics											
Benzene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethylbenzene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Total Xylenes	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Purgeable hydrocarbons											
Total hydrocarbon (C5-C10)	0.01	<0.01	<0.01	0.16	<0.01	<0.01	<0.01	0.04	<0.01	<0.01	<0.01
Extractable hydrocarbons											
Total (C11-C40+)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Polycyclic aromatic hydrocarbons											
Naphthalene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acenaphthylene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acenaphtene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Fluorene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Phenanthrene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Anthracene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acridine	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Fluoranthene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Pyrene	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Benzo(a)anthracene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Chrysene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Benzo(b)fluoranthene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(k)fluoranthene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(a)pyrene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Indeno(1,2,3-c,d)pyrene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dibenzo(a,h)anthracene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(g,h,I)perylene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Adsorbable organic halides in water											
Adsorbable organic halides in water	0.016	0.0066	0.0046	0.098	0.0053	0.0074	0.035	0.02	0.016	0.0038	0.0044
Anions and Cations by NAA											
F	1.9	2.5	<0.5	<0.5	3.9	2.8	1.1	3.2	3.2	3.1	1.2
Cl	<0.71	21	19	2.8	182	23	3.8	111	**379**	22	2.3
Br	<0.076	1.04	0.08	0.02	2.74	0.21	<0.064	0.74	2.82	0.17	0.06
I	<0.031	0.42	<0.016	<0.0069	0.72	0.07	<0.024	0.39	0.82	0.09	0.04
Sc	0.09	0.05	0.08	0.08	0.06	0.11	0.09	0.09	0.11	0.06	0.04
Rb	<6.6	<8	<6.3	<5.7	<7.5	11	15	<7.8	<7.8	<7.4	24
Notes:											
AO = Aesthetic Objective											
MAC = Maximum Allowable Concentration											
IMAC = Interim Maximum Allowable Concentration											
* Values in bold indicate possible exceedance of wa											

Appendix A - Chemistry Datasets - Table 183. Aquifer water chemistry.

Element or Compound or Measurement	**Sample AERI 02-28***	**Sample AERI 02-29***	**Sample AERI 02-30***	**Sample AERI 02-31***	**Sample AERI 02-32***	**Sample AERI 02-33***	**Sample AERI 02-34***	**Sample AERI 02-35***	**Sample AERI 02-36***	**Sample AERI 02-37***	**Sample AERI 02-38***
Site ID	25	26	27	28	29	30	31	32	33	34	35
Sample Date	10/15/2002	10/16/2002	10/16/2002	10/17/2002	10/18/2002	10/21/2002	10/22/2002	10/22/2002	10/23/2002	10/25/2002	10/25/2002
Approximate Location	056-26W4	060-16W4	060-25W4	051-22W4	048-27W4	052-01W5	047-22W4	053-22W4	050-23W4	057-01W5	059-22W4
Well Depth	33.5	29.3	90.9	24.4	19.8	59.5	53.7	38.1	30.5	54.9	21.3
Formation	HC	Belly River	Belly River	HC	Scollard	HC	HC	HC	HC	HC	Belly River
Coal Zone	Drumheller	McKay	Taber		Ardley			Drumheller		Drumheller	Taber
Water Type	Na-HCO3	Na-HCO3-SO4	Na-Cl	Na-Ca-SO4-HCO3	Ca-Na-Mg-HCO3	Na-HCO3-Cl	Na-HCO3	Na-HCO3	Na-SO4-HCO3	Na-HCO3	Na-Ca-HCO3
Routine Water Analysis											
Laboratory pH	7.27	7.85	8.26	7.12	7.29	8.17	8.32	8.02	8.36	8.45	7.72
Laboratory Conductivity	577	1800	6200	2370	777	1980	1520	2010	2740	1260	1330
Laboratory Temperature	19.9	19.9	20	20.2	20.3	21.6	21.6	21.6	21.6	21.7	22.2
Field measured pH	7.12	7.78	8.46	7.18	7.20	8.35	8.19	7.71	8.19	**8.58**	7.33
Field measured Conductivity	412	1397	6330	1650	535	1358	1031	1327	3730	821	878
Field measured Dissolved Oxygen	0.24	0.36	0.08	4.42	0.41	0.13	0.12	0.16		0.25	0.18
Field measured Temperature	6.9	10.3	7.7	7.5	6.9	6.3	6.4	6.2	13	6.1	6.3
Field measured Eh	31.1	345.7	49.3	-62	357.1	126.7	-95.4	116.8	404	69.9	202.7
Calcium	21.8	25.6	44.4	222	96.3	7.3	5.6	11.4	27	3.3	70.6
Magnesium	6.6	7.7	5.8	58.6	22.1	0.4	0.6	0.8	3	<0.2	22.1
Sodium	112	**424**	**1340**	**281**	50	**500**	**406**	**547**	**715**	**351**	**247**
Sodium by NAA	107	**380**	**1310**	**331**	68.2	**639**	**209**	**688**	**882**	**401**	**296**
Potassium	1.8	4.8	4.6	6.7	3.1	1.6	1.5	2.7	3.1	1.2	6.6
Iron	0.16	0.02	<0.1	<0.05	<0.01	0.04	0.07	0.07	<0.05	<0.01	<0.01
Manganese	**0.07**	0.016	**0.053**	**0.413**	**0.151**	<0.005	0.015	0.027	0.038	<0.005	**0.714**
Chloride	6.3	3.7	**1990**	135	11.6	**229**	10.9	79.5	2.4	21	1.2
Nitrate-N	<0.004	0.098	<0.04	<0.02	0.274	<0.004	<0.004	<0.004	0.601	<0.004	0.067
Nitrite-N	<0.002	<0.002	<0.02	<0.01	<0.002	<0.002	0.107	<0.002	<0.01	<0.002	<0.002
Nitrate and Nitrite - N	<0.006	0.098	<0.06	<0.03	0.274	<0.006	0.107	<0.006	0.601	<0.006	0.067
Sulphate	16.6	340	<2	**670**	10.6	1.4	93.8	1.6	**877**	2.5	77.3
Hydroxide	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Carbonate	<6	<6	<6	<6	<6	<6	<6	<6	16	32	<6
Bicarbonate	384	874	457	723	525	931	975	1320	798	810	876
P-Alkalinity	<5	<5	<5	<5	<5	<5	<5	<5	13	26	<5
T-Alkalinity	315	717	375	593	431	764	799	1080	680	717	719
Field measured T-Alkalinity	360	696	398	662	442	760	754	860	684	694	
Total Dissolved Solids	354	**1240**	**3610**	**1730**	452	**1200**	**998**	**1290**	**2040**	**809**	**856**
Hardness	81.6	95.6	135	796	332	19.9	16.6	31.6	79	8.2	267
Ionic Balance	96	95	96	96	97	102	99	102	102	103	102
Charge Balance Error	-2%	-3%	-2%	-3%	-2%	1%	-1%	1%	1%	1%	0%
Turbidity	**2.5**	0.9	**5.8**	**111**	**5.3**	0.3	**11.3**	0.6	0.3	**1.4**	**1.6**
Sodium adsorption ratio (SAR)	5	**19**	**50**	4	1	**49**	**44**	**42**	**35**	**53**	7
Dissolved Metals											
Silicon	12.3	5.19	4	10.2	6.84	5.25	3.89	12.8	5.51	4.91	7.97
Sulphur	5.52	113	<0.5	223	3.55	0.47	31.3	0.52	292	0.84	25.8
Mercury	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Aluminum	<0.005	<0.005	<0.05	<0.03	<0.005	<0.005	<0.005	<0.03	<0.05	<0.005	<0.005
Antimony	<0.0002	<0.0002	<0.002	<0.001	<0.0002	0.0004	0.0002	<0.001	<0.002	<0.0002	<0.0002
Arsenic	0.0009	0.0004	<0.002	0.0168	0.0005	0.0007	0.0007	<0.001	<0.002	0.0005	0.0025
Barium	0.123	0.013	2.02	0.016	0.299	0.121	0.048	0.193	0.127	0.042	0.044
Beryllium	<0.0001	<0.0001	<0.001	<0.0005	<0.0001	<0.0001	<0.0001	<0.0005	<0.001	<0.0001	<0.0001
Bismuth	<0.0005	<0.0005	<0.005	<0.003	<0.0005	<0.0005	<0.0005	<0.003	<0.005	<0.0005	<0.0005
Boron	0.415	**0.666**	**0.761**	0.329	0.083	0.139	0.225	0.201	0.309	0.125	0.18
Cadmium	<0.00001	<0.00001	<0.0001	<0.00005	0.00008	<0.00001	<0.00001	<0.00005	<0.0001	<0.00001	<0.00001
Chromium	0.0012	0.0033	**0.021**	**0.0057**	0.0019	**0.0091**	**0.0066**	**0.012**	**0.0058**	**0.0058**	**0.0053**
Cobalt	0.0002	0.0003	<0.001	0.0008	<0.0001	0.0002	0.0005	<0.0005	<0.001	0.0002	0.0001
Copper	<0.001	0.002	<0.01	<0.005	<0.001	<0.001	<0.001	<0.005	<0.01	<0.001	0.002
Lead	<0.0001	<0.0001	<0.001	<0.0005	<0.0001	<0.0001	0.0005	<0.0005	<0.001	<0.0001	<0.0001
Lithium	0.062	0.098	0.162	0.204	0.048	0.076	0.081	0.133	0.158	0.05	0.106

Appendix A - Chemistry Datasets - Table 183. Aquifer water chemistry.

	Sample	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**
Element or Compound or Measurement	**AERI 02-28***	**AERI 02-29***	**AERI 02-30***	**AERI 02-31***	**AERI 02-32***	**AERI 02-33***	**AERI 02-34***	**AERI 02-35***	**AERI 02-36***	**AERI 02-37***	**AERI 02-38***
Molybdenum	<0.001	0.001	<0.01	0.005	<0.001	0.002	0.007	<0.005	<0.01	0.004	<0.001
Nickel	<0.0005	<0.0005	<0.005	<0.0025	<0.0005	<0.0005	0.0006	<0.003	0.011	<0.0005	<0.0005
Selenium	<0.0002	<0.0002	<0.002	<0.001	<0.0002	<0.0002	0.0002	<0.001	<0.002	<0.0002	<0.0002
Silver	<0.0001	<0.0001	<0.001	<0.0005	<0.0001	<0.0001	<0.0001	<0.0005	<0.001	<0.0001	<0.0001
Strontium	0.22	0.656	1.69	1.7	1.69	0.093	0.077	0.177	0.342	0.04	0.832
Thalium	<0.00005	<0.00005	<0.0005	<0.0003	<0.00005	<0.00005	<0.00005	<0.0003	<0.0005	<0.00005	<0.00005
Thorium	<0.21	<0.21	<0.64	<0.18	<0.14	<0.23	<0.16	<0.21	<0.16	0.2	0.3
Titanium	<0.0005	0.0027	<0.005	0.0071	<0.0005	0.0007	0.001	<0.003	0.01	<0.0005	0.0007
Uranium	<2	<2	<4	5	<1	<4	<2	<3	<3	<2	3
Vanadium	<0.0001	<0.0001	<0.001	<0.0005	<0.0001	<0.0001	0.0001	<0.0005	<0.001	<0.0001	<0.0001
Zinc	0.001	0.003	0.081	0.191	0.002	0.002	0.05	<0.005	0.021	0.003	0.002
Extractable Metals											
Silicon	11.8	4.75	3.71	10.3	6.65	4.95	3.55	11.1	5.57	4.21	7.21
Silica	25.2	10.2	7.9	22.1	14.2	10.6	7.6	23.8	11.9	9	15.4
Agregate organic constituents											
Phenol	0.001	0.001	**0.002**	0.001	0.001	<0.001	**0.005**	<0.001	<0.001	<0.001	<0.001
Non-halogenated aromatics											
Benzene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethylbenzene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Total Xylenes	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Purgeable hydrocarbons											
Total hydrocarbon (C5-C10)	<0.01	0.02	<0.01	0.7	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Extractable hydrocarbons											
Total (C11-C40+)	0.5	<0.1	<0.1	<0.1	0.2	0.2	<0.1	<0.1	<0.1	<0.1	0.4
Polycyclic aromatic hydrocarbons											
Naphthalene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acenaphthylene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acenaphtene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Fluorene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Phenanthrene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Anthracene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acridine	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Fluoranthene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Pyrene	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Benzo(a)anthracene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Chrysene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Benzo(b)fluoranthene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(k)fluoranthene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(a)pyrene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Indeno(1,2,3-c,d)pyrene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dibenzo(a,h)anthracene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(g,h,I)perylene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Adsorbable organic halides in water											
Adsorbable organic halides in water	0.0041	0.007	0.11	0.054	0.0046	0.0031	0.01	0.048	0.011	0.0038	0.0046
Anions and Cations by NAA											
F	0.6	2	6.1	1	0.6	2.3	2.3	1.6	2.6	1.9	1.1
Cl	5.8	2.3	**1600**	122	2.6	205	7.9	68	3.0	16	0.6
Br	<0.035	0.16	14.60	0.11	<0.013	1.73	0.15	0.80	0.10	0.21	<0.046
I	<0.013	<0.023	6.30	<0.022	<0.0048	0.34	0.07	0.21	0.03	0.02	<0.017
Sc	0.05	0.07	0.07	0.05	0.09	0.06	0.06	0.03	0.06	0.05	0.08
Rb	<7.4	<7.6	<11	<8.4	<5.6	<8.6	<5.3	<7.4	<7.1	<4.8	<5.7
Notes:											
AO = Aesthetic Objective											
MAC = Maximum Allowable Concentration											
IMAC = Interim Maximum Allowable Concentration											
* Values in bold indicate possible exceedance of wa											

Appendix A - Chemistry Datasets - Table 183. Aquifer water chemistry.

	Sample	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**	**Sample**
Element or Compound or Measurement	**AERI 02-39***	**AERI 02-40***	**AERI 02-41***	**AERI 02-42***	**AERI 02-43***	**AERI-02-44***	**AERI-02-45***	**AERI 02-46***	**AERI 02-47***	**AERI 02-48***	**AERI 02-49***
Site ID	36	37	38	39	40	41	42	43	44	45	46
Sample Date	10/28/2002	10/29/2002	10/29/2002	10/30/2002	10/30/2002	10/31/2002	11/1/2002	11/4/2002	11/12/2002	11/14/2002	11/14/2002
Approximate Location	050-23W4	037-01W4	037-02W4	045-11W4	045-11W4	056-24W4	054-05W5	042-17W4	046-27W4	054-04W5	054-04W5
Well Depth	36.6	112.8	98.5	67.7	80.8	43.6	48.8	36.6	22.9	57.9	51.5
Formation	HC	Belly River	Belly River	Belly River	Belly River	HC	Scollard	HC	Scollard	Scollard	Scollard
Coal Zone						Drumheller	Ardley	Drumheller		Ardley	Ardley
Water Type	Na-HCO3-SO4	Na-HCO3-SO4	Na-HCO3-SO4	Na-SO4-HCO3	Na-HCO3-SO4	Na-HCO3	Na-HCO3	Na-HCO3	Na-HCO3	Ca-Na-Mg-HCO3	Ca-Na-HCO3
Routine Water Analysis											
Laboratory pH	8.31	**8.64**	**8.58**	8.49	**8.63**	8.32	8.45	**8.6**	8.33	7.68	7.48
Laboratory Conductivity	2420	1310	1580	2060	1410	1510	1290	1380	1290	597	703
Laboratory Temperature	19.1	19.2	18.8	18.5	18.5	18.6	19	19.4	20.9	21.5	21.3
Field measured pH	8.44	**8.95**	**8.82**	**8.66**	**8.80**	8.29	**8.59**	**8.86**	8.38	8.25	7.19
Field measured Conductivity	6.6	929	1174	1510	1018	1138	894	998	833	389	460
Field measured Dissolved Oxygen	0.19	0.1	0.09	0.13	3.32	0.34	0.08	0.56	0.13	6.7	10.5
Field measured Temperature	6.6	6	7.2	6.5	6.6	8.2	6.1	8.8	5.7	5.7	5.7
Field measured Eh	135.4	41	165.8	264.5	353.4	332.8	32.9	-70.8	34.3	399.3	378.3
Calcium	13.8	4.2	3.2	5.1	3	8	3.6	2.7	5.1	70.9	92
Magnesium	2.9	0.8	0.5	<1	0.4	0.9	0.2	<0.2	1	19.4	19.7
Sodium	**633**	**327**	**407**	**562**	**375**	**401**	**354**	**374**	**339**	42.7	50.3
Sodium by NAA	**766**	**394**	**525**	**648**	**456**	**508**	**418**	**473**	**431**	50	63.7
Potassium	<2	2.1	2.5	3.7	2.7	2.3	1.2	1.2	1.7	3.8	2.4
Iron	<0.05	0.09	0.05	<0.05	0.03	<0.01	<0.01	0.03	0.05	<0.01	<0.01
Manganese	**0.057**	0.009	0.008	<0.02	<0.005	0.01	<0.005	<0.005	<0.005	**0.376**	**0.183**
Chloride	5.4	25.1	60.7	11.8	7.6	30.9	3.3	9.7	4.6	0.5	<0.5
Nitrate-N	<0.02	<0.004	<0.004	<0.02	0.017	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Nitrite-N	<0.01	<0.002	<0.002	<0.01	0.029	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Nitrate and Nitrite - N	<0.03	<0.006	<0.006	<0.03	0.045	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Sulphate	**608**	170	218	**567**	173	42.2	0.3	2.5	6.7	12.3	14
Hydroxide	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Carbonate	<6	59	57	42	63	7	44	66	8	<6	<6
Bicarbonate	947	520	607	671	659	982	854	840	912	408	494
P-Alkalinity	<5	49	48	35	52	6	37	55	7	<5	<5
T-Alkalinity	776	524	593	620	645	817	774	799	761	334	405
Field measured T-Alkalinity	780	550		616	652	808	682	784	674	378	466
Total Dissolved Solids	**1730**	**844**	**1050**	**1520**	**949**	**975**	**827**	**869**	**815**	350	421
Hardness	46	13.8	10	13	9.1	23.9	9.8	6.8	16.9	257	311
Ionic Balance	100	99	99	101	99	99	100	101	98	102	101
Charge Balance Error	0%	-1%	-1%	0%	-1%	0%	0%	0%	-1%	0%	0%
Turbidity	0.1	0.3	0.2	0.2	0.3	<0.1	0.4	0.3	0.1	0.6	**1.1**
Sodium adsorption ratio (SAR)	**40**	**38**	**56**	**64**	**54**	**36**	**49**	**61**	**36**	1	1
Dissolved Metals											
Silicon	5.34	4.27	4.63	4.41	4.38	5.71	4.87	4.69	7.11	9.73	14.4
Sulphur	203	56.8	72.6	189	57.8	14.1	0.09	0.85	2.22	4.09	4.68
Mercury	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Aluminum	<0.03	<0.005	<0.005	<0.03	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Antimony	<0.001	<0.0002	<0.0002	<0.001	<0.0002	<0.0002	<0.0002	<0.0002	0.0005	<0.0002	<0.0002
Arsenic	<0.001	0.0004	0.0007	<0.001	0.0003	0.0004	0.0003	0.0004	0.0011	0.0006	<0.0002
Barium	0.007	0.017	0.017	0.009	0.014	0.158	0.069	0.053	0.105	0.266	0.189
Beryllium	<0.0005	<0.0001	<0.0001	<0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Bismuth	<0.003	<0.0005	<0.0005	<0.003	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Boron	0.303	0.494	**1.01**	**0.668**	**0.651**	0.204	0.113	0.31	0.271	0.041	0.102
Cadmium	<0.00005	<0.00001	<0.00001	<0.00005	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
Chromium	0.0047	0.0036	0.0046	0.004	0.0038	**0.0052**	0.0047	0.0048	**0.0059**	0.0022	0.0023
Cobalt	<0.0005	0.0002	0.0003	<0.0005	0.0002	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	<0.0001
Copper	<0.005	0.001	<0.001	<0.005	0.003	<0.001	0.001	<0.001	<0.001	<0.001	<0.001
Lead	<0.0005	0.0003	0.0006	<0.0005	0.0004	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Lithium	0.112	0.051	0.06	0.104	0.047	0.061	0.042	0.054	0.044	0.014	0.029

Appendix A - Chemistry Datasets - Table 183. Aquifer water chemistry.

	Sample	Sample	Sample	Sample	Sample	Sample	Sample	Sample	Sample	Sample	Sample
Element or Compound or Measurement	**AERI 02-39***	**AERI 02-40***	**AERI 02-41***	**AERI 02-42***	**AERI 02-43***	**AERI-02-44***	**AERI-02-45***	**AERI 02-46***	**AERI 02-47***	**AERI 02-48***	**AERI 02-49***
Molybdenum	<0.005	0.004	0.002	<0.005	0.002	<0.001	0.003	0.004	0.003	<0.001	<0.001
Nickel	<0.003	<0.0005	<0.0005	<0.003	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Selenium	<0.001	<0.0002	<0.0002	<0.001	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Silver	<0.0005	<0.0001	<0.0001	<0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Strontium	0.177	0.059	0.046	0.121	0.059	0.161	0.05	0.051	0.086	0.272	0.817
Thalium	<0.0003	<0.00005	<0.00005	<0.0003	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
Thorium	<0.2	1.0	0.7	<0.16	0.6	<0.14	0.2	<0.12	<0.15	0.2	
Titanium	0.0068	0.13	0.263	0.014	0.0812	0.0013	0.0024	<0.0005	<0.0005	<0.0005	<0.0005
Uranium	<2	<2	<2	<2	<2	<2	<2	<2	<2	<1	<2
Vanadium	<0.0005	0.0008	0.0021	<0.0005	0.0015	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Zinc	<0.005	0.001	0.003	<0.005	0.003	0.002	<0.001	<0.001	0.002	0.007	0.006
Extractable Metals											
Silicon	5.04	3.57	3.74	3.44	3.61	4.72	4.18	3.96	6.56	9.21	13.2
Silica	10.8	7.6	8	7.4	7.7	10.1	9	8.5	14	19.7	28.2
Agregate organic constituents											
Phenol	<0.001	<0.001	<0.001	<0.001	**0.011**	**0.004**	<0.001	<0.001	<0.001	<0.001	<0.001
Non-halogenated aromatics											
Benzene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethylbenzene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Total Xylenes	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Purgeable hydrocarbons											
Total hydrocarbon (C5-C10)	0.11	0.02	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01
Extractable hydrocarbons											
Total (C11-C40+)	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	0.1	<0.1	0.4	<0.1	<0.1
Polycyclic aromatic hydrocarbons											
Naphthalene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	0.4
Acenaphthylene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acenaphtene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Fluorene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Phenanthrene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Anthracene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Acridine	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Fluoranthene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Pyrene	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Benzo(a)anthracene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Chrysene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Benzo(b)fluoranthene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(k)fluoranthene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(a)pyrene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Indeno(1,2,3-c,d)pyrene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dibenzo(a,h)anthracene	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Benzo(g,h,I)perylene	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Adsorbable organic halides in water											
Adsorbable organic halides in water	0.053	0.011	0.0091	0.0038	0.006	0.0055	0.0038	0.0027	0.0042	<0.0025	<0.0025
Anions and Cations by NAA											
F	3	1.6	2	1.3	2.2	1.4	1.8	2	2	<0.5	<0.5
Cl	3.0	20	52	9.1	5.2	27	1.6	6.9	3.7	0.4	0.4
Br	<0.071	0.27	0.55	<0.066	0.08	0.31	<0.056	0.12	0.08	<0.027	<0.026
I	0.04	0.08	0.22	<0.025	0.14	<0.021	0.09	0.04	0.04	<0.01	<0.01
Sc	0.08	0.25	0.15	0.06	0.14	0.04	0.04	0.04	0.04	0.03	0.04
Rb	<5.5	<5.2	<5.8	<5.4	<5.2	<5.5	<5.2	<5.4	<4.5	<6.1	<6
Notes:											
AO = Aesthetic Objective											
MAC = Maximum Allowable Concentration											
IMAC = Interim Maximum Allowable Concentration											
* Values in bold indicate possible exceedance of wa											

Appendix A - Chemistry Datasets - Table 184. Aquifer isotope chemistry.

Element or Compound or Measurement	**Units**	**Detection Limit**	**AERI 02-01***	**AERI 02-02***	**AERI 02-05***	**AERI 02-06***	**AERI 02-07***	**AERI 02-08***	**AERI 02-09***	**AERI 02-10***	**AERI 02-11***
Site ID			1	2	5	6	7	8	9	10	11
Sample Date	mm/dd/yyyy		9/30/2002	9/30/2002	10/1/2002	10/1/2002	10/2/2002	10/2/2002	10/3/2002	10/3/2002	10/4/2002
Approximate location			051-20W4	051-204	068-24W4	065-26W4	061-23W4	057-25W5	054-12W4	052-14W4	054-25W4
Well Depth	m		64.0	52.4	16.2	100.6	67.1	36.6	91.5	32.0	61.0
Formation			HC	HC	Belly River	Belly River	Belly River	HC	Belly River	Belly River	HC
Coal Zone			Drumheller	Drumheller	McKay	Taber		Drumheller	McKay	Taber	Drumheller
Water Type			Na-HCO3	Na-HCO3	Ca-Mg-HCO3	Na-HCO3	Na-HCO3-SO4	Na-HCO3-SO4	Na-HCO3	Na-HCO3-SO4	Na-HCO3-SO4
Stable Isotopes											
$^{18}O/^{16}O$ in H_2O	permil		-19.3	-19.5	-17.4	-19.0	-18.5	-18.5	-18.4	-19.3	-17.8
$^{2}H/^{1}H$ in H_2O	permil		-156	-157	-143	-153	-150	-148	-149	-153	-146
^{13}C in CO_2	permil										
^{13}C in DIC from $Sr(HCO_3)_2$	permil		-15.1	-13.3	-13.9	-12.8	-13.9	-15.1	-9.9	-12.8	-24.9
$^{18}O/^{16}O$ in DIC from $Sr(HCO_3)_2$	permil		-14	-15.4	-14.8	-14.4	-13.6	-13.9	-13.9	-14.7	-13.3
$^{34}S/^{32}S$ in SO_4	permil		2.4	3.4	-5.4	12.4	-2.3	-3.8	5.1	-7.0	-5.4
$^{34}S/^{32}S$ in sulphide	permil		4.5	8.4	i.s	0.7	7.1	2.9	0.5	3.7	-1.4
$^{11}B/^{10}B$	permil		43	40	15	59	47	28	39	44	20
Radiogenic Parameters and Isotopes											
$^{87}Sr/^{86}Sr$			0.705428	0.705465	0.706915	0.705240	0.705330	0.705486	0.705955	0.706307	0.705129
$^{87}Sr/^{86}Sr$ standard error			0.000003	0.000005	0.000005	0.000003	0.000009	0.000003	0.000003	0.000003	0.000001
^{14}C	pmC		Analytical difficulties								
^{14}C error	pmC		Analytical difficulties								
Mean $^{36}Cl/Cl$	$x10^{-15}$		362								
Mean $^{36}Cl/Cl$ error	$x10^{-15}$		18								
^{129}I	$x10^{6}$ atoms/L		Insufficient yield								
^{129}I standard error	$x10^{6}$ atoms/L		Insufficient yield								
$^{129}I/I$	$x10^{-15}$										
Gross alpha	Bq/L	varied	<0.1	<0.2	0.5	<0.1	<0.1	0.6	0.6	<0.4	<0.1
Gross beta	Bq/L	varied	<0.1	<0.1	0.3	0.1	0.1	0.3	0.2	0.2	<0.1
^{232}Th	Bq/L	varied	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001
^{234}U	Bq/L	varied									
^{235}U	Bq/L	varied									
^{238}U	Bq/L	varied	<0.03	<0.03	0.02	<0.03	<0.03	<0.03	<0.04	<0.03	<0.03
^{226}Ra	Bq/L	varied		0.13	0.1			0.29	0.2		
^{228}Ra	Bq/L	varied									
^{210}Po	Bq/L	varied		0.05	<0.05			<0.04	0.14		
Notes:											
AO = Aesthetic Objective											
MAC = Maximum Allowable Concentration											
IMAC = Interim Maximum Allowable Concentration											
* Values in bold indicate possible exceedance of water quality guidelines											

Appendix A - Chemistry Datasets - Table 184. Aquifer isotope chemistry.

Element or Compound or Measurement	AERI 02-12*	AERI 02-15*	AERI 02-16AQ*	AERI 02-18*	AERI 02-20*	AERI 02-21*	AERI 02-22*	AERI 02-23*	AERI 02-24*	AERI 02-25*	AERI 02-26*
Site ID	12	15	16	17	18	19	20	21	22	23	24
Sample Date	10/4/2002	10/7/2002	10/8/2002	10/8/2002	10/9/2002	10/9/2002	10/10/2002	10/10/2002	10/11/2002	10/11/2002	10/15/2002
Approximate location	054-25W4	013-06W4	008-02W4	012-06W4	028-06W4	035-17W4	032-14W4	027-21W4	042-25W4	043-23W4	052-21W4
Well Depth	42.7	91.5	50.3	15.2	193.3	53.4	36.6	54.9	132.6	42.1	44.2
Formation	HC	Belly River	Belly River	Belly River	Belly River	HC	HC	HC	Scollard	Paskapoo	HC
Coal Zone	Drumheller			McKay				Daly Weaver	Ardley		Drumheller
Water Type	Na-SO4-HCO3	Na-HCO3-SO4	Ca-Mg-HCO3	Mg-Ca-HCO3	Na-HCO3-Cl	Na-HCO3	Na-HCO3-SO4	Na-HCO3	Na-Cl-HCO3	Na-HCO3	Na-Ca-HCO3-SO4
Stable Isotopes											
$^{18}O/^{16}O$ in H_2O	-18.2	-21.6	-15.9	-13.8	-16.1	-19.9	-19.2	-16.1	-13.0	-17.8	-15.9
$^{2}H/^{1}H$ in H_2O	-148	-164	-137	-118	-137	-164	-160	-138	-117	-151	-134
^{13}C in CO_2											
^{13}C in DIC from $Sr(HCO_3)_2$	-13.0	-17.0	-13.5	-12.3	-27.9	-10.8	-13.7	6.8	17.0	-6.5	-13.9
$^{18}O/^{16}O$ in DIC from $Sr(HCO_3)_2$	-13.3	-16.6	-13.7	-11.3	-12.2	-16	-15.1	-11.2	-9.3	-13.8	-17.4
$^{34}S/^{32}S$ in SO_4	-10.5	1.9	7.6	-0.6	2.9	-4.0	5.5	-0.3	3.3	3.1	-8.0
$^{34}S/^{32}S$ in sulphide	-4.0	7.3	3.9	3.9	i.s	2.3	11.5	5.0	1.2	1.0	-4.2
$^{11}B/^{10}B$	24	40	18	2	37	21	35	24	31	32	11
Radiogenic Parameters and Isotopes											
$^{87}Sr/^{86}Sr$	0.705144	0.707393	0.710181	0.709042	0.706289	0.705982	0.706115	0.705161	0.705513	0.705375	0.705576
$^{87}Sr/^{86}Sr$ standard error	0.000007	0.000005	0.000006	0.000003	0.000007	0.000004	0.000006	0.000008	0.000005	0.000007	0.000006
^{14}C				93.93					<0.36		
^{14}C error				0.46							
Mean $^{36}Cl/Cl$				2160					0.00001		
Mean $^{36}Cl/Cl$ error				80					5.3		
^{129}I				75.5					10.6		
^{129}I standard error				2					0.9		
$^{129}I/I$									2724		
Gross alpha	<0.2	<0.3	0.2	0.1	<0.1	<0.1	0.4	<0.1	<0.1	<0.1	<0.1
Gross beta	0.2	0.1	0.2	0.2	<0.1	<0.1	0.6	<0.1	<0.1	<0.1	0.2
^{232}Th	<0.001	<0.001	0.001	0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
^{234}U											
^{235}U											
^{238}U	<0.04	<0.04	0.12	0.05	<0.05	<0.04	<0.03	<0.04	<0.06	<0.03	<0.03
^{226}Ra			0.1	0.1			0.25				
^{228}Ra											
^{210}Po			0.07	<0.01			<0.09				
Notes:											
AO = Aesthetic Objective											
MAC = Maximum Allowable Concentration											
IMAC = Interim Maximum Allowable Concentration											
* Values in bold indicate possible exceedance of wat											

Appendix A - Chemistry Datasets - Table 184. Aquifer isotope chemistry.

Element or Compound or Measurement	**AERI 02-28***	**AERI 02-29***	**AERI 02-30***	**AERI 02-31***	**AERI 02-32***	**AERI 02-33***	**AERI 02-34***	**AERI 02-35***	**AERI 02-36***	**AERI 02-37***	**AERI 02-38***
Site ID	25	26	27	28	29	30	31	32	33	34	35
Sample Date	10/15/2002	10/16/2002	10/16/2002	10/17/2002	10/18/2002	10/21/2002	10/22/2002	10/22/2002	10/23/2002	10/25/2002	10/25/2002
Approximate location	056-26W4	060-16W4	060-25W4	051-22W4	048-27W4	052-01W5	047-22W4	053-22W4	050-23W4	057-01W5	059-22W4
Well Depth	33.5	29.3	90.9	24.4	19.8	59.5	53.7	38.1	30.5	54.9	21.3
Formation	HC	Belly River	Belly River	HC	Scollard	HC	HC	HC	HC	HC	Belly River
Coal Zone	Drumheller	McKay	Taber		Ardley			Drumheller		Drumheller	Taber
Water Type	Na-HCO3	Na-HCO3-SO4	Na-Cl	Na-Ca-SO4-HCO3	Ca-Na-Mg-HCO3	Na-HCO3-Cl	Na-HCO3	Na-HCO3	Na-SO4-HCO3	Na-HCO3	Na-Ca-HCO3
Stable Isotopes											
$^{18}O/^{16}O$ in H_2O	-13.7	-17.8	-15.0	-17.2	-17.9	-15.8	-19.8	-16.6	-16.8	-16.1	-15.9
$^{2}H/^{1}H$ in H_2O	-129	-150	-126	-143	-143	-132	-164	-146	-145	-133	-137
^{13}C in CO_2											
^{13}C in DIC from $Sr(HCO_3)_2$	-16.6	-16.6	-17.4	-18.4	-14.0	-3.3	-18.8	-14.2	-15.8	0.6	-12.6
$^{18}O/^{16}O$ in DIC from $Sr(HCO_3)_2$	-13.4	-14.4	-13.5	-19.4	-13.2	-10.3	-15.4	-14.2	-12.6	-12.6	-11.1
$^{34}S/^{32}S$ in SO_4	16.5	7.1	-13.5	2.5	5.2	6.7	7.7	4.5	-13.1	n.e.	-5.8
$^{34}S/^{32}S$ in sulphide	n.s.	4.9	3.2	4.4	-11.8	4.0	1.6	-25.8	34.0	-11.9	-8.8
$^{11}B/^{10}B$	23	28	40	17	5	22	4	17	16	15	35
Radiogenic Parameters and Isotopes											
$^{87}Sr/^{86}Sr$	0.706015	0.706036	0.705310	0.707849	0.706325	0.705593	0.705212	0.705276	0.705591	0.705205	0.706200
$^{87}Sr/^{86}Sr$ standard error	0.000003	0.000006	0.000005	0.000008	0.000007	0.000003	0.000003	0.000003	0.000003	0.000004	0.000006
^{14}C			1.09	55.98							
^{14}C error			0.07	0.3							
Mean $^{36}Cl/Cl$			0.00001	4.9							
Mean $^{36}Cl/Cl$ error			3.5	5.7							
^{129}I			1.8	4.3							
^{129}I standard error			0.2	0.3							
$^{129}I/I$			60.2								
Gross alpha	<0.1	<0.3	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2
Gross beta	<0.1	<0.1	<0.1	0.2	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2
^{232}Th	<0.001	<0.001	<0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.001
^{234}U											
^{235}U											
^{238}U	<0.02	<0.03	<0.05	0.06	<0.02	<0.05	<0.03	<0.03	<0.03	<0.02	0.03
^{226}Ra											
^{228}Ra											
^{210}Po											
Notes:											
AO = Aesthetic Objective											
MAC = Maximum Allowable Concentration											
IMAC = Interim Maximum Allowable Concentration											
* Values in bold indicate possible exceedance of wat											

Appendix A - Chemistry Datasets - Table 184. Aquifer isotope chemistry.

Element or Compound or Measurement	**AERI 02-39***	**AERI 02-40***	**AERI 02-41***	**AERI 02-42***	**AERI 02-43***	**AERI-02-44***	**AERI-02-45***	**AERI 02-46***	**AERI 02-47***	**AERI 02-48***	**AERI 02-49***
Site ID	36	37	38	39	40	41	42	43	44	45	46
Sample Date	10/28/2002	10/29/2002	10/29/2002	10/30/2002	10/30/2002	10/31/2002	11/1/2002	11/4/2002	11/12/2002	11/14/2002	11/14/2002
Approximate location	050-23W4	037-01W4	037-02W4	045-11W4	045-11W4	056-24W4	054-05W5	042-17W4	046-27W4	054-04W5	054-04W5
Well Depth	36.6	112.8	98.5	67.7	80.8	43.6	48.8	36.6	22.9	57.9	51.5
Formation	HC	Belly River	Belly River	Belly River	Belly River	HC	Scollard	HC	Scollard	Scollard	Scollard
Coal Zone						Drumheller	Ardley	Drumheller		Ardley	Ardley
Water Type	Na-HCO3-SO4	Na-HCO3-SO4	Na-HCO3-SO4	Na-SO4-HCO3	Na-HCO3-SO4	Na-HCO3	Na-HCO3	Na-HCO3	Na-HCO3	Ca-Na-Mg-HCO3	Ca-Na-HCO3
Stable Isotopes											
$^{18}O/^{16}O$ in H_2O	-16.5	-18.4	-18.4	-18.8	-18.3	-17.7	-17.9	-17.3	-17.6	-16.0	-15.2
$^{2}H/^{1}H$ in H_2O	-141	-154	-151	-155	-151	-145	-147	-144	-146	-137	-131
^{13}C in CO_2											
^{13}C in DIC from $Sr(HCO_3)_2$	-15.0	-14.7	-12.0	-12.3	-10.1	-9.5	-4.9	-13.4	-12.4	-12.8	-12.8
$^{18}O/^{16}O$ in DIC from $Sr(HCO_3)_2$	-11.8	-13.6	-14	-14.5	-13.3	-13.2	-12.2	-11.1	-12.6	-12.1	-12.1
$^{34}S/^{32}S$ in SO_4	-9.6	-4.3	6.3	-10.4	11.5	3.6	n.e.	10.0	6.4	13.5	34.8
$^{34}S/^{32}S$ in sulphide	-6.4	-8.8	-7.8	9.0	-8.6	n.s.	-2.1	0.3	1.9	1.9	6.8
$^{11}B/^{10}B$	0	24	36	30	35	28		24			
Radiogenic Parameters and Isotopes											
$^{87}Sr/^{86}Sr$	0.705260	0.706257	0.706229	0.705733	0.705421	0.705779	0.705353	0.705306	0.705694	0.707659	0.706020
$^{87}Sr/^{86}Sr$ standard error	0.000003	0.000005	0.000005	0.000011	0.000003	0.000005	0.000003	0.000003	0.000009	0.000009	0.000004
^{14}C											
^{14}C error											
Mean $^{36}Cl/Cl$											
Mean $^{36}Cl/Cl$ error											
^{129}I											
^{129}I standard error											
$^{129}I/I$											
Gross alpha	<0.1	<0.1	0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	0.2
Gross beta	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2	0.1
^{232}Th	<0.001	0.004	0.003	<0.001	0.002	<0.001	0.001	<0.001	<0.001	0.001	<0.001
^{234}U											
^{235}U											
^{238}U	<0.03	<0.02	<0.03	<0.03	<0.02	<0.03	<0.03	<0.02	<0.03	<0.02	<0.02
^{226}Ra			0.1	0.12							0.13
^{228}Ra											
^{210}Po			<0.06	<0.09							<0.07
Notes:											
AO = Aesthetic Objective											
MAC = Maximum Allowable Concentration											
IMAC = Interim Maximum Allowable Concentration											
* Values in bold indicate possible exceedance of wat											

Appendix B – Characteristics of Analytical Parameters

Calcium

Calcium (Z = 20, mass = 40.078 ± 4 g/mol) is a Group 2, Period 4 element generally classed as lithophile. Five stable isotopes exist (Firestone, 2000): ^{40}Ca (96.94118% abundance), ^{42}Ca (0.6479%), ^{43}Ca (0.1356%), ^{44}Ca (2.08612%) and ^{46}Ca (0.0043%). A small amount of ^{40}Ca is produced through the radioactive decay of ^{40}K. Nineteen radiogenic isotopes have been observed, with half-lives ranging from 50 ms to 6×10^{18} years (Firestone, 2000). Calcium is used as a chemical reducing agent, as an alloying agent and in the production of vacuum tubes; one of its compounds, CaO, is used in the production of cement (Los Alamos National Laboratory, 2001).

The co-ordination numbers of Ca ions in different mineral structures, and even within the same mineral structure, can vary between 6 and 12. The most common co-ordination numbers are 6 and 8. This variety of co-ordination numbers results in irregularly shaped polyhedral crystal structures and helps explains the complex polymorphism observed in such Ca compounds as CaC_2, $CaCO_3$, $CaSO_4$, CaB_2O_4, $Ca_3(PO_4)_2$, Ca_3SiO_5,Ca_3GeO_5, Ca_2SiO_2, $CaSiO_3$ and $CaAl_2Si_2O_5$ (Hahn and Eysel, 1969).

The cations Na^+, Mg^{2+}, Mn^{2+}, Ce^{3+} and others often are substituted for Ca^{2+} in minerals and other inorganic materials. The results of these common substitutions are the solid-solution series of Ca-compounds in multicomponent systems (e.g., the solid-solution series between $Na(AlSi_3O_8)$ and $Ca(Al_2Si_2O_8)$; Hahn and Eysel, 1969). Calcium is introduced into the hydrosphere through weathering reactions of Ca-bearing minerals such as feldspar, calcite and dolomite.

The Ca content of igneous and metamorphic rocks varies from 5100 ppm in low-Ca granite to 72 000 ppm for basalt (Hitchon et al., 1999). In sedimentary rocks, the range in values is even greater, between 22 100 ppm in shale and 302 300 ppm in carbonate rocks (Hitchon et al., 1999).

An average Ca concentration for Alberta precipitation collected between 1992 and 1999 is 0.50 mg/L. The global mean for Ca concentrations in stream water is 15 mg/L. Most shallow groundwater Ca concentrations vary between 1 and 100 mg/L, with maximum values exceeding 4500 mg/L (Hitchon et al., 1999). Seawater contains approximately 400 mg/L Ca (Usdowski, 1975; Hitchon et al., 1999). Formation water can contain up to 206 000 mg/L Ca (Hitchon et al., 1999).

Magnesium

Magnesium (Z = 12, mass = 24.3050±6 g/mol) is a Group 2, Period 3 element generally classed as a lithophile. Three stable isotopes exist (Firestone 2000): ^{24}Mg (78.993%), ^{25}Mg (10.001%) and ^{26}Mg (11.012%). Fifteen radiogenic isotopes have been observed with half-lives between 20 ms and 20.91 h (Firestone, 2000). Magnesium is used in flares, pyrotechnics and incendiary bombs. It is also used as an alloying agent as well as a reducing agent. In addition, magnesium is added to some conventional propellants; magnesium compounds are used in medicinal and refractory applications (Los Alamos National Laboratory, 2001).

Most magnesium minerals contain Mg in octahedral coordination (Burns and Burns, 1973a). However, magnesium will also be present in four, five and eight-fold coordination (Burns and Burns, 1973a). Rarely, magnesium minerals will form a rock salt type crystal structure (Burns and Burns, 1973a).

Magnesium occurs in a number of silicate minerals in the crust and mantle, many of which form a solid solution series between Mg and Fe end members (Burns and Burns, 1973a). These minerals will host a number of other cations with similar ionic radii to Mg and Fe. These include Mn^{2+}, Co^{2+}, Ni^{2+}, Zn^{2+},

Li^+ and Sc^+ (Burns and Burns, 1973a). Weathering and alteration of these silicate minerals leads to the formation of sheet silicates as well as other products that can be expected to participate in additional reactions (Burns and Burns, 1973a). Chemical weathering of crustal minerals results in the removal of Mg in solution and can lead to the precipitation of evaporite minerals rich in magnesium (Burns and Burns, 1973a). Subsequent weathering and dissolution of these minerals introduces Mg into the hydrosphere.

The Mg content of igneous and metamorphic rocks varies from 1600 ppm in low-Ca granite to 232 000 ppm for ultramafic rocks (Hitchon et al., 1999). In sedimentary rocks, the range in values is less. Magnesium concentrations vary between 7000 ppm in sandstone to 47 000 ppm in carbonate rocks (Hitchon et al., 1999).

An average Mg concentration for Alberta precipitation collected between 1992 and 1999 is 0.09 mg/L. The global mean for Mg concentrations in stream water is 4.1 mg/L (Hitchon et al., 1999). Most shallow groundwater Mg concentrations vary between 0.5 and 50 mg/L with maximum values exceeding 40 000 mg/L (Hitchon et al., 1999). Seawater contains approximately 1290 mg/L (Drever, 1997). Formation water can contain up to 109 000 mg/L (Hitchon et al., 1999).

Sodium

Sodium (Z = 11, mass = 22.989768±6 g/mol) is a Group 1, Period 3 element generally classed as a lithophile. Only one stable isotope exists, ^{23}Na (Firestone, 2000). Eighteen radiogenic isotopes have been observed with half-lives between 1.5 ms and 2.6019 years (Firestone, 2000). Sodium metal is used in the preparation of organic compounds, as an alloying agent, in the descaling process of metals, and in the purification of molten metals (Los Alamos National Laboratory, 2001). Sodium compounds are used in the paper, glass, soap, textile, petroleum, chemical and metal industries (Los Alamos National Laboratory, 2001).

Sodium occurs only in coordination with oxygen and halogen atoms (Cocco et al., 1970a). Coordination numbers vary between 4 and 9, with the majority being either 6 or 8 (Cocco et al., 1970a). The resulting crystal structures resemble distorted octahedron.

As previously discussed, a close relationship exists between sodium and calcium with substitution of Na for Ca and Ca for Na common. The result of this is a number of solid solution series between Na and Ca end members of various minerals. Because both Na and Ca are abundant within the lithosphere, this potential for substitution can affect a large number of natural compounds. Substitution of Na with Li and K takes place only to a very limited extent unless the reactions occur at elevated temperatures at which point substitution reactions are enhanced (Cocco et al., 1970a). Na is introduced into the hydrosphere through weathering reactions of Na-bearing minerals such as feldspars and by the dissolution of evaporite minerals such as halite.

The Na content of igneous and metamorphic rocks varies between 4900 ppm in ultramafic rocks to 28 400 ppm in high-Ca granite (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Sodium concentrations vary between 400 ppm in carbonate rocks to 40 000 ppm in deep-sea clay (Hitchon et al., 1999).

An average Na concentration for Alberta precipitation collected between 1992 and 1999 is 0.11 mg/L. The global mean for Na concentrations in stream water is 6.3 mg/L (Hitchon et al., 1999). Most shallow groundwater Na concentrations vary between 1 and 200 mg/L with maximum values exceeding

130 000 mg/L (Hitchon et al., 1999). Seawater contains approximately 10 760 mg/L (Drever, 1997). Formation water can contain up to 133 000 mg/L (Hitchon et al., 1999).

Potassium

Potassium (Z = 19, mass = 39.0983 g/mol) is a Group 1, Period 4 element generally classed as a lithophile. Two stable isotopes exist (Firestone, 2000): ^{39}K (93.258144% abundance) and ^{41}K (6.730244%). Twenty-three radiogenic isotopes have been observed with half-lives between 10 ms and 1.277 x 10^9 years, only one of which, ^{40}K (half-life 1.277 x 10^9 years), is naturally occurring (Firestone, 2000). This radiogenic isotope is commonly used in dating rocks and minerals. Potassium is used chiefly as a fertilizing agent; potassium compounds have been used as heat transfer mediums (Los Alamos National Laboratory, 2001).

Like Na, K occurs in coordination only with oxygen and halogen atoms. Coordination numbers vary between 6 and 12 with the majority of the atoms forming mineral crystals in six-fold coordination (Cocco et al., 1970b).

The ionic radii of K^+, Rb^+, Ba^{2+}, H_3O^+ and NH_4^+ are similar and as such, traces of these elements can be found in K-rich minerals (Cocco et al., 1970b). The K^+ Ba^{2+} relationship is similar to the Na^+ Ca^{2+} relationship, however because of the lower concentration of Ba^{2+} in nature Ba^{2+} only occurs as a minor constituent in K minerals rather than as a solid solution series (Cocco et al., 1970b). Despite many similarities, substitution of Na for K rarely occurs. When it does occur, elevated temperatures in excess of 600^{o}C are generally required, for instance, at temperatures above 600^{o}C, a solid solution series develops between K-feldspar and albite (Cocco et al., 1970b). Potassium is preferentially fixed in cation exchange reactions with clay minerals and is easily adsorbed on colloids owing to its lower affinity for hydration as compared with Na^+ and Ca^{2+} (Cocco et al., 1970b). K is introduced into the hydrosphere through weathering reactions of K-bearing minerals such as feldspars and by the dissolution of evaporite minerals such as sylvite.

The K content of igneous and metamorphic rocks varies between 170 ppm in ultramafic rocks and 42 000 ppm in low-Ca granite (Hitchon et al., 1999). In sedimentary rocks, the range in values is less. Potassium concentrations vary between 2700 ppm in carbonate rocks and 26 600 ppm in shale (Hitchon et al., 1999).

An average K concentration for Alberta precipitation collected between 1992 and 1999 is 0.088 mg/L. The global mean for K concentrations in stream water is 2.3 mg/L (Hitchon et al., 1999). Most shallow groundwater K concentration vary between 0.5 and 12 mg/L with maximum values exceeding 23 000 mg/L (Hitchon et al., 1999). Seawater contains approximately 399 mg/L (Drever, 1997). Formation water can contain up to 21 800 mg/L (Hitchon et al., 1999).

Iron

Iron (Z = 26, mass = 55.847±3 g/mol) is a Group 8, Period 4 element generally classed as a siderophile. Four stable isotopes exist (Firestone, 2000): ^{54}Fe (5.81% abundance), ^{56}Fe (91.723%), ^{57}Fe(2.21%) and ^{58}Fe (.281%). Twenty-six radiogenic isotopes have been observed with half-lives between 20 ms and 1.5 x 10^6 years (Firestone, 2000). Iron is used extensively in the production of metals and particularly steel (Los Alamos National Laboratory, 2001).

After Al, Fe is the most abundant metal in the continental crust (Ghose, 1968). It occurs in a variety of coordination states. The most common is four-fold coordination, but it will form crystal structures in 5, 6, 7 and 8-fold coordination as well (Ghose, 1968). Iron occurs in coordination with O, halides and sulphur and is present in a wide variety of mineral classes including the oxide, halide, sulphide, phosphate, arsenate and silicate minerals (Ghose, 1968).

The ionic radii of Fe^{2+} and Mg^{2+} are similar allowing for considerable exchange between the two in ferromagnesian minerals (Ghose, 1968). Much of Fe geochemistry is controlled by its valence state and the ease with which it changes from the 2+ to 3+ state and back again (Ghose, 1968). A number of redox reactions occurring in the sedimentary environment therefore influence the state and concentration of Fe. These include oxidation of ferrous minerals to form ferric oxide, reduction of ferric oxide to form iron sulphide, carbonate or glauconite, and adsorption of Fe onto clay minerals (Berner, 1969). Iron generally enters the hydrosphere through the weathering of ferromagnesian minerals and is commonly redeposited as pyrite, siderite, or iron hydroxides depending on redox conditions and ions in solution.

Fe content of igneous and metamorphic rocks varies between 7060 ppm in continental crust rocks and 96 400 ppm in ultramafic rocks (Hitchon et al., 1999). In sedimentary rocks, the range in values is less. Iron concentrations vary between 3300 ppm in carbonate rocks and 65 000 ppm in deep-sea clay (Hitchon et al., 1999).

The global mean for Fe concentrations in stream water is 0.04 mg/L (Hitchon et al., 1999). Most shallow groundwater Fe concentrations generally vary between 0.01 and 1.0 mg/L with maximum values exceeding 8000 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.001 mg/L Fe (Drever, 1997). Formation water can contain up to 490 mg/L (Hitchon et al., 1999).

Manganese

Manganese (Z = 25, mass = 54.93805 g/mol) is a Group 7, Period 4 element generally classed as a lithophile. One stable isotope exists, ^{57}Mn (Firestone, 2000). Twenty-nine radiogenic isotopes have been observed with half-lives between 41 ms and 3.74×10^6 years (Firestone, 2000). Manganese compounds are used in the glass industry, in the manufacture of dry cells, in the preparation of oxygen and chlorine, as drying agents for paints, and as oxidizing agents (Los Alamos National Laboratory, 2001).

Mn may occur in minerals as Mn^{2+}, Mn^{3+} or Mn^{4+} and occasionally, in more than one valence state in the same mineral phase (Peacor, 1970). It occurs in 8 and 4-fold coordination with O, S, OH, F, Cl, Se and As (Peacor, 1970). Mn in coordination with these atoms and molecule forms oxide, sulphide, hydroxide, telluride, selenide, halide, arsenate and silicate minerals.

The ionic radius of Mn^{2+} is similar to that of Fe^{2+}, Mg^{2+} and Ca^{2+}. Substitution between these cations is observed in igneous and metamorphic minerals (Peacor, 1970). Substitution can also be seen in sedimentary rocks such as calcites and dolomites (Peacor, 1970). Manganese enters the hydrosphere through normal rock-weathering reactions.

The Mn content of igneous and metamorphic rocks varies between 390 ppm in low-Ca granite and 1750 ppm in basaltic rocks (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Manganese concentrations vary between 850 ppm in shale and 6700 ppm in deep-sea clay (Hitchon et al., 1970).

The global mean for Mn concentrations in stream water is 0.007 mg/L (Hitchon et al., 1999). Most shallow groundwater Mn concentrations vary between 0.001 and 1.0 mg/L with maximum values exceeding 75 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.0002 mg/L (Drever, 1997). Formation water can contain up to 344 mg/L (Hitchon et al., 1999).

Chlorine

Chlorine (Z = 17, mass = 35.4527±9 g/mol) is a Group 17, Period 3 element generally classed as a lithophile. Two stable isotopes exist (Firestone 2000): ^{35}Cl (75.777% abundance) and ^{37}Cl (24.237%) (Firestone, 2000). Twenty-four radiogenic isotopes exist with half-lives between 150 ms and 3.01 x 10^5 years (Firestone, 2000). One of the radiogenic nuclides of chlorine, ^{36}Cl (half-life 3.01x10^5 years), is used for dating purposes.

This radiogenic isotope is created either cosmogenically, or epigenically. Atmospheric interaction of cosmic radiation with argon gas or ^{35}Cl produces ^{36}Cl. Atmospheric nuclear weapons testing has also generated ^{36}Cl through the interaction of nuclear material with atmospheric gases. Cosmic radiation can penetrate the upper portion of the Earth's crust and interact with isotopes such as ^{35}Cl, ^{39}K and ^{40}Ca to generate ^{36}Cl, radiation and/or subatomic particles. Decay of radionuclides below the penetration depth of cosmic radiation will result in an in-situ neutron flux acting upon the ^{35}Cl present, generating ^{36}Cl (Clark and Fritz, 1997). Although ^{36}Cl primarily enters the hydrological system through precipitation or dry deposition, epigenic ^{36}Cl will also contribute to the total ^{36}Cl content. Because of its conservative nature, Cl tends to remain in solution as it travels through the groundwater system. This fact makes it an excellent tool in the determination of groundwater flow directions and for dating of groundwater, particularly in the Quaternary and latest Tertiary (Clark and Fritz, 1997).

Chlorine compounds are used in the production of paper products, for sanitation purposes, as disinfectants, in pulp bleaching, in textiles processing and in the extraction of bromine (Los Alamos National Laboratory, 2001). Chlorine is used in the production of dyestuffs, petroleum products, medicines, insecticides, food, solvents, paints and plastics (Los Alamos National Laboratory, 2001). Chlorine is a widely used reactant in the preparation of organic compounds, where it is used as an oxidizing and substitution agent (Los Alamos National Laboratory, 2001).

The most abundant halogen in the continental crust is Cl (Brehler, 1973a). Its migration is not affected by acid-alkaline or oxidizing-reducing environments. Cl forms practically no insoluble salts. It occurs in nature only as Cl^- and has a large ionic radius and high electronegativity. As a result, most of the crustal chlorine is found in the oceans and to a lesser extent in inland closed-basin lakes (Brehler, 1973a). Chlorine occurs in 2, 3, 4, 5, 6 and 8-fold coordination (Brehler, 1973a). All elements except the inert gases form chlorides (Brehler, 1973a). Some metal chlorides will form hydrates that contain different numbers of water molecules per formula weight (Brehler, 1973a). Chlorine can also form ion pairs or complex ions with some of the cations present in natural waters such as Na, K, Ca, Cu, Ag, Zn, Hg, Mn, Fe and Pb (Brehler, 1973a). This generally occurs only in waters with high ionic strengths.

In igneous rocks Cl can replace hydroxide in apatite, hornblende and mica (Hitchon et al., 1999). It is difficult to determine the true content of Cl in sedimentary rocks because Cl is present in entrained formation water and it can be easily leached with fresh water (Hitchon et al., 1999). Values listed for Cl in sedimentary rocks are the subject of continued debate (Hitchon et al., 1999).

The Cl content of igneous and metamorphic rocks varies between 45 ppm in ultramafic rocks and 200 ppm in low-Ca granite (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater.

Chlorine concentrations vary between 10 ppm in sandstone and 21 000 ppm in deep-sea clay (Hitchon et al., 1999).

An average Cl concentration for Alberta precipitation collected between 1992 and 1999 is 0.155 mg/L. The global mean for Cl concentrations in stream water is 7.8 mg/L (Hitchon et al., 1999). Most shallow groundwater Cl concentrations vary between 1 and 250 mg/L with maximum values exceeding 180 000 mg/L (Hitchon et al., 1999). Seawater contains approximately 19 350 mg/L (Drever, 1997). Formation water can contain up to 403 000 mg/L (Hitchon et al., 1999).

Nitrogen

Nitrogen (Z = 7, mass = 14.00674±7 g/mol) is a Group 15, Period 2 element generally classed as an atmophile. Two stable isotopes exist (Firestone, 2000): ^{14}N (99.6349% abundance) and ^{15}N (0.3669%). Thirteen radiogenic isotopes have been observed with half-lives between 11 ms and 9.965 m (Firestone, 2000). Nitrogen compounds are used as fertilizers, in the plastics industry, in the livestock industry and as propellants (Los Alamos National Laboratory, 2001).

Nitrogen constitutes 78.084% of the terrestrial atmosphere (Hitchon et al., 1999). It exists in all the oxidation states between +5 to –3 (Baur, 1972). On and below the Earth's surface, the most abundant valence states are 0, -3 and +5 (Hitchon et al., 1999). NO_3^- is the principle form in which nitrogen occurs in groundwater. Dissolved nitrogen is also present as ammonium (NH_4^+), ammonia (NH_3), nitrite (NO_2^-), nitrogen (N_2), nitrous oxide (N_2O) and organic nitrogen. Nitrate consists of one N atom and three oxygen atoms. The oxygen atoms are arranged around the N atom in three-fold coordination. Nitrogen can enter the hydrosphere through a number of mechanisms. Nitrogen oxides occur in the atmosphere naturally and in part because of the combustion of fossil fuels. These oxides undergo various chemical reactions that eventually form $NO_3^-$and ammonia. The nitrate can then be introduced into groundwater through precipitation and aquifer recharge. Nitrate can be directly introduced into groundwater systems from nitrate sources on the land surface, in the soil zone or in shallow subsoil zones through the application of wastes or fertilizers. It can also enter through the ammonification conversion process of organic nitrogen to NH_4^+ followed by the nitrification conversion process of the NH_4^+ to NO_3^-. Ammonification and nitrification generally occur above the water table with the produced NO_3^- leached into groundwater as water migrates through the soil zone to the water table. Nitrate can be removed from groundwater through the reduction of NO_3^- by bacteria to nitrous oxide or nitrogen gas. This process is called denitrification. Because of its high solubility and anionic form, NO_3^- is highly mobile in groundwater systems and migrates along flow paths with little transformation or retardation.

An average NO_3 concentration for Alberta precipitation collected between 1992 and 1999 is 1.109 mg/L. The global mean for NO_3 concentrations in stream water is 1 mg/L (Hitchon et al., 1999). Most shallow groundwater NO_3 concentrations vary between 1 and 10 mg/L with maximum values exceeding 100 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.00031 mg/L (Hitchon et al., 1999). Formation water can contain up to 1150 mg/L (Hitchon et al., 1999).

Sulphur

Sulphur (Z = 16, mass = 32.066±6 g/mol) is a Group 16, Period 3 element generally classed as a chalcophile. Four stable isotopes exist (Firestone, 2000): ^{32}S (95.029% abundance), ^{33}S (0.754%), ^{34}S (4.218%) and ^{36}S (0.021%). Twenty radiogenic isotopes have been observed with half-lives between 21 ms and 87.32 d (Firestone, 2000). Sulphur is used in the manufacture of gunpowder, in the production of rubber, in the production of fungicides and fumigants, in the manufacture of paper and in the production of fertilizers and other chemicals (Los Alamos National Laboratory, 2001).

Sulphur compounds possess many coordination numbers, with three, four and six being the most common (Wuensch, 1970). However, coordination numbers vary between 1 and 17, producing regularly shaped polyhedra to very distorted crystal structures (Wuensch, 1970). In nature, sulphur occurs in four oxidation states, these being –2, +2, +4 and +6, with –2 and +6 being the most common (Hitchon et al., 1999). The sulphide, sulphosalt and sulphate mineral families contain sulphur as their primary constituent. In igneous rocks, sulphur is usually present as metallic sulphide minerals. In sedimentary sequences, sulphur is present in, evaporite deposits as gypsum, anhydrite, barite, celestite and anglesite; in shale as pyrite or other metallic sulphide minerals; and in coal as pyrite or organic sulphur. In most natural water, sulphur is present as dissolved sulphate depending on Eh and pH conditions. Sulphate is introduced into the hydrosphere through the oxidation of sulphide minerals as aerated water comes into contact with these minerals. Reduced sulphur may be volatilized and released in volcanic regions and subsequently oxidized and introduced into groundwater through precipitation, dry fallout or water-rock interaction. Dissolution of evaporite minerals such as gypsum, anhydrite, barite, celestite and anglesite can also introduce sulphate into the groundwater system. Under suitable Eh, pH and temperature conditions, sulphate can be removed from the system by reduction to H_2S or HS^-, either through the action of sulphate reducing bacteria or through thermogenic sulphate reduction. Sulphate can also be removed by precipitation of insoluble sulphate minerals such as barite.

An average SO_4 concentration for Alberta precipitation collected between 1992 and 1999 is 1.217 mg/L. The global mean for SO_4 concentrations in stream water is 11 mg/L (Hitchon et al., 1999). Most shallow groundwater SO_4 concentrations vary between 1 and 250 mg/L with maximum values exceeding 55 000 mg/L (Hitchon et al., 1999). Seawater contains approximately 2710 mg/L (Drever, 1997). Formation water can contain up to 9230 mg/L (Hitchon et al., 1999).

Carbon

Carbon (Z = 6, mass =12.011 g/mol) is a Group 14, Period 2 element generally classed as a siderophile. Two stable isotopes exist (Firestone, 2000): ^{12}C (98.903% abundance) and ^{13}C (1.103%). Thirteen radiogenic isotopes have been observed with half-lives between 14 ms and 5730 years (Firestone, 2000). Carbon-14 (half-life 5730 years) is used in age-dating a variety of materials, including plant material, bones, teeth, textiles and water. It is produced in the upper atmosphere by the bombardment of nitrogen atoms with neutrons generated through the interaction of cosmic rays with atmospheric gases. Spontaneous fission of uranium and other radionuclides can produce hypogenic ^{14}C in the subsurface by neutron activation of ^{14}N or neutron capture by ^{17}O with subsequent α decay. An anthropogenic source of ^{14}C to the atmosphere and biosphere is atmospheric nuclear weapons testing. The neutrons produced by the detonation activate ^{14}N and generate ^{14}C. Approximately ten million carbon compounds have been identified many of which are vital to organic and life processes.

Carbon possesses four valence states, +4, +2, -4 and 0 (Zemann, 1968). Native carbon occurs in 4 or 3 coordination, forming tetrahedral or planar triangular molecular structures with O, H, C and some metals, such as Fe (Zemann, 1968). The most common C containing minerals are the carbonates. Carbon also forms bicarbonate and oxalate minerals and is a dominant constituent in hydrocarbons, and organic matter such as peat and coal. Carbon can be found in igneous rocks such as granite, basalt, ultramafic rocks and carbonatite as elemental carbon or as carbonate.

The geochemistry of carbon in the aqueous environment is determined by the concentration of various dissolved carbon dioxide species and is controlled by pH. These three species are H_2CO_3, HCO_3^- and CO_3^{2-}. Each species occupies a specific pH range, with HCO_3^- being the dominant species in the pH range of most natural waters. The possible sources of carbon dioxide are: CO_2 gas from the atmosphere, gases present in the soil or unsaturated zone generated by respiration of plants and oxidation of organic matter, biologically mediated sulphate reduction, metamorphism of carbonate rocks and mantle outgassing. The various sources can be determined through the use of the stable carbon isotopes (Fritz and Clark, 1997).

The global mean for HCO_3^- in stream water is 53 mg/L (Hitchon et al., 1999). Most shallow groundwater HCO_3^- concentrations vary between 10 and 500 mg/L with maximum values exceeding 7500 mg/L (Hitchon et al., 1999). Seawater contains approximately 142 mg/L (Drever, 1997). Formation waters can contain up to 15 200 mg/L (Hitchon et al., 1999).

Fluorine

Fluorine (Z = 9, mass = 18.9984 g/mol) is a Group 17, Period 2 element generally classed as a lithophile. One stable isotope ^{19}F exists (Firestone, 2000). Fifteen radiogenic isotopes have been observed with half-lives between 59 ms and 109.77 m (Firestone, 2000). Fluorine is used in the isotopic fractionation of uranium for nuclear weapons research, in the manufacture of plastics, in the etching of glass, in refrigerants, in water supplies and toothpaste to prevent tooth decay, and is being considered as a rocket propellant (LANL, 2001).

Fluorine is chemically, the most reactive and electronegative of all the elements (Allman, 1974). Fluorine possesses only one valence state, -1 and is found in 1, 2, 3, 4 and 6-fold coordination in minerals. Fluorine forms simple halide minerals with Na, K, Mg, Ca and Pb. It also forms halides with fluoro anions, oxides, carbonates, borates, sulphates, phosphates and silicates. Because of the similar ionic radii of F^- and OH^-, F^- and OH^- will substitute for one another in crystal structures. This substitution is controlled by the nature of the bond the OH^- molecules are involved in, as well as the H_2O and HF fugacities of the environment (Allman, 1974). Under certain conditions, a complete solid solution series between OH^- and F^- end members is observed (Allman, 1974).

Fluorine is almost all tied up in rock minerals, and only a small percentage of the total is contained in water (Hem, 1989). Weathering of fluorine containing minerals is a source of fluoride to groundwater. Fluoride is commonly associated with volcanic or fumarolic gases, and may in some areas be important contributors to groundwater (Hem, 1989). The substitution of F- by OH- under appropriate pH conditions can also contribute F- to groundwater (Hem, 1989). The dominant form of fluoride in groundwater is F-, while at pH < 3.5, the HF form will occur (Hem, 1989). Fluoride will form complexes with aluminum, beryllium, ferric iron, boron and silica (Hem, 1989) depending on pH conditions. Dissolved fluoride is controlled by fluoride mineral solubility as well as by adsorption onto clay minerals (Hem, 1989).

F content of igneous and metamorphic rocks varies from 100 ppm in ultramafic rocks to 850 ppm in low-Ca granites (Hitchon et al, 1999). In sedimentary rocks, the range in values is greater. Fluorine concentrations vary between 270 ppm in sandstone to 1300 ppm in deep sea clay (Hitchon et al., 1999).

The global mean for F concentrations in stream water is 0.001 mg/L (Hitchon et al., 1999). Most shallow groundwater F concentrations vary between approximately 0.01 and 1.5 mg/L with maximums up to 30 mg/L (Hitchon et al., 1999). Seawater contains approximately 1.3 mg/L (Drever, 1997). Formation waters can contain in excess of 25 mg/L (Hitchon et al., 1999).

Bromine

Bromine (Z = 35, mass = 79.904 g/mol) is a Group 17, Period 4 element generally classed as a lithophile. Two stable isotopes exist (Firestone, 2000): ^{79}Br (50.697% abundance) and ^{81}Br (49.317%). Thirty-nine radiogenic isotopes have been observed with half-lives between 1.5 µs and 57.036 h (Firestone, 2000). Bromine is used in the manufacture of fumigants, flame-proofing agents, water purification compounds, dyes, medicinals, sanitizers and photographic materials (Los Alamos National Laboratory, 2001).

Most Br compounds are similar to corresponding Cl compounds. However, Br is considerably less abundant than Cl and therefore Br compounds are not as common (Hitchon et al., 1999). Four valence states are known for Br. They are –1, +1, +3 and +5 (Brehler, 1973b). Bromine will form mineral structures with a wide range of coordination numbers. Coordination numbers include 1, 2, 3, 4, 5, 6, and 8 (Brehler, 1973b). At low temperatures, Br will form crystals of Br_2 as well as gas hydrates such as $Br_2 \cdot 7^2/_3H_2O$ (Brehler, 1973b). Additionally, Br will form binary bromides with H_2O, complexes with metals such as Cs, Zn, Pt, Na, Cu, Cd, Hg, Al, As, Sn, P and Pb, oxybromides with oxygen and metals like Bi, polyhalides with I, Cl and metals including Cs, and bromates (Brehler, 1973b).

Its large ionic radius prevents Br from being incorporated in most minerals. Bromine can substitute for OH- groups in minerals such as hornblendes, mica and clay minerals (Hitchon et al., 1999). Bromine in natural waters will always be present as Br^- (Hem, 1989). High concentrations in deep-sea clay suggest that adsorption reactions are also a significant means of incorporating Br in sediments and sedimentary rocks (Hitchon et al., 1999). Bromine is an important constituent of seawater and can accumulate through evaporation (Hem, 1989). Evaporite deposits and water associated with these deposits can contain significant amounts of Br. Anthropogenic sources of Br include gasoline additives, fumigants, fire-retardant agents and road salt (Hem, 1989). Interaction of groundwater with any of these sources of Br can introduce Br^- into the hydrogeological system.

The Br content of igneous and metamorphic rocks varies between 0.8 ppm in ultramafic rocks and 4.5 ppm in high-Ca granite (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Bromine concentrations vary between 1 ppm in sandstone and 70 ppm in deep-sea clay (Hitchon et al., 1999).

Bromide in rainwater and snow can vary between 0.005 and 0.15 mg/L (Hem, 1989). The global mean for Br concentrations in stream water is 0.02 mg/L (Hitchon et al., 1999). Most shallow groundwater Br concentrations vary between approximately 0.01 and 0.5 mg/L with maximum values exceeding 1500 mg/L (Hitchon et al., 1999). Seawater contains approximately 67 mg/L (Drever, 1997). Formation water can contain up to 12 300 mg/L (Hitchon et al., 1999).

Iodine

Iodine (Z = 53, mass = 126.90447±3 g/mol) is a Group 17, Period 5 element generally classed as a lithophile. Only one stable isotope exists, ^{127}I (Firestone, 2000). Forty-six radiogenic isotopes have been observed with half-lives between 3.27 µs and $1.57x10^7$ years (Firestone, 2000). Iodine is used as a disinfectant and for other medicinal purposes including the treatment of thyroid gland related diseases, and in the manufacture of photographic materials (Los Alamos National Laboratory, 2001).

Iodine rarely forms separate minerals and is usually found as a minor constituent in other minerals (Hitchon et al., 1999). Its large ionic radius generally precludes most substitution reactions (Hitchon et al., 1999). Five valence states have been identified. They are –1, +1, +3, +5 and + 7 (Brehler, 1973c). Iodine is always univalent in nature but may exist in more than one valence state (Hitchon, 1999). Iodine will form minerals in 1, 2, 3, 4, 5, 6, 7 and 8-fold coordination relationships (Brehler, 1973c). At very low temperatures (below 110°K) I_2 crystallizes (Brehler, 1973c). In addition, I will form interhalogen compounds such as I_2Cl_6, binary iodides like BaHI, oxyiodides of the form BiOI, polyhalides like $Cs(BrI_2)$, iodates such as HI_3O_8, and periodates like $Na(IO_4)$ (Brehler, 1973c).

Iodine is not a particularly abundant element but is widely distributed and is essential to the nutrition of higher animals (Hem, 1989). In turn, the circulation of the element appears to be strongly influenced by biochemical processes (Hem, 1989). Seawater appears to be the most likely source of available I, as evaporation of seawater can lead to concentration of I and even to precipitation of evaporite minerals containing I. In addition, the volatility of the element and some of its salts allows for atmospheric distribution of I (Hem, 1989). Groundwater interaction with any of these sources can transfer I to the groundwater flow system. Thermodynamic calculations show that the IO_3^- form is most stable in both groundwater and seawater (Hem, 1989). Yet both I^- and IO_3^- are present in seawater and Eh pH considerations indicate that I- is the dominant I species in the Eh pH range of natural water (Hem, 1989).

The I content of igneous and metamorphic rocks varies slightly between 0.3 ppm in ultramafic rocks and 0.5 ppm in high-Ca granite, low-Ca granite and basalt (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Iodine concentrations vary between 0.05 ppm in deep-sea clay and 2.2 ppm in shale (Hitchon et al., 1999).

Iodide concentrations in precipitation vary between 0.001 and 0.003 mg/L (Hem, 1989). The global mean for I concentrations in stream water is 0.007 mg/L (Hitchon et al., 1999). Most shallow groundwater I concentrations vary between approximately 0.007 and 10 mg/L with maximum values up to 130 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.064 mg/L (Drever, 1997). Formation waters can contain up to 519 mg/L (Hitchon et al., 1999).

Arsenic

Arsenic (Z = 33, mass = 74.92159±2 g/mol) is a Group 15, Period 4 element generally classed as a chalcophile and therefore tends to concentrate in sulphide minerals and ores. One stable isotope of arsenic exists, ^{75}As (Firestone, 2000). Thirty-four radiogenic isotopes have been observed with half-lives between 16.79 ms and 80.30 d (Firestone, 2000). Arsenic is used in bronzing and pyrotechnic applications (Los Alamos National Laboratory, 2001). Arsenic compounds are used as insecticides, poisons and preservatives; they are also being used increasingly in the production of electronic components (Los Alamos National Laboratory, 2001).

Arsenic possesses five valence states: +5, +3, +1, 0 and –3 (Baur, 1974). In natural water however, arsenic is generally present only in the +5 (arsenate or As(V)) and/or +3 (arsenite or As(III)) state(s) as an oxyanion with the general form(s) $H_nAsO_4^{3-n}$ and/or $H_nAsO_3^{3-n}$ respectively (Welch et al., 1988). Arsenic speciation is thought to be controlled by both pH and Eh. However, the determination of arsenic speciation between arsenite and arsenate is complicated by the fact that speciation is not necessarily predictable from field Eh measurements nor from calculated Eh values based on other measured redox couple concentrations (Welch et al., 1988). Both Cherry et al. (1979) and Yan et al. (2000) however have correlated field measured Eh with calculated Eh values from arsenite and arsenate concentrations. The following general statements about arsenic speciation with respect to pH and Eh (Smedley and Kinniburgh, 2002) can be made.

Under oxidizing conditions:

- under highly acidic conditions, H_3AsO_4 may be present as the dominant species;
- $H_2AsO_4^-$ is the dominant species at pH values below approximately 6.9;
- at pH values greater than 6.9, $HAsO_4^{2-}$ becomes dominant; and
- under highly alkaline conditions, AsO_4^{3-} may be present as the dominant species.

Under reducing conditions:

- at pH less than about 9.2, H_3AsO_3 will predominate;
- at pH greater than 9.2 and less than approximately 12, $H_2AsO_3^-$ will be dominant;
- at pH greater than approximately 12, $HAsO_3^{2-}$ becomes dominant; and
- under highly alkaline conditions, AsO_3^{3-} may be present.

Sources of arsenic are varied and include minerals, rocks, sediments, soil, anthropogenic sources and the atmosphere. Because of its ionic radii in both the As^{3+} and As^{5+} forms, arsenic can substitute for Si^{4+}, Al^{3+}, Fe^{3+} Ti^{4+} and S in numerous minerals (Smedley and Kinniburgh, 2002). Common mineral types include arsenate, sulphide, sulphosalt, arsenide, arsenite oxide minerals, and native arsenic. Two of the most abundant arsenic bearing minerals are arsenopyrite (Smedley and Kinniburgh, 2002) and arsenian pyrite (Nordstrom, 2000). Anthropogenic inputs of arsenic to the environment include: 1) agricultural application of pesticides; 2) use of arsenic as a wood preservative; and 3) use of arsenic in glass manufacturing operations. Arsenic is released into the atmosphere through sources such as volcanic gases and geothermal vents as well as through the burning of fossil fuels and releases from industrial operations.

Processes that lead to release of arsenic into the groundwater system include:

- arsenic-bearing mineral dissolution;
- desorption of arsenic from soil material;
- chemical transformation of arsenic through redox or other processes;
- ion exchange between arsenic and other elements;
- release of arsenic through biological activity;
- release of arsenic through anthropogenic activity; and
- wet or dry deposition of atmospheric arsenic.

Important factors affecting these processes include:

- pH and Eh;
- solution composition;
- competing and complexing ions concentrations;
- aquifer mineralogy;
- reaction kinetics;
- rate of diffusion of gases through the sediment;
- rate of sedimentation; and
- hydraulics of the groundwater system.

Arsenic is removed from the aqueous system through a number of mechanisms, including:

- adsorption or co-precipitation by or with oxides of Fe, Al and Mn;
- adsorption onto clay, carbonate and phosphate minerals;

- adsorption onto organic material;
- co-precipitation with sulphide minerals; and
- oxidation of the more mobile As(III) to the less mobile As(V) by Mn(IV) with subsequent adsorption to oxide or clay minerals.

Arsenic content of igneous and metamorphic rocks varies slightly between 0.8 ppm in ultramafic rocks and 2.2 ppm in basalt (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Arsenic concentrations vary between 1 ppm in sandstone and carbonate rocks and 13 ppm in shale and deep-sea clay (Hitchon et al., 1999).

As concentrations in stream water are approximately 0.002 mg/L (Hitchon et al., 1999). Most shallow groundwater As concentrations vary between approximately <0.001 and 0.05 mg/L with maximum values exceeding 100 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.003 mg/L (Drever, 1997). Formation water can contain approximately 86 mg/L (Hitchon et al., 1999).

Aluminum

Aluminum (Z = 13, mass = 26.981539±5 g/mol) is a Group 13, Period 3 element generally classed as a lithophile. Only one stable isotope exists, ^{27}Al (Firestone, 2000). Twenty radiogenic isotopes have been observed with half-lives between 33 ms and 7.17×10^5 years (Firestone, 2000). Aluminum is used as a construction material, in electrical transmission lines, as an alloying agent and in reflective coatings for heat and light reflection; aluminum compounds are used in glassmaking and as refractory materials (Los Alamos National Laboratory, 2001).

Aluminum is the third most abundant element in the Earth's outer crust (Hem, 1989). It possesses only one valence state in natural systems, +3, and forms minerals with 4, 5 and 6 coordination numbers (Moore, 1971). Aluminum is found in all silicate mineral types, as well as some hydroxide, oxide, sulphate, phosphate and fluoroaluminate minerals (Moore, 1971).

The ionic radius of Al^{3+} allows for substitution into a number of crystal structures (Moore, 1971). Al^{3+} commonly substitutes for Cr^{3+}, Fe^{3+} and Si^{4+}, less commonly for As^{5+}, Be^{2+}, Mn^{2+}, Mn^{3+}, Nb^{5+}, Ti^{4+}, V^{3+}, and rarely for Mg^{2+}, Mo^{6+}, Sn^{4+} and W^{6+} (Moore, 1971). Elements that will substitute for Al^{3+} include B^{3+}, Cr^{3+}, Fe^{3+}, Ga^{3+}, Ge^{4+}, Li^{+}, Mg^{2+}, Mn^{3+}, Sc^{3+}, Si^{4+}, Ti^{4+}, and V^{3+} (Moore, 1971). Weathering of Al-bearing minerals will introduce Al into natural water. However, Al is mostly retained in new solid species such as Al-hydroxides and clay minerals. In solutions with pH < 4, Al occurs as Al^{3+} surrounded by six water molecules (Hem, 1989). At 4 > pH < 4.5, one of the water molecules is replaced by an OH^- molecule (Hem, 1989). Between pH 4.5 and 6.5, polymerization of Al^{3+} and OH^- begins. These polymers will form hexagonal rings of aluminum and hydroxide molecules stretching up to a few hundredths of a micrometer in size (Hem, 1989). Above pH 6.5, Al is present predominantly as $Al(OH)_4^-$ (Hem, 1989). In the presence of sufficient silica, aluminum will precipitate to form poorly crystallized clay minerals (Hem, 1989). If in addition, an organic complexing agent is also present, kaolinite can form (Hem, 1989). Aluminum complexes can occur in the presence of fluoride, phosphate, sulphate and organic compounds such as humic acid. Colloidal and polymerized forms of Al are small enough to pass through 0.45 μm and even 0.1μm filters making absolute determination of dissolved Al in solution difficult (Hem, 1989; Hitchon et al., 1999).

Aluminum content of igneous and metamorphic rocks varies between 12 000 ppm in ultramafic rocks and 82 800 ppm in basalt (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater.

Aluminum concentrations vary between 4200 ppm in carbonate rocks and 84 000 ppm in deep-sea clay (Hitchon et al., 1999).

The global mean for Al concentrations in stream water is 0.05 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.001 mg/L (Drever, 1997).

Antimony

Antimony (Z = 51, mass = 121.757±3 g/mol) is a Group 15, Period 5 element generally classed as a chalcophile. Two stable isotopes exist (Firestone, 2000): ^{121}Sb (57.368% abundance) and ^{123}Sb (42.648%). Forty-nine radiogenic isotopes have been observed with half-lives between 0.44 s and 2.7582 years (Firestone, 2000). Antimony is used in the semiconductor industry to produce infrared detectors, diodes and Hall-effect devices as well as an alloying agent with lead (Los Alamos National Laboratory, 2001). Antimony compounds are used in the manufacture of flame-proofing compounds, paints, enamels and glass (Los Alamos National Laboratory, 2001).

Crystallographically and chemically, antimony is closely related to As and Bi (Kupčík, 1974). Antimony appears to be only about one- tenth as abundant in rocks however (Hem, 1989). Antimony possesses 2 valence states, +3 and +5, with +3 being most common (Kupčík, 1974). Coordination numbers vary according to valence state. In the +3 valence state, Sb-crystals exhibit 4, 5 and 6-fold coordination (Kupčík, 1974). In the +5 valence state, crystals form in 6-fold coordination around the Sb atom (Kupčík, 1974). Antimony is found as metallic Sb; metal alloys; antimonide, sulphide, sulphosalt, sulpho-oxide and sulphohalogenide minerals; and oxygen-containing compounds (Kupčík, 1974).

The ionic radii of +3 and +5 Sb allows for limited substitution of Sb for Fe^{2+}, Fe^{3+}, As^{3+}, Pb^{2+}, Zn^{2+} and Cu^{2+} in rock forming minerals (Kupčík, 1974). Weathering of Sb-containing minerals will release Sb to water. In addition, Sb is thought to possess volatilization tendencies and so could be transported atmospherically (Hem, 1989). In water, under reducing conditions and $4 < pH < 6.5$, Sb can be found as SbO^+ and Sb^{3+}. In the range of natural waters, under reducing conditions with $6.5 < pH < 8$, Sb appears to occur as SbO_2^- or Sb^{5+}. Under oxidizing conditions and $0 < pH < 8$, Sb_2O_5 and SbO^+ appear to be dominant. At pH greater than 8 Sb can exist in a number of forms depending on the extent of the reducing conditions. Under very reducing conditions, Sb^{5+} and SbO_2^- are likely. At pH's greater than 8 and under moderately reducing to oxidizing conditions, Sb is found as SbO_3^-.

The Sb content of igneous and metamorphic rocks varies slightly between 0.1 ppm in ultramafic rocks and 0.3 ppm in basalt (Onishi, 1967a). In sedimentary rocks, the range in values is greater. Antimony concentrations vary between 0.3 ppm in carbonate rocks and approximately 1 ppm in deep-sea clay and shale (Onishi, 1967b).

The Sb concentration in stream water is approximately 0.00007 mg/L (Onishi, 1967c). The range for groundwater is approximately 0.00001 mg/L to 0.00005 mg/L (Onishi, 1967c) with maximums for groundwater approaching 6 mg/L (Hem, 1989). Seawater contains approximately 0.0003 mg/L (Drever, 1997).

Barium

Barium (Z = 56, mass = 137.327±7 g/mol) is a Period 2, Group 6 element generally classed as a lithophile. Seven stable isotopes exist (Firestone, 2000): ^{130}Ba (0.1062% abundance), ^{132}Ba (0.1012%),

^{134}Ba (2.41727%), ^{135}Ba (6.59218%), ^{136}Ba (7.85436%), ^{137}Ba (11.234%) and ^{138}Ba (71.707%). Forty-two radiogenic isotopes exist with half-lives between 2.63 µs and 10.51 years (Firestone, 2000). Barium is used in the manufacture of vacuum tubes (Los Alamos National Laboratory, 2001). Barium compounds are used in white paint, in X-ray applications, in glassmaking, in oil well drilling fluids, as poisons and in pyrotechnics (Los Alamos National Laboratory, 2001).

Barium possesses only one valence state, +2 and forms crystals with 6, 7, 8, 9, 10, 11 and 12-fold coordination (Fischer, 1970a). Of the divalent ions, Ba has the largest ionic radius (Hitchon et al., 1999). Substitution of Ba for Pb^{2+} and Sr^{2+} is common, whereas substitution for K^+ and Ca^{2+} is less extensive (Fischer, 1970a). In turn, Pb^{2+} and Sr^{2+} can substitute for Ba^{2+} in crystal lattices (Fischer, 1970a). Barium forms a variety of minerals, including oxide, halide, nitrate, carbonate, borate, sulphate, phosphate and silicate minerals. Weathering of Ba-minerals will release Ba into water. In dilute solutions barium will be present as Ba^{2+}. As ionic strength increases, ion pairs and complexes form between Ba and CO_3^{2-}, HCO_3^-, OH^-, SO_4^{2-}, acetate, oxalate and succinate (Hitchon et al., 1999). Its concentration in water is controlled to a large extent by the solubility of $BaSO_4$ and $BaCO_3$ (Hem, 1989). The solubility of $BaSO_4$ is very low, on the order of 10^{-10}, whereas the solubility of $BaCO_3$ is similar to that of calcite. In addition, barium can be adsorbed by clay and hydroxide minerals, and by organic matter (Hitchon et al., 1999).

The Ba content of igneous and metamorphic rocks varies between 0.7 ppm in ultramafic rocks and 840 ppm in low-Ca granite (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Barium concentrations vary between 10 ppm in carbonate rocks and sandstone and 2300 ppm in deep-sea clay (Hitchon et al., 1999).

The global mean barium concentration in stream water is 0.02 mg/L (Hitchon et al., 1999). Values for groundwater vary between <0.01 and 1 mg/L with maximum values exceeding 100 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.010 mg/L (Drever, 1997). Formation water can contain up to 5530 mg/L (Hitchon et al., 1999).

Beryllium

Beryllium (Z = 4, mass = 9.012182±3 g/mol) is a Group 2, Period 2 element generally classed as a lithophile. One stable isotope exists, ^{9}Be (Firestone, 2000). Nine radiogenic isotopes have been observed with half-lives between 4.35 ms and 1.51×10^6 years (Firestone, 2000). Beryllium is used as an alloying agent, in X-ray lithography and as a reflector or moderator in nuclear reactors (Los Alamos National Laboratory, 2001).

Beryllium has one valence state, +2 and can form crystals with 3 and 4-fold coordination (Hörmann, 1972a). The small ionic radius of Be prevents its replacement by other ions in crystals making beryllium-containing minerals distinct phases within rocks (Hörmann, 1972a). Because of their small size, Be ions can replace Si in igneous-rock minerals (Hem, 1989). Therefore, Be minerals are predominantly silicates, however, phosphates and borates also occur (Hörmann, 1972a). The concentration of Be in water tends to be controlled by beryllium hydroxide and beryllium oxide solubilities (Hem, 1989). Species in water include Be^{2+}, $BeOH^+$, $Be(OH)_2$ and $Be(OH)_3^-$. Because of its small ionic size and divalent charge, Be is easily fixed to dispersed particles such as organic matter, and essentially removed from solution (Hörmann, 1972b). Beryllium can also form anionic fluoride complexes (Hem, 1989). These complexes are highly mobile in water and are assumed to be the principal means of transportation of Be (Hem, 1989).

The Be content of igneous and metamorphic rocks varies between 0.3 ppm in ultramafic rocks and 4.8 ppm in granite (Hörmann, 1972c). In sedimentary rocks, the range in values is smaller. Beryllium concentrations vary between 0.95 ppm in carbonate rocks and 5.5 ppm in deep-sea clay (Hörmann, 1972d).

Beryllium concentration in stream water is approximately 0.0002 mg/L (Hörmann, 1972e). Values for groundwater vary between 0.0005 and 0.057 mg/L (Hörmann, 1972e). Seawater contains approximately 0.0000006 mg/L (Drever, 1997).

Bismuth

Bismuth (Z = 83, mass = 208.98037±3 g/mol) is a Group 15, Period 6 element generally classed as a chalcophile. It has only one stable isotope ^{209}Bi (Firestone, 2000). Fifty-nine radiogenic isotopes have been observed with half-lives between 44 µs and 3.04×10^6 years (Firestone, 2000). Five of these radiogenic isotopes are naturally occurring. Bismuth-214 (half-life 19.9 m) and -210 (5.013 d) are part of the ^{238}U decay series (Firestone, 2000). Bismuth-212 (half-life 60.55 m) is part of the ^{232}Th decay series (Firestone, 2000). Bismuth-215 (half-life 7.6 m) and -211 (2.14 m) are part of the ^{235}U decay series (Firestone, 2000). Bismuth is used as an alloying agent, as a catalyst for making acrylic fibres, as a thermocouple material and as a carrier for ^{235}U or ^{233}U fuel in nuclear reactors (Los Alamos National Laboratory, 2001). Bismuth compounds are used in cosmetics and for medicinal purposes (Los Alamos National Laboratory, 2001).

Bismuth has one valence state +3 and will form crystals with coordination number of 5, 6 and 8 (Kupčík, 1972). Bismuth is closely related to As, Sb and Pb both crystallographically and chemically (Kupčík, 1972). It shares a similar electronic structure to that of Pb as well as a common geochemical occurrence (Kupčík, 1972). Bismuth is found mainly in sulphide ore deposits and their oxidation zones (Kupčík, 1972). Bismuth can also occurs as a trace element in other rocks. Bismuth minerals include metallic Bi; metal alloys; and sulphide, selenide, telluride, sulphosalt, oxide, oxosalt and halogen oxosalt minerals (Kupčík, 1972). Possible substitution relationships exist between Bi^{3+} and the cations in sulphide minerals such as galena (Kupčík, 1972). Substitution has also been noted between Bi and rare earth elements as well as with Y^{3+} (Kupčík, 1972). A possible association with Ca^{2+} is predicted based on ionic radius considerations, but no such substitution has been observed (Kupčík, 1972). In geological environments Bi is thought to occur as Bi^{3+}, BiO^+, Bi_2S_3 or as BiO(OH) (Ahrens, 1968a). In seawater, BiCl- and BiOCl bismuth species are also thought to exist (Ahrens, 1968a). Bismuth concentration in water is thought to be controlled by the solubilities of Bi_2S_3, BiO(OH) and bismuth carbonate minerals (Ahrens, 1968a).

Bismuth content of igneous and metamorphic rocks varies between 0.18 ppm in basaltic rocks and 0.61 ppm in ultramafic rocks (Ahrens, 1968b). In sedimentary rocks, the range in values is greater. Bi concentrations vary between 0.06 ppm in deep-sea clay and 0.3 ppm in carbonate rocks (Ahrens, 1968c).

The concentration of bismuth in stream water is approximately 0.0003 mg/L (Ahrens, 1968d). Values for groundwater have not been extensively compiled. Seawater contains approximately 0.00002 mg/L (Ahrens, 1968d).

Boron

Boron (Z = 5, mass = 10.811±5 g/mol) is a Group 13, Period 2 element generally classed as a lithophile. Two stable isotopes exist (Firestone, 2000) ^{10}B (19.92% abundance) and ^{11}B (80.12%). Ten radiogenic isotopes have been observed with half-lives between 200 ps and 770 ms (Firestone, 2000). Boron is used in flares, as a rocket igniter, as a control material for nuclear reactors, in radiation shields and in neutron detectors (Los Alamos National Laboratory, 2001). Boron compounds are used in the manufacture of fibreglass insulation, bleach, textiles, antiseptics, glass, pharmaceuticals, electrical insulators, heat conductors, lubricants and aerospace materials (Los Alamos National Laboratory, 2001).

Boron has one valence state, +3 and forms crystal structures with 3 and 4-fold coordination (Christ, 1968). Although it possesses a positive valence, B never behaves as a cation (Christ, 1968). With the exception of two minerals that contain BF_4- tetrahedra, B always occurs in chemical combination with oxygen such as BO_3^{3-}, $H_2BO_3^-$ or $B(OH)_3$ (Hitchon et al., 1999). As such, B does not substitute for cations in crystal structures and instead enters as a B-oxygen group (Christ, 1968). On their own, these groups can polymerize to form polyanions of various complexities possibly including B species of different co-ordinations (Christ, 1968). These crystal structures can contain silicate, phosphate, arsenate, or carbonate groups. The resulting minerals are termed borosilicates, borophosphates, boroarsenates or borocarbonates, of which the borosilicates form the largest group (Christ, 1968). Boron can enter the hydrosphere through the weathering of B-containing minerals such as feldspars, micas, and evaporite minerals. Boron is volatile and may be liberated in volcanic gases and through hydrothermal systems (Hem, 1989). It has a number of industrial applications such as in cleaning products that contain borax. Boron can therefore also enter the hydrosphere through sewage and industrial waste (Hem, 1989). It is present as $H_2BO_3^-$, or $B(OH)_3$ in freshwater solutions and also as $NaB(OH)_4$ in seawater (Harder, 1973). Under most natural water conditions, B is present as $B(OH)_3$ (Hem, 1989). The concentration of B in water is primarily controlled by adsorption or incorporation into clay minerals (Harder, 1973).

The B content of igneous rocks varies between 2 ppm in ultramafic rocks and 10 ppm in low-Ca granite (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Boron concentrations vary between 20 ppm in carbonate rocks and 230 ppm in deep-sea clay (Hitchon et al., 1999).

The global mean for B concentrations in stream water is 0.01 mg/L (Hitchon et al., 1999). Groundwater B concentrations vary between 0.05 to 1 mg/L with maximums exceeding 200 mg/L (Hitchon et al., 1999). Seawater contains approximately 4.5 mg/L (Drever, 1997). Formation water can contain approximately 920 mg/L (Hitchon et al., 1999).

Cadmium

Cadmium (Z = 48, mass = 112.411±8 g/mol) is a Group 12, Period 5 element generally classed as a chalcophile. Seven stable isotopes exist (Firestone, 2001): ^{106}Cd (1.254% abundance), ^{108}Cd (0.892%), ^{110}Cd (12.4912%), ^{111}Cd (12.808%), ^{112}Cd (24.1314%), ^{114}Cd (28.7328 and ^{116}Cd (7.4912%). Thirty-six radiogenic isotopes have been observed with half-lives between 0.20 s and $7.7x10^{15}$ years (Firestone, 2000). Cadmium is used as an alloying agent, in solder, in batteries, in E.M.F. cells and as a nuclear fission control material (Los Alamos National Laboratory, 2001). Cadmium compounds are used in the manufacture of television tubes and as pigments (Los Alamos National Laboratory, 2001).

Cadmium has only one valence state, +2, and can form crystal structures with coordination numbers of 4, 5, 6, 7, 8 and 12 (Brehler, 1972). Cadmium can replace Zn and possibly Ca in mineral structures and forms a number of crystal molecules and complexes including, halogenides, hydroxides, chalcogenides, silicates, complexes with oxygen, water and organic compounds, and metal alloys (Brehler, 1972). In solution, Cd is present as Cd^{2+} or forms complex ions with ammonium, cyanide, halide, sulphide, carbonate, hydroxide or oxygen depending on Eh pH conditions (Wakita, 1969). In the range of natural waters, Cd^{2+} tends to be favoured (Wakita, 1969). Cadmium enters the hydrosphere through weathering of Cd-bearing minerals, through industrial wastes and vaporization through metallurgical processes and combustion of fossil fuels (Hem, 1989). Cadmium concentration in solution appear to be controlled by solubility of $CdCO_3$, coprecipitation with manganese oxides or adsorption onto mineral surfaces (Hem, 1989).

The Cd content of igneous rocks varies between 0.05 ppm in ultramafic rocks and 0.21 ppm in basalt (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Cadmium concentrations vary between 0.035 ppm in carbonate rocks and 0.42 ppm in deep-sea clay (Hitchon et al., 1999).

The global mean for Cd concentrations in stream water is 0.00001 mg/L (Hitchon et al., 1999). Groundwater cadmium concentrations vary between <0.0001 to 0.005 mg/L with maximum values exceeding 3 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.00005 mg/L (Drever, 1997). Formation water can contain approximately 1.02 mg/L (Hitchon et al., 1999).

Chromium

Chromium (Z = 24, mass = 51.9961±6 g/mol) is a Group 6, Period 4 element generally classed as a lithophile. Three stable isotopes exist (Firestone, 2000): ^{52}Cr (83.78918% abundance), ^{53}Cr (9.50117%) and ^{54}Cr (2.3657%). Twenty-three radiogenic isotopes have been observed with half-lives between 21 ms and $1.8x10^{17}$ years (Firestone, 2000). Chromium is used as an alloying agent, as a catalyst and in the glass industry as a pigment (Los Alamos National Laboratory, 2001). Chromium compounds are used for refractory purposes (Los Alamos National Laboratory, 2001).

Chromium has 3 valence states, +2, +3 and +6. In nature, the +3 and +6 valence states are predominant with the +3 state most common (Hitchon et al., 1999). In the +2 and +3 valence states, Cr crystals form with a coordination number of 6. In the +6 valence state, crystals form in 4 and 6-fold coordination with Cr (Matzat, 1970). Trivalent Cr can replace Al^{3+}, Fe^{3+}, Fe^{2+}, Mg^{2+} and Ti^{4+} in crystal structures (Matzat, 1970). Chromium minerals fall into seven categories including: oxides, hydroxides, carbonates, sulphides, chromates and silicates (Matzat, 1970). Because of its ionic size and chemical properties, the Cr^{3+} released through weathering of Cr-bearing minerals is effectively fixed in its residual weathering products (Shiraki, 1975a). Under continued oxidation, Cr^{3+} will form the soluble anion CrO_4^{2-} (Shiraki, 1975a). Six different ionic forms of chromium are considered stable under aqueous conditions. The reduced forms are Cr^{3+}, $CrOH^{2+}$, $Cr(OH)_2^+$ and $Cr(OH)_4^-$ (Hem, 1989). The oxidized forms are $Cr_2O_7^{2-}$ and CrO_4^{2-} (Hem, 1989). In the range of natural waters, $CrOH^{2+}$ and $Cr(OH)_2^+$ are thought to be the dominant forms (Hem, 1989). Chromium concentrations in water are thought to be controlled by the solubility of $Cr(OH)_3$ and CrO_4^{2-}, as well as adsorption onto Fe and Mn-oxides, hydrous Fe and Mn-oxides, apatite, clay and organic matter (Shiraki, 1975b).

The Cr content of igneous rocks varies between 4.1 ppm in low-Ca granite and 1800 ppm in ultramafic rocks (Hitchon et al., 1999). In sedimentary rocks, the range in values is less. Chromium concentrations vary between 11 ppm in carbonate rocks and 90 ppm in deep-sea clay and shale (Hitchon et al., 1999).

The global mean for Cr concentrations in stream water is 0.001 mg/L (Hitchon et al., 1999). Groundwater Cr concentrations vary between <0.001 to 0.005 mg/L with maximum values exceeding 1 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.0002 mg/L (Drever, 1997). Formation water can contain up to 6.7 mg/L (Hitchon et al., 1999).

Cobalt

Cobalt (Z = 27, mass = 58.93320 g/mol) is a Group 9, Period 4 element generally classed as a siderophile. One stable isotope exists, ^{59}Co (Firestone, 2000). Thirty-two radiogenic isotopes have been observed with half-lives between 21 ms and 87.32 d (Firestone, 2000). Cobalt is used as an alloying agent to produce magnetic steel and stainless steel, as well as in electroplating (Los Alamos National Laboratory, 2001). Cobalt compounds are used as pigments in porcelain, glass, pottery tiles and enamels and for medicinal purposes (Los Alamos National Laboratory, 2001).

Cobalt has two valence states, +2 and +3 and forms crystals with a coordination number of 6 (Burns and Burns, 1973b). In the Co^{2+} form, Co can substitute for Mg^{2+} and Fe^{2+} in several silicate minerals (Burns and Burns, 1973b). Cobalt forms metal alloys and sulphide, arsenide and sulphosalt minerals (Burns and Burns, 1973b). The crystal chemistry of Co closely resembles that of Ni, and Co frequently occurs with Ni in a number of minerals (Burns and Burns, 1973b). Cobalt is easily dissolved during weathering and can therefore easily enter the hydrosphere (Turekian, 1976a). Control of cobalt in aqueous solutions appears to be by coprecipitation or adsorption of cobalt by oxides of manganese and iron, the solubilities of $CoCO_3$, Co-phosphates and –hydroxides, and the adsorption of Co onto clay minerals (Turekian, 1976b; Hem, 1989).

The Co content of igneous rocks varies between 3.9 ppm in granite and 110 ppm in ultramafic rocks (Turekian, 1976c). In sedimentary rocks, the range in values is less. Cobalt concentrations vary between 0.8 ppm in carbonate rocks and 48 ppm in deep-sea clay (Turekian, 1976d).

Precipitation concentrations vary from urban to rural areas. In rural areas, concentrations can approach 0.00043 mg/L (Turekian, 1976e). In urban areas the value are greater and approach 0.0014 mg/L (Turekian, 1976e). Co concentrations in stream water are approximately 0.00019 mg/L (Turekian, 1976e). Groundwater cobalt concentrations have not been extensively determined. Seawater contains approximately 0.00003 mg/L (Hem, 1989).

Copper

Copper (Z = 29, mass = 63.546±3 g/mol) is a Group 11, Period 4 element generally classed as a chalcophile. Two stable isotopes exist (Firestone, 2000): ^{63}Cu (69.173% abundance) and ^{65}Cu (30.833%). Thirty radiogenic isotopes have been observed with half-lives between 188 ms and 61.83 h (Firestone, 2000). Copper is extensively used in the electrical industry because of its conductive nature. Copper is also used as an alloying agent to produce brass and bronze (Los Alamos National Laboratory, 2001). Copper is used as a poison and algicide (Los Alamos National Laboratory, 2001).

Copper possesses three valence states, 0, +1 and +2, but only two are common in solution, +1 and +2 (Hem, 1989). In the +1 valence state, Cu has a coordination number of 2, while in the +2 state it has coordination numbers of 4, 5 and 6 (Zemann, 1971). Copper will form metallic Cu, alloy-like phases, sulphides, sulphosalts, selenides, tellurides, arsenides, oxides, hydroxides, oxygen-containing salts, halides, arsenites, tellurites, selenites, iodates, carbonates, sulphates, nitrates, phosphates, arsenates, vanadates, chromates, molybdates, selenates and silicates as well as organic complexes (Zemann, 1971). Copper is extracted from silicates, sulphides and oxides during rock weathering (Wedepohl, 1973a). Industrial uses of Cu can lead to the distribution of Cu in the environment. Copper also can be dissolved from water distribution pipes (Hem, 1989). Copper is present as both Cu^{+} and Cu^{2+} in solution, however the more oxidized form is generally favoured (Hem, 1989). Depending on CO_3, Fe and S concentrations a variety of Cu complexes are likely to make up the Cu species present under most natural water conditions. Copper concentration in solution is therefore controlled by the solubility of the various mineral phases as well as by adsorption onto clay and organic matter (Wedepohl, 1973b).

Copper content of igneous rocks varies between 10 ppm in low Ca-granite and 94 ppm in basalt (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Copper concentrations vary between 4 ppm in carbonate rocks and 250 ppm in deep-sea clay (Hitchon et al., 1999).

Precipitation concentrations can approach 0.0013 mg/L (Wedepohl, 1973c). Copper concentrations in stream water are approximately 0.007 mg/L (Hitchon et al., 1999). Groundwater Cu concentrations vary between <0.001 and 0.1 mg/L, with maximum values exceeding 150 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.0005 mg/L (Drever, 1997). Formation water can contain up to 2.1 mg/L (Hitchon et al., 1999).

Lead

Lead (Z = 82, mass = 207.2 g/mol) is a Group 14, Period 6 element generally classed as a chalcophile. It has three stable isotopes (Firestone, 2000): ^{206}Pb (24.11% abundance), ^{207}Pb (22.11%) and ^{208}Pb (52.41%). Forty-five radiogenic isotopes exist with half-lives between 5.54 ms and 1.4×10^{17} years (Firestone, 2000). Seven of these radiogenic isotopes are naturally occurring. They are ^{214}Pb (half-life 26.8 m), ^{212}Pb (10.64 h), ^{211}Pb (36.1 m) and ^{210}Pb (22.3 years) (Firestone, 2000). Lead-214 and 210 are part of the ^{238}U decay series. Lead-212 is part of the ^{232}Th decay series. Lead-211 is part of the ^{235}U decay series. Lead is used as an alloying agent and is used in solder and antifriction metals (Los Alamos National Laboratory, 2001). Lead is used in storage batteries, as a construction material, as a sound and vibration absorber and as radiation shielding around X-ray equipment and nuclear reactors (Los Alamos National Laboratory, 2001). Lead compounds have been used in paints and insecticides (Los Alamos National Laboratory, 2001). Lead oxide is used in the manufacture of glass (Los Alamos National Laboratory, 2001).

Lead is the most abundant heavy element (atomic number greater than 60) in the Earth's crust (Hitchon et al., 1999). Approximately one third of the Pb present today is from the decay of uranium and thorium (Hitchon et al., 1999). Lead occurs in two valence states, +2 and +4. In the +2 valence state Pb forms mineral crystals with coordination numbers of 4, 6, 8, 9 and 12 (Sahl, 1968). Crystals form in 5, 6 and 8-fold coordination around Pb when it is in its +4 state (Sahl, 1968). Lead forms sulphide, selenide, telluride, sulphosalt, oxide, hydroxide, halogenide, arsenite, selenite, iodate, carbonate, sulphate, tellurate, selenate, chromate, wolframate, molybdate, arsenate, phosphate, vanadate and silicate minerals as well as metallic Pb (Sahl, 1968). Pb^{2+} will substitute for K+ in feldspar and mica and is the dominant form of Pb in the hydrosphere (Wedepohl, 1974). Lead is mobilized during chemical weathering of Pb-bearing minerals. However most if not all the released Pb is adsorbed by the also-generated clay minerals (Wedepohl, 1974). Lead is also release to the environment through the burning of fossil fuels and coal as well as through the smelting of ores (Hem, 1989). Lead pipe used to convey drinking water and solder used to join copper piping are also potential sources of Pb (Hem, 1989). Lead additives in gasoline release Pb to the atmosphere as an aerosol in exhaust gases (Hem, 1989). Lead is present in solution principally as Pb^{2+}, hydroxide complexes, carbonate-sulphate ion pairs and most probably organic complexes (Hem, 1989). The concentration of Pb in natural water is controlled by the low solubility of lead compounds, the adsorption of Pb onto organic surfaces and clay minerals, and the coprecipitation of Pb with manganese dioxide (Hem, 1989).

Lead content of igneous rocks varies between 0.5 ppm in ultramafic rocks and 19 ppm in low-Ca granite

(Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Lead concentrations vary between 9 ppm in carbonate rocks and 80 ppm in deep-sea clay (Hitchon et al., 1999).

Lead concentrations in precipitation vary between 0.0001 mg/L and 0.2 mg/L (Hem, 1989). Lead concentrations in stream water are approximately 0.001 mg/L (Hitchon et al., 1999). Groundwater lead concentrations vary between <0.001 and 0.05 mg/L, with maximum values exceeding 3 mg/L (Hitchon, 1999). Seawater contains approximately 0.0003 mg/L (Drever, 1997). Formation water can contain up to 360 mg/L (Hitchon et al., 1999).

Lithium

Lithium (Z = 3, mass = 6.941±2 g/mol) is a Group 1, Period 2 element generally classed as a lithophile. Two stable isotopes exist (Firestone, 2000): ^{6}Li (7.52% abundance) and ^{7}Li (92.52%). Seven radiogenic isotopes have been observed with half-lives between 8.5 ms and 838 ms (Firestone, 2000). Lithium is used in the manufacture of heat transfer devices, as an alloying agent, in the synthesis of organic compounds, and in the manufacture of glass and ceramics (Los Alamos National Laboratory, 2001). Lithium compounds are used in industrial drying systems, in lubricants and in storage batteries (Los Alamos National Laboratory, 2001).

Lithium possesses only one valence state, +1 and forms mineral crystals with coordination number of 4 or 6 (Cocco et al., 1970c). Lithium forms silicate, phosphate and halide minerals, and can be found as a minor constituent in minerals such as tourmaline, spodumene and lepidolite (Cocco et al., 1970c). Some limited substitution of Na^{+} by Li^{+} is possible (Cocco et al., 1970c). Weathering releases Li^{+} into solution and because of its physical and chemical characteristics it tends to remain in solution (Hitchon et al., 1999). Lithium accumulates in the oceans and is adsorbed onto clay minerals, and into manganese hydroxide and glauconite (Hitchon et al., 1999).

Lithium content of igneous rocks varies between 0.5 ppm in ultramafic rocks and 40 ppm in low-Ca granite (Hitchon et al., 1999). In sedimentary rocks, the range in values is similar. Lithium concentrations vary between 5 ppm in carbonate rocks and 66 ppm in shale (Hitchon et al., 1999).

The lithium concentration in rainwater approaches 0.0005 mg/L (Hitchon et al., 1999). Li concentrations in stream water are approximately 0.003 mg/L (Hitchon et al., 1999). Groundwater lithium concentrations vary between <0.01 and 0.5 mg/L, with maximum values exceeding 10 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.17 mg/L (Drever, 1997). Formation water can contain up to 505 mg/L (Hitchon et al., 1999).

Mercury

Mercury (Z = 80, mass = 200.59±2 g/mol) is a Group 12, Period 6 element generally classed as a chalcophile. It has seven stable isotopes (Firestone, 2000): ^{196}Hg (0.151% abundance), ^{198}Hg (9.978%), ^{199}Hg (16.871%), ^{200}Hg (23.1016%), ^{201}Hg (13.188%), ^{202}Hg (29.862%) and ^{204}Hg (6.874%). Thirty-six radiogenic isotopes have been observed with half-lives between 1.1 ms and 444 years (Firestone, 2000). One radiogenic isotope of mercury, ^{206}Hg (half-life 8.15 m), is naturally occurring (Firestone, 2000). Mercury is used for making thermometers, barometers, diffusion pumps, mercury-vapour lamps, advertising signs, electronic apparatus, pesticides, dental preparations, paint, batteries and catalysts (Los Alamos National Laboratory, 2001). Mercury is also used in the synthesis of other chemical compounds (Los Alamos National Laboratory, 2001).

Mercury has two valence states, +1 and +2 (Grdenić, 1967). In the univalent state, crystals form in three-fold coordination with Hg (Grdenić, 1967). Coordination numbers of 2, 4, 6 and 8 mark crystals that form with divalent Hg (Grdenić, 1967). Mercury forms solid Hg, metal alloys, halogenide, oxide, hydroxide, sulphide, and sulphate minerals, as well as organic complexes (Grdenić, 1967). Mercury can also be found in trace amounts in rock-forming minerals such as feldspars, pyroxenes, amphiboles, calcite and apatite. Weathering of Hg-bearing minerals can introduce Hg into the hydrosphere. Organic complexes are produced by methane-generating bacteria as well as by man (Hem, 1989). Mercury was produced as a byproduct of the electrolysis of sodium chloride to produce sodium hydroxide and chlorine, and is released during smelting operations and fossil fuel combustion (Hem, 1989). Although rare, Hg is well distributed because of its volatile nature. In aqueous solution, under natural water conditions, Hg is present predominantly as Hg_{aq} (Hem, 1989). If sulphur is also present then the possibility of forming HgS in solution is probable. Mercury will also react with organic material and form complexes. The concentration of Hg in solution is controlled by the solubility of HgS, the potential for Hg to volatilize, adsorption onto clay particles and bioconcentration along aquatic food chains (Hem, 1989).

Mercury content of igneous rocks varies between 0.01 ppm in ultramafic rocks and 0.09 ppm in basalt (Hitchon et al., 1999). In sedimentary rocks, the range in values is greater. Mercury concentrations vary between 0.04 ppm in carbonate rocks and 0.4 ppm in shale (Hitchon et al., 1999).

Mercury concentrations in precipitation vary between 0.00005 mg/L and 0.00048 mg/L. Hg concentrations in stream water are approximately 0.00007 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.00003 mg/L Hg (Drever, 1997).

Molybdenum

Molybdenum (Z = 42, mass = 95.94 g/mol) is a Group 6, Period 5 element generally classed as a siderophile. Six stable isotopes exist (Firestone, 2000): ^{92}Mo (14.844% abundance), ^{94}Mo (9.253%), ^{95}Mo (15.925%), ^{96}Mo (16.685%), ^{97}Mo (9.553%) and ^{98}Mo (24.137%). Twenty-nine radiogenic isotopes have been observed with half-lives between 190 ms and 1.00×10^{19} years (Firestone, 2000). Molybdenum is used as an alloying agent, as an electrode and filament material in electronic and electrical applications and as a catalyst in petroleum refining (Los Alamos National Laboratory, 2001). Molybdenum is also used by the nuclear energy industry.

Molybdenum has four valence states, +3, +4, +5 and +6 (Evans, 1973). The most common solid and aqueous species are tetra or hexavalent (Hem, 1989). In the +3, +4 and +5 valence states, Mo forms mineral crystals with a single coordination number, 6 (Evans, 1973). In the hexavalent state, crystals can form in 4, 5, 6 and 7-fold coordination around the Mo atom (Evans, 1973). Molybdenum forms the following mineral types, oxides, sulphides, selenides and molybdates. Solid solution systems have been observed between Mo^{6+}-bearing minerals and W^{6+}-minerals (Evans, 1973). In addition, minor traces of Mo can be found in feldspars, pyroxenes, amphiboles, biotite and sulphide minerals and ores such as sphalerite, pyrite, chalcopyrite, pyrrhotite and galena (Evans, 1973). Under oxidizing conditions, Mo-bearing minerals will undergo oxidation to more soluble Mo^{6+} or molybdates and these compounds will then be leached from the rock and can potentially reach the hydrosphere (Manheim and Landergren, 1978a). Molybdenum is present in fossil fuels and can therefore enter the environment through combustion of these materials (Hem, 1989). Other potential sources include mining and processing operations (Hem, 1989). There are three predominant Mo species present in the aqueous environment. The dominant species at pH's less than 2 is $H_2MoO_4(aq)$, whereas at $2 < pH < 5$, $HMoO_4^-$ is dominant, and at $pH > 5$, MoO_4^{2-} is most common (Hem, 1989). Controls on concentration include solubility metal molybdate solubility, adsorption to ferric oxyhydroxides and bioaccumulation in plants (Hem, 1989).

Molybdenum content of igneous rocks varies between 0.3 ppm in ultramafic rocks and 1.6 ppm in granite (Manheim and Landergren, 1978b). In sedimentary rocks, the range in values is greater. Molybdenum concentrations vary between 0.3 ppm in sandstone and 10.5 ppm in deep-sea clay (Manheim and Landergren, 1978c).

The Mo concentration in rainwater approaches 0.00006 mg/L (Manheim and Landergren, 1978d). Mo concentrations in stream water are approximately 0.0005 mg/L (Manheim and Landergren, 1978d). Groundwater Mo concentrations are approximately the same as stream water 0.0005 mg/L with maximums exceeding 10 mg/L (Manheim and Landergren, 1978d). Seawater contains approximately 0.010 mg/L (Drever, 1997). Formation water can contain up to 0.15 mg/L (Manheim and Landergren, 1978d).

Nickel

Nickel (Z = 28, mass = 58.6934±2 g/mol) is a Group 10, period 4 element generally classes as a siderophile. Five stable isotopes exist (Firestone, 2000): ^{58}Ni (68.0779% abundance), ^{60}Ni (26.2238%), ^{61}Ni (1.1401%), ^{62}Ni (3.6342%) and ^{64}Ni (0.9261%). Twenty-four radiogenic isotopes have been observed with half-lives between 38 ms and 7.6x10^{4} years (Firestone, 2000). Nickel is used as an alloying agent, as a pigment in glass, as a protective coating for other metals, as a catalyst and in storage batteries (Los Alamos National Laboratory, 2001).

Nickel has two valence states, +2 and +3 (Burns and Burns, 1977). In both valence states, Ni forms mineral crystals with a coordination number of 6 (Burns and Burns, 1977). Nickel forms metal alloys, as well as phosphide, carbide, sulphide, selenide, telluride, arsenide, antimonide, sulphosalt, chloride, selenite, carbonate, sulphate, arsenate, phosphate and silicate minerals (Burns and Burns, 1977). Nickel will substitute for Fe in ferrous sulphide and ferromagnesian minerals such as olivine, hornblende, biotite and chlorite (Burns and Burns, 1977). Nickel can also be found as a minor constituent in feldspars and spinel (Burns and Burns, 1977). Nickel is easily mobilized during weathering reactions, but many times it is re-precipitated shortly after dissolution (Turekian, 1977a). Nickel is used in many industrial applications and can therefore make its way into the environment through waste products. Nickel concentrations in aqueous solution appear to be controlled by the solubility of Ni-phosphate, -carbonate, -sulphide and -hydroxide, as well as by the potential for Ni to coprecipitate with manganese oxides (Turekian, 1977b).

The Ni content of igneous rocks varies between 9.6 ppm in granite and 1300 ppm in ultramafic rocks (Turekian, 1977c). In sedimentary rocks the range is values is less. Nickel concentrations vary between 4.5 ppm in carbonate rocks and 55.6 ppm in shale (Turekian, 1977d).

The Ni concentration in stream water is approximately 0.010 mg/L (Hem, 1989). Groundwater Ni concentrations are approximately 0.00056 mg/L (Turekian, 1977e). Seawater contains approximately 0.0005 mg/L (Drever, 1997).

Rubidium

Rubidium (Z = 37, mass = 85.4678±3 g/mol) is a Group 1, Period 5 element generally classed as a lithophile. One stable isotope exists, ^{85}Rb (Firestone, 2000). Thirty-nine radiogenic isotopes have been observed with half-lives between 7.8 ms and 4.75x10^{10} years (Firestone, 2000). Only one of these radiogenic isotopes, ^{87}Rb (half-life 4.75x10^{10} years) is naturally occurring (Friedlander et al., 1981). Rubidium is used in the manufacture of vacuum tubes, photocells and glass (Los Alamos National Laboratory, 2001).

Rubidium occurs most commonly in the +1 valence state (Cocco et al., 1970d). In this state, it attains the electronic configuration of the noble gas krypton. Rubidium does not form minerals of its own, but is dispersed in other minerals (Cocco et al., 1970d). Because of similarities between their ionic radii, Rb is associated with K, Tl, Cs and H_3O^+ in a variety of minerals, including leucite, lepidolite, potassium chloride, microcline, muscovite, biotite, pollucite and rhodizite (Cocco et al., 1970d). Rubidium crystals tend to form with coordination numbers of 4, 6, 7, 8, 9, 10, 12 and 14 (Cocco et al., 1970d). Rubidium is released through weathering reactions and forms soluble weathering products. Adsorption and ion exchange can contribute to the removal of Rb from solution (Heier and Billings, 1970a).

The Rb content of igneous rocks varies between 0.072 ppm in some dunite and 910 ppm in some granite (Heier and Billings, 1970d). In sedimentary rocks the range in values is less. Rubidium concentrations vary between 45 ppm in some dolomites and 164 ppm in some shale (Heier and Billings, 1970b).

The Rb concentration in stream water is approximately 0.001 mg/L (Heier and Billings, 1970c). Groundwater Rb concentrations are similar to that of stream water and are approximately 0.0001 mg/L (Drever, 1997). Seawater contains approximately 0.12 mg/L (Drever, 1997). Formation water can contain upwards of 18.8 mg/L (Heier and Billings, 1970c). Hydrothermal water can contain between 0.01 and 7.7 mg/L (Heier and Billings, 1970c).

Scandium

Scandium (Z = 21, mass = 44.955910±9 g/mol) is a Group 3, Period 3 element generally classed as a lithophile. One stable isotope exists, ^{45}Sc (Firestone, 2000). Twenty-eight radiogenic isotopes have been observed with half-lives between 182.3 ms and 83.79 d (Firestone, 2000). Scandium is used in the manufacture of high-intensity lights and as a tracing agent in the petroleum industry (Los Alamos National Laboratory, 2001). Scandium compounds are used in the manufacture of mercury vapour lamps (Los Alamos National Laboratory, 2001).

Under natural conditions, Sc occurs only in the +3 valence state (Frondel, 1969a). Because of its electronic configuration, Sc has, in the past, been classed with the lanthanides (Z between 57 and 71) and shares certain chemical behaviours with these elements (Frondel, 1969a). However, the crystal chemistry of Sc is significantly different from that of the other lanthanides. In fact Sc in this respect is related more closely to Fe^{3+}, Al^{3+} and In^{3+} (Frondel, 1969a). Scandium does not form its own minerals and is therefore introduced into mineral crystals through substitution. Scandium may substitute for Fe^{2+}, Fe^{3+}, Al^{3+}, Y^{3+}, Ti^{4+}, Zr^{4+}, U^{4+}, Th^{4+}, Ce^{4+} and W^{6+} (Frondel, 1969a). The atoms surrounding the Sc atom are generally in 6, 7 or 8-fold coordination (Frondel, 1969a). Minerals associated with Sc include garnets, micas, pyroxenes, cassiterite, wolframite and rutile (Frondel, 1969a). Weathering of Sc-bearing minerals followed by complexation is the most likely pathway for release of Sc into groundwater (Frondel, 1969b). Sc can form hydrated complexes, as well as complexes with SO_4, CO_3, HCO_3, F and amines. The hydrated complexes form the more soluble compounds (Frondel, 1969b). Scandium concentration is controlled by the presence of alkali species in solution, by the presence of the phosphate ion in solution and by the presence of hydrous iron and aluminum oxide and clay minerals (Frondel, 1969b). Alkali compounds can form insoluble basic salts below a pH of 8.5 (Frondel, 1969b). Phosphate ions and phosphorus complexes are also effective at removing Sc from solution (Frondel, 1969b).

Scandium content of igneous rocks varies between 1 ppm in some granite, syenite, peridotite and dunite and 200 ppm in some pyroxenite and hornblendite (Frondel, 1969c). In sedimentary rocks the range in values is greater. Scandium concentrations vary between 0.4 ppm in some limestone and 500 ppm in some phosphatic shale (Frondel, 1969d).

The scandium concentration in stream water is approximately 0.000004 mg/L (Drever, 1997). Seawater contains approximately 0.0000004 mg/L (Drever, 1997).

Selenium

Selenium (Z = 34, mass = 78.96±3 g/mol) is a Group 16, Period 4 element generally classed as a chalcophile. Five stable isotopes exist (Firestone, 2000): ^{74}Se (0.892% abundance), ^{76}Se (9.3611%), ^{77}Se (7.636%), ^{78}Se (23.789%) and ^{80}Se (49.611%). Thirty radiogenic isotopes have been observed with half-lives between 60 ms and 1.08×10^{20} years (Firestone, 2000). Selenium is used as a photographic toner, an alloying agent, to decolourise glass and as a pigment for glass and enamel (Los Alamos National Laboratory, 2001). Selenium is also used in the manufacture of photocells, exposure meters for photographic use, solar cells, rectifiers and semiconductors (Los Alamos National Laboratory, 2001).

Selenium has four valence states, -2, 0, +4 and +6 (Fischer and Zemann, 1973). The most commonly displayed states are –2 and +6 (Fischer and Zemann, 1973). In the –2 state, crystals form with coordination numbers of 6 or 8 whereas in the hexavalent state, mineral crystals form in 4 or 6-fold coordination around the Se atom (Fischer and Zemann, 1973). Selenium forms the following mineral types, native selenium, selenide, sulphosalt, oxide, selenate and selenite minerals (Fischer and Zemann, 1973). Selenium substitutes for sulphur in many sulphide minerals including galena, sphalerite, pyrite, chalcopyrite, pyrrhotite, arsenopyrite and marcasite (Fischer and Zemann, 1973). Weathering reactions will oxidize Se-bearing minerals releasing Se in its +6 form. In this form, Se is highly mobile and is not readily adsorbed onto iron oxyhydroxide surfaces (Hitchon et al., 1999). Selenium can also be introduced through metal mining, smelting and refining activities. Under groundwater conditions, Se can be present in a number of forms depending upon Eh pH conditions and the concentrations of other elements such as iron and sulphur. Under oxidizing conditions, Se is present as SeO_4^{2-} (Hitchon et al., 1999). At intermediate redox levels, the SeO_3^{2-} species are dominant with native Se becoming predominant as reducing conditions continue to develop until under highly reducing conditions, H_2Se and HSe^- occur (Hitchon et al., 1999). Controls on Se concentration in aqueous solutions include coprecipitation as pyrite (if iron is present in solution), the low solubilities of elemental Se and SeO_3^{2-} species, the potential of the SeO_3^{2-} to be adsorbed to iron oxyhydroxides and the uptake and concentration by plant material (Hem, 1989).

Because Se does not occur in silicate minerals, Se content of igneous rocks does not vary from rock type to rock type and is typically 0.05 ppm (Leutwein, 1971). In sedimentary rocks the range in values is greater. Selenium concentrations vary between 0.05 ppm in sandstone and 0.6 ppm in shale (Hitchon et al., 1999).

The selenium concentration in stream water is approximately 0.00006 mg/L (Hitchon et al., 1999). Groundwater selenium concentrations vary between <0.0001 and 0.01 mg/L, with maximum values exceeding 0.1 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.0001 mg/L (Drever, 1997). Formation water can contain upwards of 10 mg/L (Hitchon et al., 1999).

Silicon

Silicon (Z = 14, mass = 28.0855±3 g/mol) is a Group 14, Period 3 element generally classed as a lithophile. Three stable isotopes exist (Firestone, 2000): ^{28}Si (92.23% abundance), ^{29}Si (4.67%) and ^{30}Si (3.10%). Eighteen radiogenic isotopes have been observed with half-lives between 6 ms and 150 years (Firestone, 2000). Silicon compounds are used in the construction industry, as a refractory materials and in the manufacture of enamels, pottery, glass, stainless steel, electronic components, abrasives and silicones (Los Alamos National Laboratory, 2001).

Silicon is second only to oxygen in abundance in the Earth's crust (Hem, 1989). It has a valence state of +4 and forms mineral crystals with coordination numbers of 4 or 6 (Liebau, 1972). Silicon occurs predominantly at the centre of a tetrahedral arrangement with oxygen. This molecule is the fundamental building block of most silicate minerals. These tetrahedra link to form six principle patterns. The resulting mineral crystal structure is a function of the relative abundance of oxygen in the rock compared to the abundance of Si. Silicate minerals are classed as nesosilicates, sorosilicates, cyclosilicates, inosilicates, phyllosilicates or tectosilicates based on these abundances. Silicon also occurs as elementary silica, SiC, SiC-6H, SiO_2 and SiO_6 octahedra (Liebau, 1972). Cations such as B^{3+}, Be^{2+}, Al^{3+}, Ge^{4+}, Fe^{3+} and Ti^{4+} can substitute for Si^{4+} (Liebau, 1972). Weathering reactions of silicate rocks are the most important source of Si in the hydrosphere. In aqueous solutions, Si is present predominantly as $Si(OH)_4$ or H_4SiO_4. Fluorosilicate complexes are believed to occur in water associated with volcanism (Hem, 1989). Silicon concentration in natural waters is thought to be controlled by the solubility of amorphous silica and perhaps by the solubility of amorphous clay minerals (Hem, 1989).

The Si content of igneous rocks varies between 198 000 ppm in ultramafic rocks and 347 000 ppm in low-Ca granite (Hitchon et al., 1999). In sedimentary rocks the range in values is greater. Silicon concentrations vary between 24 000 ppm in carbonate rocks and 368 000 ppm in sandstone (Hitchon et al., 1999).

The silicon concentration in stream water is approximately 13.9 mg/L (Hitchon et al., 1999). Groundwater silicon concentrations vary between 5 and 50 mg/L, with maximum values exceeding 1700 mg/L (Hitchon et al., 1999). Seawater contains approximately 2.8 mg/L (Hitchon et al., 1999). Formation water can contain upwards of 3250 mg/L (Hitchon et al., 1999).

Silver

Silver (Z = 47, mass = 107.8682±2 g/mol) is a Group 11, Period 5 element generally classed as a chalcophile. Two stable isotopes exist (Firestone, 2000): ^{107}Ag (51.8397% abundance) and ^{109}Ag (48.1617%). Fifty-eight radiogenic isotopes have been observed with half-lives between 1.5 ms and 418 years (Firestone, 2000). Silver is used as an alloying agent, in the manufacture of jewellery, paints, electrical contacts, printed circuits, mirrors, batteries, photographic supplies, glass and currency (Los Alamos National Laboratory, 2001).

Silver has 2 valence states, +1 and +3 (Frueh, 1967). In the univalent form, mineral crystals have coordination numbers of 2, 4, 5, 6, 7 or 8 (Frueh, 1967). In its trivalent state, Ag crystals form in four-fold coordination around the Ag atom (Frueh, 1967). Silver mineral types include, telluride, selenide, arsenide, antimonide, sulphide, sulphosalt, halide, carbonate, sulphate, phosphate, and oxide minerals, native silver and metal alloys (Frueh, 1967). Silver is most commonly found in its univalent state in nature and as a sulphide or a sulphosalt mineral forming distorted polyhedra (Frueh, 1967). Silver can also be found as a minor constituent in feldspars, micas, hornblende and pyroxenes (Frueh, 1967). Weathering of Ag-containing minerals can introduce Ag into the environment. However, most Ag salts are insoluble and Ag^+ is rapidly adsorbed by oxide minerals and organic matter (Vincent, 1974). Industrial wastes, biocidal treatment of water and cloud seeding can also introduce Ag into the hydrosphere (Hem, 1989). Silver is generally present as Ag^+ in dilute aqueous solutions and under reducing conditions will form native Ag (Hitchon et al., 1999). In the presence of S or Cl, Ag will form ion pairs so that under reducing conditions, Ag_2S can form in addition to native Ag, whereas under oxidizing conditions Ag^+, $AgCl_2^-$ and $Ag(OH)_2^-$ can be present (Hitchon et al., 1999). The concentration of Ag in aqueous solutions is controlled by the solubility of Ag metal, the Eh pH regime as well as the presence of organic matter and the concentration of Fe and Mn in solution. The Eh pH regime does not directly affect the state of the Ag^+ ion, but affects the mobility of Ag salts and the stability of other ions in solution. Under acidic conditions in soils, Ag salts are generally more mobile and soluble , whereas under more alkaline conditions the oxide or hydroxide form can precipitate immediately (Vincent, 1974). Silver forms mobile species with SO_4^{2-}, $S_2O_3^-$, NO_3^-, HCO_3^- and Cl^- and immobile species with H_2S, S_2^-, PO_4^{3-}, Br^-, I^-, CrO_4^{2-} and AsO_4^{3-} (Vincent, 1974).

The Ag content of igneous rocks varies between 0.05 ppm in ultramafic rocks and 0.11 ppm in basalt (Hitchon et al., 1999). In sedimentary rocks the range in values is less. Silver concentrations vary slightly between 0.01 ppm in carbonate rocks and sandstone and 0.11 ppm in deep-sea clay (Hitchon et al., 1999).

The Ag concentration in stream water is approximately 0.0003 mg/L (Hitchon et al., 1999). Groundwater Ag concentrations have not been extensively compiled. Seawater contains approximately 0.00004 mg/L (Drever, 1997). Formation water can contain upwards of 7.9 mg/L (Hitchon et al., 1999).

Strontium

Strontium (Z = 38, mass = 87.62 g/mol) is a Group 2, Period 5 element generally classed as a lithophile. Four stable isotopes exist (Firestone, 2000): ^{84}Sr (0.561% abundance), ^{86}Sr (9.861%), ^{87}Sr (7.001%) and ^{88}Sr (82.581%). Strontium-87 is also produced through the radioactive decay of ^{87}Rb. Thirty-two radiogenic isotopes have been observed with half-lives between 69 ms and 28.79 years (Firestone, 2000). Strontium is used in the manufacture of colour television picture tubes, magnets, pyrotechnics and flares (Los Alamos National Laboratory, 2001). Strontium is also used in the refining of zinc (Los Alamos National Laboratory, 2001).

Strontium occurs in the +2 valence state only and forms mineral crystals with coordination numbers of 6, 7, 8, 10 and 12 (Fischer, 1970b). Strontium forms halide, oxide, carbonate, borate, sulphate, phosphate, arsenate, vanadate and silicate minerals (Fischer, 1970b). Because of its ionic size, Sr^{2+} will substitute for, and be substituted for by, Ca^{2+}, Ba^{2+} and Pb^{2+} (Hitchon et al., 1999). Strontium can therefore be found as a trace element in feldspars, micas, amphiboles, pyroxenes, olivine, garnet, apatite, calcite and sphene (Fischer, 1970b). Weathering of Sr-bearing minerals releases Sr into solution as Sr^{2+} and under dilute conditions, this is the dominant form. As ionic strength and pH increase ion pairs such as $Sr(OH)_3^-$, $SrCO_3$, $SrHCO_3^+$, $SrSO_4$ and organic complexes become important (Hitchon et al., 1999). Up to a pH of approximately 4.5, Sr^{2+} is the dominant form, whereas from $4.5 < pH < 8$, $SrSO_4$ is predominant, and at $pH > 8$, $SrCO_3$ is most likely (Hitchon et al., 1999). The concentration of Sr in solution is controlled mainly by the solubility of $SrCO_3$ or $SrSO_4$ (Hitchon et al., 1999). Adsorption of Sr onto clay minerals is also thought to be of importance.

The Sr content of igneous rocks varies between 0.7 ppm in ultramafic rocks and 840 ppm in low-

Ca granite (Hitchon et al., 1999). In sedimentary rocks the range in values is greater. Strontium concentrations vary between 10 ppm in carbonate rocks and sandstone to 2300 ppm in deep-sea clay (Hitchon et al., 1999).

The Sr concentration in stream water is approximately 0.02 mg/L (Hitchon et al., 1999). Groundwater Sr concentrations vary between < 0.01 to 1 mg/L with maximum values exceeding 100 mg/L (Hitchon et al., 1999). Seawater contains approximately 8.1 mg/L (Drever, 1997). Formation water can contain upwards of 5530 mg/L (Hitchon et al., 1999).

Thallium

Thallium (Z = 81, mass = 204.3833 g/mol) is a Group 13, Period 6 element generally classed as a chalcophile. Two stable isotopes exist (Firestone, 2000): ^{203}Tl (29.52414% abundance) and ^{205}Tl (70.47614%). Fifty-seven radiogenic isotopes have been observed with half-lives between 572 μs and 3.78 years (Firestone, 2000). Four of the radiogenic isotopes are naturally occurring, ^{210}Tl (half-life 1.3 m) and ^{206}Tl (4.199 m) are part of the ^{238}U decay series, ^{208}Tl (3.053 m) is part of the ^{232}Th decay series, and ^{207}Tl (4.77 m) is part of the ^{235}U decay series (Firestone, 2000). Thallium compounds are used in the manufacture of photocells, infrared optical materials and glass (Los Alamos National Laboratory, 2001). Thallium compounds have been used as rodenticides and insecticides, as well as for medicinal purposes (Los Alamos National Laboratory, 2001).

Thallium has two valence states, +1 and +3 (Sahl, 1972). In the univalent state, mineral crystals have coordination numbers of 6, 8 or 12 (Sahl, 1972). Crystals form in 6 or 8-fold coordination around the Tl^{3+} ion (Sahl, 1972). Thallium forms oxide, sulphide and selenide minerals (Sahl, 1972). Tl can also be found in trace amounts in feldspars, olivine, pyroxenes, micas, amphiboles, apatite, garnet, tourmaline, beryl, leucite and even opal (Sahl, 1972). Thallium appears to be largely retained during the weathering process (de Albuquerque and Shaw, 1970a). Therefore the weathered rock Tl content will be similar to that of the unaltered rock. In the natural environment Tl is present as Tl^{+} and only under strongly oxidizing conditions will it be present in the +3 form (de Albuquerque and Shaw, 1970b). Tl^{3+} is commonly encountered in the oxidized zones of mineral deposits (de Albuquerque and Shaw, 1970b). Its presence in sedimentary rocks suggests that it is somewhat mobile, but thallium's low concentrations in water and enrichment in sedimentary rocks suggest it is effectively removed (de Albuquerque and Shaw, 1970b). The Tl concentration in aqueous solutions appears to be principally controlled by adsorption onto clay minerals (de Albuquerque and Shaw, 1970b).

The Tl content of igneous rocks varies between 0.28 ppm in basalt and 1.62 ppm in granite (de Albuquerque and Shaw, 1970c). In sedimentary rocks the range in values is similar. Thallium concentrations vary between 0.055 ppm in carbonate rocks and 1.05 ppm in sandstone (de Albuquerque and Shaw, 1970d).

Groundwater Tl concentrations are approximately 0.0023 mg/L (de Albuquerque and Shaw, 1970e). Seawater generally contains <0.00001 mg/L (Drever, 1997). Formation water can contain upwards of 0.007 mg/L (de Albuquerque and Shaw, 1970e).

Thorium

Thorium (Z = 90, mass = 232.0381 g/mol) is a Group 4 actinoid element generally as a lithophile. No stable isotopes exist. Thirty radiogenic isotopes have been observed with half-lives between 109 ns and 1.405x10^{10} years. Six of these radiogenic isotopes, ^{227}Th (half-life 18.72 d), ^{228}Th (1.9116 years), ^{230}Th (7.538x10^4 years), ^{231}Th (25.52 h), ^{232}Th (1.405x10^{10} years), ^{234}Th (24.10 d) are naturally occurring (Firestone, 2000). Thorium is used in the preparation of the 'Welsbach mantle' used for portable gas lights, as an alloying element for magnesium, as a tungsten wire coating used in electronic equipment, to control the grain size of tungsten used for electric lamps, for high-temperature laboratory crucibles, as a catalyst for the conversion of ammonia to nitric acid, in petroleum cracking, in sulphuric acid production and as a nuclear fuel (Winter, 2003a).

Thorium only has one valence state, +4. It predominantly forms oxides, but will also form phosphates and replace other atoms in crystal lattices. Thorium is more abundant than U in most types of rock (Hem, 1989) and is now thought to be about as abundant as Pb or Mo in the Earth's crust (Los Alamos National Laboratory, 2001). Thorium is recovered commercially from the mineral monazite as well as from thorite and thorianite (Winter, 2003a). The low solubility of thorium oxides tends to keep Th in mineral structures (Hem, 1989). However, complexation with organic and inorganic ligands can enhance Th mobility (Hem, 1989).

Thorium concentrations in igneous rocks are between 2.7 ppm in basalt and 14 ppm in granite (Drever, 1997). In sedimentary rocks the range in values is similar. Thorium concentrations vary between 2 ppm in limestone and 12 ppm in shale (Drever, 1997).

Stream water thorium concentrations are approximately 0.0001 mg/L (Drever, 1997). Seawater contains approximately 0.00004 mg/L (Winter, 2003a).

Titanium

Titanium (Z = 22, mass = 47.88±3 g/mol) is a Group 4, Period 4 element generally classed as a lithophile. Five stable isotopes exist (Firestone, 2000): ^{46}Ti (8.01% abundance), ^{47}Ti (7.31%), ^{48}Ti (73.81%), ^{49}Ti (5.51%) and ^{50}Ti (5.41%). Nineteen radiogenic isotopes have been observed with half-lives between 26 ms and 63 years (Firestone, 2000). Titanium is used as an alloying agent, as a pigment in paint and as a reflector of infrared radiation (Los Alamos National Laboratory, 2001).

Titanium is widely distributed in rocks and soil. It possesses 3 valence states, +2, +3 and +4 (Tillmans, 1972). Both the divalent and trivalent species form mineral crystals with 6-fold coordination around the Ti ion (Tillmans, 1972). Coordination numbers of 5 or 6 characterize crystals formed with Ti^{4+} (Tillmans, 1972). Only the Ti^{4+} species is expected to be present in the natural environment (Hem, 1989). Titanium forms titanate, silicate, borate, nitride, sulphide, oxide and hydroxide minerals (Tillmans, 1972). Titanium can substitute for Al^{3+}, Fe^{3+}, Nb^{5+}, Ta^{5+} and Mn^{3+} and can therefore be found as a trace constituent in a number of other mineral types such as iron oxides, sulphides, garnets, amphiboles, pyroxenes, micas and feldspars (Tillmans, 1972). Titanium oxides and Fe-Ti oxides are resistant to weathering and are commonly nondecomposed in sediment (Correns, 1976a). Any Ti that enters solution would normally be transformed into $Ti(OH)_4$ that would be converted to amorphous rutile and be re-precipitated into the weathering product (Correns, 1976a). Titanium can enter the hydrosphere through industrial waste and processes as well. At $3 < pH < 8$, Ti is thought to enter solution as a uncharged hydroxide species $Ti(OH)_4$, and may form ionic polymers that could evolve to form solid crystals (Hem, 1989). At low pH ($pH < 3$), Ti is present as TiO_2 or $Ti(OH)_2^{2+}$ (Hem, 1989). The concentration of Ti in aqueous solutions is therefore tied to the solubility of the above aqueous species, to the formation of organic complexes and to adsorption of Ti ions onto clay minerals (Hem, 1989). Titanium oxides are highly insoluble, whereas the association with organic matter increases the solubility of Ti (Hem, 1989).

Ti content of igneous rocks varies between 0.45 wt% TiO_2 in granite and 2.4 wt% TiO_2 in basalt (Correns, 1976b). In sedimentary rocks the range in values is less. Titanium concentrations vary between 0.14 wt% TiO_2 in carbonate rocks to 0.89 wt % shale (Correns, 1976c).

Stream water Ti concentrations are approximately 0.01 mg/L (Drever, 1997). Seawater contains 0.0001 mg/L (Drever, 1997). Formation water can contain upwards of 1 mg/L (Correns, 1976d). The range of groundwater Ti concentrations has not been extensively quantified.

Uranium

Uranium (Z = 92, mass = 238.0289 g/mol) is a Group 6 actinoid element generally classed as a lithophile. No stable isotopes exist. Twenty-eight radiogenic isotopes have been observed with half-lives between 1 ns and 4.468×10^9 years (Firestone, 2000). Three of these radiogenic isotopes, ^{238}U (half-life 4.468×10^9 years, abundance 0.00555%), ^{235}U (7.038×10^8 years 0.720012%) and ^{234}U (2.455×10^5 years, 99.27456%) are naturally occurring (Firestone, 2000). Uranium is of great importance as a nuclear fuel and is used in inertial guidance devices, in gyro compasses, as counterweights for aircraft control surfaces, as ballast for missile re-entry vehicles, and as a shielding material (Los Alamos National Laboratory, 2001). Uranium metal is used for X-ray targets for production of high-energy X-rays; the nitrate has been used as a photographic toner, and the acetate is used in analytical chemistry (Los Alamos National Laboratory, 2001). Crystals of uranium nitrate are triboluminescent (Los Alamos National Laboratory, 2001). Uranium salts have also been used for producing yellow ‘Vaseline’ glass and glazes (Los Alamos National Laboratory, 2001).

Uranium is more common than Hg, Ag, or Cd in the earth’s crust, and is about as abundant as Mo or As (Winter, 2003b). Uranium possesses four valence states, +3, +4, +5 and +6. The two dominant oxidation states are +4 and +6. Uranium tends to form tetragonal, monoclinic and octahedral crystals, but cubic and dodecahedral faces have been observed (Klein and Hurlbut, 1985). Thorium can substitute for U as can Pb, Ra, Ce, Y, N and He (Klein and Hurlbut, 1985). Uraninite (UO_2) is an important uranium ore. It occurs as a primary constituent of granitic and pegmatitic rocks (Klein and Hurlbut, 1985). Uraninite is also found in association with cassiterite, chalcopyrite, pyrite, arsenopyrite, native silver and Co-Ni-As minerals in hydrothermal vein deposits (Klein and Hurlbut, 1985). Under oxidizing conditions typical of recharge areas the U^{6+} species (UO_2^{2+}) is favoured, whereas at greater depths and distances along aquifer flow paths the less soluble U^{4+} species (UO_2) is dominant (Clark and Fritz, 1997). Complex formation between U, P, F and SO_4 along with pH and Eh, are the likely controls on solubility of U in natural water (Drever, 1997; Clark and Fritz, 1997; Hem, 1989).

The U concentration estimates in crustal rocks vary between approximately 1.8 ppm (Winter, 2003b) and 1 – 3 ppm (Drever, 1989). In sedimentary rocks the range in values is similar. Uranium concentrations vary between 2 ppm in sandstone and limestone and 4 ppm in shale (Drever, 1989).

Uranium concentration in streams is approximately 0.0001 mg/L (Drever, 1997). Uranium concentration in the ocean is approximately 0.0033 mg/L (Drever, 1997).

Vanadium

Vanadium (Z = 23, mass = 50.9415 g/mol) is a Group 5, Period 4 element generally classed as a lithophile. Only one stable isotope exists, ^{51}V (Firestone, 2000). Twenty-six radiogenic isotopes have been observed with half-lives between 1.02 ms and 1.4×10^{17} years (Firestone, 2000). Vanadium is used as an alloying agent, as a catalyst and in the manufacture of ceramics and magnets (Los Alamos National Laboratory, 2001).

Vanadium has 4 valence states, +2, +3, +4 and +5 (Evans, 1967). In the +2, +3 and +4 states, mineral crystals form with a coordination number of 6 (Evans, 1967). The pentavalent cation forms crystals with 4, 5, or 6-fold coordination around the V^{5+} ion (Evans, 1967). Vanadium does not form primary magmatic minerals (Evans, 1967). All V-bearing minerals are secondary and were formed under surface conditions at low temperature (Evans, 1967). These minerals include V-sulphide compounds, secondary vanadates, vanadium micas and oxide deposits (Evans, 1967). In the V^{3+} states, V has a similar ionic radius to that of Fe^{3+} and will substitute for the Fe^{3+} ion in magnetite, pyroxene, amphibole and biotite (Evans, 1967). Vanadium can also be found in trace amounts in other rock forming minerals such as olivine, feldspars, apatite and garnet (Evans, 1967). Vanadium is present in plants, coal and petroleum (Hem, 1989). Combustion of these materials can release V into the environment and potentially into the hydrosphere. The dominant ionic form of V in aqueous solutions is most likely V^{5+} or a V^{5+} anionic complex with oxygen and hydroxide (Hem, 1989). The low solubility of metal vanadates, adsorption onto clay minerals and metal oxides, coprecipitation with other mineral phases such as metal sulphides and uptake by plants can control V concentrations in natural waters (Landergren, 1974a; Hem, 1989).

The V content of igneous rocks varies between 72 ppm in granite and 266 ppm in basalt (Landergren, 1974b). In sedimentary rocks the range in values is less. Vanadium concentrations vary between 12 ppm in sandstone and 148 ppm in shale (Landergren, 1974c).

Stream water V concentrations are approximately 0.0001 mg/L (Drever, 1997). Groundwater concentration approaches 0.0005 mg/L (Landergren, 1974d). Seawater contains approximately 0.0002 mg/L (Drever, 1997).

Zinc

Zinc (Z = 30, mass = 65.39±2 g/mol) is a Group 12, Period 4 element generally classed as a chalcophile. Four stable isotopes exist (Firestone, 2000): ^{64}Zn (48.63% abundance), ^{66}Zn (27.92%), ^{67}Zn (4.11%) and ^{68}Zn (18.84%). Thirty radiogenic isotopes have been identified with half-lives between 40 ms and $5x10^{14}$ years (Firestone, 2000). Zinc is used as an alloying agent and as a galvanization agent (Los Alamos National Laboratory, 2001). Zinc compounds are used in the manufacture of paints, rubber products, cosmetics, pharmaceuticals, floor coverings, plastics, inks, soap, storage batteries, textiles, electrical equipment, pigments, luminous dials, X-ray and TV screens and fluorescent lights (Los Alamos National Laboratory, 2001).

Zinc has only one valence state, +2 and forms mineral crystals with coordination numbers of 4, 5, 6 or 8 (Brehler, 1968). Zinc forms metallic Zn, as well as sulphide, selenide, sulphosalt, oxide, hydroxide, telluride, carbonate, sulphate, phosphate, arsenite, arsenate, vanadate, tungstate and silicate minerals (Brehler, 1968). Zinc is also found in trace amounts in other rock-forming minerals such as magnetite, olivine, garnet, pyroxenes, amphiboles, biotite, feldspars and quartz (Brehler, 1968). In the Zn^{2+} state, Zn has a similar ionic radius to those of Mg^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+} and Mn^{2+}, partially explaining its presence in the above rock-forming minerals (Brehler, 1968). Zinc is introduced primarily through the weathering of Zn silicate and oxide minerals (Wedepohl, 1972a). Zinc is also used extensively in industry and can therefore also be introduced into the environment through industrial activities. In dilute solutions, Zn is present as Zn^{2+} (Hitchon et al., 1999). As the ionic strength increases, ion pairs and Zn complexes begin to form and become more important zinc-bearing constituents (Hitchon et al., 1999). Zinc concentration in aqueous solutions is controlled by the solubility of Zn sulphide, phosphate, hydroxide, oxide and carbonate minerals, as well as ion exchange and adsorption onto clay minerals, organic matter and various metal oxides (Wedepohl, 1972b; Hem, 1989).

The Zn content of igneous rocks varies between 39 ppm in low-Ca granite and 118 ppm in basalt (Hitchon et al., 1999). In sedimentary rocks the range in values is slightly greater. Zinc concentrations vary between 16 ppm in sandstone and 165 ppm in deep-sea clay (Hitchon et al., 1999).

Stream water zinc concentrations are approximately 0.02 mg/L (Hitchon et al., 1999). Groundwater concentrations vary between 0.001 and 1 mg/L, with maximum values exceeding 30 mg/L (Hitchon et al., 1999). Seawater contains approximately 0.0002 mg/L (Drever, 1997). Formation water can contain in excess of 575 mg/L (Hitchon et al., 1999).

Appendix C – Coal and Sandstone Aquifer Pump Tests on File with AENV

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
096204	Paskapoo Formation	Tertiary
096211	Paskapoo Formation	Tertiary
096719	Paskapoo Formation	Tertiary
096757	Paskapoo Formation	Tertiary
097595	Paskapoo Formation	Tertiary
099113	Paskapoo Formation	Tertiary
099627	Paskapoo Formation	Tertiary
099687	Paskapoo Formation	Tertiary
099750	Paskapoo Formation	Tertiary
099754	Paskapoo Formation	Tertiary
099756	Paskapoo Formation	Tertiary
099774	Paskapoo Formation	Tertiary
102391	Paskapoo Formation	Tertiary
102802	Paskapoo Formation	Tertiary
102871	Paskapoo Formation	Tertiary
110628	Paskapoo Formation	Tertiary
110650	Paskapoo Formation	Tertiary
113205	Paskapoo Formation	Tertiary
114151	Paskapoo Formation	Tertiary
114507	Paskapoo Formation	Tertiary
126218	Paskapoo Formation	Tertiary
126958	Paskapoo Formation	Tertiary
132914	Paskapoo Formation	Tertiary
141398	Paskapoo Formation	Tertiary
147503	Paskapoo Formation	Tertiary
147565	Paskapoo Formation	Tertiary
147566	Paskapoo Formation	Tertiary
147606	Paskapoo Formation	Tertiary
155881	Paskapoo Formation	Tertiary
167395	Paskapoo Formation	Tertiary
201564	Paskapoo Formation	Tertiary
215630	Paskapoo Formation	Tertiary
216860	Paskapoo Formation	Tertiary
222139	Paskapoo Formation	Tertiary
226928	Paskapoo Formation	Tertiary
229078	Paskapoo Formation	Tertiary
229588	Paskapoo Formation	Tertiary
235379	Paskapoo Formation	Tertiary
235590	Paskapoo Formation	Tertiary
237381	Paskapoo Formation	Tertiary
242005	Paskapoo Formation	Tertiary
250098	Paskapoo Formation	Tertiary
255147	Paskapoo Formation	Tertiary
255773	Paskapoo Formation	Tertiary
257515	Paskapoo Formation	Tertiary
259052	Paskapoo Formation	Tertiary
262072	Paskapoo Formation	Tertiary
272661	Paskapoo Formation	Tertiary
273189	Paskapoo Formation	Tertiary
273985	Paskapoo Formation	Tertiary

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
275605	Paskapoo Formation	Tertiary
278667	Paskapoo Formation	Tertiary
278678	Paskapoo Formation	Tertiary
278681	Paskapoo Formation	Tertiary
285143	Paskapoo Formation	Tertiary
285482	Paskapoo Formation	Tertiary
286278	Paskapoo Formation	Tertiary
288427	Paskapoo Formation	Tertiary
288447	Paskapoo Formation	Tertiary
288449	Paskapoo Formation	Tertiary
288646	Paskapoo Formation	Tertiary
288724	Paskapoo Formation	Tertiary
289603	Paskapoo Formation	Tertiary
289611	Paskapoo Formation	Tertiary
289612	Paskapoo Formation	Tertiary
289621	Paskapoo Formation	Tertiary
290039	Paskapoo Formation	Tertiary
291557	Paskapoo Formation	Tertiary
291558	Paskapoo Formation	Tertiary
291560	Paskapoo Formation	Tertiary
291586	Paskapoo Formation	Tertiary
291586	Paskapoo Formation	Tertiary
292596	Paskapoo Formation	Tertiary
292599	Paskapoo Formation	Tertiary
292601	Paskapoo Formation	Tertiary
292602	Paskapoo Formation	Tertiary
293480	Paskapoo Formation	Tertiary
293495	Paskapoo Formation	Tertiary
293496	Paskapoo Formation	Tertiary
293497	Paskapoo Formation	Tertiary
293498	Paskapoo Formation	Tertiary
293499	Paskapoo Formation	Tertiary
293500	Paskapoo Formation	Tertiary
293863	Paskapoo Formation	Tertiary
294044	Paskapoo Formation	Tertiary
294631	Paskapoo Formation	Tertiary
294632	Paskapoo Formation	Tertiary
294878	Paskapoo Formation	Tertiary
294879	Paskapoo Formation	Tertiary
294880	Paskapoo Formation	Tertiary
349655	Paskapoo Formation	Tertiary
349659	Paskapoo Formation	Tertiary
349766	Paskapoo Formation	Tertiary
349767	Paskapoo Formation	Tertiary
349835	Paskapoo Formation	Tertiary
349880	Paskapoo Formation	Tertiary
349904	Paskapoo Formation	Tertiary
349983	Paskapoo Formation	Tertiary
349989	Paskapoo Formation	Tertiary
350017	Paskapoo Formation	Tertiary

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
350070	Paskapoo Formation	Tertiary
350070	Paskapoo Formation	Tertiary
350471	Paskapoo Formation	Tertiary
353094	Paskapoo Formation	Tertiary
353636	Paskapoo Formation	Tertiary
353680	Paskapoo Formation	Tertiary
353770	Paskapoo Formation	Tertiary
355608	Paskapoo Formation	Tertiary
355986	Paskapoo Formation	Tertiary
356443	Paskapoo Formation	Tertiary
357781	Paskapoo Formation	Tertiary
357828	Paskapoo Formation	Tertiary
360223	Paskapoo Formation	Tertiary
360228	Paskapoo Formation	Tertiary
360229	Paskapoo Formation	Tertiary
361011	Paskapoo Formation	Tertiary
365500	Paskapoo Formation	Tertiary
365501	Paskapoo Formation	Tertiary
366578	Paskapoo Formation	Tertiary
366579	Paskapoo Formation	Tertiary
366580	Paskapoo Formation	Tertiary
368675	Paskapoo Formation	Tertiary
368715	Paskapoo Formation	Tertiary
375014	Paskapoo Formation	Tertiary
375015	Paskapoo Formation	Tertiary
375016	Paskapoo Formation	Tertiary
376434	Paskapoo Formation	Tertiary
376435	Paskapoo Formation	Tertiary
376455	Paskapoo Formation	Tertiary
376576	Paskapoo Formation	Tertiary
379184	Paskapoo Formation	Tertiary
380369	Paskapoo Formation	Tertiary
380402	Paskapoo Formation	Tertiary
381691	Paskapoo Formation	Tertiary
382085	Paskapoo Formation	Tertiary
385968	Paskapoo Formation	Tertiary
387918	Paskapoo Formation	Tertiary
390400	Paskapoo Formation	Tertiary
391002	Paskapoo Formation	Tertiary
391371	Paskapoo Formation	Tertiary
391448	Paskapoo Formation	Tertiary
399656	Paskapoo Formation	Tertiary
399661	Paskapoo Formation	Tertiary
402921	Paskapoo Formation	Tertiary
404469	Paskapoo Formation	Tertiary
404470	Paskapoo Formation	Tertiary
404471	Paskapoo Formation	Tertiary
404472	Paskapoo Formation	Tertiary
404726	Paskapoo Formation	Tertiary
406551	Paskapoo Formation	Tertiary

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
406613	Paskapoo Formation	Tertiary
407388	Paskapoo Formation	Tertiary
408551	Paskapoo Formation	Tertiary
408687	Paskapoo Formation	Tertiary
410063	Paskapoo Formation	Tertiary
411840	Paskapoo Formation	Tertiary
412049	Paskapoo Formation	Tertiary
412894	Paskapoo Formation	Tertiary
413014	Paskapoo Formation	Tertiary
413952	Paskapoo Formation	Tertiary
414377	Paskapoo Formation	Tertiary
414738	Paskapoo Formation	Tertiary
415891	Paskapoo Formation	Tertiary
416639	Paskapoo Formation	Tertiary
416736	Paskapoo Formation	Tertiary
418345	Paskapoo Formation	Tertiary
424871	Paskapoo Formation	Tertiary
432215	Paskapoo Formation	Tertiary
438321	Paskapoo Formation	Tertiary
438779	Paskapoo Formation	Tertiary
439097	Paskapoo Formation	Tertiary
454882	Paskapoo Formation	Tertiary
461307	Paskapoo Formation	Tertiary
463365	Paskapoo Formation	Tertiary
466081	Paskapoo Formation	Tertiary
466096	Paskapoo Formation	Tertiary
466134	Paskapoo Formation	Tertiary
467058	Paskapoo Formation	Tertiary
467107	Paskapoo Formation	Tertiary
467110	Paskapoo Formation	Tertiary
467148	Paskapoo Formation	Tertiary
467262	Paskapoo Formation	Tertiary
467797	Paskapoo Formation	Tertiary
467798	Paskapoo Formation	Tertiary
467799	Paskapoo Formation	Tertiary
469143	Paskapoo Formation	Tertiary
469147	Paskapoo Formation	Tertiary
469148	Paskapoo Formation	Tertiary
469150	Paskapoo Formation	Tertiary
469201	Paskapoo Formation	Tertiary
469223	Paskapoo Formation	Tertiary
469230	Paskapoo Formation	Tertiary
469320	Paskapoo Formation	Tertiary
469972	Paskapoo Formation	Tertiary
485061	Paskapoo Formation	Tertiary
490027	Paskapoo Formation	Tertiary
491192	Paskapoo Formation	Tertiary
491202	Paskapoo Formation	Tertiary
491206	Paskapoo Formation	Tertiary
491207	Paskapoo Formation	Tertiary

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
491209	Paskapoo Formation	Tertiary
491464	Paskapoo Formation	Tertiary
491760	Paskapoo Formation	Tertiary
491777	Paskapoo Formation	Tertiary
491778	Paskapoo Formation	Tertiary
491788	Paskapoo Formation	Tertiary
492940	Paskapoo Formation	Tertiary
494354	Paskapoo Formation	Tertiary
494382	Paskapoo Formation	Tertiary
494383	Paskapoo Formation	Tertiary
494534	Paskapoo Formation	Tertiary
494562	Paskapoo Formation	Tertiary
494705	Paskapoo Formation	Tertiary
494763	Paskapoo Formation	Tertiary
494769	Paskapoo Formation	Tertiary
495253	Paskapoo Formation	Tertiary
495514	Paskapoo Formation	Tertiary
495515	Paskapoo Formation	Tertiary
496093	Paskapoo Formation	Tertiary
496565	Paskapoo Formation	Tertiary
496566	Paskapoo Formation	Tertiary
496567	Paskapoo Formation	Tertiary
496570	Paskapoo Formation	Tertiary
496809	Paskapoo Formation	Tertiary
496959	Paskapoo Formation	Tertiary
497365	Paskapoo Formation	Tertiary
497366	Paskapoo Formation	Tertiary
497367	Paskapoo Formation	Tertiary
497368	Paskapoo Formation	Tertiary
497369	Paskapoo Formation	Tertiary
497370	Paskapoo Formation	Tertiary
497372	Paskapoo Formation	Tertiary
497373	Paskapoo Formation	Tertiary
497374	Paskapoo Formation	Tertiary
497375	Paskapoo Formation	Tertiary
497376	Paskapoo Formation	Tertiary
497377	Paskapoo Formation	Tertiary
103278	Porcupine Hills Formation	Tertiary
133631	Porcupine Hills Formation	Tertiary
134870	Porcupine Hills Formation	Tertiary
147022	Porcupine Hills Formation	Tertiary
147027	Porcupine Hills Formation	Tertiary
147029	Porcupine Hills Formation	Tertiary
147138	Porcupine Hills Formation	Tertiary
147139	Porcupine Hills Formation	Tertiary
147164	Porcupine Hills Formation	Tertiary
147207	Porcupine Hills Formation	Tertiary
147208	Porcupine Hills Formation	Tertiary
147478	Porcupine Hills Formation	Tertiary
147505	Porcupine Hills Formation	Tertiary

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
147533	Porcupine Hills Formation	Tertiary
147547	Porcupine Hills Formation	Tertiary
147559	Porcupine Hills Formation	Tertiary
147567	Porcupine Hills Formation	Tertiary
147568	Porcupine Hills Formation	Tertiary
147569	Porcupine Hills Formation	Tertiary
147571	Porcupine Hills Formation	Tertiary
147574	Porcupine Hills Formation	Tertiary
147575	Porcupine Hills Formation	Tertiary
147576	Porcupine Hills Formation	Tertiary
147634	Porcupine Hills Formation	Tertiary
147664	Porcupine Hills Formation	Tertiary
147674	Porcupine Hills Formation	Tertiary
147675	Porcupine Hills Formation	Tertiary
147691	Porcupine Hills Formation	Tertiary
153836	Porcupine Hills Formation	Tertiary
154073	Porcupine Hills Formation	Tertiary
155076	Porcupine Hills Formation	Tertiary
155077	Porcupine Hills Formation	Tertiary
160336	Porcupine Hills Formation	Tertiary
185482	Porcupine Hills Formation	Tertiary
218467	Porcupine Hills Formation	Tertiary
235401	Porcupine Hills Formation	Tertiary
235447	Porcupine Hills Formation	Tertiary
241033	Porcupine Hills Formation	Tertiary
241041	Porcupine Hills Formation	Tertiary
241041	Porcupine Hills Formation	Tertiary
241042	Porcupine Hills Formation	Tertiary
241783	Porcupine Hills Formation	Tertiary
244850	Porcupine Hills Formation	Tertiary
244956	Porcupine Hills Formation	Tertiary
245020	Porcupine Hills Formation	Tertiary
278927	Porcupine Hills Formation	Tertiary
278928	Porcupine Hills Formation	Tertiary
280305	Porcupine Hills Formation	Tertiary
282134	Porcupine Hills Formation	Tertiary
285114	Porcupine Hills Formation	Tertiary
286233	Porcupine Hills Formation	Tertiary
286355	Porcupine Hills Formation	Tertiary
286359	Porcupine Hills Formation	Tertiary
287238	Porcupine Hills Formation	Tertiary
287239	Porcupine Hills Formation	Tertiary
287240	Porcupine Hills Formation	Tertiary
288190	Porcupine Hills Formation	Tertiary
288333	Porcupine Hills Formation	Tertiary
288336	Porcupine Hills Formation	Tertiary
288381	Porcupine Hills Formation	Tertiary
288382	Porcupine Hills Formation	Tertiary
289559	Porcupine Hills Formation	Tertiary
289560	Porcupine Hills Formation	Tertiary

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
289582	Porcupine Hills Formation	Tertiary
289992	Porcupine Hills Formation	Tertiary
290559	Porcupine Hills Formation	Tertiary
291411	Porcupine Hills Formation	Tertiary
291442	Porcupine Hills Formation	Tertiary
291444	Porcupine Hills Formation	Tertiary
291454	Porcupine Hills Formation	Tertiary
291461	Porcupine Hills Formation	Tertiary
291463	Porcupine Hills Formation	Tertiary
291482	Porcupine Hills Formation	Tertiary
291483	Porcupine Hills Formation	Tertiary
292942	Porcupine Hills Formation	Tertiary
293435	Porcupine Hills Formation	Tertiary
293436	Porcupine Hills Formation	Tertiary
293442	Porcupine Hills Formation	Tertiary
293443	Porcupine Hills Formation	Tertiary
293856	Porcupine Hills Formation	Tertiary
293857	Porcupine Hills Formation	Tertiary
293858	Porcupine Hills Formation	Tertiary
293859	Porcupine Hills Formation	Tertiary
294027	Porcupine Hills Formation	Tertiary
294028	Porcupine Hills Formation	Tertiary
294029	Porcupine Hills Formation	Tertiary
294239	Porcupine Hills Formation	Tertiary
294240	Porcupine Hills Formation	Tertiary
294764	Porcupine Hills Formation	Tertiary
294765	Porcupine Hills Formation	Tertiary
294766	Porcupine Hills Formation	Tertiary
294767	Porcupine Hills Formation	Tertiary
294768	Porcupine Hills Formation	Tertiary
349355	Porcupine Hills Formation	Tertiary
349363	Porcupine Hills Formation	Tertiary
349579	Porcupine Hills Formation	Tertiary
349763	Porcupine Hills Formation	Tertiary
349876	Porcupine Hills Formation	Tertiary
349911	Porcupine Hills Formation	Tertiary
349912	Porcupine Hills Formation	Tertiary
349913	Porcupine Hills Formation	Tertiary
349981	Porcupine Hills Formation	Tertiary
350018	Porcupine Hills Formation	Tertiary
350019	Porcupine Hills Formation	Tertiary
350022	Porcupine Hills Formation	Tertiary
350023	Porcupine Hills Formation	Tertiary
350049	Porcupine Hills Formation	Tertiary
353398	Porcupine Hills Formation	Tertiary
354314	Porcupine Hills Formation	Tertiary
358205	Porcupine Hills Formation	Tertiary
368713	Porcupine Hills Formation	Tertiary
372329	Porcupine Hills Formation	Tertiary
373736	Porcupine Hills Formation	Tertiary

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
373750	Porcupine Hills Formation	Tertiary
376790	Porcupine Hills Formation	Tertiary
378758	Porcupine Hills Formation	Tertiary
378947	Porcupine Hills Formation	Tertiary
380573	Porcupine Hills Formation	Tertiary
388386	Porcupine Hills Formation	Tertiary
388390	Porcupine Hills Formation	Tertiary
400294	Porcupine Hills Formation	Tertiary
400346	Porcupine Hills Formation	Tertiary
400347	Porcupine Hills Formation	Tertiary
400348	Porcupine Hills Formation	Tertiary
405587	Porcupine Hills Formation	Tertiary
442944	Porcupine Hills Formation	Tertiary
442945	Porcupine Hills Formation	Tertiary
442985	Porcupine Hills Formation	Tertiary
442996	Porcupine Hills Formation	Tertiary
443009	Porcupine Hills Formation	Tertiary
466021	Porcupine Hills Formation	Tertiary
466022	Porcupine Hills Formation	Tertiary
466041	Porcupine Hills Formation	Tertiary
466054	Porcupine Hills Formation	Tertiary
466055	Porcupine Hills Formation	Tertiary
467025	Porcupine Hills Formation	Tertiary
467026	Porcupine Hills Formation	Tertiary
467056	Porcupine Hills Formation	Tertiary
467094	Porcupine Hills Formation	Tertiary
469044	Porcupine Hills Formation	Tertiary
469058	Porcupine Hills Formation	Tertiary
469061	Porcupine Hills Formation	Tertiary
469078	Porcupine Hills Formation	Tertiary
469109	Porcupine Hills Formation	Tertiary
469119	Porcupine Hills Formation	Tertiary
491159	Porcupine Hills Formation	Tertiary
491172	Porcupine Hills Formation	Tertiary
491173	Porcupine Hills Formation	Tertiary
491186	Porcupine Hills Formation	Tertiary
491189	Porcupine Hills Formation	Tertiary
491524	Porcupine Hills Formation	Tertiary
491766	Porcupine Hills Formation	Tertiary
491770	Porcupine Hills Formation	Tertiary
491771	Porcupine Hills Formation	Tertiary
492911	Porcupine Hills Formation	Tertiary
492917	Porcupine Hills Formation	Tertiary
492918	Porcupine Hills Formation	Tertiary
493312	Porcupine Hills Formation	Tertiary
493313	Porcupine Hills Formation	Tertiary
493314	Porcupine Hills Formation	Tertiary
493318	Porcupine Hills Formation	Tertiary
494521	Porcupine Hills Formation	Tertiary
494751	Porcupine Hills Formation	Tertiary

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
494752	Porcupine Hills Formation	Tertiary
494756	Porcupine Hills Formation	Tertiary
494757	Porcupine Hills Formation	Tertiary
495521	Porcupine Hills Formation	Tertiary
495522	Porcupine Hills Formation	Tertiary
495523	Porcupine Hills Formation	Tertiary
496556	Porcupine Hills Formation	Tertiary
496557	Porcupine Hills Formation	Tertiary
496561	Porcupine Hills Formation	Tertiary
496562	Porcupine Hills Formation	Tertiary
136295	Belly River Group	Upper Cretaceous
140879	Belly River Group	Upper Cretaceous
141994	Belly River Group	Upper Cretaceous
152753	Belly River Group	Upper Cretaceous
152755	Belly River Group	Upper Cretaceous
152755	Belly River Group	Upper Cretaceous
163202	Belly River Group	Upper Cretaceous
163219	Belly River Group	Upper Cretaceous
171894	Belly River Group	Upper Cretaceous
172633	Belly River Group	Upper Cretaceous
173171	Belly River Group	Upper Cretaceous
174023	Belly River Group	Upper Cretaceous
174024	Belly River Group	Upper Cretaceous
177216	Belly River Group	Upper Cretaceous
180172	Belly River Group	Upper Cretaceous
185062	Belly River Group	Upper Cretaceous
196993	Belly River Group	Upper Cretaceous
215463	Belly River Group	Upper Cretaceous
219408	Belly River Group	Upper Cretaceous
220441	Belly River Group	Upper Cretaceous
262106	Belly River Group	Upper Cretaceous
264560	Belly River Group	Upper Cretaceous
266464	Belly River Group	Upper Cretaceous
267255	Belly River Group	Upper Cretaceous
288412	Belly River Group	Upper Cretaceous
289093	Belly River Group	Upper Cretaceous
402315	Coalspur Formation	Upper Cretaceous
466060	Coalspur Formation	Upper Cretaceous
466061	Coalspur Formation	Upper Cretaceous
469151	Coalspur Formation	Upper Cretaceous
492932	Coalspur Formation	Upper Cretaceous
492935	Coalspur Formation	Upper Cretaceous
359086	Dunvegan Formation	Upper Cretaceous
079631	Horseshoe Canyon Formation	Upper Cretaceous
094813	Horseshoe Canyon Formation	Upper Cretaceous
094814	Horseshoe Canyon Formation	Upper Cretaceous
097353	Horseshoe Canyon Formation	Upper Cretaceous
155684	Horseshoe Canyon Formation	Upper Cretaceous
155685	Horseshoe Canyon Formation	Upper Cretaceous
160728	Horseshoe Canyon Formation	Upper Cretaceous

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
179074	Horseshoe Canyon Formation	Upper Cretaceous
215392	Horseshoe Canyon Formation	Upper Cretaceous
231265	Horseshoe Canyon Formation	Upper Cretaceous
258552	Horseshoe Canyon Formation	Upper Cretaceous
258880	Horseshoe Canyon Formation	Upper Cretaceous
277062	Horseshoe Canyon Formation	Upper Cretaceous
277062	Horseshoe Canyon Formation	Upper Cretaceous
278932	Horseshoe Canyon Formation	Upper Cretaceous
286811	Horseshoe Canyon Formation	Upper Cretaceous
286824	Horseshoe Canyon Formation	Upper Cretaceous
286827	Horseshoe Canyon Formation	Upper Cretaceous
293644	Horseshoe Canyon Formation	Upper Cretaceous
386537	Horseshoe Canyon Formation	Upper Cretaceous
386545	Horseshoe Canyon Formation	Upper Cretaceous
444270	Horseshoe Canyon Formation	Upper Cretaceous
453062	Horseshoe Canyon Formation	Upper Cretaceous
459689	Horseshoe Canyon Formation	Upper Cretaceous
459802	Horseshoe Canyon Formation	Upper Cretaceous
293902	Labiche Formation	Upper Cretaceous
285966	Lea Park Formation	Upper Cretaceous
112084	Scollard Formation	Upper Cretaceous
141257	Scollard Formation	Upper Cretaceous
147167	Scollard Formation	Upper Cretaceous
147168	Scollard Formation	Upper Cretaceous
147329	Scollard Formation	Upper Cretaceous
147475	Scollard Formation	Upper Cretaceous
147502	Scollard Formation	Upper Cretaceous
147510	Scollard Formation	Upper Cretaceous
147511	Scollard Formation	Upper Cretaceous
147554	Scollard Formation	Upper Cretaceous
147555	Scollard Formation	Upper Cretaceous
147556	Scollard Formation	Upper Cretaceous
147585	Scollard Formation	Upper Cretaceous
147595	Scollard Formation	Upper Cretaceous
147602	Scollard Formation	Upper Cretaceous
147637	Scollard Formation	Upper Cretaceous
147638	Scollard Formation	Upper Cretaceous
160520	Scollard Formation	Upper Cretaceous
169391	Scollard Formation	Upper Cretaceous
216470	Scollard Formation	Upper Cretaceous
230694	Scollard Formation	Upper Cretaceous
230895	Scollard Formation	Upper Cretaceous
235397	Scollard Formation	Upper Cretaceous
236486	Scollard Formation	Upper Cretaceous
236600	Scollard Formation	Upper Cretaceous
237006	Scollard Formation	Upper Cretaceous
237401	Scollard Formation	Upper Cretaceous
237422	Scollard Formation	Upper Cretaceous
237542	Scollard Formation	Upper Cretaceous
237658	Scollard Formation	Upper Cretaceous

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
241137	Scollard Formation	Upper Cretaceous
241148	Scollard Formation	Upper Cretaceous
241788	Scollard Formation	Upper Cretaceous
241789	Scollard Formation	Upper Cretaceous
241790	Scollard Formation	Upper Cretaceous
250080	Scollard Formation	Upper Cretaceous
256588	Scollard Formation	Upper Cretaceous
258192	Scollard Formation	Upper Cretaceous
258207	Scollard Formation	Upper Cretaceous
258208	Scollard Formation	Upper Cretaceous
258869	Scollard Formation	Upper Cretaceous
264485	Scollard Formation	Upper Cretaceous
264607	Scollard Formation	Upper Cretaceous
279977	Scollard Formation	Upper Cretaceous
281209	Scollard Formation	Upper Cretaceous
285087	Scollard Formation	Upper Cretaceous
285146	Scollard Formation	Upper Cretaceous
285147	Scollard Formation	Upper Cretaceous
285148	Scollard Formation	Upper Cretaceous
285149	Scollard Formation	Upper Cretaceous
285150	Scollard Formation	Upper Cretaceous
286230	Scollard Formation	Upper Cretaceous
286248	Scollard Formation	Upper Cretaceous
286249	Scollard Formation	Upper Cretaceous
286400	Scollard Formation	Upper Cretaceous
288372	Scollard Formation	Upper Cretaceous
288374	Scollard Formation	Upper Cretaceous
288378	Scollard Formation	Upper Cretaceous
288383	Scollard Formation	Upper Cretaceous
288384	Scollard Formation	Upper Cretaceous
288385	Scollard Formation	Upper Cretaceous
288386	Scollard Formation	Upper Cretaceous
289568	Scollard Formation	Upper Cretaceous
289581	Scollard Formation	Upper Cretaceous
289683	Scollard Formation	Upper Cretaceous
289697	Scollard Formation	Upper Cretaceous
289964	Scollard Formation	Upper Cretaceous
289980	Scollard Formation	Upper Cretaceous
289981	Scollard Formation	Upper Cretaceous
290002	Scollard Formation	Upper Cretaceous
290004	Scollard Formation	Upper Cretaceous
290026	Scollard Formation	Upper Cretaceous
290068	Scollard Formation	Upper Cretaceous
291404	Scollard Formation	Upper Cretaceous
291406	Scollard Formation	Upper Cretaceous
291477	Scollard Formation	Upper Cretaceous
291478	Scollard Formation	Upper Cretaceous
291479	Scollard Formation	Upper Cretaceous
291480	Scollard Formation	Upper Cretaceous
291740	Scollard Formation	Upper Cretaceous

Appendix C - Table 185 -Sandstone Aquifer Pump Tests.

Wellid	Formation	Period
293474	Scollard Formation	Upper Cretaceous
294611	Scollard Formation	Upper Cretaceous
294620	Scollard Formation	Upper Cretaceous
350057	Scollard Formation	Upper Cretaceous
406246	Scollard Formation	Upper Cretaceous
294593	St. Mary River Formation	Upper Cretaceous
246667	Wapiti Group	Upper Cretaceous
358232	Wapiti Group	Upper Cretaceous
358232	Wapiti Group	Upper Cretaceous
376537	Wapiti Group	Upper Cretaceous
419908	Wapiti Group	Upper Cretaceous
224129	Willow Creek Formation	Upper Cretaceous
278642	Willow Creek Formation	Upper Cretaceous
278648	Willow Creek Formation	Upper Cretaceous
290547	Willow Creek Formation	Upper Cretaceous
290548	Willow Creek Formation	Upper Cretaceous
291393	Willow Creek Formation	Upper Cretaceous
293854	Willow Creek Formation	Upper Cretaceous
293855	Willow Creek Formation	Upper Cretaceous
294607	Willow Creek Formation	Upper Cretaceous
294608	Willow Creek Formation	Upper Cretaceous
374106	Willow Creek Formation	Upper Cretaceous