EUB/AGS Special Report 081

Water Chemistry of Coalbed Methane Reservoirs

Alberta Energy and Utilities Board

Alberta Geological Survey

EUB/AGS Special Report 081

Water Chemistry of Coalbed Methane Reservoirs

T.G. Lemay[1], K.O. Konhauser[2]

[1]Alberta Energy and Utilities Board
Alberta Geological Survey
[2]University of Alberta

September 2006

ISBN# 0-7785-1512-5

If this product is an EUB/AGS Special Report, the information is provided as received from the author and has not been edited for conformity to EUB/AGS standards.

When using information from this publication in other publications or presentations, due acknowledgment should be given to the EUB/AGS. The following reference format is recommended:

Lemay, T.G. and Konhauser, K.O. (2006): Water chemistry of coalbed methane reservoirs; Alberta Energy and Utilities Board, EUB/AGS Special Report 081, 372 p.

Author address:
K.O. Konhauser
Canada Research Chair in Geomicrobiology
Department of Earth & Atmospheric Sciences
University of Alberta
Edmonton, AB, T6G 2E3
(780) 492-2571
E-mail: Kurtk@ualberta.ca

Published September 2006:
Alberta Energy and Utilities Board
Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, Alberta
T6B 2X3
Canada

Tel: (780) 422-3767 (Information Sales)
Fax: (780) 422-1918
E-mail: EUB.AGS-Infosales@gov.ab.ca
Website: www.ags.gov.ab.ca

Contents

Tables

Figures

Acknowledgments

The authors would like to thank the following individuals and organizations for their assistance in completing this project.

- The various water well owners for permission to sample their water wells.
- The various representatives of Trident Energy and MGV Energy for their permission to collect water and gas samples from their CBM wells and for their assistance during the planning and completion of the project.
- Gordon Jean, Leanne Kryger, Dan Magee and Dustin Shauer of the AGS, and Carrie Dickinson of the Energy and Utilities Board for their assistance in planning and carrying out the water sampling of water wells and CBM wells.
- Dr Kevin Parks of the Alberta Geological Survey (AGS) and Mr. Richard Nelson of the Alberta Energy Research Institute for their comments on the draft of this report and for their suggestions on how to improve it.
- Maryanne Protz for her timely and professional preparation of this document

Executive Summary

The stated purposes of this project were to: 1) develop a better understanding of coalbed methane (CBM) generation processes and its resource potential in Alberta; 2) investigate the potential use of water chemistry and geomicrobiology as an exploration tool; 3) collect geochemical information that could be used in the assessment of the connection between gas-producing and domestic or agricultural water use zones of coalbeds; 4) collect additional data on coal-bearing formation water chemistry to continue to build a baseline dataset as well as to assist development companies better understand the issues surrounding the management of any produced water from these formations. The following discussion provides a summary of the results of the project in relation to the goals above.

- Develop a better understanding of coalbed methane generation processes and its resource potential in Alberta

The results of the sampling program showed that methane generating micro organisms are present throughout the study area (Section 5.2.1 and Figure 52) and that there is evidence that some of the methane in the CBM wells and water wells could have a biogenic source (Section 5.2.1, Figure 27, Figure 28 and Figure 29). The sampling program was designed to provide a general and regional overview of the geomicrobiology within these formations and as such, the exact mechanisms responsible for the generation of methane can not be specified. The results of this project suggest that targeted research on the methane generation process within these areas should be carried out.

- Investigate the potential use of water chemistry and geomicrobiology as an exploration tool

Current strategies for CBM exploration look for coal accumulations with indications of gas content. There may be another method of exploration however. A set of criteria that indicate whether groundwater chemistry is compatible with the presence of CBM has been developed by others for U.S. CBM producing areas (Section 6). As an outcome of this study, these criteria have been modified for Alberta circumstances and can now be applied to available water chemistry datasets in Alberta (Section 6). A number of CBM-compatible water chemistries were identified in the study area using the modified criteria that may have been missed with the original American criteria (Figure 57, Figure 58, Figure 60 and Figure 61).

The incorporation of geomicrobiological information into the assessment showed that the wells with a CBM-compatible water chemistry signature and sufficiently high dissolved gas concentrations also have a unique geomicrobiological signature (Section 6.1 and Section 6.2). This suggests that a combined chemical/geomicrobiological signature could exist in water associated with CBM. Further investigation into this possibility could help exploration and development efforts in the Province.

- Collect geochemical information that could be used in the assessment of the connection between gas-producing and domestic or agricultural water use zones of coalbeds

There are concerns that water and gas production from CBM wells could affect domestic and agricultural water wells completed in the same formations. The data collected in this study suggests that the water chemistry in the shallower coal-bearing formations is the result of mixing between formation water and meteoric water (Section 4.4.2.1, Section 4.4.2.2, Figure 21, Figure 22, Section 4.6.1.1, Section 4.6.1.2, Figure 23, Figure 24, Section 4.7.1.2, Figure 34, Section 4.8.1.2, Section 4.8.1.3, Figure 37, Section 4.8.2.1, Section 4.8.2.2 and Figure 43). This suggests a hydraulic connection could exist between the different portions of the coal-bearing formations on the regional scale.

However, this observation gives no information on what time scale the mixing takes place on and therefore no information on the potential strength of the hydraulic connection. This study attempted age dating of the groundwater to help better constrain the degree of hydraulic interconnection with geochemistry. Unfortunately, the age dating attempts yielded somewhat inconclusive results (Section 4.8.1.1, Section 4.8.1.2, Section 4.8.2.1 and Section 4.8.2.2). Using the ion filtration model to calculate ages, the $^{36}Cl/Cl$ results suggest that the ages of groundwater in the shallow portions of the Horseshoe Canyon Formation are with one exception much younger than the groundwater collected from the CBM wells and appear to coincide with historically colder climatic periods (Section 4.8.1.1, Table 22 and Figure 39). This could indicate that the shallower and deeper portions are not well connected and that mixing takes place over long time periods with recharge occurring during colder climatic periods. The $^{129}I/I$ results could not support the conclusions drawn using the $^{36}Cl/Cl$ results however. Moreover, both sets of results suggest that geochemical factors such as in-situ generation of radionuclides used for age dating or anthropogenic inputs have complicated the age dating results (Section 4.8.1.1, Section 4.8.1.2, Figure 37, Section 4.8.2.1, Section 4.8.2.2 and Figure 43). To clarify the nature of the connection, more complex geochemical fingerprinting and age-dating methods could be employed. These methods require drilling of dedicated groundwater sampling wells, collection of meteoric water samples and collection of rock samples, all of which were beyond the scope of this study which relied on access to existing wells for sampling, but if undertaken could clarify this connection issue as well as aid other investigations on groundwater age in Alberta by providing a reference dataset.

- Collect additional data on coal-bearing formation water chemistry to continue to build a baseline dataset. The baseline dataset will help development companies better understand the issues surrounding the management of any produced water from these formations

Development in an area in advance of characterization of the environment can sometimes raise questions about the impact of development versus the original state of the area. The detailed dataset compiled in this report will help clarify the state of the environment within the area as well as help in the development of any water management plans that might be put into place for the management of any water produced from CBM wells. When combined with other water quality datasets, this project's data will add to the information base of water chemistry for coal-bearing formations in Alberta. These data can be used to understand the current state of the groundwater in these coal-bearing formations as well as to model or simulate past or future geochemical processes that occurred or could occur within these formations.

1 Introduction

Unconventional natural gas resources such as coalbed methane are likely to become more important as conventional natural gas supplies in the Western Canada Sedimentary Basin continue to decline. Keys to discovering and developing these unconventional resources include a fuller understanding of the processes leading to the generation of gas in these reservoirs, and a sound strategy for handling produced water associated with gas production. Groundwater sampling, including innovative techniques such as groundwater age-dating and geomicrobial identification in groundwater, along with more standard chemical analysis of water samples will lead to breakthroughs in our understanding of unconventional gas production in Alberta's unconventional gas reservoirs, as well as provide information vital to the responsible and safe handling of produced water. Information on groundwater microbiology, age and standard chemistry is highly beneficial to CBM development companies allowing them to conduct more efficient exploration programs and implement more economical water handling practices.

With this in mind, the AGS initiated a sampling program to collect water samples from gas producing wells and adjacent wells used for domestic or agricultural purposes. The interpretation of the results will help enable: 1) the development of a better understanding of coalbed methane generation and its resource potential in Alberta; 2) the development of potentially new exploration strategies based on water chemistry and geomicrobiology; 3) the assessment of the connection between gas-producing and domestic or agricultural water use zones of coalbeds; 4) the development of water handling and disposal strategies consistent with the goals of regulators, stakeholders and developers; and 5) the compilation of baseline datasets for future reference.

1.1 Project Scope

The project was designed to collect water samples from water wells and CBM wells completed in coal intervals of coal-bearing formations in Alberta. The project as envisioned during its conception would employ novel and innovative techniques to characterize the water samples beyond typical analytical approaches. This approach was adopted in support of seeing the 5 main goals of the project achieved. The work conducted as part of this study has generated valuable and unique information on the geochemical processes occurring in coalbeds within the study area. This information will help formulate possible theories and hypotheses that will ultimately lead to the fulfillment of the listed goals.

1.2 Study Area Description

The study area is located within central Alberta between 52^{o} and 54^{o}N latitude and 112.5^{o} and 115^{o}W longitude. It includes all or portions of Townships 35 to 58, Range 1 to 29 W4M and Range 1 to 7 W5M. Climate within the study area is classified as being cold with cool summers. The study area covers approximately 38,300 km^2 and contains 4 major drainage basins, those of the Athabasca, North Saskatchewan, Battle and Red Deer rivers. Approximately 1.2 million people live within the study area, the majority of which live in the cities of Edmonton, Red Deer, St. Albert, Fort Saskatchewan, Camrose, Wetaskiwin, Leduc and Spruce Grove. Industrial activity and population growth in the area continue to increase as Alberta's economy grows. A depiction of the study area is presented in Figure 1. The following sections provide additional information on the study area climate, hydrology and demographics.

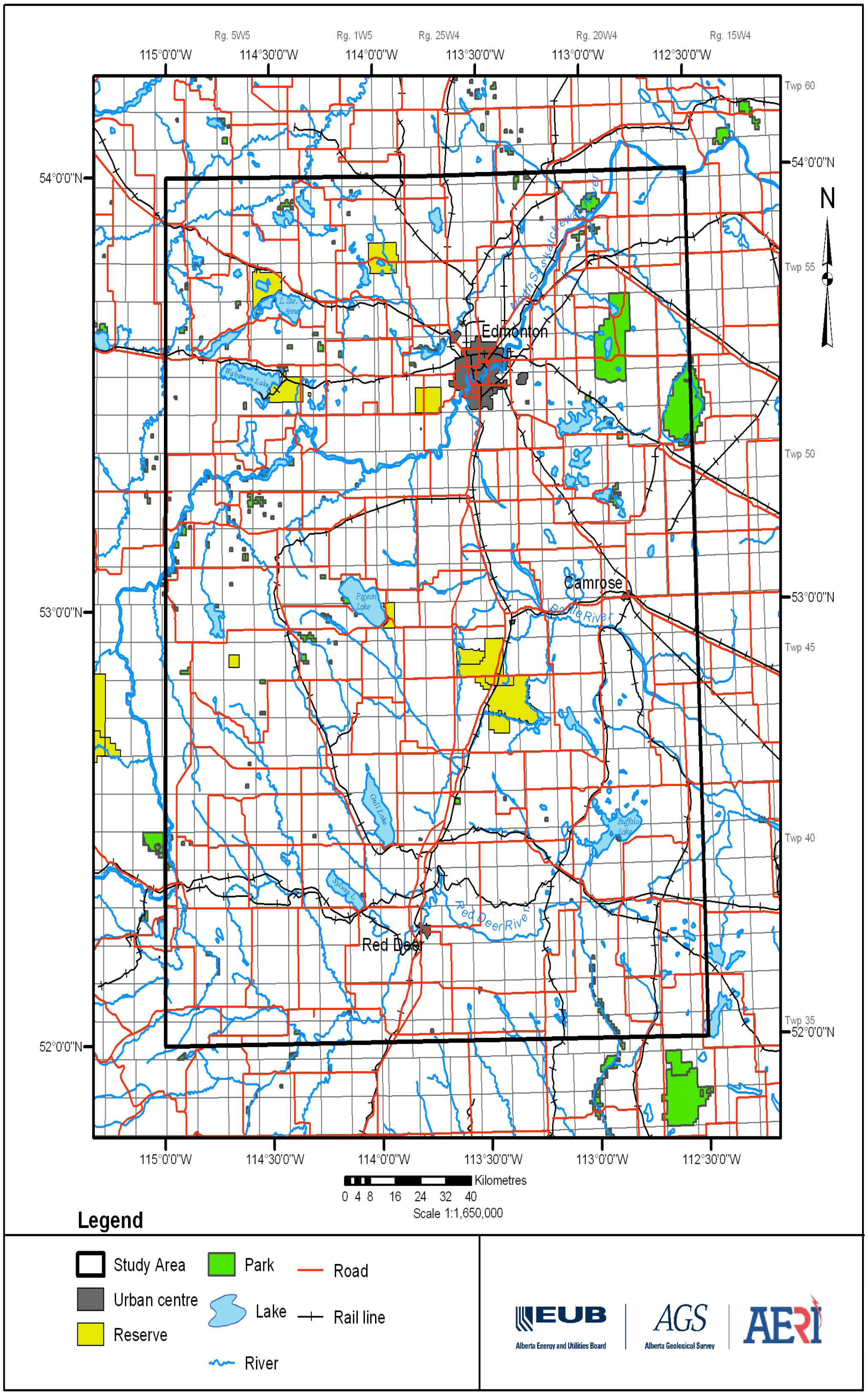


Figure 1. Study area map.

1.3 Climate and Hydrology

The climate and hydrology of the study area are discussed briefly in the following section. This information is important for the interpretation of the geochemical results produced in this study.

1.3.1 Climate

Seven climate stations were used to summarize the climate of the study area. Four of the stations were used to present information on temperature and precipitation patterns within the study area, while three were used to illustrate trends in evaporation and evapotranspiration. They were selected based on the length of time the stations have collected data and the proximity of the stations to the water sample sites. The locations of all of the climate stations are presented in Figure 2, while the following table (Table 1) provides additional information on the stations.

Table 1. Details of selected climate station locations within the study area.

Station Name	Station Data Type	Latitude	Longitude	Elevation (masl)	Data Collection Start Date (mm/dd/yyy)	Data Collection End Date (mm/dd/yyy)
Calmar	T, P	53°16’N	113°51W	720.0	08/01/1914	Ongoing
Camrose	T, P	53°1’N	112°49’W	739.0	01/01/1947	Ongoing
Edmonton City Centre Airport	Ev, Evt	53°34’N*	113°31’W*	670.6	1912	1996
Edmonton International Airport	Ev, Evt	53°19’N*	113°34’W*	715.0	1961	1996
Edmonton Stony Plain	T, P	53°33’N	114°6’W	766.3	02/01/1966	Ongoing
Lacombe	Ev, Evt	52°28’N*	113°45’W*	847.3	1941	1992
Red Deer Airport	T, P	52°10’N	113°53’W	904.6m	02/01/1938	Ongoing

Notes:
*Approximate location
T=temperature
P=precipitation
Ev=evaporation
Evt=evapotranspiration

1.3.1.1 Climate Type Classification

One of the most commonly used climate classification systems was developed by Koeppen during the 19th and 20th centuries (Koeppen, 1936). This system classifies climate based on temperature and precipitation into 5 general classes that include: A) Tropical; B) Dry; C) Temperate; D) Cold; and E) Polar. Three of the 4 stations fall into the D class and can be further subdivided into the D_{fb} or cold with cool summer class. These stations include the Calmar, Camrose and Edmonton Stony Plain climate stations. The characteristics of this class are that: 1) the warmest month has a daily average temperature of >10°C; 2) the coldest month has a daily average temperature of <-3°C; 3) the average daily temperature of the hottest month is <22°C; and 4) the amount of precipitation that falls throughout the year is more or less consistent from month to month. The Red Deer Airport climate station data indicates that it falls into the D_{fc} or cold with cool, short summer class of the Koeppen Climate Classification system. The characteristics of this class are similar to those described above, except that in the D_{fc} class, the average

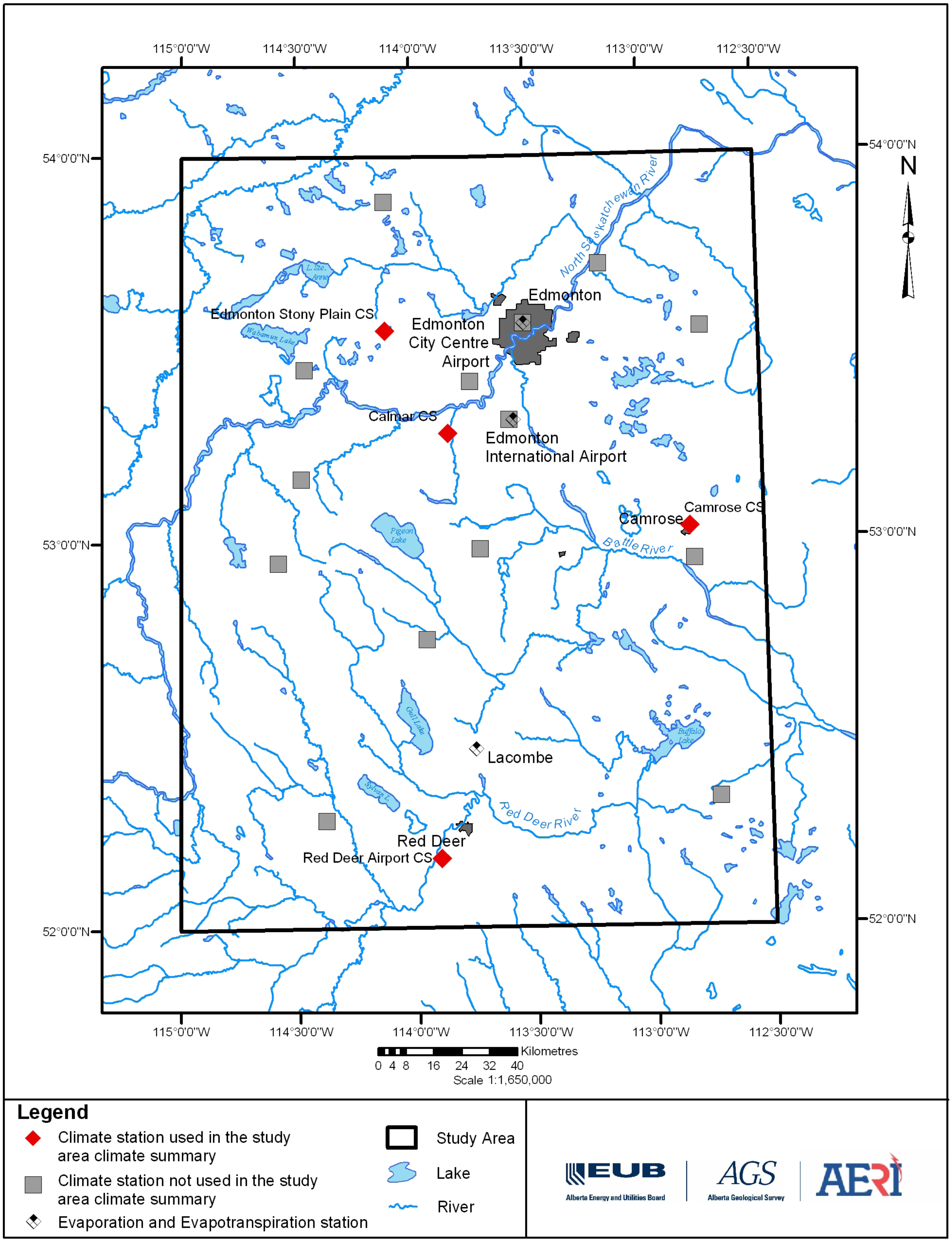


Figure 2. Climate station locations within the study area.

daily temperature is <10^{o}C for 8 or more months of the year. The following tables present the data collected by Environment Canada (Environment Canada, 2005) used to support these classifications (Table 2, Table 3, Table 4 and Table 5)

Table 2. Calmar climate station mean temperature and precipitation values summary 1971-2000.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (^{o}C)													
Daily average	-12.9	-9.7	-3.8	4.8	10.9	14.4	16.2	15.4	10.6	4.9	-5.1	-10.8	2.9
Daily maximum	-7.1	-3.5	2.1	11.6	18.2	21.2	22.8	22.4	17.5	11.6	0.3	-5.2	9.3
Daily minimum	-18.7	-15.8	-9.8	-2	3.5	7.6	9.5	8.4	3.7	-1.7	-10.4	-16.4	-3.5
Precipitation (mm)													
Rainfall	1.5	0.8	1.5	13.5	53.6	88.4	104.2	68.3	45.2	15.1	3.0	0.7	395.7
Snowfall	26.4	16.5	19.6	10.7	2.9	0.0	0.0	0.0	0.8	10.0	18.7	19.7	125.2
Precipitation	27.9	17.3	21.0	24.2	56.5	88.4	104.2	68.3	46.1	25.1	21.6	20.4	520.9

Table 3. Camrose climate station mean temperature and precipitation values summary 1971-2000.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (^{o}C)													
Daily average	-13.4	-10.4	-4.5	4.4	10.7	14.6	16.5	15.8	10.3	4.6	-5.2	-11.1	2.7
Daily maximum	-7.9	-4.7	0.9	10.4	16.9	20.2	22.2	21.9	16.2	10.6	-0.4	-6.0	8.4
Daily minimum	-18.8	-16.1	-9.7	-1.6	4.5	8.9	10.8	9.7	4.4	-1.3	-10.0	-16.3	-3.0
Precipitation (mm)													
Rainfall	0.8	0.3	1.0	14.2	44.0	87.3	87.9	62.1	42.0	11.6	2.6	0.7	354.4
Snowfall	25.8	17.2	22.6	10.0	3.0	0.0	0.0	0.0	0.3	7.4	16.0	20.6	122.9
Precipitation	26.5	17.5	23.6	24.6	46.9	87.3	87.9	62.1	42.4	19.0	18.7	21.3	477.7

Table 4. Edmonton Stony Plain climate station mean temperature and precipitation values summary 1971-2000.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (^{o}C)													
Daily average	-11.7	-8.5	-3.0	4.9	10.9	14.5	16.5	15.7	10.7	5.3	-4.4	-9.7	3.4
Daily maximum	-7.3	-3.9	1.5	10.4	16.7	19.9	21.8	21.0	16.0	10.2	-0.6	-5.7	8.3
Daily minimum	-15.9	-12.9	-7.6	-0.5	5.1	9.1	11.2	10.3	5.3	0.3	-8.1	-13.6	-1.5
Precipitation (mm)													
Rainfall	1.7	1.4	1.8	14.0	49.5	98.1	106.2	73.5	46.3	13.3	3.0	1.3	410.0
Snowfall	25.2	18.0	18.6	12.8	4.7	0.0	0.0	0.1	1.6	9.5	20.2	23.2	133.9
Precipitation	24.1	18.3	19.3	26.6	54.0	98.1	106.2	73.6	47.9	22.7	21.8	23.5	536.0

Table 5. Red Deer Airport climate station mean temperature and precipitation values summary 1971-2000.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)													
Daily average	-13.2	-10.0	-4.1	4.2	9.8	13.7	15.6	14.9	9.9	4.1	-5.4	-11.1	2.4
Daily maximum	-7.2	-3.7	1.9	10.9	16.9	20.2	22.3	21.9	17.1	11.4	0.4	-5.2	1.1
Daily minimum	-19.1	-16.2	-10.1	-2.6	2.8	7.1	8.8	7.8	2.6	-3.2	-11.2	-17.0	-4.2
Precipitation (mm)													
Rainfall	1.0	0.5	1.3	12.0	51.2	92.0	93.1	70.0	46.4	11.9	1.1	0.8	381.4
Snowfall	21.4	12.5	18.4	11.4	4.9	0.0	0.0	0.0	3.2	8.5	16.9	18.9	116.2
Precipitation	19.0	10.8	16.9	22.6	56.0	92.1	93.1	70.1	49.5	19.8	15.9	17.1	482.7

1.3.1.2 Temperature and Precipitation

Despite some similarities in climate classification type and average values, certain differences become apparent after a closer inspection of the climate station data. The greatest variability between and within station data sets appears to consistently be in precipitation patterns, while despite some differences, temperature trends suggest a more consistent pattern over time and between stations. Appendix 1 contains figures that were constructed from data obtained from Environment Canada (Environment Canada, 2005). They show decadal variations in daily mean temperature and daily total precipitation over the data collection periods for each of the stations (Figure 64, Figure 65, Figure 66, Figure 67, Figure 68, Figure 69, Figure 70 and Figure 71).

1.3.1.3 Evaporation and Evapotranspiration

Evaporation describes loss of moisture from a water body open to the atmosphere whereas evapotranspiration describes the process of loss of moisture through transpiration and evaporation of water by plant processes that draw water from the soil and transpire it to the atmosphere. Evaporation estimates assist in understanding water balances in lakes and reservoirs, while estimates of evapotranspiration help understand watershed response to precipitation events and how land-use and climate change could affect the hydrology of an area (Abraham, 1999).

Evaporation and evapotranspiration values for the three stations were calculated using the complementary relationship lake evaporation (CRLE) and the complementary relationship areal evapotranspiration (CRAE) models. The CRAE model requires information on monthly air temperature, dew point temperature or relative humidity, the ratio of observed to maximum possible sunshine duration, latitude, elevation and annual precipitation (Abraham, 1999). The CRLE model utilizes the same data for the calculation of evaporation values.

The average evaporation values for the Edmonton City Centre Airport, Edmonton International Airport and Lacombe stations are 897 mm, 865 mm and 852 mm respectively, with standard deviations of 91 mm (N=81), 66 mm (N=36) and 86 mm (N=44) respectively. The average evapotranspiration values for the study area are approximately 875 mm, 840 mm and 829 mm respectively with standard deviations of 93 mm (N=81), 67 mm (N=36) and 89 mm (N=44) respectively. Evaporation and evapotranspiration values appear to decrease in a southerly direction. The yearly evaporation and evapotranspiration values are presented in Appendix 2 in Table 31, Table 32 and Table 33.

Based on the work of Malmström (1969) the study area is categorized as sub-humid to humid after taking into account evapotranspiration values, water needs and temperature considerations.

1.3.2 Hydrology

The study area encompasses portions of 4 major drainage basins in the Province. These include the Athabasca, North Saskatchewan, Battle and Red Deer rivers. Within the study area, there are a total of 70 hydrologic stations that measure flow and another 31 stations that measure water levels within these basins. The locations of the major drainage basins and hydrologic stations are presented in Figure 3. Details of the stations used to describe the hydrology of the study area are presented in Table 6.

Table 6. Study area hydrologic station details.

Station Name	Envirnoment Canada ID	Data Start Date	Data End Date	Latitude (°N) NAD83	Longitude (°W) NAD83	DLS Location
Water Level Data						
Buffalo Lake near Erskine	05CD005	1965	1997	52.45722	112.87667	NW-19-40-20W4
Cooking Lake at Cooking Lake	05EB012	1972	1995	53.41639	113.12083	SW-24-51-22W4
Gull Lake at Aspen Beach	05CC006	1924	1997	52.45778	113.96750	NE-21-40-28W4
Isle Lake at Eureka Beach	05EA008	1972	1997	53.62500	114.68861	NE-32-53-05W5
Lac Ste. Anne at Alberta Beach	05EA006	1933	1997	53.67639	114.35750	22-54-03W5
Pigeon Lake at Grandview	05FA013	1972	1997	52.98750	114.05278	NE-22-46-01W5
Sylvan Lake at Sylvan Lake	05CC003	1918	1997	52.31222	114.10222	NE-32-38-01W5
Wabamun Lake at Wabamun	05DE002	1915	1997	53.55667	114.34111	SW-11-53-04W5
Stations with Discharge Data						
N. Saskatchewan River near Rocky Mountain House	05DC001	1913	1997	52.38083	114.93917	NE-21-39-07W5
N. Saskatchewan River near Edmonton	05DF001	1911	1997	53.53750	113.48444	NW-33-52-24W4
Battle River near Ponoka	05FA001	1913	1997	52.66222	113.58222	NE-31-42-25W4
Red Deer River at Red Deer	05CC002	1912	1997	52.27667	113.81583	SE-20-38-27W4

The river stations have mean discharge values between 2.62 m^3/s for the Battle River near Ponoka to 48.58 m^3/s for the Red Deer River near Red Deer, to 149.26 m^3/s and 213.98m^3/s for the North Saskatchewan River near Rocky Mountain House and Edmonton respectively. Plots of the discharge over time are presented in Figure 4 and Figure 5. Trends in the data are difficult to assess but appear related to seasonal discharge variations and typical flooding and drought cycles, but one cause and effect relationship appears likely. The Big Horn Dam was completed in 1972 in order to address ongoing water supply and pollution problems. It is at about this time that the discharge values in Figure 5 begin to show less variability in discharge values. Since the North Saskatchewan River near Edmonton occurs further downstream of the dam than the station near Rocky Mountain House, the signal appears more variable, but still subdued as compared to the pre 1972 data.

Lake levels vary between approximately 1 and 3 metres over the measurement periods for the different

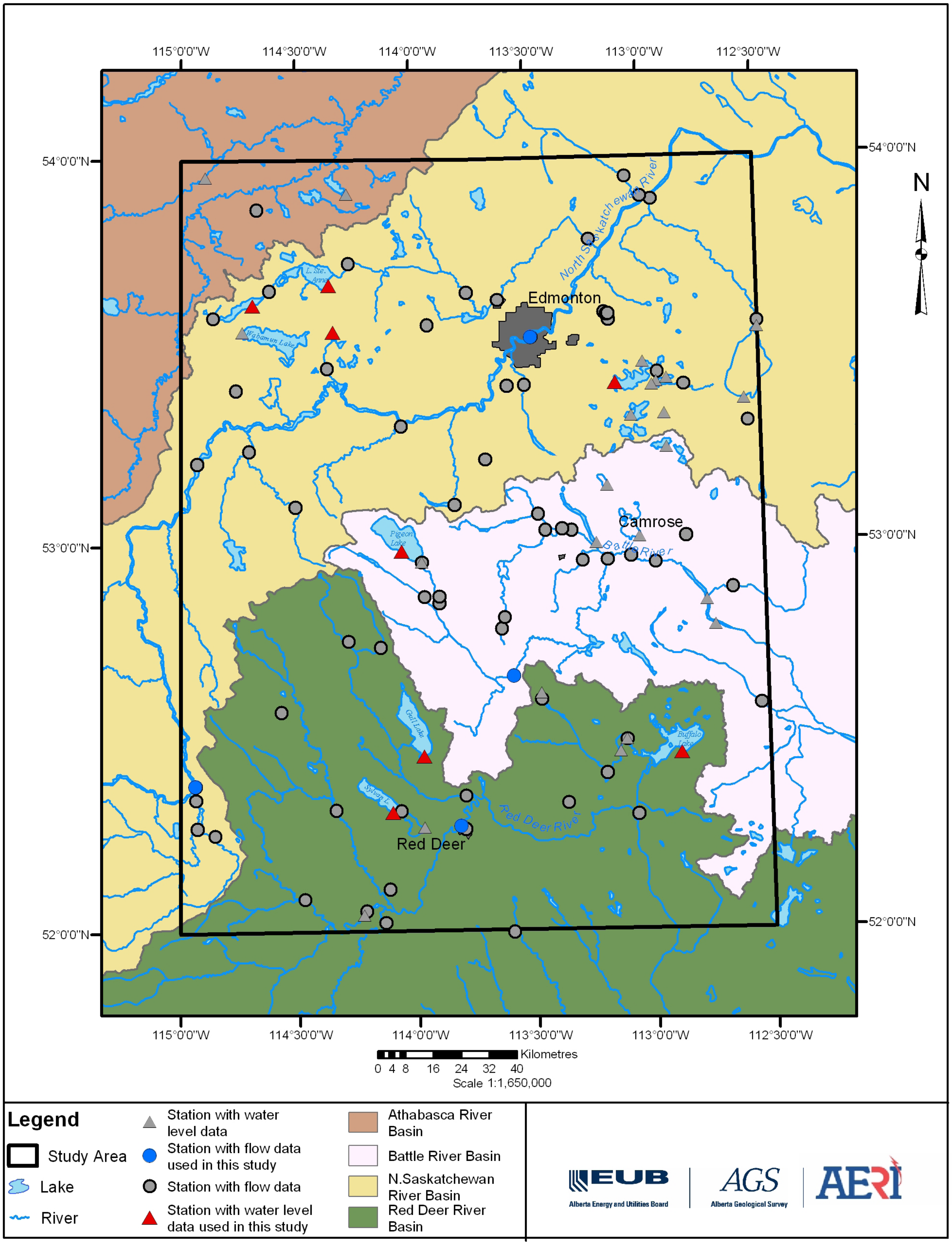


Figure 3. Study area hydrology summary map.

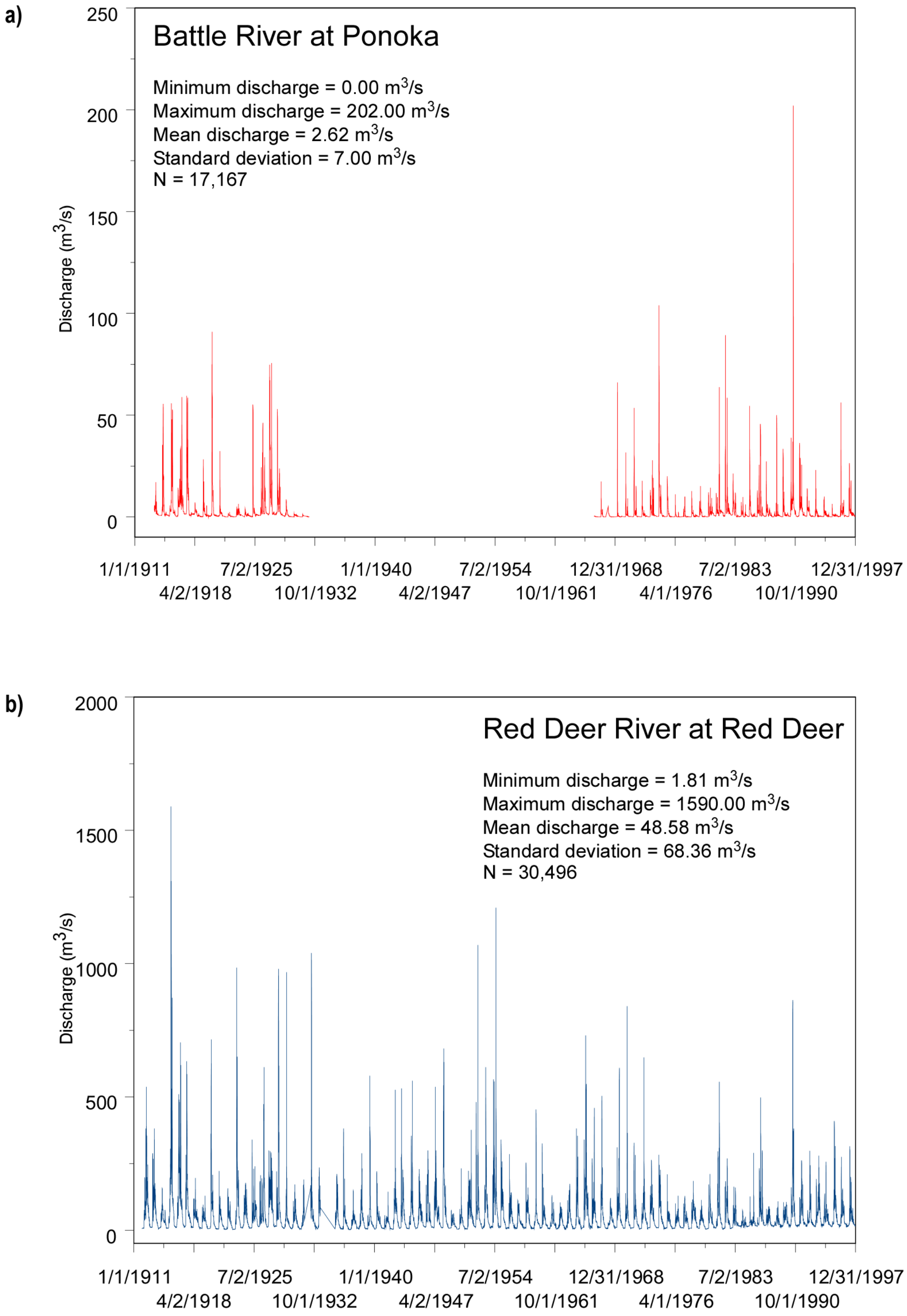


Figure 4. Discharge summary plots: a) Battle River; and b) Red Deer River.

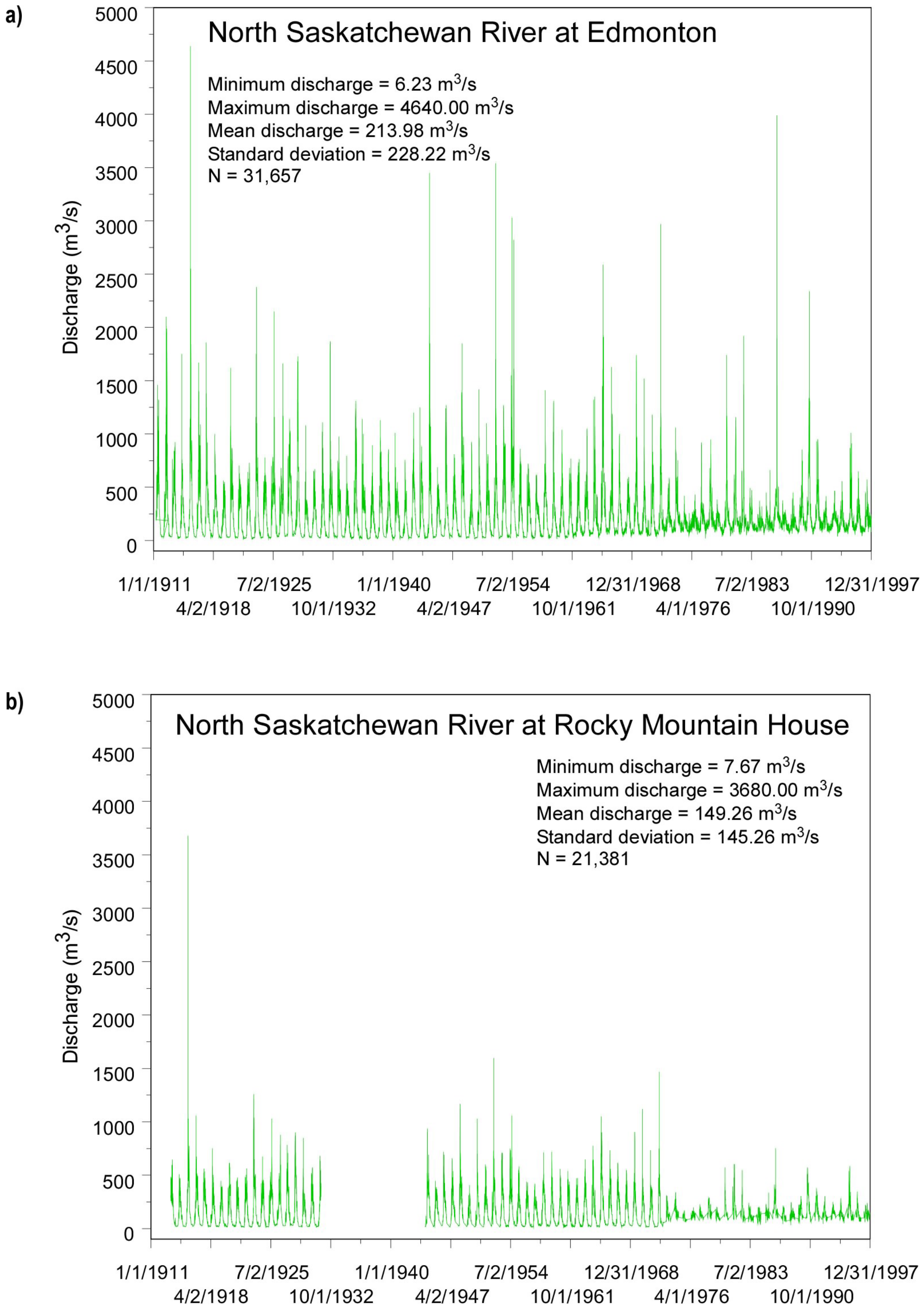


Figure 5. North Saskatchewan River discharge summary plots near: a) Edmonton; and b) Rocky Mountain House.

lakes. Lake levels for the various lakes used to describe the hydrology in the study area show similar trends in the data depending on the proximity of the lakes to one another (Figure 6, Figure 7, Figure 8 and Figure 9). For instance, the diagrams for Isle Lake, Lake Wabamun and Lac Ste Anne have a number of overlapping high and low areas which suggest they are recording similar hydrologic events over time. There are some distinct differences however, most notably in the late 1970's to early 1980's between the Lake Wabamun plot and those of Isle Lake and Lac Ste Anne. Similar relationships are visible in the other plots, but no consistent matches occur over time.

1.4 Demographics

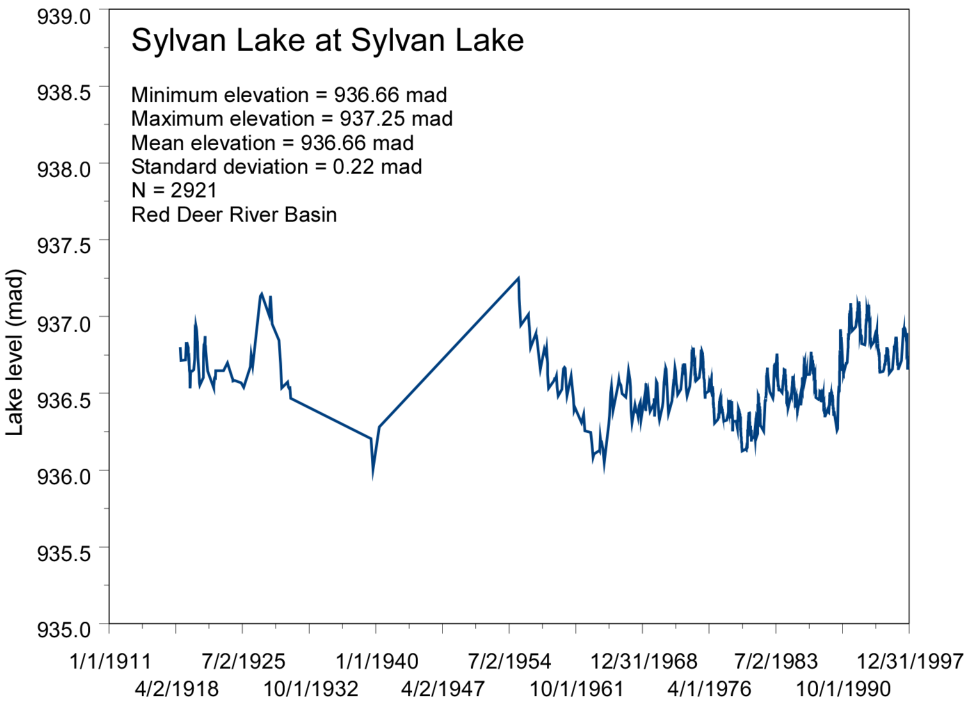
A cursory overview of demographics and population distribution in the study area is presented in this section. This information is important for understanding geochemical data because the presence of human populations, industry, and agriculture can have pronounced local and regional impacts on groundwater chemistry and, presumably, on geomicrobiology. This information shows that while our geochemical data may be used to establish an environmental baseline for future reference, this baseline already is from a time of intense rural and urban development and may not represent natural or virgin geochemical conditions. Knowledge of the state of human development is also important when interpreting individual geochemical results because industrial and agricultural practices have known impacts on the types and amounts of various chemical constituents in groundwater.

Based on the 2001 Canadian census (Statistics Canada, 2005a), the study area population is approximately 1,184,463, corresponding to a population density of approximately 30.9 people/km^2. By comparison, the population of Alberta is approximately 2,974,807 (population density of 4.5 people/km^2) and that of Canada 30,007,094 (population density of 3.0 people/km^2). One hundred and fourteen distinct population centres were identified within the area based on Statistics Canada census divisions. These included 8 cities, 9 counties, 1 improvement district, 2 municipal districts, 9 Indian reserves, 1 specialized municipality, 36 summer villages, 26 towns and 22 villages. The majority of the population is considered to be urban, but the majority of the population centres are rural in nature. The urban population is estimated at 1,004,617 and comprises approximately 84.8% of the study area population whereas the rural population is estimated at 179,846 or approximately 15.2% of the study area population. The largest population centre is the city of Edmonton with a population of 666,104, while the smallest centres include the summer villages of Betula Beach, Castle Island, Itaska Beach and Point Alison each with a population of 10. A table of population broken down by population centre type is presented below (Table 7) while the complete list of population centres is presented in Appendix 3.

Table 7. Population breakdown by population centre type.

Population Centre Type	Total Population	Urban Population		Rural Population	
		Total	% of Total	Total	% of Total
City (C)	857,036	856,500	99.9	536	0.1
County (CM)	104,943	1,670	1.6	103,273	98.4
Improvement District (ID)	27	0	0.0	27	100.0
Municipal District (MD)	27,015	3,356	12.4	23,659	87.6
Indian Reserve (R)	8,675	0	0.0	8,675	100.0
Specialized Municipality (SM)	71,986	47,610	66.1	24,376	33.9
Summer Village (SV)	2,966	391	13.2	2,575	86.8
Town (T)	101,298	95,090	93.9	6,208	6.1
Village (VL)	10,517	0	0.0	10,517	100.0

a)



b)

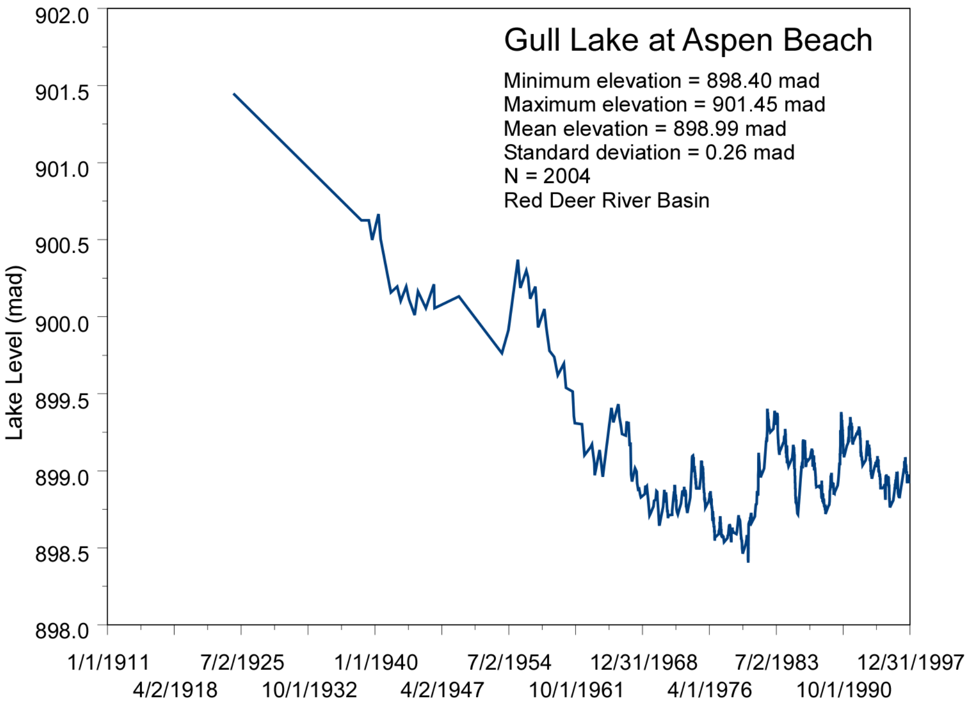


Figure 6. Water level summary plots: a) Sylvan Lake; and b) Gull Lake. Note: mad=metres abouve datum

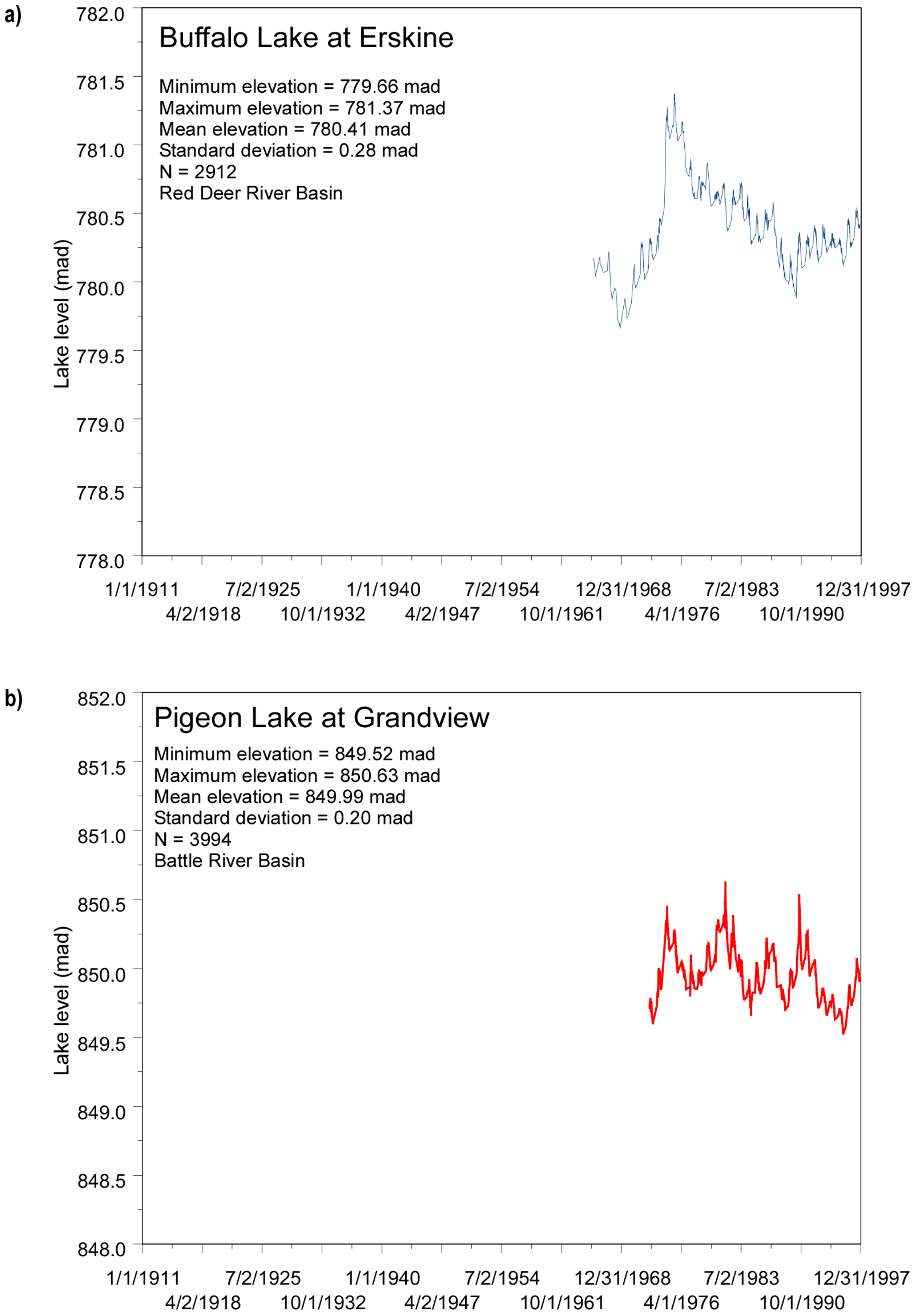
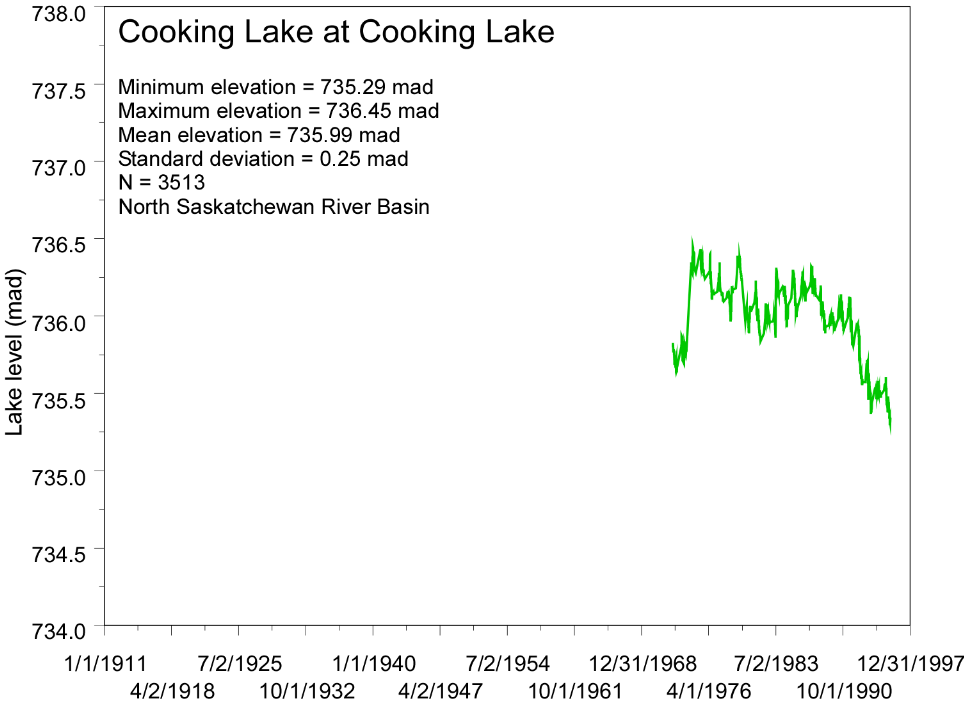


Figure 7. Water level summary plots: a) Buffalo Lake; and b) Pigeon Lake. Note: mad=metres abouve datum

a)



b)

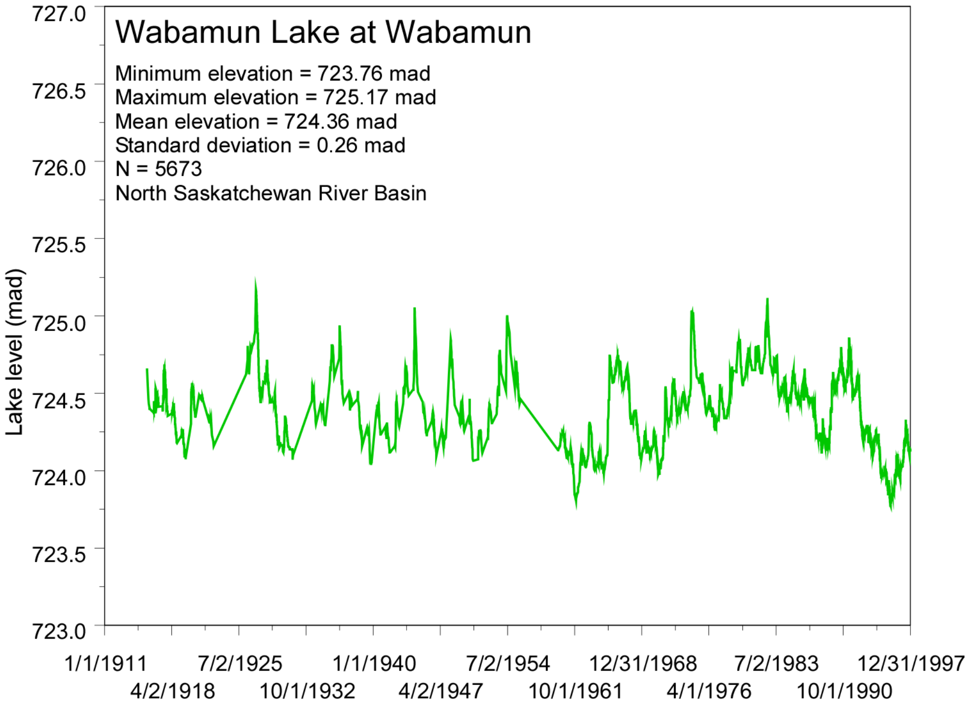
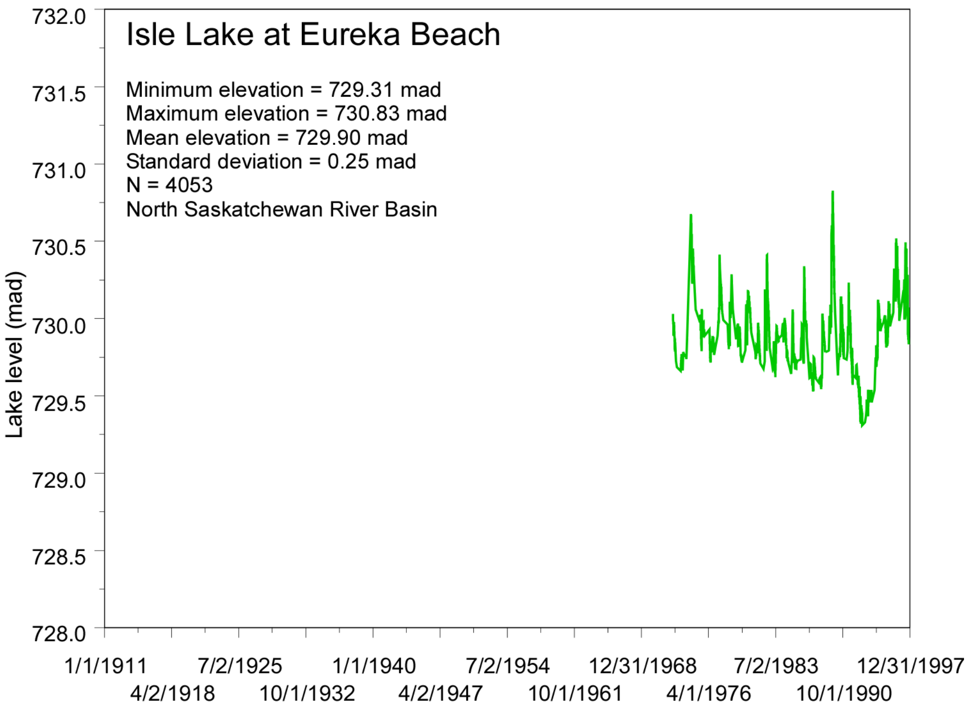


Figure 8. Water level summary plots: a) Cooking Lake; and b) Lake Wabamun. Note: mad=metres abouve datum

a)



b)

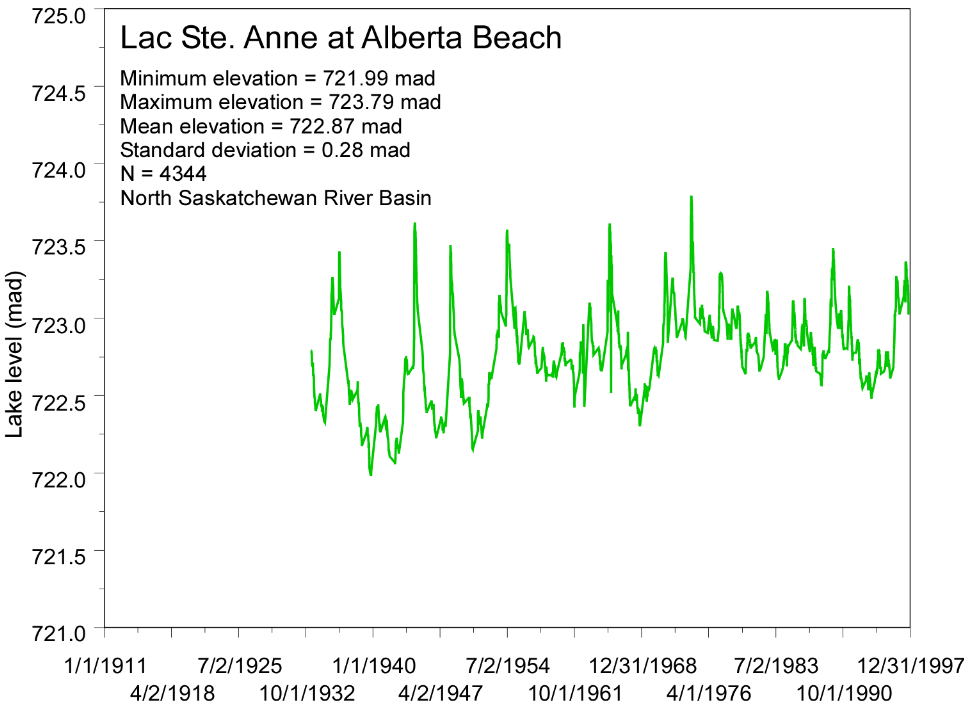


Figure 9. Water level summary plots: a) Isle Lake; and b) Lac Ste. Anne. Note: mad=metres abouve datum

Information on population distribution based on age and sex is available for 46 of the 114 population centres within the study area (Statistics Canada, 2005a, b). Included within this data set is information on all 8 cities, 8 of the 9 counties, both municipal districts, 3 of the 9 Indian reserves, the specialized municipality, 2 of the 36 summer villages, 17 of the 26 towns and 5 of the 22 villages. The following tables in Appendix 3 (Table 34, Table 35 and Table 36) summarize the data available on population proportion by age and sex for the study area.

A number of interesting observations can be made regarding the age and sex differences between the various population centres for which data is available. These observations are important in consideration of establishing a geochemical baseline for future reference because land-use and the nature of anthropogenic contaminants are controlled not only by population size and density but by the make up of the population. The linkages between demographics, contaminants and the slow change of geochemical baselines in the environment is a relatively new area of investigation and will not be explored further in this report except as these comments for future reference.

In general, at the time of this study, the proportion of the population between the ages of 0 and 19 in the study area is greater than both the provincial and national proportions and is most prominent in the male population. The proportion of the population between the ages of 20 and 64 in the study area is almost always less than both the provincial and national proportions with the male population exhibiting this trend most clearly. The proportion of the population 65 years old or older is generally less than the provincial or national averages with the female population exhibiting this trend most clearly.

Median age data is also available for the same 46 population centres within the study area (Statistics Canada, 2005a, b). The following tables in Appendix 3 (Table 37, Table 38 and Table 39) summarize the data available on median age by sex. In general, the median ages for both females and males within the study area has increased by approximately 2 to 2.5 years between 1996 and 2001. Despite this increase, the median ages have generally remained less than the provincial and national median ages. This trend is most obvious for almost all females within the study area and for males within cities, on Indian reserves and in most towns.

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 shoreface and then 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 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 and Depositional Setting of the Coal-Bearing Formations

2.1.1 Horseshoe Canyon Formation

The Horseshoe Canyon Formation was deposited during late Cretaceous time, as the sea that previously occupied a portion of the Alberta Basin regressed. The clastic sedimentary rocks of the Horseshoe Canyon Formation then prograded into the basin in an east-south-easterly 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 extent of the Horseshoe Canyon Formation is presented in Figure 10.

2.1.2 Scollard and Paskapoo Formations

The Scollard Formation 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 areal extent of the Scollard Formation is presented in Figure 11.

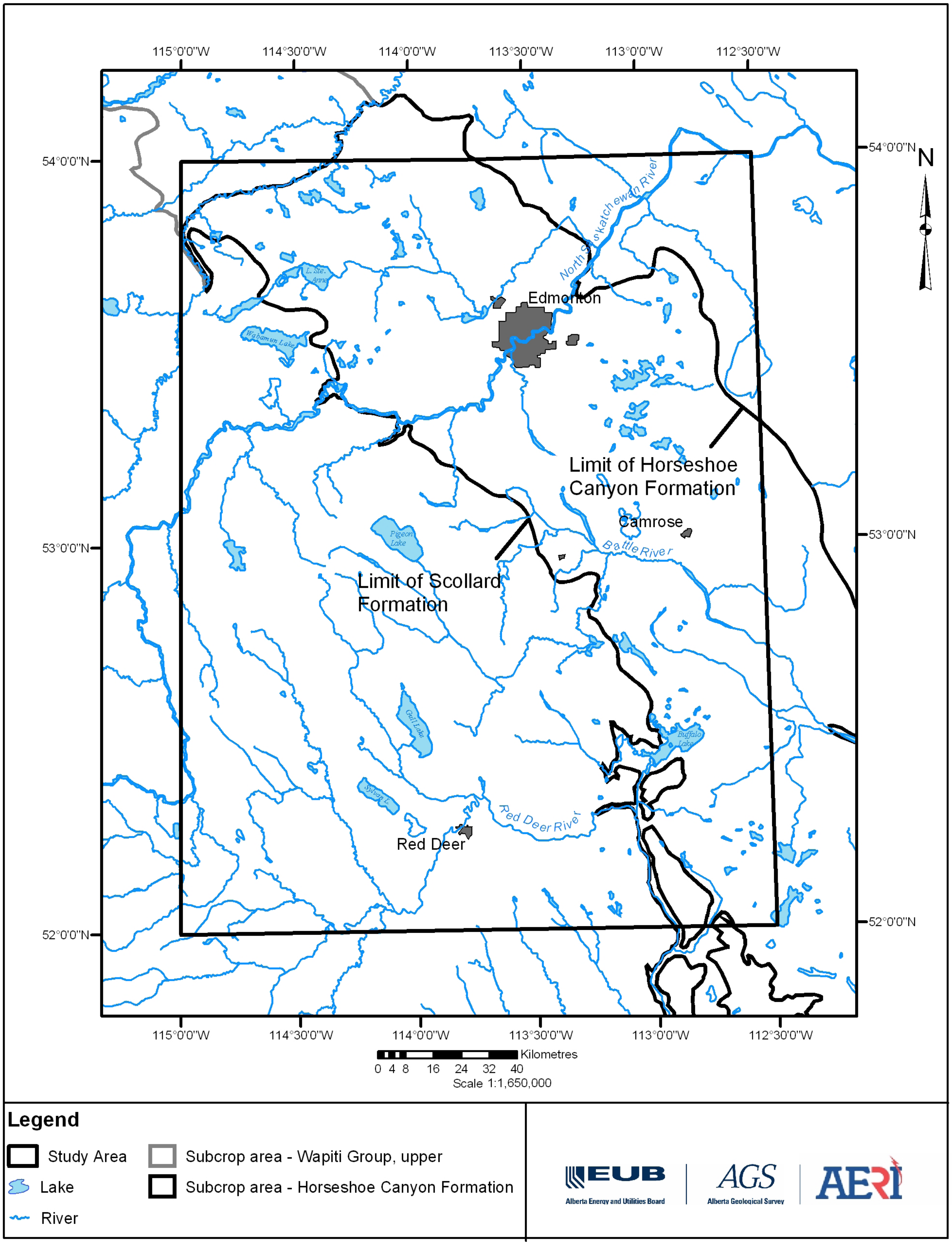


Figure 10. Areal extent of the Horseshoe Canyon Formation.

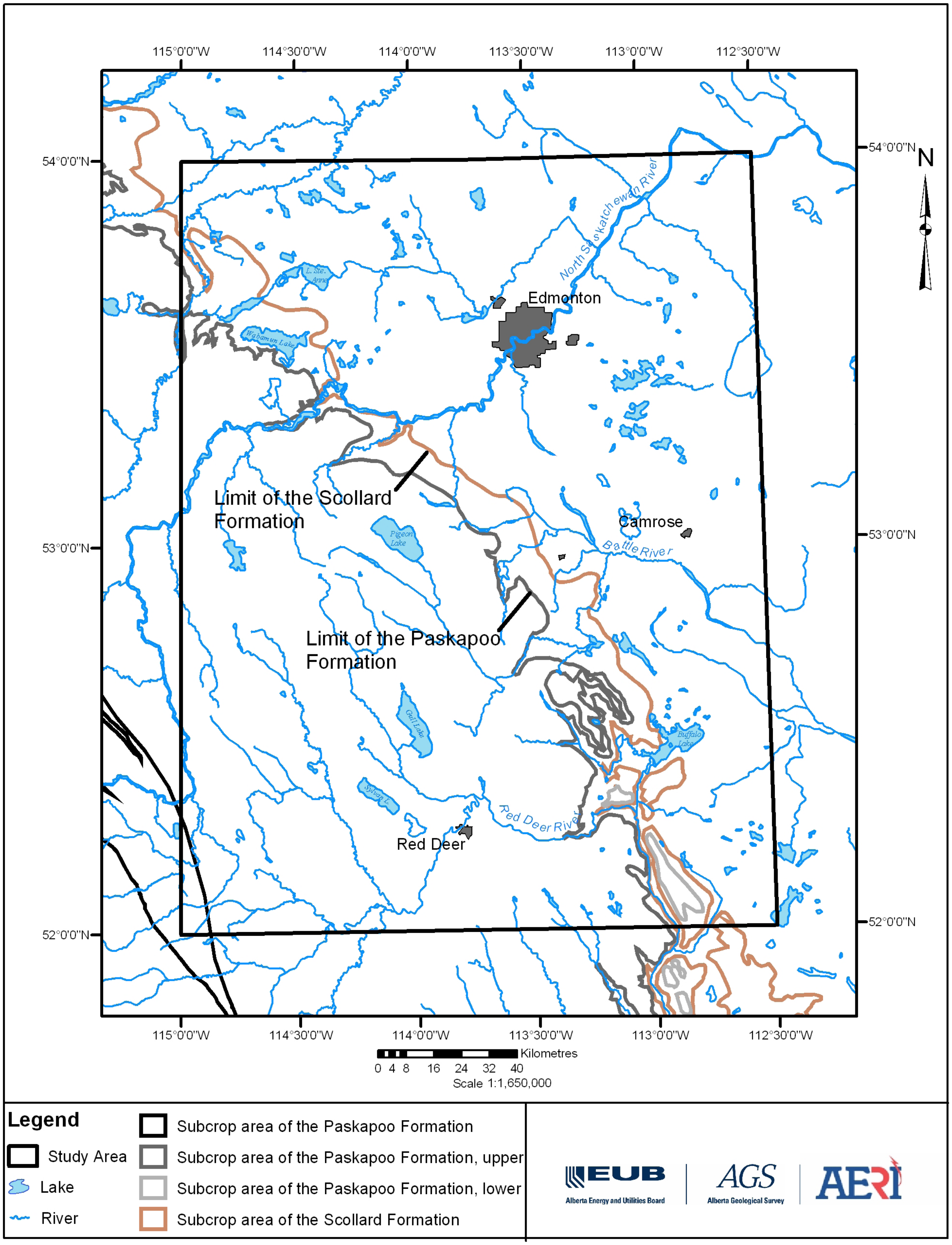


Figure 11. Areal extent of the Scollard and Paskapoo formations.

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. The areal extent of the Paskapoo Formation is presented in Figure 11.

3 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.

3.1 General Concepts

The flow of fluid through porous media has been mathematically described through the work of many researchers. Alberta has been a proving ground for many theories regarding the flow of water and fluids through geological media. The following sections highlight many of the relevant and significant contributions to the field.

3.2 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 semi confined 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 post erosional 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.

Lemay (2003) compiled and analyzed a number of pump tests from coal-bearing formations in the Alberta Basin as well as aquifer tests completed on sandstone intervals devoid of coal. The preliminary analysis of the data revealed that a number of different flow-regime types are present within these formations substantiating some of the previous hypotheses put forward in the Chorley and Vogwill report.

3.3 Potentiometric Surfaces and Groundwater Flow

Data are available from Alberta Environment holdings on static water levels for over 100,000 water wells within the study area. Through the use of surfaces generated for the Atlas of the Western Canadian Sedimentary Basin as well as other surfaces generated for various project specific purposes, The AGS assigned these water wells to hydrostratigraphic units as described by Bachu (1995) and undertook to generate general, unconfirmed maps of the static water level elevations for the Horseshoe Canyon Formation, Scollard and Paskapoo formations and drift hydrostratigraphic units based primarily on water well data.

3.3.1 Horseshoe Canyon Formation

Over 17,000 data points were used to create the Horseshoe Canyon Formation water level elevation map (Figure 12).In general, regional groundwater flow appears to be towards the northeast. Certain local higher and lower than expected water level elevation values suggest the local influence of topography on groundwater flow within this Formation. Hydrologic features in the area are also likely to play an important role as discharge areas for variously scaled flow systems within the Formation. The water level elevations appear generally consistent with water level elevations presented by Bachu and Michael (2002).

3.3.2 Scollard and Paskapoo Formations

The Scollard and Paskapoo formations hydrostratigraphic unit contains the most data points with over 26,000 static water level records available for the area. Once again, the general direction of groundwater flow appears to be towards the northeast, with topography and hydrology impacting the direction of flow in various areas (Figure 13). Of particular note is the likely influence of the North Saskatchewan River and Wabamun Lake. Static water level elevation values in proximity to these features suggest that they are acting as discharge areas in certain portions of the study area. Hydraulic head values are consistent with those reported in Bachu and Michael (2002). Initial comparisons between Horseshoe Canyon and Scollard-Paskapoo formations hydrostratigraphic units suggest that a downward gradient of flow exists between the two where the two formations are present.

3.3.3 Drift Interval

The drift interval consists of the sediments deposited following the deposition of the Paskapoo Formation and are most commonly attributed to glacial processes. The water level elevation map was created using over 8,000 data points. The regional direction of groundwater flow appears to be towards the northeast and generally mirrors topography (Figure 14). Certain areas of elevated water levels present in the drift water level elevation map area also present in the Horseshoe Canyon or Scollard and Paskapoo water level elevation maps further strengthening the idea that local topography is controlling certain aspects of groundwater flow in the study area.

4 Chemical Hydrogeology

4.1 General Concepts

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.

4.1.1 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.

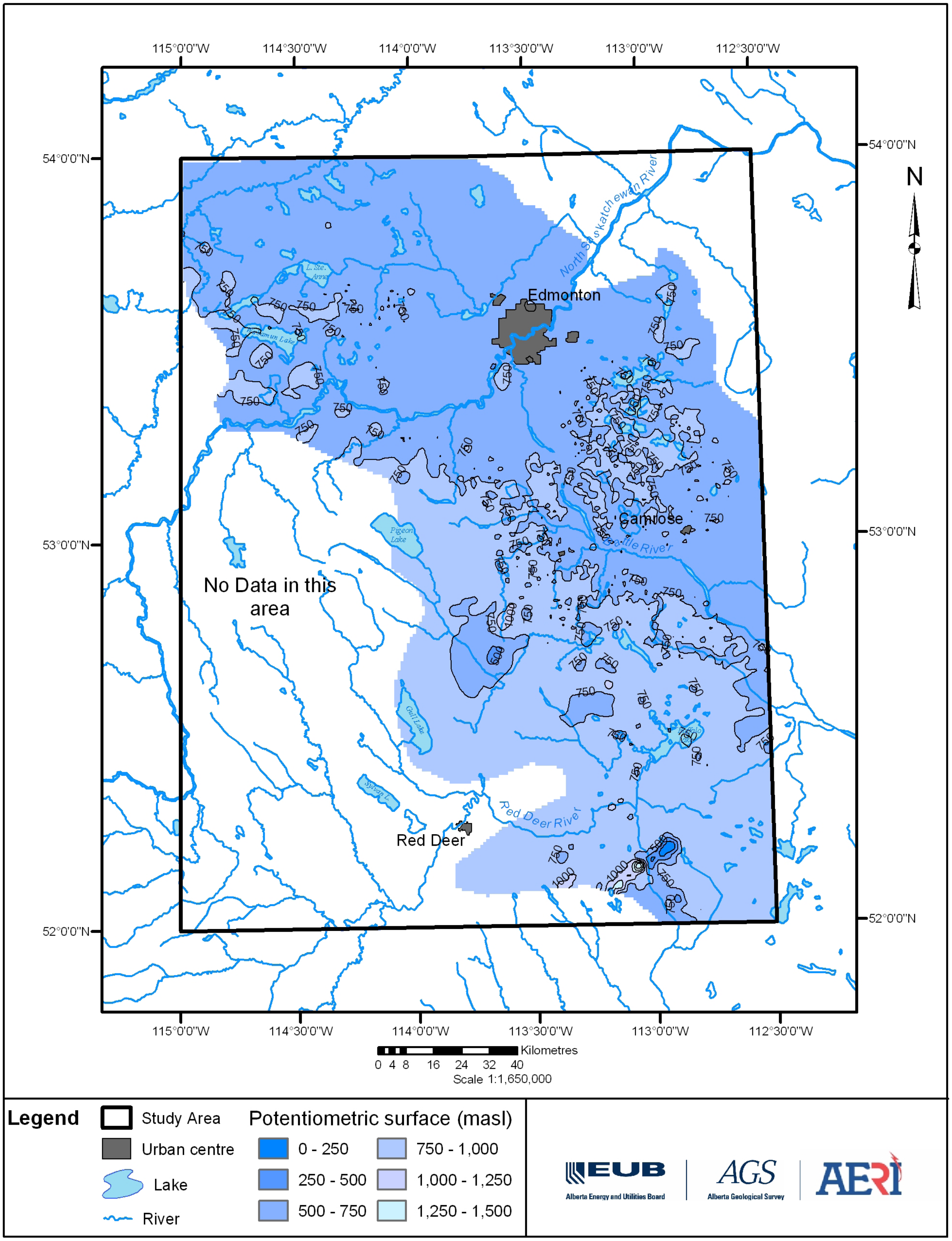


Figure 12. Horseshoe Canyon Formation water level elevation map. Note: masl=metres above sea level

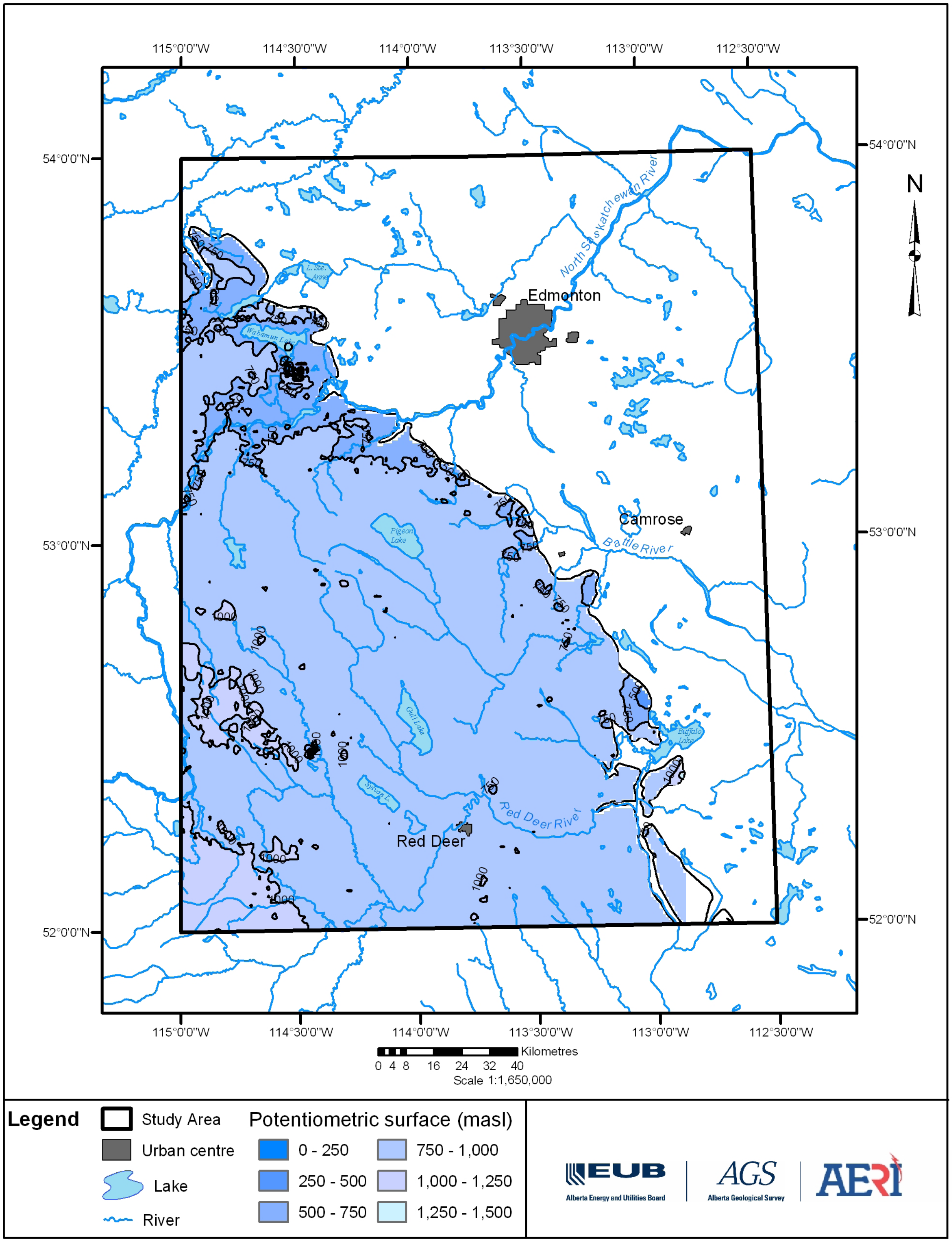


Figure 13. Scollard and Paskapoo formations water level elevation map. Note: masl=metres above sea level

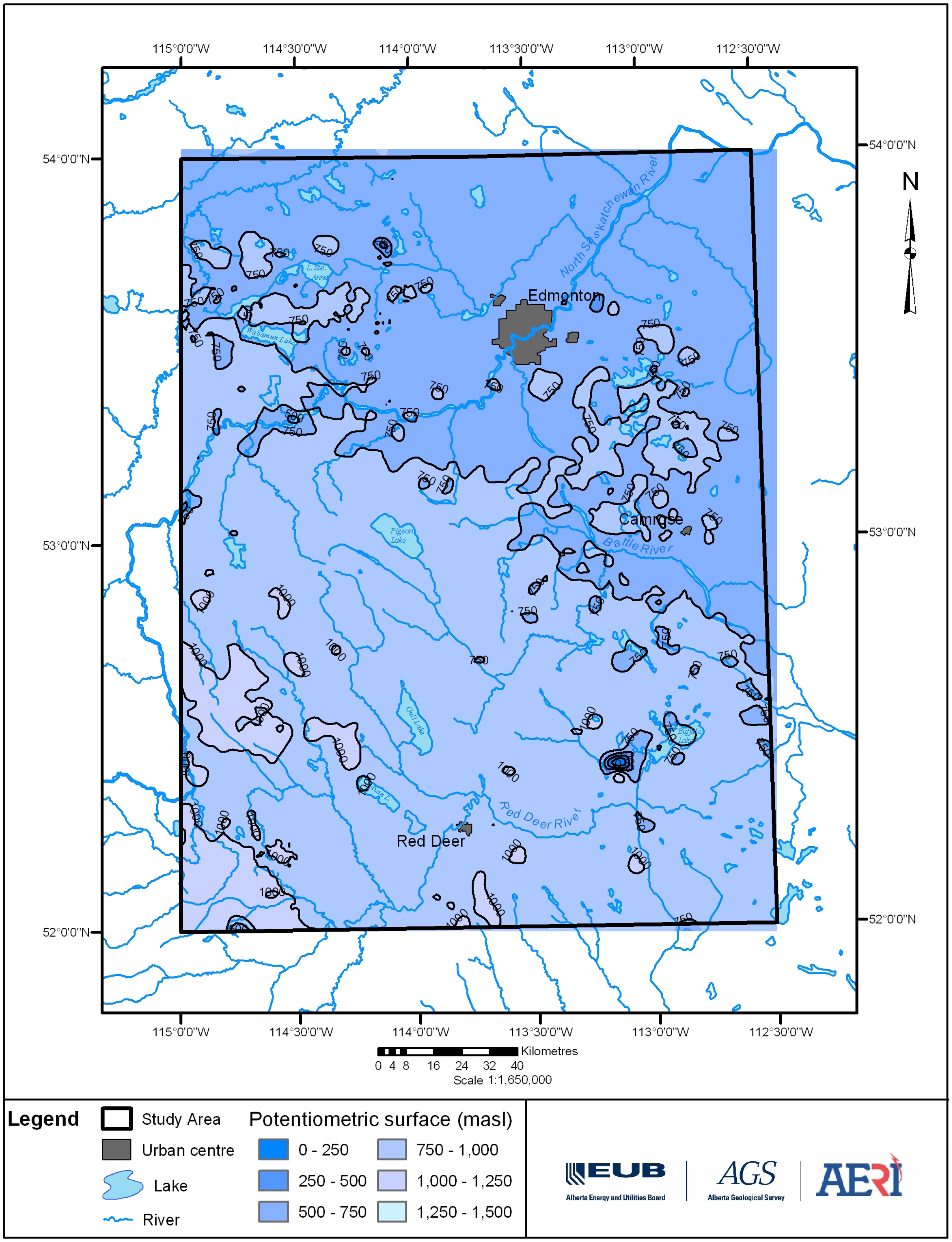


Figure 14. Drift interval water level elevation map. Note: masl=metres above sea level

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.

4.1.2 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.

4.1.3 Hydrochemical Facies

As is evident from the preceding sections, 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 15). 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.

4.2 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),

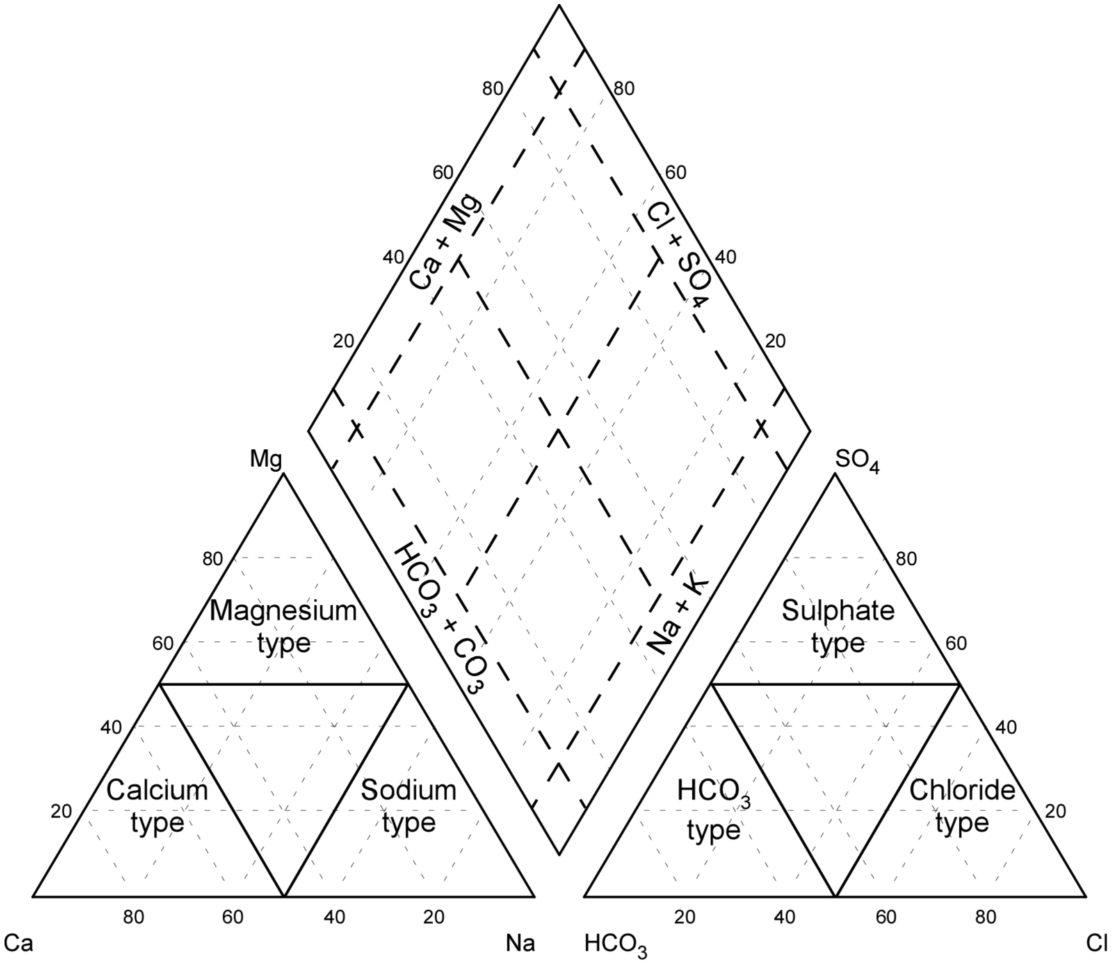


Figure 15. Hydrochemical facies diagram or Piper plot.

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, thirty-two 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.

Lemay (2003) completed a detailed and extensive sampling program of water wells completed in coal-bearing formations throughout the central and southern portions of the Alberta Basin. This work looked at major, minor and trace element concentrations in groundwater as well as organic compound concentrations, stable and radiogenic isotope values and calculated groundwater ages based on ^{14}C, ^{36}Cl and ^{129}I. The results of the analyses suggested 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. These analytical results also indicated that a number of the water sample compositions exceeded aesthetic objective, irrigation, livestock or drinking water quality guidelines. Chloride/bromide ratios, stable-isotope ratios of O, H and B and ^{87}Sr/^{86}Sr ratios indicated that mixing reactions are occurring within the various aquifers. Lemay surmised that similar mixing reactions with similar end members are possibly occurring within the entire Tertiary–Upper Cretaceous succession. The interpretation of the carbon and sulphur stable isotopic compositions also provided evidence to support the idea that biological processes are affecting water chemistry.

4.3 Groundwater Sampling

The process of collecting groundwater samples is well documented in numerous publications. Each author emphasizes the need for careful site selection, the use of rigorous sampling protocols, and the submission of samples to reputable laboratories. The sections below provide details on how the sampling program was carried out with these three items in mind.

4.3.1 Sample Site Selection

Two types of water sampling activities occurred as part of this study. The first involved the sampling of existing domestic water wells completed wholly or partially in coal. The second involved the sampling of existing CBM wells. No new test holes were drilled and no new wells were constructed in this study for the purpose of sample collection. The site selection process was slightly different in each case. Details on these methods are provided below.

4.3.1.1 Water Well Sample Site Selection

Alberta Environment maintains a database of water well information as submitted by water well drillers following the completion of a water well. The database contains information on:

- water well depth
- completion intervals
- lithologies encountered
- the types of materials used in well construction
- pump test results
- the availability of water chemistry data
- the well owner
- the water well driller
- the well location
- the availability of water well geophysical logs

In order to select potential water wells for this study, the database was queried in order to:

- locate wells within the proposed study area
- select wells with the proper construction characteristics
- identify wells where coal is within the completion interval of the well

Following these searches, the returned wells were scrutinized individually to determine their suitability as sample sites. Well owner information was then used to contact the well owners in order to confirm well details, make a final assessment of the sites potential suitability, to obtain permission to sample the well in question and then to schedule the site visit.

4.3.1.2 CBM Well Sample Site Selection

During the course of its CBM research initiatives, the AGS has developed a number of contacts with oil and gas companies involved in the development of CBM resources. These companies were contacted in order to determine the possibility of obtaining water samples from existing CBM wells. The criteria for site selection were simplified slightly as compared to those used in selecting water wells so as to accommodate the differences between these two types of wells. The selection criteria specified that:

- The well must be located within the study area
- The well had to be producing from a zone of interest
- Both a water sample and a gas sample could be obtained from the well
- Safety of AGS staff would not be put at risk

The sampling of these wells was dependent on the well maintenance or testing activities of the oil and gas companies. The AGS would normally receive notice of these activities 1 to 2 days in advance and would make arrangements to be on site for these scheduled events in order to collect its samples. The sampling of water from Scollard Formation CBM wells was not possible over the course of the sampling program as production from these wells was suspended.

4.3.2 Sample Location Descriptions

A total of 22 samples were collected during the sampling program. Water samples were collected from wells completed in the Belly River Group, the Horseshoe Canyon Formation, the Scollard Formation and the Paskapoo Formation. The locations of the samples are presented in Figure 16. Descriptions of the sample locations are provided below.

4.3.2.1 Belly River Group Sample Location

One sample (Sample 59) was collected from a CBM well completed in the Belly River Group. It is located in 043-26W4 (Figure 16). Based on an anomalous pH values it was rejected for further analysis. The gas sample from this well was submitted for analyses however as there was no reason to suspect the gas was contaminated. Additional information on the well and the site is provided in Appendix 4.

4.3.2.2 Horseshoe Canyon Formation Sample Locations

Six samples (samples 43, 44, 45, 47, 51 and 52) including one duplicate sample (Sample 52), were collected from water wells completed in the Drumheller coal zone equivalent of the Horseshoe Canyon Formation. Six samples (samples 55, 56, 57, 58, 25 and 26) including one duplicate (Sample 57), were also collected from CBM wells completed in the Drumheller coal zone of the Horseshoe Canyon Formation. Sample locations are identified in Figure 16. Following the return of the major, minor and trace element chemical analyses, one of these samples (Sample 58) was rejected for further analyses because of an anomalous pH value suggesting it was contaminated. The gas samples from this well were submitted for analysis however as there was no reason to suspect they were affected. The following table (Table 8) provides general details on the wells. Additional information on the wells and the sites is provided in Appendix 4.

Table 8. Horseshoe Canyon Formation sample site details.

Sample Name	Sample Identifier	Approximate Location	Formation	Coal Zone	Well Type
AERI 0501	43	53-22W4	Horseshoe Canyon	Drumheller equivalent	Water well
AERI 0502	44	48-19W4	Horseshoe Canyon	Drumheller equivalent	Water well
AERI 0503	45	49-20W4	Horseshoe Canyon	Drumheller equivalent	Water well
AERI 0506	47	50-23W4	Horseshoe Canyon	Drumheller equivalent	Water well
AERI 0510	51	41-18W4	Horseshoe Canyon	Drumheller equivalent	Water well
AERI 0511	52	41-18W4	Horseshoe Canyon	Drumheller equivalent	Water well
AERI 0516	55	39-20W4	Horseshoe Canyon	Drumheller	CBM well
AERI 0517	56	47-23W4	Horseshoe Canyon	Drumheller	CBM well
AERI 0518	57	47-23W4	Horseshoe Canyon	Drumheller	CBM well
AERI 0519	58	38-23W4	Horseshoe Canyon	Drumheller	CBM well
AERI 0525	64	45-22W4	Horseshoe Canyon	Drumheller	CBM well
AERI 0526	65	44-22W4	Horseshoe Canyon	Drumheller	CBM well

4.3.2.3 Scollard and Paskapoo Formations Sample Locations

Eight samples (samples 46, 49, 50, 54, 60, 61, 62 and 63) including 1 duplicate (Sample 50) were collected from water wells completed in the Ardley coal zone of the Scollard Formation. Two samples (samples 48

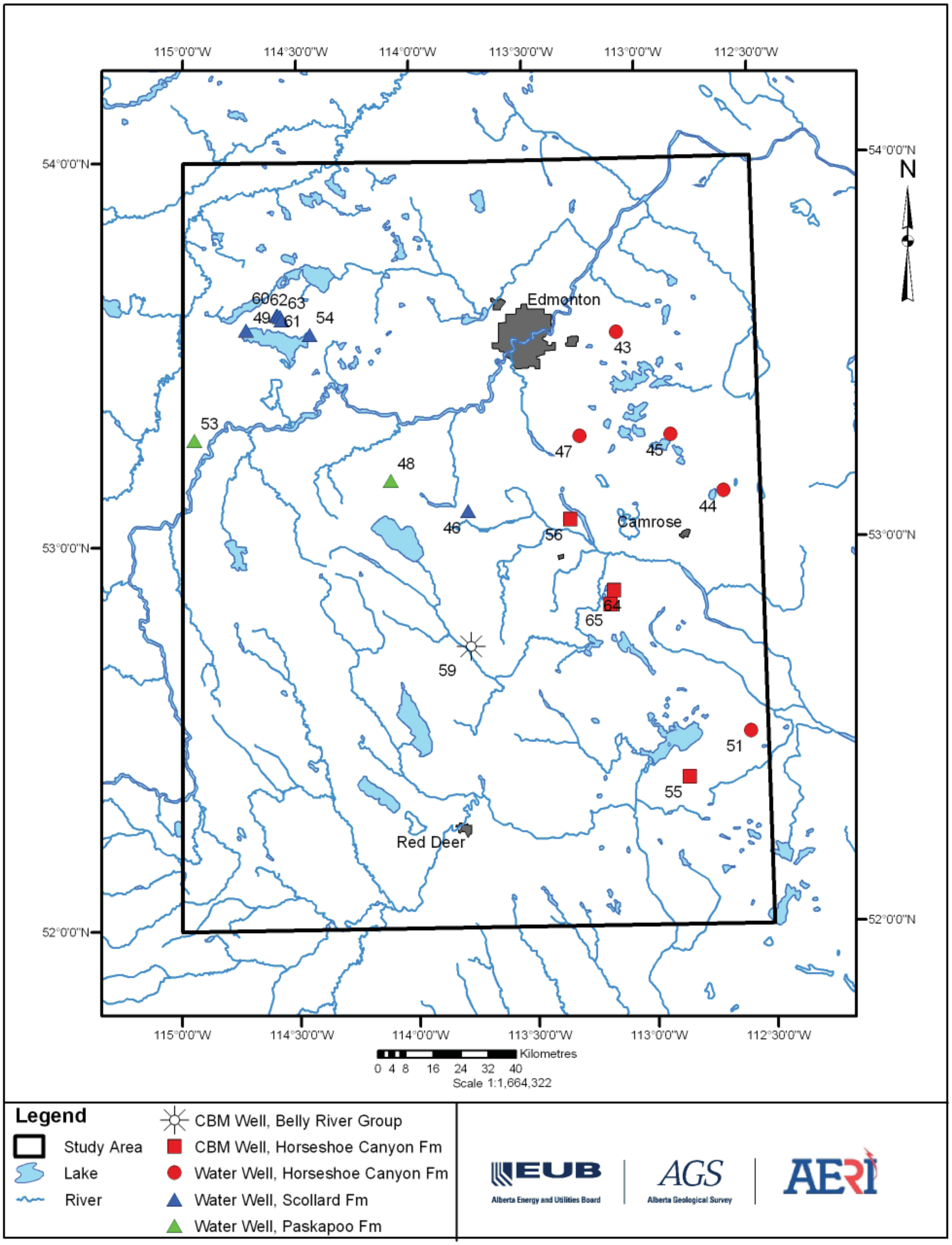


Figure 16. Sample locations.

and 53) were collected from coal zones within the Paskapoo Formation. Sample locations are identified in Figure 16. The following table (Table 9) provides general details on the wells. Additional information on the wells and the sites is provided in Appendix 4.

Table 9. Scollard and Paskapoo formations sample site details.

Sample Name	Sample Identifier	Approximate Location	Formation	Coal Zone	Well Type
AERI 0505	46	47-26W4	Scollard	Ardley	Water well
AERI 0507	48	48-01W5	Paskapoo	Undefined	Water well
AERI 0508	49	53-05W5	Scollard	Ardley	Water well
AERI 0509	50	53-05W5	Scollard	Ardley	Water well
AERI 0512	53	50-07W5	Paskapoo	Undefined	Water well
AERI 0513	54	53-04W5	Scollard	Ardley	Water well
AERI 0521	60	53-04W5	Scollard	Ardley	Dewatering well
AERI 0522	61	53-04W5	Scollard	Ardley	Dewatering well
AERI 0523	62	53-04W5	Scollard	Ardley	Dewatering well
AERI 0524	63	53-04W5	Scollard	Ardley	Dewatering well

4.3.3 Sampling Protocols and Sample Submission

Sampling was completed according to protocols developed by the AGS (Lemay (2002a) and Lemay (2002b)) from a number of sources. These included the United States Geological Survey, the Geological Survey of Canada, and the universities of Alberta, Calgary and Saskatchewan. These protocols ensure consistency in sample collection and preservation and provide a method for developing and carrying out a quality assurance/quality control program. In developing these protocols, the AGS benefited from the expertise of these organizations and institutions that are considered to be experts in the field of hydrogeology. The sampling protocols are provided in Appendix 5.

Samples were submitted for analysis to a number of accredited and reputable laboratories. The types of analyses included:

- Inorganic major, minor and trace elemental analyses
- Organic compounds analyses
- Dissolved and CBM gas analysis
- Stable isotopic analyses of water and dissolved constituents
    - Oxygen and hydrogen of water
    - Carbon and oxygen of dissolved inorganic carbon
    - Sulphur and oxygen of dissolved sulphate
    - Sulphur of dissolved sulphide
- Stable isotopic analyses of carbon and hydrogen of gases
    - Carbon of the C1-C5 gases and hydrogen of methane
- Radiogenic isotope analyses
    - Uranium

    - Thorium
    - ^{226}Ra
    - ^{129}I
    - ^{36}Cl
    - ^{87}Sr/^{86}Sr
- Microbiological characterization
    - Phospholipid fatty acid methodology
    - q-PCR methodology
    - DGGE methodology

Nine laboratories were employed to complete the analyses of the samples. The list of laboratories along with the type of analyses each performed is provided below (Table 10).

Table 10. Analyses summary and laboratory listing.

Analysis type	Laboratory	Laboratory Location		
		City	Province or State	Country
Inorganic major, minor and trace elements	Norwest Labs	Edmonton	Alberta	Canada
Inorganic major, minor and trace elements	Becquerel Laboratories	Mississauga	Ontario	Canada
Organic compounds	Norwest Labs	Edmonton	Alberta	Canada
Dissolved and CBM gas	Maxxam Analytics	Edmonton	Alberta	Canada
Isotopic analysis of gases	University of Alberta	Edmonton	Alberta	Canada
Stable isotopes of water and dissolved constituents	University of Calgary	Calgary	Alberta	Canada
Radiogenic isotopes	Becquerel Laboratories	Mississauga	Ontario	Canada
Radiogenic isotopes	University of Toronto	Toronto	Ontario	Canada
Radiogenic isotopes	Purdue University	West Lafayette	Indiana	USA
Radiogenic isotopes	University of Saskatchewan	Saskatoon	Saskatchewan	Canada
Microbiological characterization	Microbial Insights	Rockford	Tennessee	USA

4.4 Inorganic Geochemistry

The most common types of analyses performed on water samples are those to determine the concentrations of inorganic compounds or elements present within the water sample. The inorganic geochemistry of the water sample provides details on:

- the general characteristics of the geochemical system
- the potential uses for and limitations on use for the water
- more specific geochemical processes occurring within the aquifer such as mixing and dissolution or precipitation reactions

The sections below discuss these items in more detail beginning with a discussion on the general characteristics of the geochemical systems. The complete geochemical data set is found in Appendix 8.

4.4.1 Hydrochemical Facies Within the Study Area

4.4.1.1 Horseshoe Canyon Formation

Four of the 5 water well samples (samples 43, 45, 47, 51 and 52) fall within the Na-HCO_3 water type, while 1 (Sample 44) falls within the Na-Cl-HCO_3 water type category. Four of the CBM well samples (samples 56, 57, 64 and 65) fall within the Na-Cl water type category, while 1 (Sample 55) falls within the Na-Cl-HCO_3 water type category. In comparison, in the Lemay (2003) report, 1 of the samples fell into the Ca-HCO_3-SO_4 water type category, 1 sample fell into the Na-Ca-SO_4-HCO_3 water type category with the other 18 falling within the Na-HCO_3 water type category. Data used by Bachu and Michael (2002) fall within the entire range of water type categories. Figure 17 and Figure 18 present the data collected as part of this study as well as the data from Lemay (2003) and Bachu and Michael (2002) for comparison purposes.

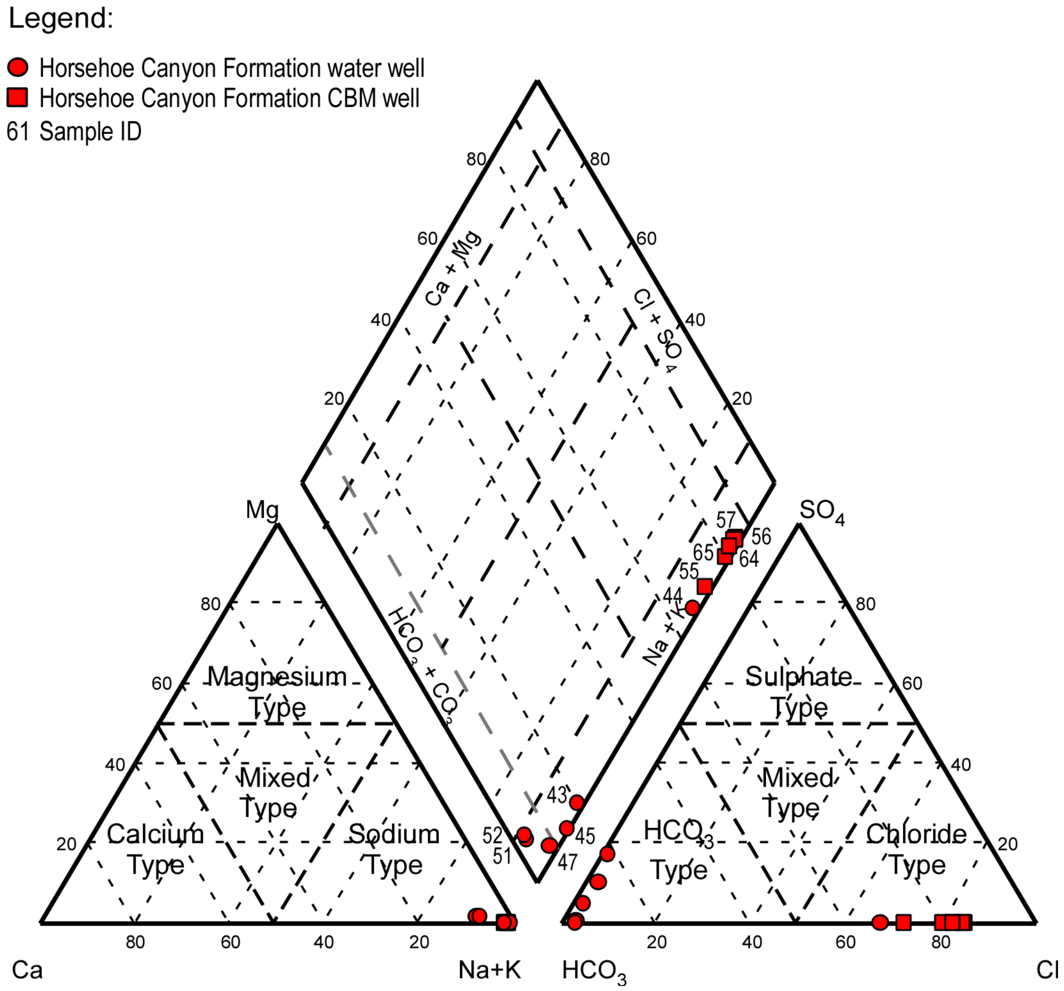


Figure 17. Horseshoe Canyon Formation hydrochemical facies plot.

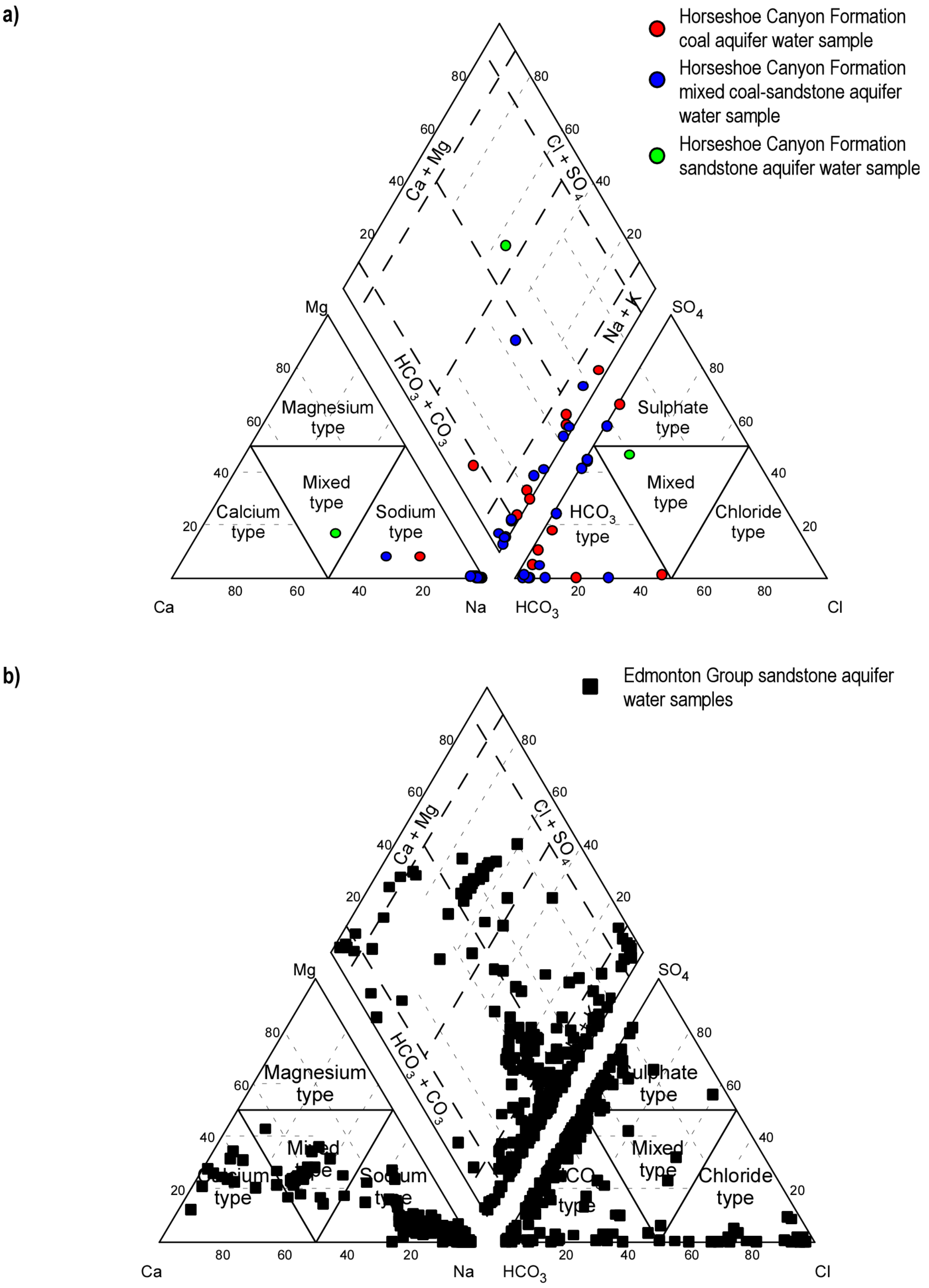


Figure 18. Edmonton Group hydrochemical facies plot of sample points used by: a) Lemay (2003) and b) Bachu and Michael (2002).

The water chemistry profiles of the water well samples (with the exception of sample 44) suggests that the water moving through the shallower portion of the Horseshoe Canyon Formation has undergone some geochemical transformations that have removed Ca and Mg and replaced them with Na, but that they have not evolved along the anion evolution pathway beyond the HCO_3 portion of the evolution sequence. This suggests that either sources of SO_4 and Cl are not available in these portions of the flow system, or that the chemical evolution sequence is still in an immature state within this portion of the flow system, or geochemical and biological processes are controlling concentrations of the major anions in such a way that HCO_3 is remaining the dominant anion in solution.

The CBM well samples (samples 55, 56, 57, 58, 64 and 65) and 1 of the water well samples (Sample 44) have evolved into either the Na-Cl or Na-Cl-HCO_3 water type categories suggesting a longer residence time for this water and contact with sources of Cl. The CBM wells are completed to deeper depths and are downgradient of the water wells and as such the more mature hydrochemical signatures are expected. The 1 water well sample with a Na-Cl-HCO_3 water type appears to be located within an area where water levels are not changing dramatically. It is not the deepest water well completed within this Formation. The nature of the water chemistry within this well could be attributed to perhaps a rather restricted flow system with input of Cl through mixing with deeper formation water or perhaps authropagenic modification.

4.4.1.2 Scollard and Paskapoo Formations

Five of the 10 water well samples (samples 46, 48, 49, 50 and 53) fall within the Na-HCO_3 water-type category, while 1 (Sample 54) falls within the Na-HCO_3-SO_4 water-type category and 4 (samples 60, 61, 62 and 63) fall within the Ca-Na-HCO_3 water-type category. In comparison, in the Lemay (2003) report, 3 of the samples fell into the Ca-HCO_3 water type category, 3 samples fell into the Na-HCO_3 water type category with the other 1 falling within the Na-Cl-HCO_3 water type category. Data used by Bachu and Michael (2002) fall within the entire range of water type categories. Figure 19 and Figure 20 present the data collected as part of this study as well as the data from Lemay (2003) and Bachu and Michael (2002) for comparison purposes.

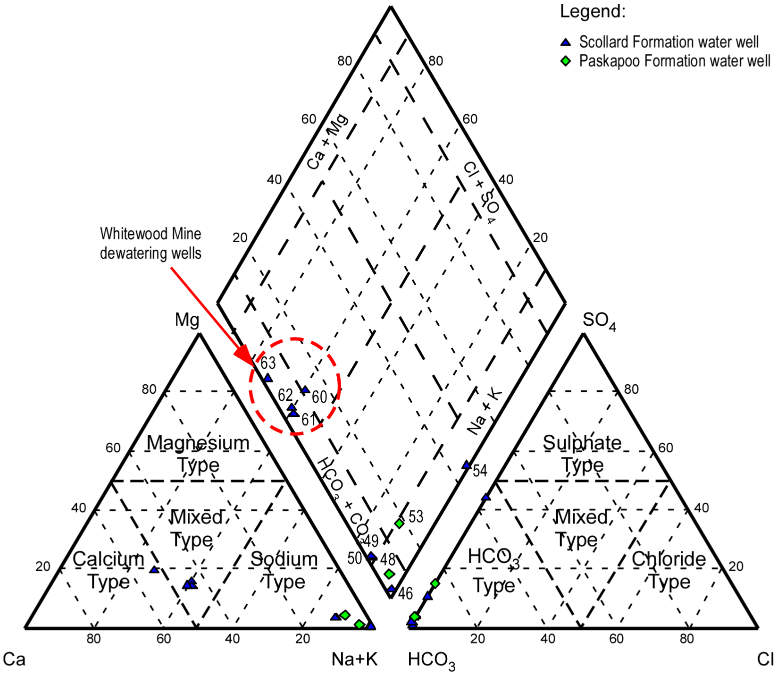


Figure 19. Scollard and Paskapoo formations hydrochemical facies plot.

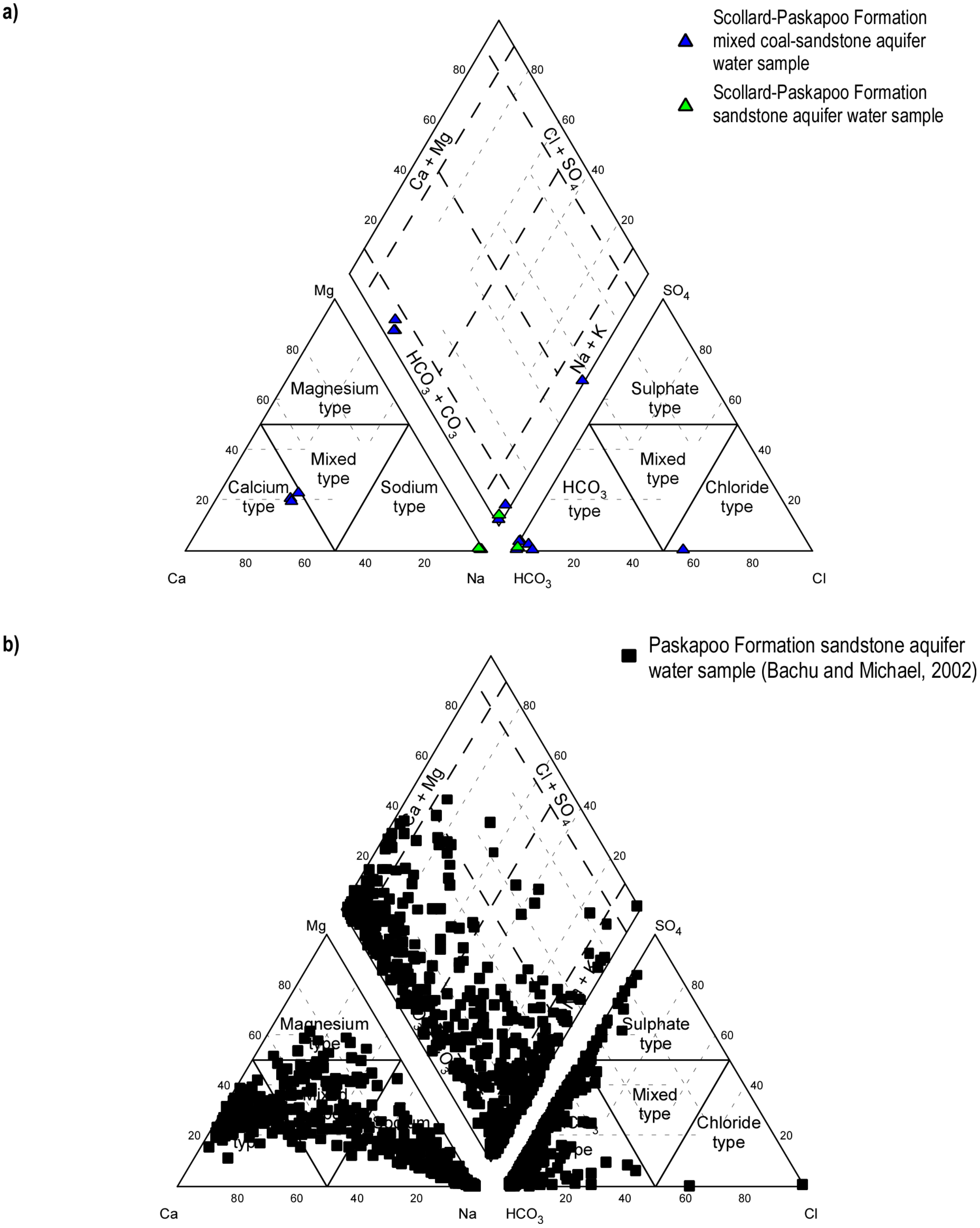


Figure 20. Tertiary-Upper Cretaceous hydrochemical facies plot of sample points used by: a) Lemay (2003) and b) Bachu and Michael (2002).

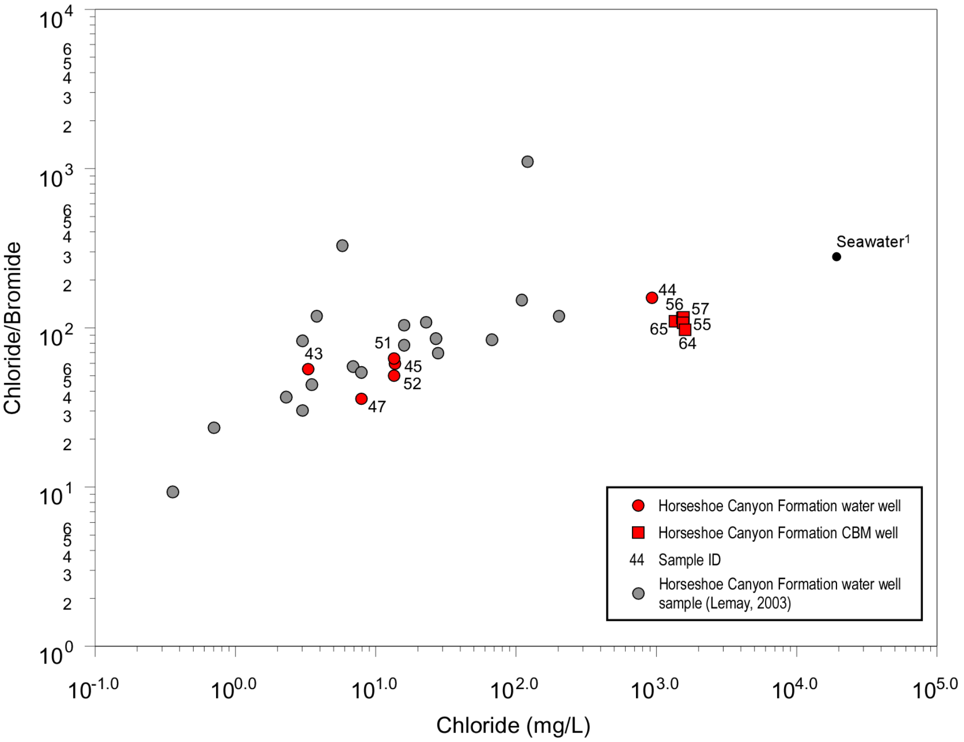
The water chemistry profiles of the water well samples (with the exception of sample 58 to 60) suggests that the water moving through the shallower portion of the Scollard and Paskapoo formations has undergone some geochemical transformations that have removed Ca and Mg and replaced them with Na, but that like certain samples within the Horseshoe Canyon Formation, they have not evolved along the anion evolution pathway beyond the HCO_3 portion of the evolution sequence. Similar reasons for why this has occurred in the Horseshoe Canyon Formation can be applied to the present case.

The mixed major cation type water samples are all from dewatering wells used to maintain mine stability at the Whitewood Mine. The nature of the dewatering activities at the mine site will mean that water not only from the Scollard Formation will be drawn into the well. The mixed hydrochemical facies type can therefore be attributed to a mixing effect between these different sources of water. Samples 45 and 46 from Lemay (2003) are also from dewatering wells from the Whitewood Mine and display the same major ion ratios.

4.4.2 Chloride/Bromide Ratios

4.4.2.1 Horseshoe Canyon Formation

All of the water well and CBM well water samples had measurable concentrations of Cl and Br. The water samples with the exception of sample 44 have Cl/Br ratios of less than 100 and generally fall within a loose cluster centred at approximately 10 mg/L Cl and a Cl/Br ratio of 50. Similarly the CBM wells and 1 of the water well samples (sample 44) fall within a cluster, but this time the cluster is much more narrow and is centred at approximately 1,500 mg/L Cl and a Cl/Br ratio of 150. All of these samples have a Cl/Br ratio less than 200. For comparison purposes, seawater has a Cl/Br ratio of 287.5 and a Cl concentration of approximately 18,000 mg/L. The data is plotted in Figure 21 as is additional data originally published in Lemay (2003).



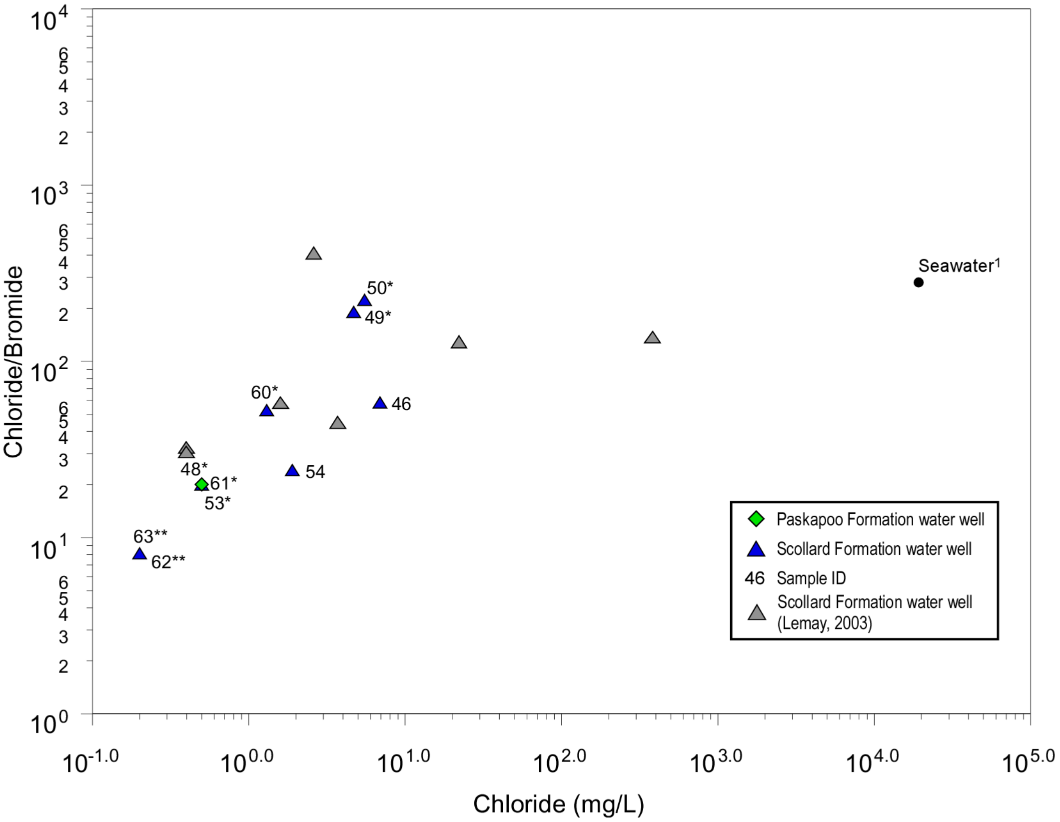
[1] Seawater Cl and Br concentrations from Drever (1997, p. 345)

Figure 21. Horseshoe Canyon Formation Chloride/Bromide ratios.

The nature of the connection between these two data clusters is not readily apparent on initial inspection. It is possible to draw a curvilinear path between the two clouds of data. Such a path would suggest a mixing trend between the two. Once data from Lemay (2003) is added to the plot, however, the possible connection between the two clusters becomes more apparent. The addition of this data more fully completes a possible curvilinear trend line and more clearly suggests mixing between a two end member system. One is likely meteoric water and the other could be a formation water end member perhaps similar to the CBM well compositions.

4.4.2.2 Scollard and Paskapoo Formations

Only samples 46 and 54 have Cl and Br concentrations above analytical detection limits. Samples 48, 49, 50, 53, 60 and 61 have Br concentrations below the analytical detection limits and as such ½ the detection limit value was used to estimate the Cl/Br ratios for these samples. Sample 62 and 63 have Cl and Br concentrations below analytical detection limits. In this case, ½ of the detection limit values for both Cl and Br were used to determined the Cl/Br ratio values. The data is plotted in Figure 22 along with data previously published in Lemay (2003) for comparison purposes.



[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 22. Scollard and Paskapoo formations Choride/Bromide ratios.

Samples 46 and 54 have Cl/Br ratios between 20 and 60 and Cl concentrations between 1 and 10 mg/L. Those samples where ½ of the Br detection limit was used have Cl/Br ratios between 15 and 300 and Cl concentrations between 0.4 and 10 mg/L. Those samples where ½ the detection limits for Cl and Br were used have the smallest Cl/Br ratios of approximately 8 and a Cl concentration of approximately 0.2 mg/L. The number of non detects present within this study data set makes an interpretation of the geochemical processes responsible for the observed ratios very difficult. The inclusion of the Lemay (2003) data set suggests that the data collected as part of this study may fall on the curvilinear trend originally proposed in that publication. This supports the idea put forward that mixing is occurring between two end members, one possibly a meteoric end member and the second a formation water end member. Once water from CBM wells completed in these formations is collected this hypothesis can be tested.

4.4.3 Parameter-Specific Observations

Water quality guidelines have been developed by Provincial and Federal authorities to ensure the protection of human, aquatic, animal and plant health. The following discussion focuses on the inorganic parameters that exceed water quality guidelines in order to provide an insight into some of the potential issues related to water use from or disposal of water from these units. The discussion is divided into two sections. Each section looks at the water quality from the 3 formations sampled during this program and begins with the Horseshoe Canyon Formation followed by a section describing the water quality within the Scollard and Paskapoo formations.

A parameter-by-parameter summary is presented in Appendix 6 and 7 for each Formation beginning with the Horseshoe Canyon Formation followed by the Scollard and Paskapoo formations. These summaries provide information on water quality guidelines, mean concentration, standard deviation, and minimum and the maximum values for each element or compound. The tables in these appendices also summarize available information from other sources of data on water chemistry and coal chemistry from coal-bearing strata in Alberta and the United States so that the results of this study can be compared with those from the other datasets. The complete water quality dataset is found in Appendix 8.

4.4.3.1 Horseshoe Canyon Formation Water Quality

A total of 12 samples were collected from the Horseshoe Canyon Formation including 6 from water wells and 6 from CBM wells. Two duplicates (1 from a water well and 1 from a CBM well) were collected during the course of the sampling program and 1 CBM water sample was rejected because of indications of contamination of the sample. The following discussion will therefore exclude these three samples and be limited to the 9 remaining samples.

The comparison of the inorganic composition of the water samples collected from the Horseshoe Canyon Formation indicated that a number of water quality guideline values were exceeded. The table below provides a summary of these exceedances (Table 11).

Table 11. Horseshoe Canyon Formation water quality summary.

Summary of the number of parameter exceedances in water wells for the various categories					
Element or Compound	**Domestic Use**	**Aesthetic Objective**	**Irrigation Water Quality Guideline**	**Livestock Use Water Quality Guideline**	**Aquatic Life Protection Guideline**
Na	-	5	-	-	-
Cl	-	1	-	-	-
TDS*	-	5	5	0	-
SAR	-	-	5	-	-
Al	0	-	0	0	1

Element or Compound	Domestic Use	Aesthetic Objective	Irrigation Water Quality Guideline	Livestock Use Water Quality Guideline	Aquatic Life Protection Guideline
As	0	-	0	0	1
Cd	1	-	1	0	1
Cu	-	0	0	0	2
Pb	0	-	0	0	1
Hg	0	-	-	0	2
Ni	-	-	0	0	1
Zn	-	0	0	0	2
F	4	-	4	4	-
Summary of the number of parameter exceedances in CBM wells for the various categories					
Na	-	4	-	-	-
Cl	-	4	-	-	-
TDS*	-	4	4	2	-
Turbidity	2	2	-	-	-
SAR	-	-	4	-	-
Al	1	-	0	0	1
As	2	-	0	2	4
Ba	2	-	-	-	-
Cd	0	-	0	0	1
Mo	-	-	1	0	1
Zn	-	0	0	0	1
F	4	-	4	4	-

Notes: guideline values from CCME (2003) and Alberta Environment (1999)
***TDS concentrations in all cases less than 4,000 mg/L**

Ultimately, if CBM development from the Horseshoe Canyon Formation involves water production and the TDS values determined for the water samples from the CBM wells are representative of the formation water in the area, then any production of water from these zones will produce non-saline groundwater and will require the submission of documentation to Alberta Environment in support of their activities. A guideline has been developed regarding the potential diversion of groundwater from CBM development by AENV (AENV, 2004). In it, AENV provides a flow chart of the process to be followed by a development company when assessing groundwater diversion options. In addition, it discusses potential operational management plans for non-saline groundwater. Such a management plan would have to take into account the other parameters listed above during its design. If further sampling of these or other CBM wells indicates that TDS values are considered to be saline in character, then different approval conditions apply, since saline groundwater management is regulated by the EUB through its various directives.

4.4.3.2 Scollard and Paskapoo Formations Water Quality

A total of 10 samples were collected from the Scollard and Paskapoo formations including 8 from water wells completed in the Scollard Formation and 2 from water wells completed in the Paskapoo Formation. One duplicate (1 water well completed in the Scollard Formation) was collected during the course of the sampling program. The following discussion will therefore exclude this sample and be limited to the 9 remaining samples.

The comparison of the inorganic composition of the water samples collected from the Scollard and Paskapoo formations indicated that a number of water quality guideline values were exceeded, but not as many as in the Horseshoe Canyon Formation. The table below provides a summary of these exceedances (Table 12).

Table 12. Scollard and Paskapoo formations water quality summary.

<table>
<tr><th colspan="6">Summary of parameter exceedances in Scollard Formation water wells for the various categories</th></tr>
<tr><th>Element or compound</th><th>Domestic use</th><th>Aesthetic objective</th><th>Irrigation water quality guideline</th><th>Livestock use water quality guideline</th><th>Aquatic Life Protection guideline</th></tr>
<tr><td>pH</td><td>-</td><td>1</td><td>-</td><td>-</td><td>0</td></tr>
<tr><td>Na</td><td>-</td><td>3</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>SO_4</td><td>-</td><td>1</td><td>-</td><td>0</td><td>-</td></tr>
<tr><td>TDS*</td><td>-</td><td>4</td><td>4</td><td>0</td><td>-</td></tr>
<tr><td>Turbidity</td><td>3</td><td>0</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>SAR</td><td>-</td><td>-</td><td>7</td><td>-</td><td>-</td></tr>
<tr><td>Mn</td><td>-</td><td>4</td><td>1</td><td>-</td><td>-</td></tr>
<tr><td>Cu</td><td>-</td><td>0</td><td>0</td><td>0</td><td>5</td></tr>
<tr><td>Mo</td><td>-</td><td>-</td><td>0</td><td>0</td><td>1</td></tr>
<tr><td>Zn</td><td>-</td><td>0</td><td>0</td><td>0</td><td>2</td></tr>
<tr><td>F</td><td>3</td><td>-</td><td>3</td><td>3</td><td>-</td></tr>
<tr><th colspan="6">Summary of parameter exceedances in Paskapoo Formation wells for the various categories</th></tr>
<tr><td>Na</td><td>-</td><td>2</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>TDS*</td><td>-</td><td>2</td><td>2</td><td>0</td><td>-</td></tr>
<tr><td>SAR</td><td>-</td><td>-</td><td>2</td><td>-</td><td>-</td></tr>
<tr><td>Cu</td><td>-</td><td>0</td><td>0</td><td>0</td><td>2</td></tr>
<tr><td>F</td><td>1</td><td>-</td><td>2</td><td>2</td><td>-</td></tr>
<tr><td>Hg</td><td>0</td><td>-</td><td>-</td><td>0</td><td>2</td></tr>
</table>

Notes: guideline values from CCME (2003) and Alberta Environment (1999)
***TDS concentrations in all cases less than 4,000 mg/L**

The wells sampled as part of this study were all water wells used for either domestic, dewatering or agricultural purposes and as such may not provide a realistic picture of the composition of formation water from deeper portions of these formations. A brief review of some third party water chemistry records showed that a CBM well completed in the Ardley coal zone of the Scollard Formation had a saline-groundwater TDS value. According to the flow chart developed by AENV (AENV, 2004) the approval of any groundwater diversion associated with a well such as this would be under the authority of the EUB. If TDS values for other wells show that water is considered non-saline, then the process for managing non-saline groundwater would have to be followed.

4.5 Organic Geochemistry

Coal is composed of organic matter and as such organic compounds should be expected to be present in groundwater associated with coal aquifers. Organic compounds are also commonly introduced to the environment through human activities. This section discusses these compounds and their concentrations in the water samples. The complete geochemical data set is found in Appendix 8.

4.5.1 Parameter Specific Observations

As is the case for inorganic compounds or elements, water quality guidelines have been developed by Provincial and Federal authorities for organic compounds in order to ensure the protection of human, aquatic, animal and plant health. The following discussion focuses on the organic compounds that exceed water quality guidelines in order to provide an insight into some of the potential issues related to water use from or disposal of water from these units. The discussion is divided into two sections. Each section looks at the water quality from the 3 formations sampled during this program and begins with the Horseshoe Canyon Formation followed by a section describing the water quality within the Scollard and Paskapoo formations.

As with the inorganic compounds and elements, a detailed organic parameter-by-parameter summary is presented in Appendix 6 and 7 for each Formation beginning with the Horseshoe Canyon Formation followed by the Scollard and Paskapoo formations. These summaries provide information on water quality guideline values, statistical parameters such as mean concentration, standard deviation, and minimum and the maximum values for each compound. The tables in these appendices also summarize available information from other sources of data on water chemistry and coal chemistry from coal-bearing strata in Alberta and the United States so that the results of this study can be compared with those from the other datasets. The complete water quality dataset is found in Appendix 8.

4.5.1.1 Horseshoe Canyon Formation Water Quality Summary

The organic compounds sampled for in this study were selected in order to provide a baseline or pre-development dataset that included some naturally occurring organic compounds as well as some associated primarily with human activities. The list of compounds includes the following:

- Polycyclic aromatic hydrocarbons (PAH)
- Petroleum hydrocarbons
- Benzene, toluene, ethylbenzene and xylenes (BTEX)
- Adsorbable organic halides
- Phenols

Very few exceedances were observed for the organic compounds. A summary is presented in the table below (Table 13).

Table 13. Horseshoe Canyon Formation organic compounds water quality guideline exceedances summary.

Summary of parameter exceedances in water wells for the various categories					
Compound	**Domestic Use**	**Aesthetic Objective**	**Irrigation Water Quality Guideline**	**Livestock Use Water Quality Guideline**	**Aquatic Life Protection Guideline**
Phenols				1	1
Summary of parameter exceedances in CBM wells for the various categories					
Phenols	-	-	-	3	3
Toluene	-	0	-	0	1
Naphthalene	-	-	-	-	2
Anthracene	-	-	-	-	1

As can be seen in the table above, total phenols are the only organic compound that shows any exceedances in both the water and CBM wells. The number of exceedances is small at 1 in 5 for the water wells, but much more significant in the CBM wells, with 3 of 4 wells having a concentration exceeding the guideline values. Any water management plan for CBM produced water would have to consider the presence of these compounds as well as the potential presence of toluene and some PAH's during the design phase.

4.5.1.2 Scollard and Paskapoo Formations Water Quality Summary

The only organic compound that exceeds any of the water quality guideline values is total phenols. In 2 of the wells (1 well in the Scollard Formation and 1 well in the Paskapoo Formation), the total phenols concentration exceeded the water quality guideline established for the protection of livestock. Any water management plan designed to deal with such water should take into account this potential organic compound in its design despite its somewhat infrequent overall occurrence at concentrations that exceed water quality guidelines.

4.6 Stable Isotope Geochemistry

An atom of most elements is composed of protons, neutrons and electrons. The nuclear identity of an element is defined by the number of protons (Z) in the nucleus, while the isotopic identity of an element is defined by the number of neutrons (N) in the nucleus. Carbon for instance has a Z value of 6, or possesses 6 protons in its nucleus. Carbon can have a variable number of neutrons in the nucleus, but N is limited because of the instabilities created by too many or too few neutrons in the nucleus. The greatest level of stability is created when the Z:N ratio is close to 1 and as such, most carbon has 6 neutrons in the nucleus, but can have as many as 7 without creating an unstable nucleus. Instabilities lead to spontaneous disintegrations of the nucleus and many times a release of energy. Stable isotopes do not spontaneously disintegrate by any known mode of decay (Clark and Fritz, 1997, p. 2).

Stable environmental isotopes are used widely in hydrogeology. Clark and Fritz (1997, p. 2) list the following uses of environmental isotopes:

- to understand groundwater provenance
- to understand renewability
- to understand geochemical evolution processes
- to understand recharge processes
- to understand rock-water interactions
- to understand the origin of salinity

The complete isotope dataset is found in Appendix 8. The following sections describe the uses of three stable isotopes in understanding certain processes occurring within the coal-bearing units in the study area, beginning with a discussion of the stable isotopes of oxygen and hydrogen of water.

4.6.1 StableIsotopes of Oxygen and Hydrogen in Water

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 δ^{18}O and δ^2H 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 reasons for any differences can be inferred. 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:

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

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:

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

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:

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

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:

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

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

4.6.1.1 Horseshoe Canyon Formation

The data along with additional data points from Lemay (2003) are plotted in Figure 23. All of the samples plot below the GMWL and the AEMWL. With the exception of sample 44, the water well samples plot below the HFFWL. Sample 44 plots above the HFFWL, but below the CFWL. The CBM well water samples form a very tight cluster and plot very close to the CFWL, but are slightly below the line. The data appear to fall along a straight line and appear consistent with previously collected data. Linear regression of the data from this study yields a line with the following equation:

$\delta^2H = 6.85\delta^{18}O - 23.09$ $(R^2=0.9860)$

The equation determined for the Horseshoe Canyon Formation water samples collected by Lemay (2003) is:

$\delta^2H = 5.99\delta^{18}O - 41.33$ $(R^2=0.9072)$

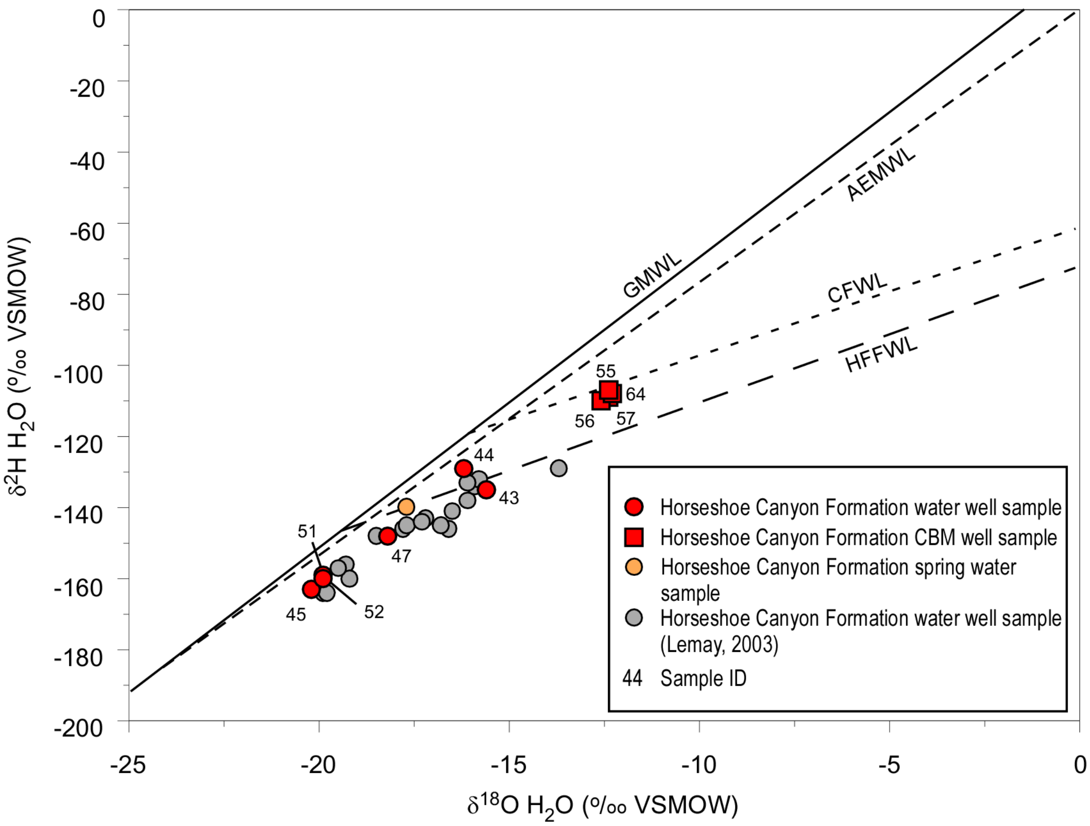


Figure 23. Horseshoe Canyon Formation δ^2H (H_2O) vs. δ^{18}O (H_2O). Abbreviations: AEMWL, Approximate Edmonton Meteoric Water Line; CFWL, Connolly Formation Water Line; GMWL, Global Meteoric Water Line; HFFWL, Hitchon Friedman Formation Water Line; VSMOW, Vienna Standard Mean Ocean Water.

If both datasets are included, the resulting line has the following equation:

$\delta^2H = 6.86\delta^{18}O - 25.62$ $(R^2=0.9356)$

It is difficult to assess whether or not this line represents a Horseshoe Canyon Formation water line. Such a relationship implies that the stable isotopic composition of any water sample collected from the Horseshoe Canyon is part of a continuum of water samples with as little as two end members. Given the complicated nature of recharge, groundwater flow, isotope fractionation and mixing, such a simple hypothesis seems difficult to accept.

4.6.1.2 Scollard and Paskapoo Formations

The δ^{18}O and δ^2H data along with additional data from Lemay (2003) are plotted in Figure 24. Much of the data plots in a cluster located at approximately $\delta^{18}O=-18‰$ and $\delta^2H=-150‰$. All of the water samples fall below the GMWL and the AEMWL. Except for sample 63, all of the samples fall below the HFFWL. Sample 63 in turn falls below the CFWL.

When linear regression is performed on the data collected during this study it generates the following equation:

$\delta^2H = 5.28\delta^{18}O - 48.90$ $(R^2=0.8661)$

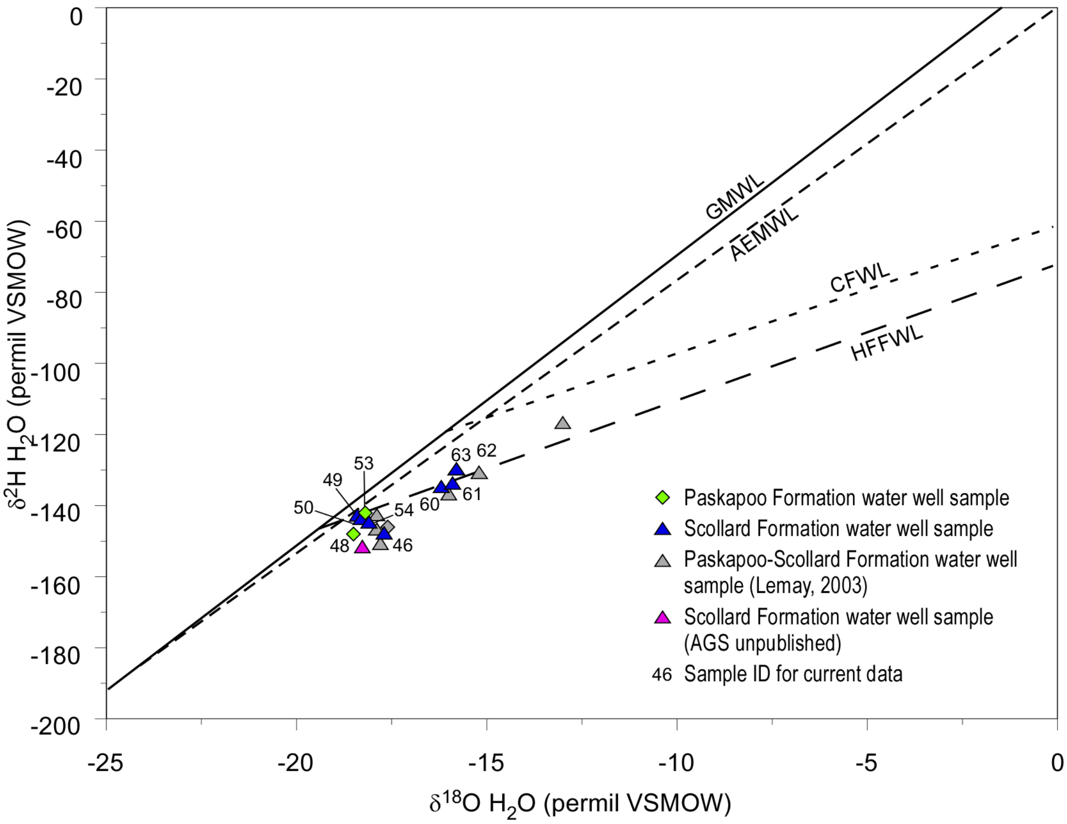


Figure 24. Scollard and Paskapoo formations δ^2H (H_2O) vs. $\delta^{18}O$ (H_2O). Abbreviations: AEMWL, Approximate Edmonton Meteoric Water Line; CFWL, Connolly Formation Water Line; GMWL, Global Meteoric Water Line; HFFWL, Hitchon Friedman Formation Water Line; VSMOW, Vienna Standard Mean Ocean Water.

The regression of the data from Lemay (2003) resulted in the following equation:

$\delta^2H = 6.12\delta^{18}O - 38.03$ $(R^2=0.9527)$

When both data sets are combined the following equation is generated:

$\delta^2H = 5.53\delta^{18}O - 46.05$ $(R^2=0.8946)$

As with the Horseshoe Canyon Formation, the possibility exists that these data could form the basis for the definition of a Scollard and Paskapoo formations water line. Given the implicit assumptions in such a line however the definitive formation water line will require additional statistical testing in order to be confirmed.

4.6.2 Stable Isotopes of Carbon and Oxygen in DIC

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).

4.6.2.1 Horseshoe Canyon Formation

A plot of $\delta^{18}O$ vs. $\delta^{13}C$ of DIC shows two distinct clusters of data (Figure 25).

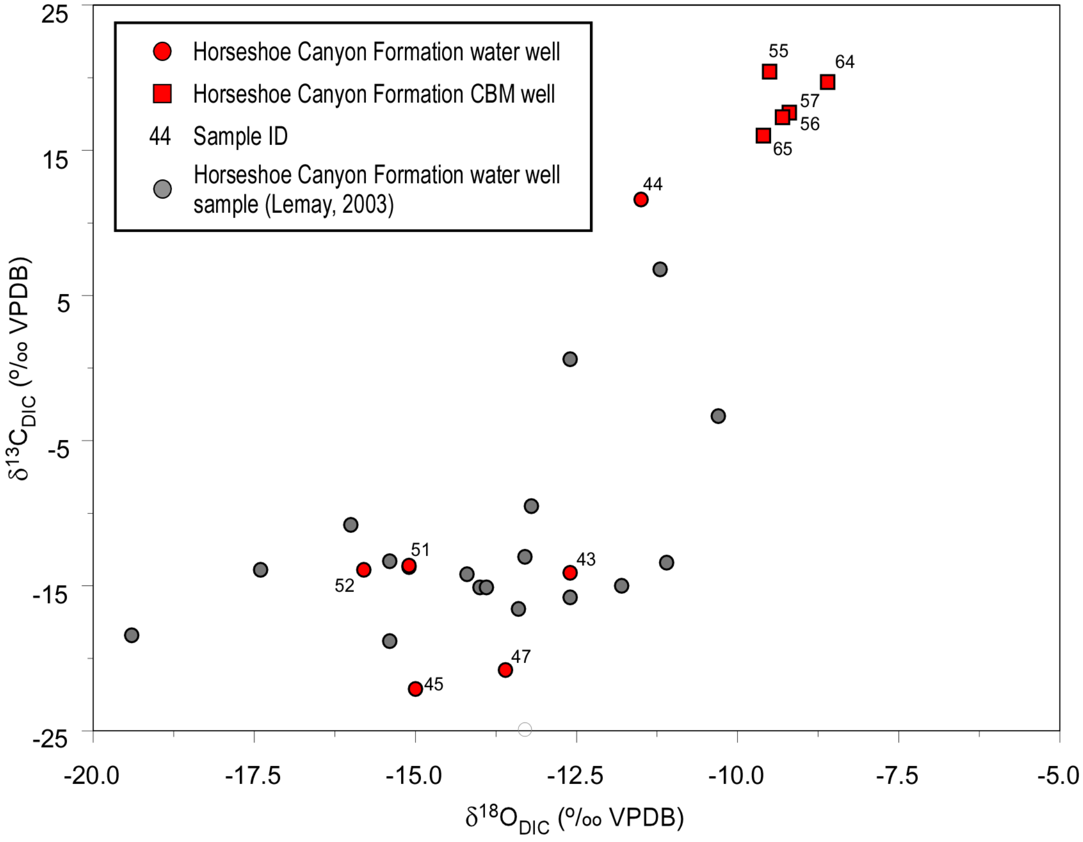


Figure 25. Horseshoe Canyon Formation $\delta^{13}C$ and $\delta^{18}O$ of DIC.

The first cluster is made up of the CBM wells and one of the water wells (sample 44), while the other cluster is composed of the remaining water well samples. The first cluster has positive $\delta^{13}C$ values and has higher $\delta^{18}O$ values than the second cluster. The second cluster has negative $\delta^{13}C$ values and lower $\delta^{18}O$ values than the first cluster. This suggests that the $\delta^{13}C$ composition in both clusters has been modified from a generally expected $\delta^{13}C$ value for DIC of approximately -15‰ VDPB. Possible mechanisms at work to generate the observed $\delta^{13}C$ values could include biological activity, dissolution of soil CO_2, incorporation of aquifer DIC and dissolution of carbonate minerals. In particular, the positive values associated with the CBM water samples are consistent with samples identified as being affected by biological processes (Lemay, 2003), whereas those samples with mid-ranged negative $\delta^{13}C$ values suggest processes dominated by dissolution of soil CO_2, incorporation of aquifer DIC or dissolution of carbonate minerals, while those with the lowest $\delta^{13}C$ values suggest the possibility that oxidation of organic matter is contributing to the DIC pool. These sources are most easily categorized by calculating possible pathways for DIC introduction into the aquifers. The interpretation of the positive $\delta^{13}C$ values is fairly straight forward in that bacterial action is commonly associated with such values. The negative values can be related to multiple processes however. In this case the examination of the effect on the isotopic compositions as soil CO_2 and as a carbonate mineral such as calcite are incorporated into the aquifer should help clarify the source of the aquifer DIC. The table below summarizes the measured values and the anticipated $\delta^{13}C$ values if the DIC were a product of soil CO_2 dissolution or of calcite dissolution (Table 14). For this exercise, soil CO_2 is assumed to have been dissolved in groundwater and has a $\delta^{13}C$ value of -23‰ VPDB, while the calcite has an ideal $\delta^{13}C$ of -14.6‰ VPDB (T=25°C, atmospheric $\delta^{13}C$ = -23‰ VPDB). Both of these values were taken from Clark and Fritz (1997), p. 120.

Table 14. Horseshoe Canyon Formation: Actual and modelled $\delta^{13}C$ values.

			Soil CO_2 Source	**Calcite Source**	
Sample	**ID**	**Measured $\delta^{13}C$‰ VPDB**	**$CO_2(aq)$ to HCO_3^- ‰ VPDB**	**CO_3^{2-} to HCO_3^- ‰ VPDB**	**Source comments**
AERI 0501	43	-14.1	-13.8	-14.5	Possibly either or mixing
AERI 0502	44	+11.6	-12.9	-14.0	Bacterial reduction
AERI 0503	45	-22.1	-12.9	-14.0	Bacterial oxidation
AERI 0506	47	-20.8	-13.0	-14.1	Bacterial oxidation
AERI 0510	51	-13.6	-13.2	-14.1	Possibly either or mixing
AERI 0511	52	-13.9	-13.2	-14.1	Possibly either or mixing
AERI 0516	55	+20.4	-13.7	-14.5	Bacterial reduction
AERI 0517	56	+17.3	-13.2	-14.2	Bacterial reduction
AERI 0518	57	+17.6	-13.2	-14.2	Bacterial reduction
AERI 0525	64	+19.7	-13.4	-14.3	Bacterial reduction
AERI 0526	65	+16.0	-13.5	-14.3	Bacterial reduction

Notes: $\delta^{13}C$ of soil CO_2 = -23 ‰ VPDB and $\delta^{13}C$ of calcite = -14.6 ‰ VPDB.

The actual and calculated values appear to suggest that the DIC in samples 43, 51 and 52 could be derived from the dissolution of soil CO_2, the incorporation of calcite, or the mixing of the two sources. The DIC in samples 44, 56, 57, 64 and 65 appears to have been affected by bacterial reduction of organic matter or CO_2. The DIC in samples 45 and 47 appear to have been affected by the contribution of DIC generated through some kind of bacterial oxidation process.

4.6.2.2 Scollard and Paskapoo Formations

None of the Scollard or Paskapoo formations water samples have positive $\delta^{13}C$ values. However, two general clusters can be identified on a $\delta^{13}C$ vs. $\delta^{18}O$ plot (Figure 26). The first cluster is formed by samples 46 and 49 have greater $\delta^{13}C$ DIC values than the remaining samples that fall within the second cluster. Dissolved gas was detected in sample 46 and the analysis of the gas indicated that methane was present. If the methane is associated with biological processes, then the $\delta^{13}C$ of the DIC could reflect these processes in conjunction with more standard DIC incorporation mechanisms. The second cluster has $\delta^{13}C$ DIC values that appear generally consistent with the expected values generated during the incorporation of soil CO_2 into groundwater through dissolution. The following table (Table 15) provides measured and calculated DIC $\delta^{13}C$ values given a soil CO_2 end member composition of -23‰ VPDB and a calcite end member composition of -15.6‰ VPDB to test the evolution of DIC within the various locations. The soil CO_2 value was taken from Clark and Fritz (1997), p. 120, while discussions with A. Beaton suggested that a value of -15.6‰ VPDB is appropriate for calcite within the Scollard Formation.

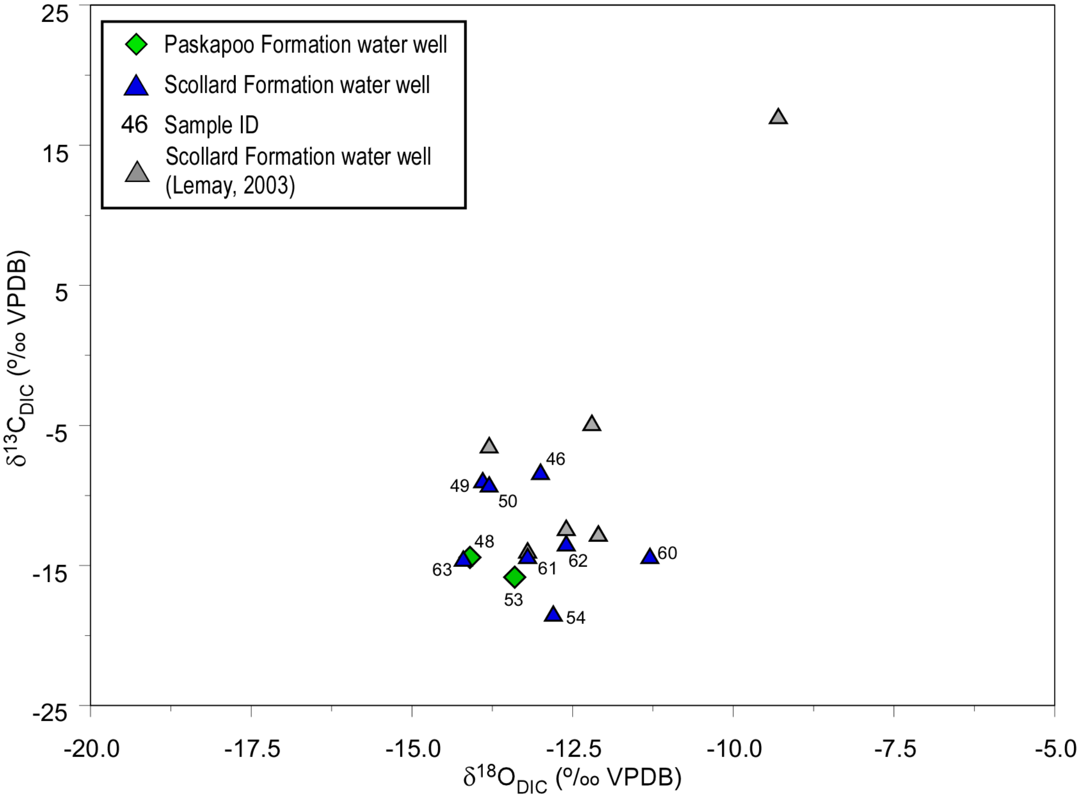


Figure 26. Scollard and Paskapoo formations $\delta^{13}C$ and $\delta^{18}O$ of DIC.

The lower values in samples 46, 49 and 50 do not approach the calculated values and therefore suggest a source different from soil CO_2 dissolution or calcite dissolution. A possibility is that these lower values could be the result of the mixing of DIC from these standard sources and from the reduction of organic matter or CO_2. Samples 48, 60, 61, 62 and 63 have DIC values consistent with either soil CO_2 dissolution, or calcite dissolution, or some combination of the two. Samples 53 and 54 have DIC values that are lower than those predicted for DIC produced from soil CO_2 or calcite dissolution. One possibility is that these DIC values have been affected by DIC generated through oxidation of organic matter and subsequent mixing with standard sources of DIC.

Table 15. Scollard and Paskapoo formations: Actual and modelled $\delta^{13}C$ values.

			Soil CO_2 Source	Calcite source	
Sample	**ID**	**Measured $\delta^{13}C$ ‰ VPDB**	**$CO_2(aq)$ to HCO_3^- ‰ VPDB**	**CO_3^{2-} to HCO_3^- ‰ VPDB**	**Source comments**
AERI 0505	46	-8.4	-13.1	-15.1	Bacterial reduction and mixing
AERI 0507	48	-14.4	-13.3	-15.2	Mixing
AERI 0508	49	-9.0	-13.0	-15.1	Bacterial reduction and mixing
AERI 0509	50	-9.3	-13.0	-15.1	Bacterial reduction and mixing
AERI 0512	53	-15.8	-12.9	-15.0	Bacterial oxidation and mixing
AERI 0513	54	-18.5	-12.9	-15.0	Bacterial oxidation and mixing
AERI 0521	60	-14.4	-12.9	-15.0	Mixing
AERI 0522	61	-14.4	-13.2	-15.1	Mixing
AERI 0523	62	-13.5	-13.0	-15.1	Possibly either or mixing
AERI 0524	63	-14.6	-12.9	-15.0	Mixing

Notes: $\delta^{13}C$ of soil CO_2 = -23 ‰ VPDB and $\delta^{13}C$ of calcite = -15.6 ‰ VPDB.

4.6.3 Stable Isotopes of Sulphur in Sulphide and Sulphur and Oxygen in Sulphate

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 constitutes 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.

Processes affecting sulphur isotopic composition include sulphate mineral dissolution reactions, biological processes, atmospheric sulphur input and sulphide oxidation.

4.6.3.1 Horseshoe Canyon Formation Results and Discussion

Only sample 45 has both a $\delta^{34}S$ SO_4 and a $\delta^{34}S$ S^{2-} value therefore affording an opportunity to assess the process leading up to sulphate and sulphide composition. The difference between the two is 31.4‰ CDT. Given the difference between these two, the possibility exists that bacterial sulphate reduction may be occurring within this well. The $\delta^{34}S$ S^{2-} value for this sample coincides with literature values for igneous rocks, volcanic sulphur, petroleum, coal, shales and limestone-derived $CaSO_4$. The most likely sulphur sources would be the host rock. These would include coal and shales. As such, the sulphur is likely derived from those sources, although atmospherically-derived sulphate can not be ruled out as a possible source.

In the case where both $\delta^{34}S$ SO_4 and $\delta^{34}S$ S^{2-} are not available for each well, only a more general assessment of sulphur source and processes is possible. Samples 51, 52 and 65 have $\delta^{34}S$ values that coincide with literature values for igneous rocks, volcanic sulphur, petroleum, coal, Cenozoic $CaSO_4$, Devonian to Permian $CaSO_4$, shales and limestone-derived $CaSO_4$. Samples 43 and 64 have $d^{34}S$ values that coincide with literature values for igneous rocks, volcanic sulphur, petroleum, coal, biogenic pyrite, shales and limestone derived $CaSO_4$. Sample 44 has a $\delta^{34}S$ SO_4 value that coincides with values for igneous rocks, volcanic sulphur, petroleum, coal, shales, atmospherically-derived sulphate and limestone-derived $CaSO_4$. A quick calculation of the Ca/SO_4 molar ratio suggests that none of the samples was derived solely from gypsum or anhydrite dissolution. The most likely sulphur sources would be the host rock, possibly the coal and shales present within the Formation.

Sample 47 has a $\delta^{34}S$ S^{2-} value that coincides with values for biogenic sulphide, shales and limestone-derived sulphides. Given the Formation lithology, the most likely sources would appear to be either biogenic sulphides, or sulphides within the shales of the Formation.

4.6.3.2 Scollard and Paskapoo Formations Results and Discussion

Samples 49 and 54 have measured values of $\delta^{34}S$ SO_4 and $\delta^{34}S$ S^{2-}, but appear to record different types of reactions leading up to the origins of these various sulphur forms.

Sample 49 has a $\delta^{34}S$ SO_4 value of 6.7 ‰ CDT and a $\delta^{34}S$ S^{2-} value of 17.3 ‰ CDT. The difference between these two ratios is 10.6 CDT consistent with the sort of fractionation that would be expected during the oxidation of sulphide to sulphate as mediated by bacteria (Clark and Fritz, 1997, p. 142). Given the sulphide $\delta^{34}S$ values for this sample, possible sources of sulphur include igneous rocks, volcanic sulphur, petroleum and coal, Cenozoic $CaSO_4$, Devonian to Permian CaSO4, shales and limestone-derived $CaSO_4$. The most likely source would appear to be the host rock composed of coal and shales.

Sample 54 has a $\delta^{34}S$ SO_4 value of -7.7 ‰ CDT and a $\delta^{34}S$ S^{2-} value of -36.2 ‰ CDT. The difference between the two is 28.5 ‰ CDT. This value is consistent with values recorded during bacterial sulphate reduction reactions (Clark and Fritz, 1997, p. 145-146). The $\delta^{34}S$ SO_4 value for sample 54 coincides with values recorded for igneous rocks, volcanic sulphur, petroleum, coal, shales and limestone-derived $CaSO_4$. A quick calculation of the Ca/SO_4 molar ratio suggests that the sample was not derived solely from gypsum or anhydrite dissolution. The most likely sulphur sources would therefore be the host rock, possibly the coal and shales present within the Formation.

The range of values present show that samples 60, 61 and 62 have $\delta^{34}S$ SO4 values that suggest the SO_4 could be coming from igneous rocks, volcanic sulphur, petroleum, coal, biogenic pyrite, or shales, with samples 61 and 62 also having values within the range of atmospherically-derived sulphate. Sample 63 has a $\delta^{34}S$ SO_4 value that coincides with those values recorded for igneous rocks, volcanic sulphur, petroleum, coal, Cenozoic $CaSO_4$, Devonian to Permian $CaSO_4$, shales and limestone-derived $CaSO_4$. Sample 46 has a $\delta^{34}S$ value that coincides with literature values for igneous rocks, volcanic sulphur, petroleum, coal, shales, atmospherically-derived sulphate and limestone-derived $CaSO_4$. Sample 53 has a $\delta^{34}S$ SO_4 value that coincides with values recorded for volcanic sulphur, petroleum, coal, biogenic pyrite, shales and limestone-derived sulphides. As above, a quick calculation of the Ca/SO_4 molar ratio suggests that these samples were not derived solely from gypsum or anhydrite dissolution. The most likely sulphur sources would therefore be the host rock, possibly the coal and shales present within the Formation, although an atmospheric source for samples 46, 61 and 62 can not be entirely ruled out.

Sample 48 has a $d^{34}S$ S^{2-} value that coincides with values recorded for biogenic sulphide, shales and limestone-derived sulphides. It is the only sample that has a Ca/SO_4 value that approaches 1 supporting a gypsum or anhydrite source for the SO_4 in the sample. Give the nature of the Formation the sample was taken from, the most likely source of the sulphide would appear to be biogenic pyrite or shale derived sulphide.

4.6.4 Stable Isotopes of Carbon and Hydrogen in Hydrocarbon Gases

Methane can be released from the thermal maturation of humic coals, but as Hunt (1995) indicates, small amounts of heavier gases such as ethane through butane also are formed during coal maturation, but are so strongly adsorbed that it is difficult to quantify their true yield. Methane can also be generated through bacterial or microbial processes such as microbial fermentation and CO_2 reduction. A more specific discussion of the microbial pathways of methane generation is provided in Section 5.2.1. Stable isotopes of carbon and hydrogen in hydrocarbon gases can be used to fingerprint gases as to their origin, as well as to their generation pathway. The following table (Table 16) provides an approximate range in carbon and hydrogen isotopes for different types of petroleum gases.

Table 16. Range of carbon and hydrogen isotopes of petroleum gases.

Gas Type	$\delta^{13}C$ (‰PDB)	$\delta^{2}H$ (‰SMOW)
Dry bacterial	-110 to -60	-250 to -150
Wet thermogenic	-60 to -30	-300 to -120
Dry thermogenic	-40 to -15	-150 to -70

Source: Hunt (1995)

These values are approximate and depend on the original C and H makeup of the organic matter. They can be used as a basis for the proposal of methane generation however and form the basis along with literature compilations of the following discussion.

4.6.4.1 Horseshoe Canyon Formation

Only one of the water samples (sample 43) had sufficient dissolved gas for analyses purposes. This sample also had sufficient concentrations of butane and CO_2 for analysis of $\delta^{13}C$. All of the CBM well samples had sufficient concentrations of methane, ethane, propane, butane and CO_2 for $\delta^{13}C$ determinations. The summary statistics for the dissolved and produced gas samples are presented in the table below (Table 17).

Table 17. Horseshoe Canyon Formation: $\delta^{13}C$ and $\delta^{2}H$ of dissolved gasses.

Location	Mean (‰ VPDB)	Std. dev. (‰ VPDB)	N	Max. (‰ VPDB)	Min. (‰ VPDB)
$\delta^{13}C$ - Methane					
Horseshoe Canyon Formation (Upper Cretaceous) water wells	-	-	1	-48.82	-
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells	-58.36	0.62	4	-57.78	-59.24
$\delta^{13}C$ - Ethane					
Horseshoe Canyon Formation (Upper Cretaceous) water wells	-	-	-	-	-
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells	-43.11	2.15	4	-40.88	-45.89
$\delta^{13}C$ – Propane					
Horseshoe Canyon Formation (Upper Cretaceous) water wells	-	-	-	-	-
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells	-30.13	1.12	4	-28.45	-30.78
$\delta^{13}C$ – i-Butane					
Horseshoe Canyon Formation (Upper Cretaceous) water wells	-	-	-	-	-
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells	-28.89	3.18	4	-26.31	-33.19
$\delta^{13}C$ – n-Butane					
Horseshoe Canyon Formation (Upper Cretaceous) water wells	-	-	1	-24.34	-
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells	-29.93	4.25	4	-26.48	-35.57
$\delta^{13}C$ – CO_2					
Horseshoe Canyon Formation (Upper Cretaceous) water wells	-	-	1	-17.59	-
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells	3.44	18.7	4	21.08	-21.83
$\delta^{2}H$ – CH_4					
Horseshoe Canyon Formation (Upper Cretaceous) water wells	-	-	1	-374	-
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells	-330	16.6	3	-313	-346

The CBM wells methane $\delta^{13}C$ values have a narrow range of values, suggesting that the gas source material and generation processes may have been similar for all of the samples. Standard plots used to ascertain the origin of gases based on $\delta^{13}C$ and $\delta^{2}H$ of methane, and $\delta^{13}C$ of CO_2 however suggest a mix of possible generation processes for these gases. A plot of $\delta^{2}H$ of methane versus $\delta^{13}C$ of methane (Figure 27) suggests that the methane from the CBM wells is biogenic in nature, while the water well sample

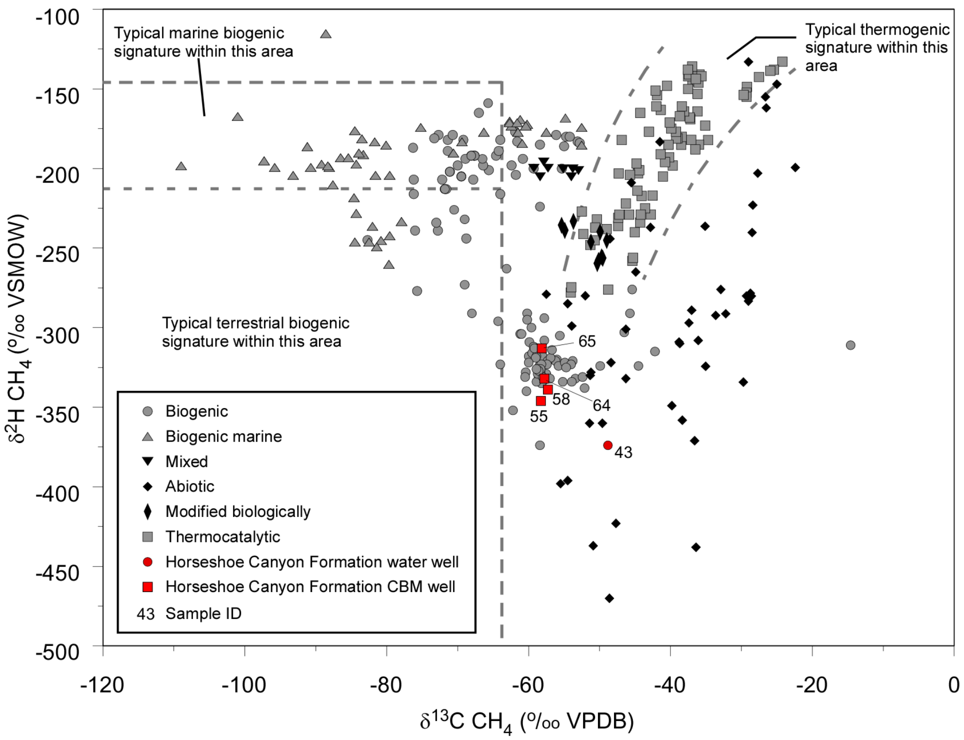


Figure 27. Horseshoe Canyon Formation δ^2H vs. δ^{13}C of methane.

dissolved methane is abiotic in nature. A plot of δ^{13}C of CO_2 versus δ^{13}C of methane (Figure 28) suggests that only some of the samples (samples 43, 55, 58, 59 and 65) are biogenic, while 2 samples (samples 56 and 64) may have δ^{13}C compositions that have been modified biologically.

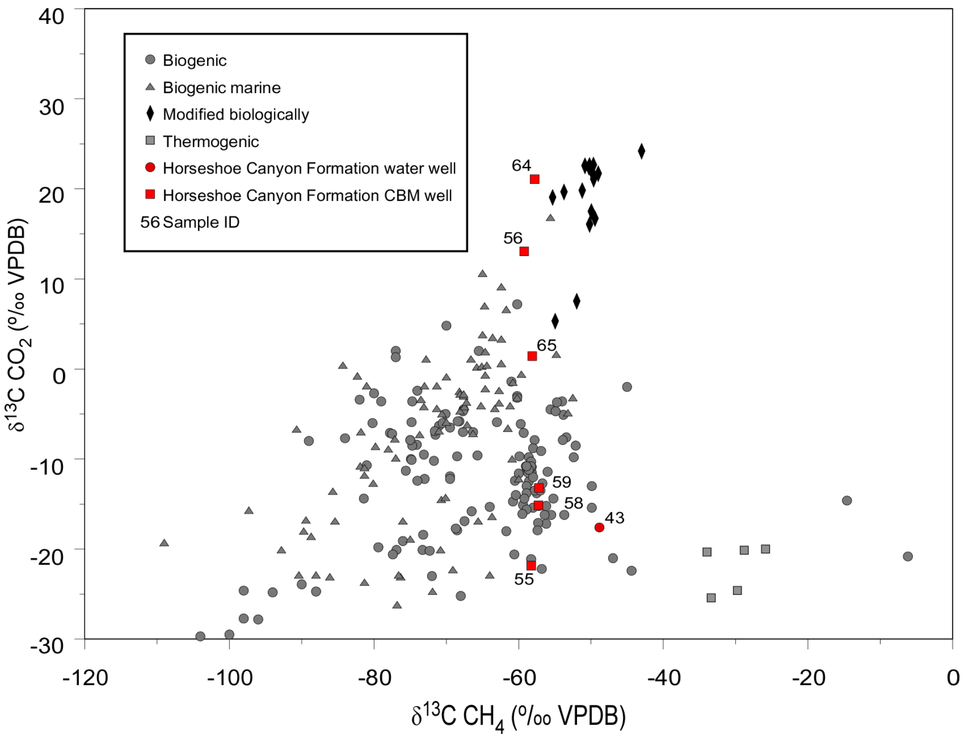


Figure 28. Horseshoe Canyon Formation δ^{13}C CO_2 vs. δ^{13}C of methane.

4.6.4.2 Scollard and Paskapoo Formations

Only one dissolved gas sample was collected from Scollard and Paskapoo formations water wells. It had a $\delta^{13}C$ value for methane of -74.51‰ VPDB and a $\delta^{13}C$ value for ethane of -49.38‰ VPDB. The table below presents a summary of available $\delta^{13}C$ and $\delta^{2}H$ data (Table 18).

Table 18. Scollard and Paskapoo formations: $\delta^{13}C$ and $\delta^{2}H$ of dissolved gasses.

Location	Mean (‰ VPDB)	Std. dev. (‰ VPDB)	N	Max. (‰ VPDB)	Min. (‰ VPDB)
$\delta^{13}C$ - Methane Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells	-	-	1	-74.51	-
$\delta^{13}C$ - Ethane Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells	-	-	1	-49.38	-
$\delta^{13}C$ – Propane Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells	-	-	-	-	-
$\delta^{13}C$ – i-Butane Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells	-	-	-	-	-
$\delta^{13}C$ – n-Butane Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells	-	-	-	-	-
$\delta^{13}C$ – CO_2 Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells	-	-	-	-	-
$\delta^{2}H$ – CH_4 Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells	-	-	1	-374	-

The $\delta^{13}C$ versus $\delta^{2}H$ of methane plot indicates that the methane within this well is biogenic (Figure 29). Since not enough CO_2 was present to complete the $\delta^{13}C$ analysis, the confirmation of the gas generation process through this additional plot can not be undertaken.

4.7 Strontium Isotope Geochemistry

4.7.1 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. Independently, Sr will form minerals such as strontianite ($SrCO_3$) and celestite ($SrSO_4$). Strontium geochemistry is also linked to the geochemistry of K and Rb. The decay

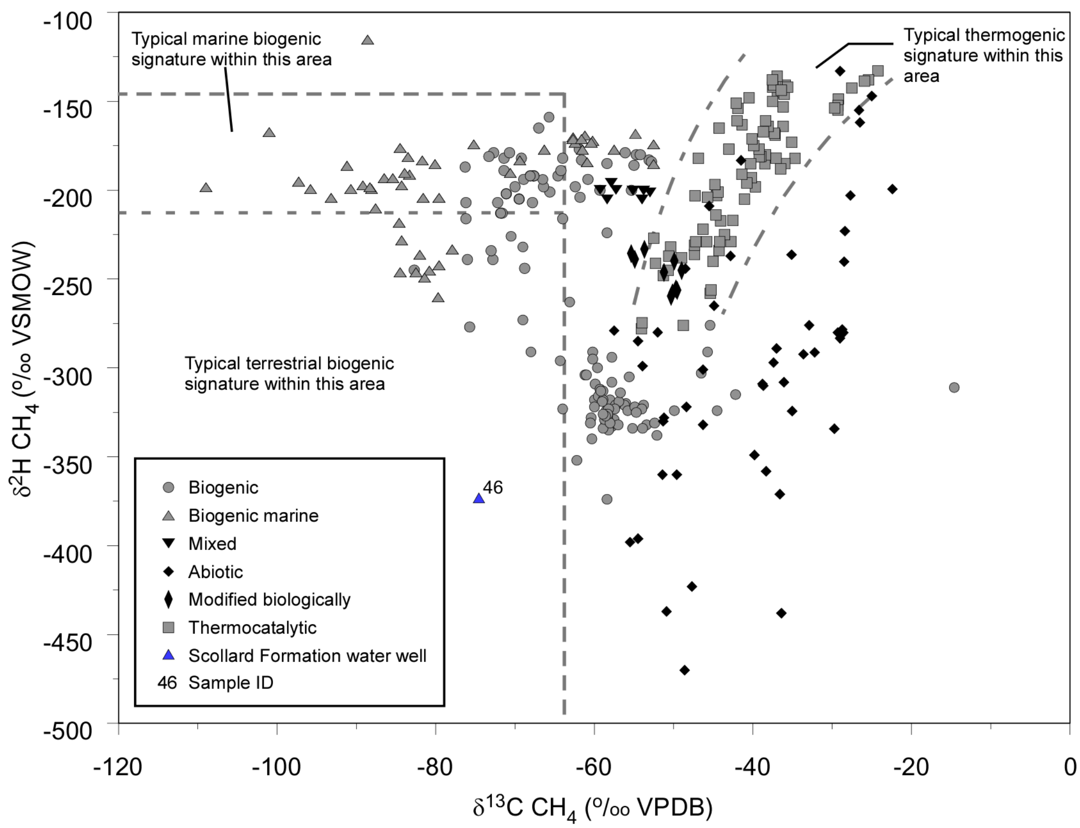


Figure 29. Scollard and Paskapoo formations δ²H vs. δ¹³C of methane.

of ^{87}Rb produces ^{87}Sr. Rubidium has similar chemical characteristics to K. Therefore K-rich rocks are likely to have relatively 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. The complete isotope data set is available in Appendix 8.

4.7.1.1 Horseshoe Canyon Formation

A plot of the Sr isotopic ratios and inverse of the Sr concentration is presented in Figure 30. The Horseshoe Canyon Formation Sr isotope ratios for the water well and CBM wells appear to fall within the Group 1 range of values reported in Lemay (2003). The CBM well values are much more clustered than the water well values, but despite the difference in Sr concentrations, the Sr isotope ratios are similar. This suggests that either the Sr source in Horseshoe Canyon Formation groundwater is similar regardless of flow system position, or that some sort of geochemical process is acting to homogenize isotopic compositions.

The Sr isotopic ratios plot within a very narrow range on a Sr isotopic ratio summary chart (Figure 31). The Horseshoe Canyon Formation water and CBM well samples have Sr isotopic values similar to those encountered in geothermal brines, continental and oceanic volcanic rocks, continental plutonic rocks, clastic sedimentary rocks and Proterozoic marine carbonate rocks. Given the rock types present within the Horseshoe Canyon Formation, the most likely rock-derived sources of Sr would be clastic sedimentary rocks, but as noted in Lemay (2003) the presence of bentonite and pyroclastic sedimentary rock fragments in the Formation could also contribute to the Sr concentration profile.

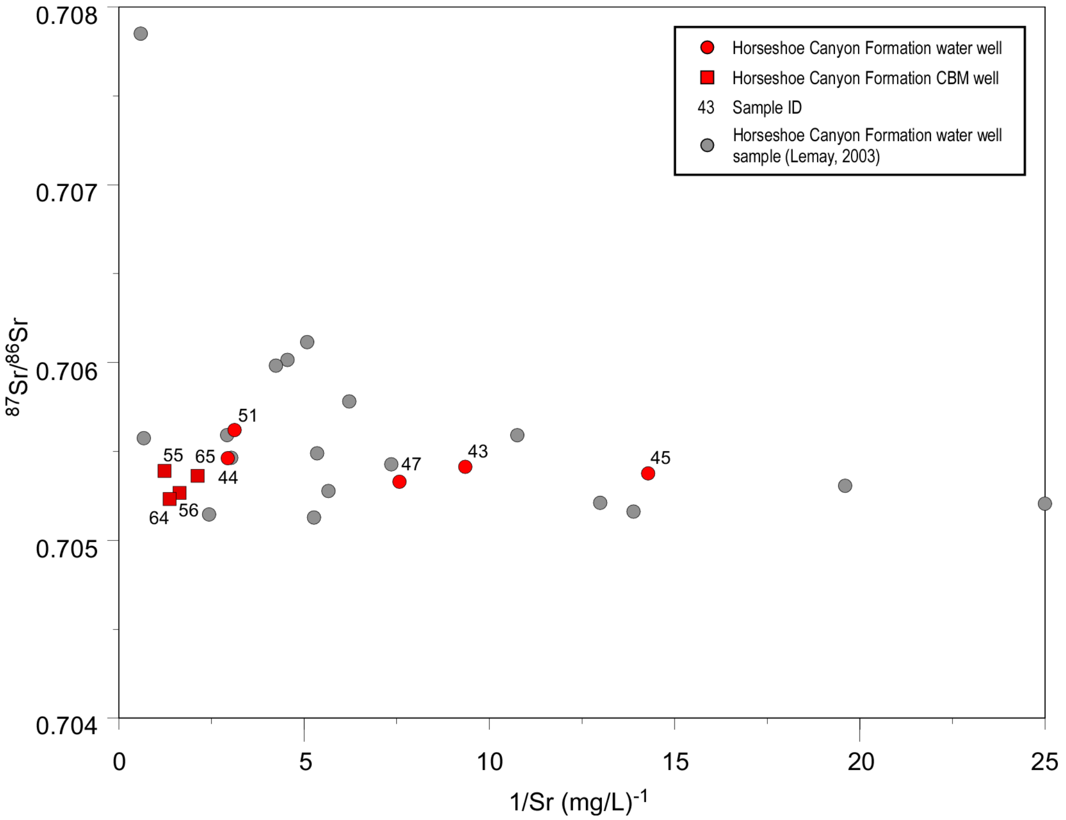


Figure 30. Horseshoe Canyon Formation: $^{87}Sr/^{86}Sr$ vs 1/Sr.

As discussed earlier, the geochemistry of Sr can be related to that of Ca and K. Plots of Sr vs. Ca and Sr vs. K can help reveal the mechanism of Sr introduction into groundwater. For the purpose of this exercise, the 2005 data and the Lemay (2003) data were used to assess any possible relationships. These comparisons showed that positive correlations exist between the concentrations of Ca and Sr as well as between the concentrations of K and Sr in the Horseshoe Canyon Formation water samples. The following table summarizes the correlation coefficients for the various test cases (Table 19).

Table 19. Horseshoe Canyon Formation: Sr vs. Ca and Sr vs. K correlation coefficient summary.

Plotted elements	Data Group	Correlation Coefficient (R^2)
Sr vs. Ca	Water wells: this study	0.9002
	Water wells: Lemay (2003)	0.8345
	Water wells: this study + Lemay (2003)	0.8318
	CBM wells	0.8870
	Water wells + CBM wells – this study	0.7187
	All data	0.5418
Sr vs. K	Water wells: this study	0.6315
	Water wells: Lemay (2003)	0.4633
	Water wells: this study + Lemay (2003)	0.5173
	CBM wells	0.2551
	Water wells + CBM wells – this study	0.4258
	All data	0.5166

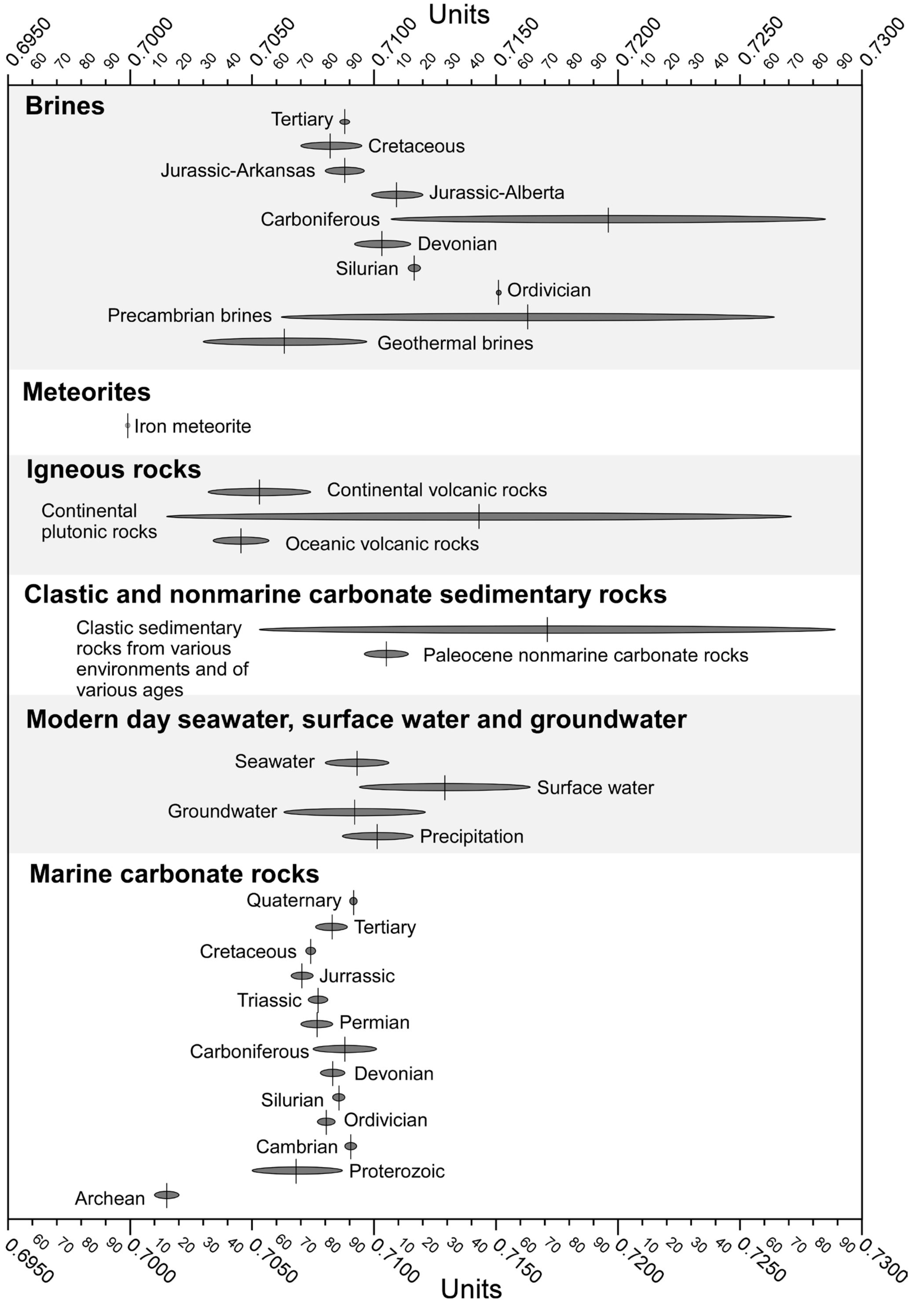


Figure 31. Range of $^{87}Sr/^{86}Sr$ values in geological materials. Compiled from: Brookins et al. (1969), Chaudhuri (1978), Connolly et al. (1990a), Dasch (1969), Denison et al. (1997), Demaiffe and Fieremans (1981), Elderfield and Greaves (1981), Ewart and Stipp (1968), Faure and Hurley (1963), Faure 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)

Strong relationships appear to exist between Ca and Sr concentrations in the various test cases, but become less pronounced as all of the data is included in the analysis. Much weaker relationships exist between the concentrations of K and Sr. This suggests that the Sr concentrations could be controlled much more by reactions involving Ca-rich minerals than by K-rich minerals especially in the shallower portions of the Formation. The elemental plots are presented in Figure 32 and Figure 33. One interesting relationship can be noted between the water well and CBM well data. The individual and pooled regression line slopes for the water well data from 2005 and from 2003 have similar slope values (0.0163, 0.0130 and 0.0134 respectively) while the CBM well regression line slope is different (0.0388). The nature of this difference is difficult to assess, but may be related to solubility changes with depth, or perhaps a greater availability of Sr at depth.

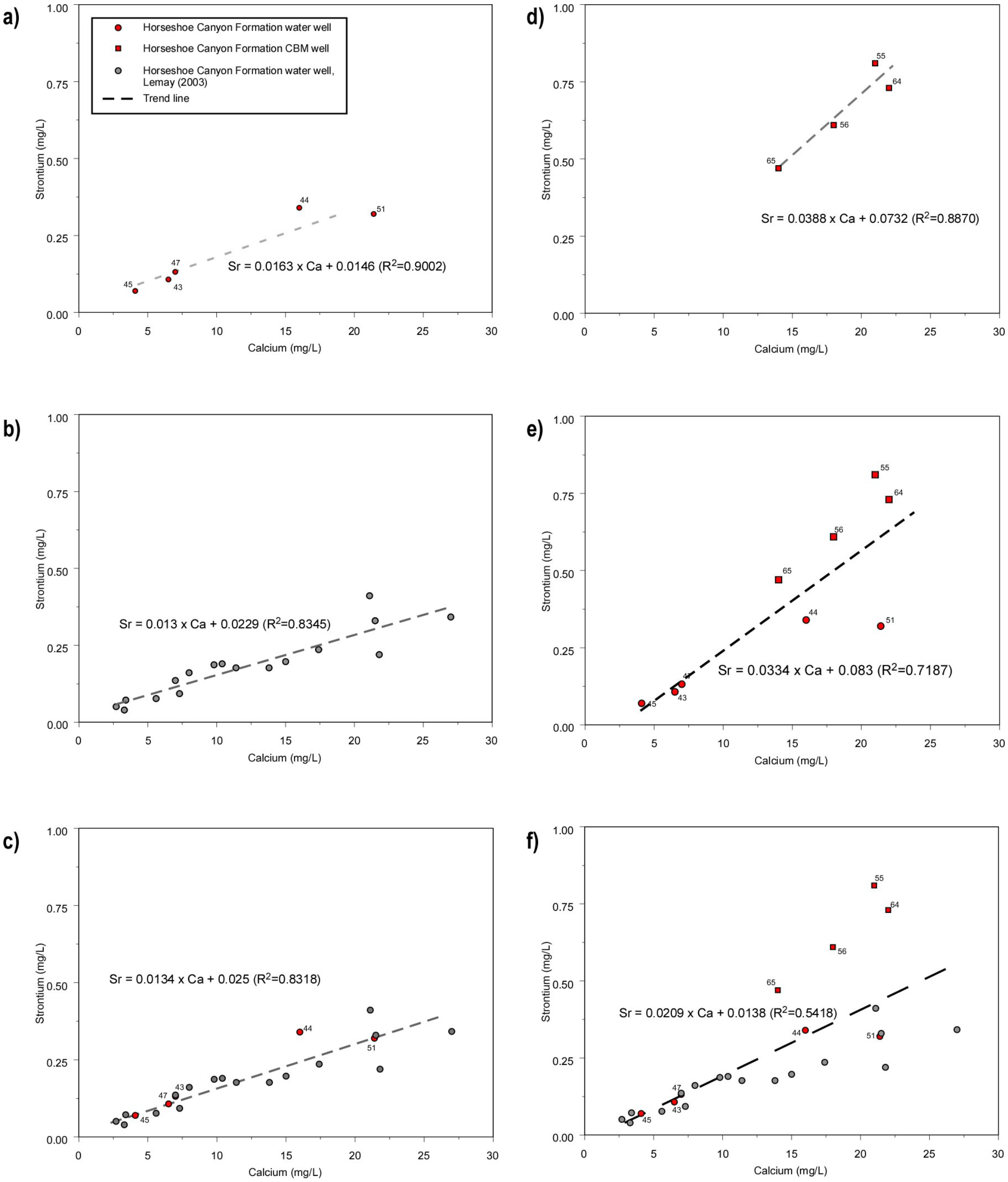


Figure 32. Horseshoe Canyon Formation: Sr vs. Ca summary plots. a) Water well data this study; b) Water well data from Lemay (2003); c) Combined water well data; c) CBM well data, this study; e) combined water well, CBM well data, this study; f) Combined data, all sources.

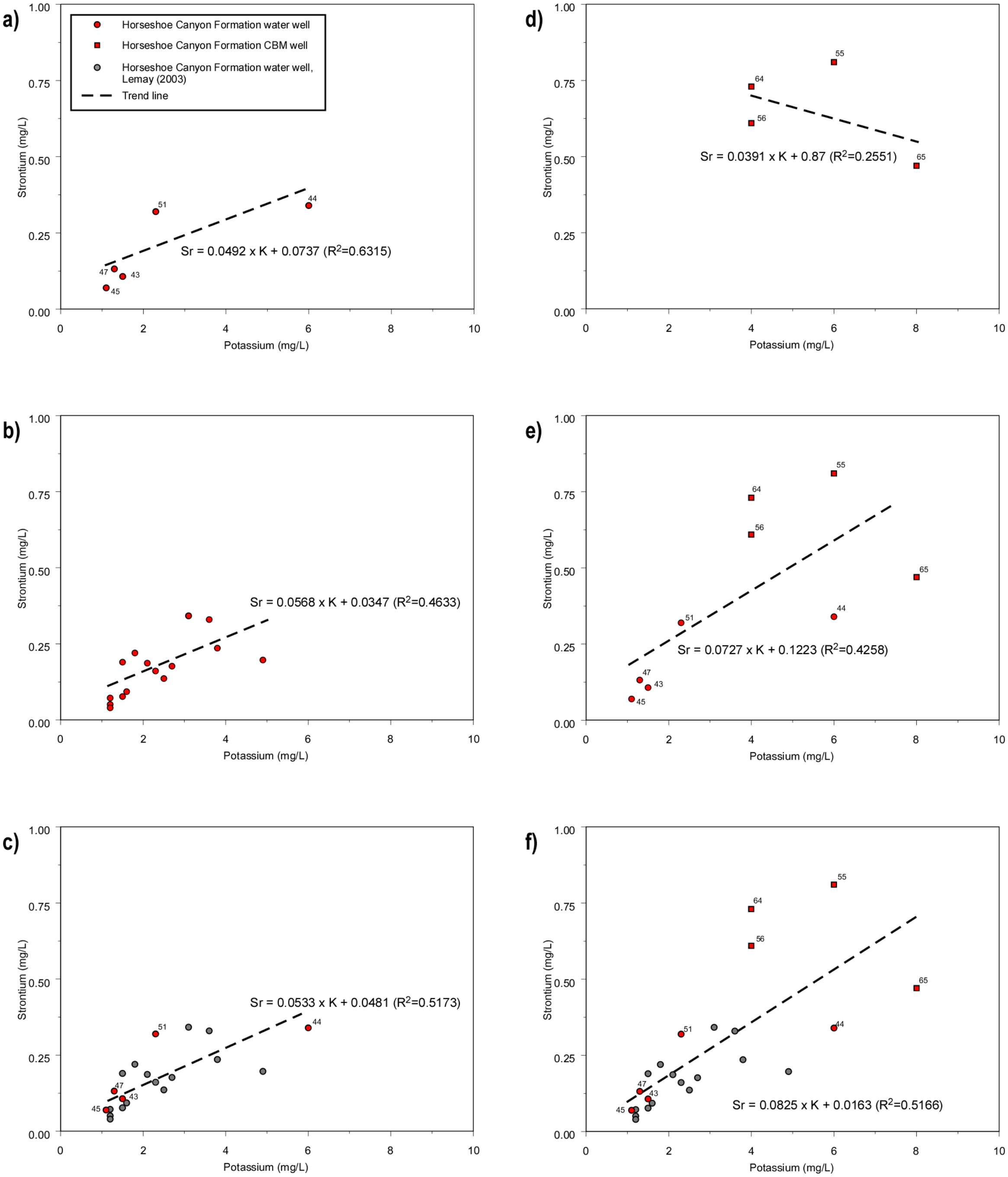


Figure 33. Horseshoe Canyon Formation: Sr vs K summary plots. a) Water well data this study; b) Water well data from Lemay (2003); c) Combined water well data; d) CBM well data, this study; e) Combined water well, CBM well data, this study; f) Combined data, all sources.

All of the above suggests that the final Sr isotopic composition is achieved through the dissolution of Sr-bearing minerals in sedimentary rocks by water with a higher Sr isotope ratio yielding water with an intermediate Sr isotopic that evolves over time to some sort of final signature that has been homogenized through ongoing water-rock interactions and mixing.

4.7.1.2 Scollard and Paskapoo Formations

The Sr isotopic ratios versus the inverse of the Sr concentration are plotted in Figure 34. Samples 46 and 54 fall within the Group I division identified in Lemay (2003). Based on Figure 31, these samples have Sr isotopic composition similar to those of geothermal brines, continental and oceanic volcanic rocks, continental plutonic rocks, clastic sedimentary rocks and Proterozoic marine carbonate rocks. Samples 48, 49, 53, 60, 61 and 62 fall within the Group II division. These samples have Sr isotope ratio values similar to those of Precambrian and geothermal brines, continental volcanic and plutonic rocks, clastic sedimentary rocks, groundwater and Proterozoic and Jurassic marine carbonate rocks. Sample 63 falls within the Group III division. It has a Sr isotopic ratio value similar to those reported for Cretaceous, Precambrian and geothermal brines, continental plutonic rocks, groundwater, and Tertiary, Triassic, Permian, Carboniferous, Devonian, Ordovician, Cambrian and Proterozoic marine carbonate rocks. Despite this range in Sr sources, the most likely Sr source as indicated by the isotopic values are the clastic and sedimentary rocks that make up the Scollard and Paskapoo formations as well as the formation water present and evolving within the rock units.

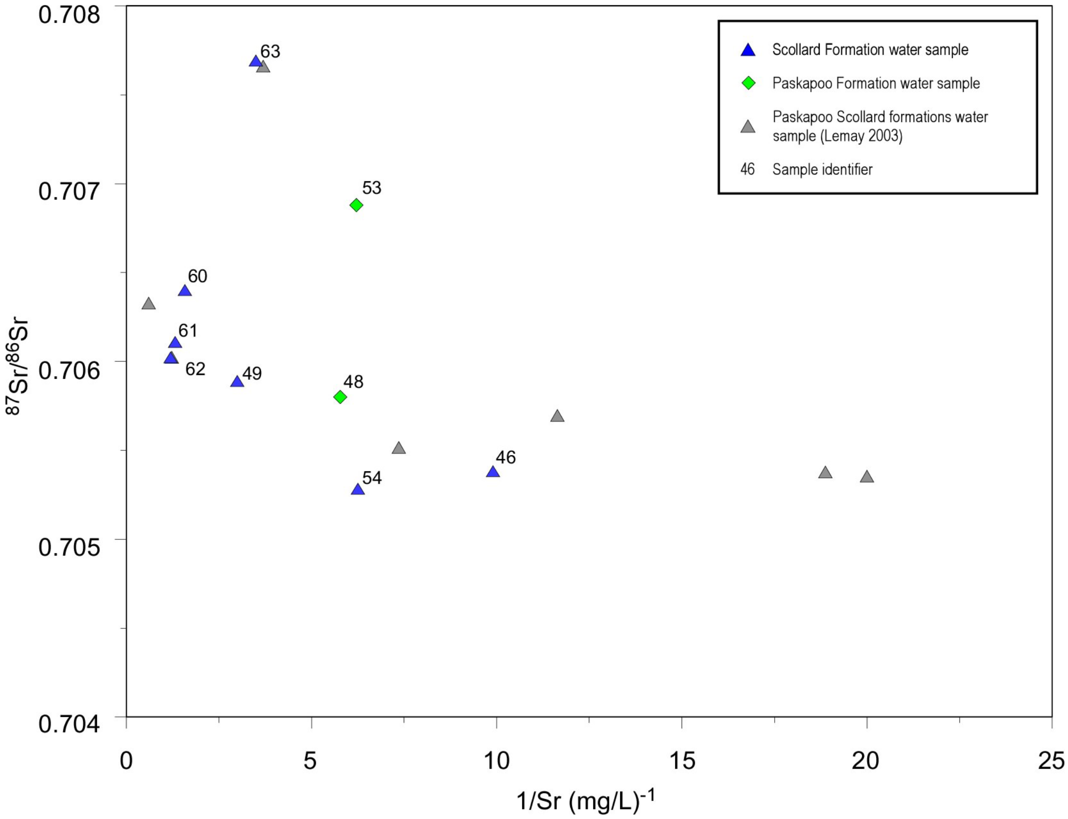


Figure 34. Scollard and Paskapoo formations: $^{87}Sr/^{86}Sr$ vs. 1/Sr.

The Scollard and Paskapoo formations data collected in 2005 and the Lemay (2003) data were used to assess any possible relationships between Sr, Ca and K in order to try and clarify Sr source and isotopic ratio evolution. These comparisons showed that positive correlations exist between the concentrations of Ca and Sr as well as between the concentrations of K and Sr in the Scollard and Paskapoo formations water samples. Somewhat surprisingly, the strongest correlations appear to be between the Sr and K concentrations. The following table summarizes the correlation coefficients for the various test cases (Table 20) and Figure 35 and Figure 36 show the graphical representation of these relationships.

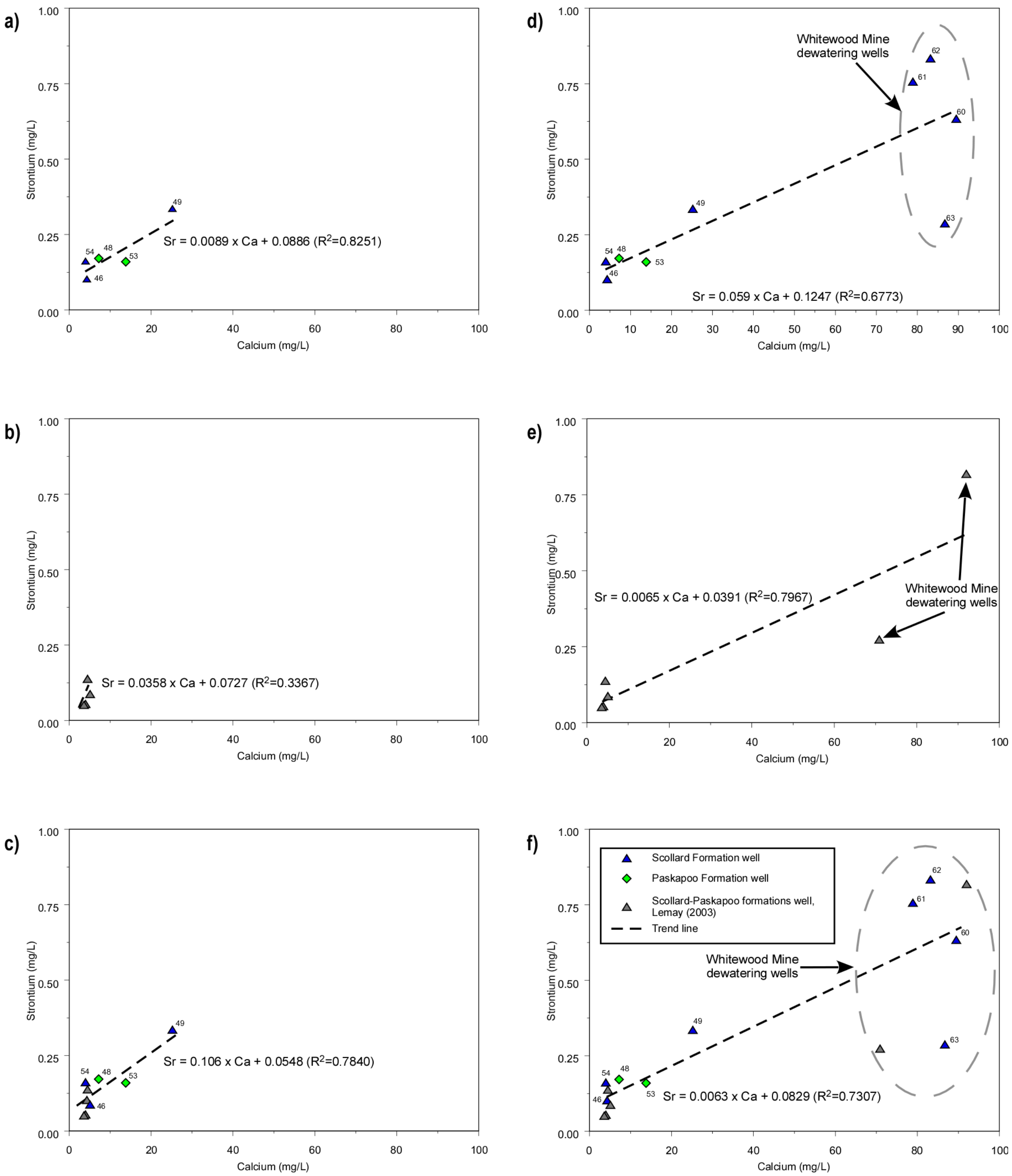


Figure 35. Scollard and Paskapoo formation: Sr vs. Ca summary plots. a) Water well data this study; b) Water well data from Lemay (2003); c) Combined water well data; d) CBM well data, this study; e) Combined water well, CBM well data, this study; f) Combined data, all sources.

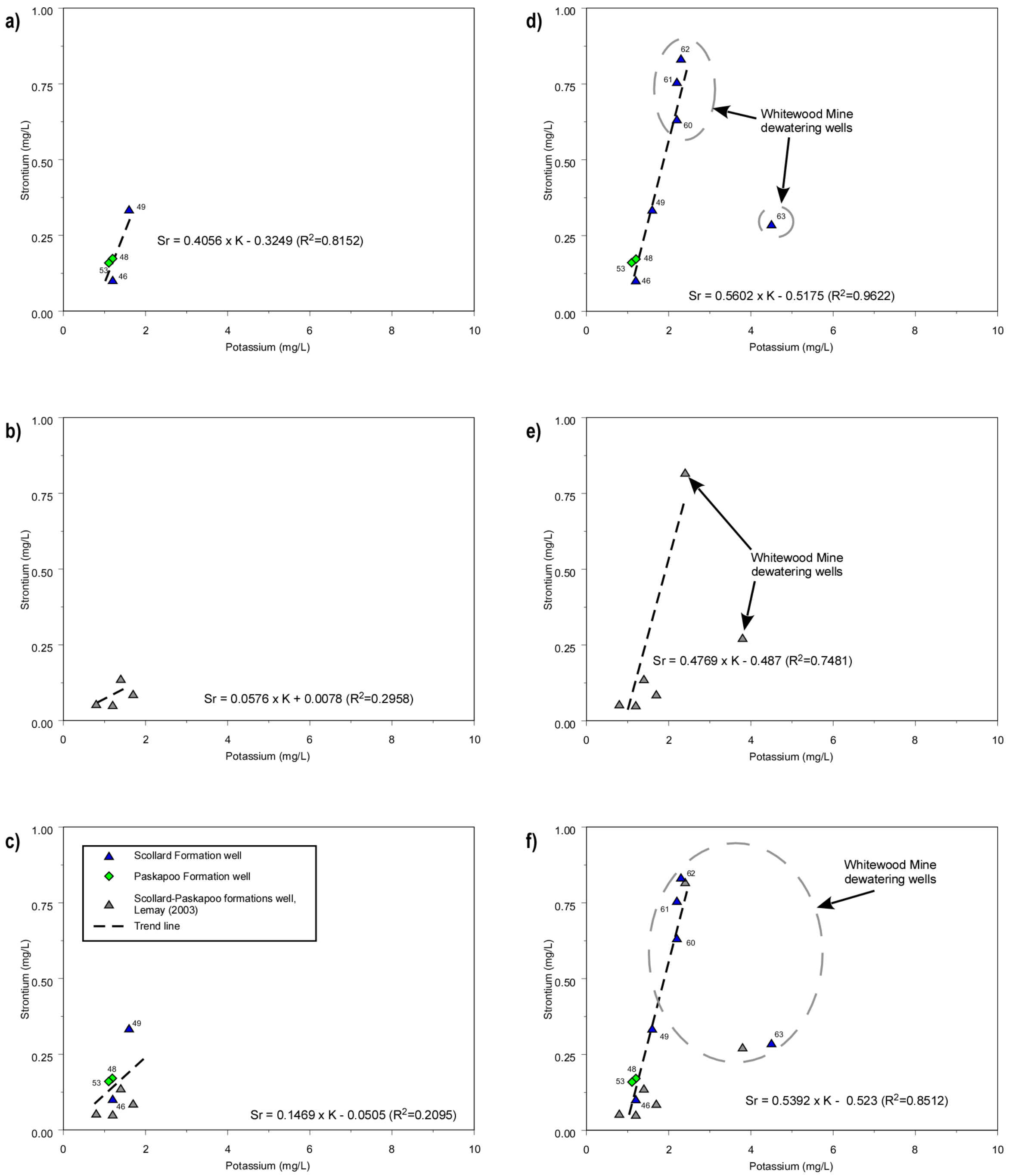


Figure 36. Scollard and Paskapoo formations: Sr vs. K summary plots. a) Water well data this study; b) Water well data from Lemay (2003); c) Combined water well data; d) CBM well data, this study; e) Combined water well, CBM well data, this study; f) Combined data, all sources.

Table 20. Scollard and Paskapoo formations: Sr vs. Ca and Sr vs. K correlation coefficient summary.

Plotted elements	Data Group	Correlation Coefficient (R^2)
Sr vs. Ca	Water wells - this study	0.8251
	Water wells - Lemay (2003)	0.3367
	Water wells - this study + Lemay (2003)	0.7840
	Dewatering wells - this study	0.2657
	Dewatering wells – this study + Lemay (2003)	0.1937
	All wells – this study	0.6773
	All wells – Lemay (2003)	0.7967
	All wells – this study + Lemay (2003)	0.7307
Sr vs. K	Water wells - this study	0.8152
	Water wells - Lemay (2003)	0.2958
	Water wells - this study + Lemay (2003)	0.2095
	Dewatering wells - this study	0.6283
	Dewatering wells – this study + Lemay (2003)	0.5230
	All wells – this study	0.9622
	All wells – Lemay (2003)	0.7481
	All wells – this study + Lemay (2003)	0.8512

The correlations suggest that both K-bearing and Ca-bearing minerals may contribute to the overall Sr content in the Scollard and Paskapoo formations. The mineral makeup of these formations as described earlier (Section 2.1.2) supports the hypothesis that the rock body could be contributing to the overall Sr composition of the water as these rock bodies contain both Ca and K-bearing minerals. Further supporting a possible contribution of Sr by K bearing minerals is the lone Rb concentration above detection limits. Decay of ^{87}Rb to ^{87}Sr could help explain the higher ratios of these samples, although with only one detection of Rb, it is difficult to attribute all of the higher values to enrichment by ^{87}Rb decay. The variation in Sr isotopic ratios in the Scollard-Paskapoo formations water samples as compared to the Horseshoe Canyon Formation water sample values may indicate a less evolved system exists within the Scollard-Paskapoo system, one that has not yet developed a homogenized isotopic signature. It may also suggest that the mineralogy of the formations is different or more heterogeneous as compared to that of the Horseshoe Canyon Formation, or that the nature of the reactions occurring within the formations is different.

One predictable relationship appears to exist within the Scollard-Paskapoo formations samples however. A plot of the isotopic ratio vs. the inverse of the Sr concentrations of the samples collected from dewatering wells in use at the Whitewood Mine, as part of this study and that conducted by Lemay (2003), shows a distinct linear trend with the following equation and correlation coefficient.

$^{87}Sr/^{86}Sr = 0.0007 \times 1/Sr + 0.7052$ (R^2=0.9931)

A linear trend on such a plot indicates a relationship exists, such as a mixing reaction. These wells are actively dewatering the area surrounding the mining operations and will have been active for various periods of time based on mine plans. As such they will likely be influencing different portions of the aquifers being dewatered. Wells AERI 0524 and AERI 0248 may be drawing the majority of their water from shallower less evolved aquifers with a more typical groundwater signature while the remaining samples may be drawing water from more evolved intervals that are further along the continuum described by the linear trend on the graph. A more in depth examination of well records and dewatering activities would be required in order to confirm these hypotheses and to validate any trend. Although the interpretation of such a straight line as a mixing or groundwater evolution line is tempting, the conclusion may be premature without additional scrutiny.

4.8 Groundwater Age Dating

The concentrations of 2 radiogenic isotopes, ^{36}Cl and ^{129}I, were determined for the water and CBM well samples from the Paskapoo-Scollard and Horseshoe Canyon formations for the purpose of calculating age dates. Age dating of groundwater has been attempted by a number of researchers, but has not been focused entirely on coal-bearing aquifers as was done for this study. This section begins with a brief description of the concept of groundwater age 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 massweighted 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.

4.8.1 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) ingrowth 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.

4.8.1.1 Previous Work

A few studies have been completed in Alberta where ^{36}Cl/Cl ratios were measured to examine groundwater age. These include studies completed by Phillips et al. (1986), Fabryka-Martin et al. (1991), and Nolte et al. (1991) that examined groundwater age in the Milk River Formation and Lemay (2003) that looked at groundwater age in the Scollard and Horseshoe Canyon formations and the Belly River Group. In addition, data pertinent to this study have been measured in U.S. CBM basins. ^{36}Cl/Cl ratios have been measured in the Fruitland Basin as documented by Snyder et al. (2003). The comparison of these various results to the measured ratios obtained for this study's samples will assist in better understanding groundwater flow within CBM-bearing formations in Alberta as well as the groundwater flow characteristics in different portions of the Alberta Basin.

4.8.1.2 Horseshoe Canyon Formation

Samples were collected from water wells and CBM wells for the purpose of determining the age of groundwater in these portions of the Horseshoe Canyon Formation. The results of the analyses are presented in the table below (Table 21).

Table 21. ^{36}Cl/Cl and ^{129}I/I analytical results for the Horseshoe Canyon Formation.

Sample Type	Well Type	Sample ID	Cl (mmol/L)	^{36}Cl/Cl (x10^{-15})	I (µmol/L)	^{129}I/I (x10^{-15})	Formation
AERI 0501	Water	43	0.09	1,920±100	0.83	1,606	Horseshoe Canyon
AERI 0502	Water	44	26.32	25±3	2.13	3,590	Horseshoe Canyon
AERI 0503	Water	45	0.39	723±13	0.71	4,662	Horseshoe Canyon
AERI 0506	Water	47	0.22	1,620±44	0.07	72,586	Horseshoe Canyon
AERI 0510	Water	51	0.38	374±13	1.12	3,413	Horseshoe Canyon
AERI 0511	Water	52	0.38	356±28	1.12	2,968	Horseshoe Canyon
AERI 0516	CBM	55	43.44	10.9±3.3	40.00	1,814	Horseshoe Canyon
AERI 0517	CBM	56	43.16	10.5±4.8	22.65	2,448	Horseshoe Canyon
AERI 0518	CBM	57	43.72	9.3±1.9	23.17	2,386	Horseshoe Canyon
AERI 0525	CBM	64	45.13	9.2±4.2	31.88	2,130	Horseshoe Canyon
AERI 0526	CBM	65	38.36	9.4±2.5	24.03	2,571	Horseshoe Canyon

A plot of ^{36}Cl/Cl and Cl concentrations (Figure 37) shows that the CBM wells and 1 of the water wells (Sample 44) plot in the same general area as water samples described as being formation water by Snyder et al. (2003) as well as in the vicinity of some of the samples described in Phillips et al. (1986), Fabryka-Martin et al. (1991) and Nolte et al. (1991) for the Milk River Formation. Samples 43 and 47 plot in the same region as meteoric water samples while the remaining water well samples (samples 45, 51 and 52) plot somewhere between these two end members. All of the samples plot to the right of the mixing line proposed by Snyder et al. (2003) suggesting that there may be in situ addition of ^{36}Cl occurring to generate the observed ratios, unless the Alberta Basin end-member compositions are significantly different from those of the Fruitland Basin. A plot of ^{129}I/I and ^{36}Cl/Cl ratio values (Figure 38) appears to support the suggestion that in situ production could be occurring. The Horseshoe Canyon Formation water sample data plots between the two mixing curves proposed by Snyder et al. (2003), but plot closer to the pre-anthropogenic mixing curve.

Despite the potential complication of in situ production of ^{36}Cl in the Horseshoe Canyon, approximate groundwater ages can be calculated to assess the general level of connection between the water wells and CBM wells. A number of different models exist to calculate groundwater age using ^{36}Cl/Cl and are described by Phillips et al. (1986). The radiometric age dating equation as presented in section 3 is modified slightly to take into account the possible introduction of connate chloride (Equation 1) as well as the impact of ion filtration on the ^{36}Cl/Cl ratio (Equation 2).

Equation 1 $$t = \frac{-1}{\lambda_{36}} \ln \frac{C(R - R_{se})}{C_o(R_o - R_{se})}$$

Equation 2 $$t = \frac{-1}{\lambda_{36}} \ln \frac{(R - R_{se})}{(R_o - R_{se})}$$

where: λ_{36} = ^{36}Cl decay constant ($2.303\text{x}10^{-6}$)
C = Cl concentration
C_o = initial Cl concentration
R = measured ^{36}Cl/Cl ratio
R_{se} = secular equilibrium ^{36}Cl/Cl ratio
R_o = initial ^{36}Cl/Cl ratio

The calculated age is dependent on the initial and secular equilibrium values chosen. Phillips et al. (1986) proposed an R_{se} value of $4\text{x}10^{-15}$ and a R_o value of $500\text{x}10^{-15}$. Other values are suggested for the R_o in Alberta however. The work of Moysey et al. (2003) suggests that the R_o in Alberta could be closer to $1{,}000\text{x}10^{-15}$. If the R_o value is similar to the value proposed by Snyder et al. (2003) for the Fruitland Formation, then the value is closer to $1{,}600\text{x}10^{-15}$. The C_o value used by Phillips et al. (1986) was 0.19 mmol/L whereas Snyder et al. (2003) used a value of 0.01 mmol/L. The lowest measured Cl concentration from the water well samples collected as part of this study from all of the formations was 0.014 mmol/L. If these various values are introduced into the above equations, a range of age values can be obtained describing the possible age dates for the groundwater within the Horseshoe Canyon Formation. The table below summarizes the results (Table 22) and highlights the importance of selecting an appropriate model as well as representative initial and reference values.

The most intuitively realistic ages appear to be provided by the ion filtration model with the R_o values suggested by Phillips et al. (1986) or Moysey et al. (2003). An interesting relationship appears to exist with North American warming and cooling trends during the Pliocene and Pleistocene when the errors in the ^{36}Cl/Cl ratios are taken into account (Figure 39). Using the ion filtration model, a relationship appears to exist between depth and age (Figure 40). A linear regression analysis of the data points shows the following relationships.

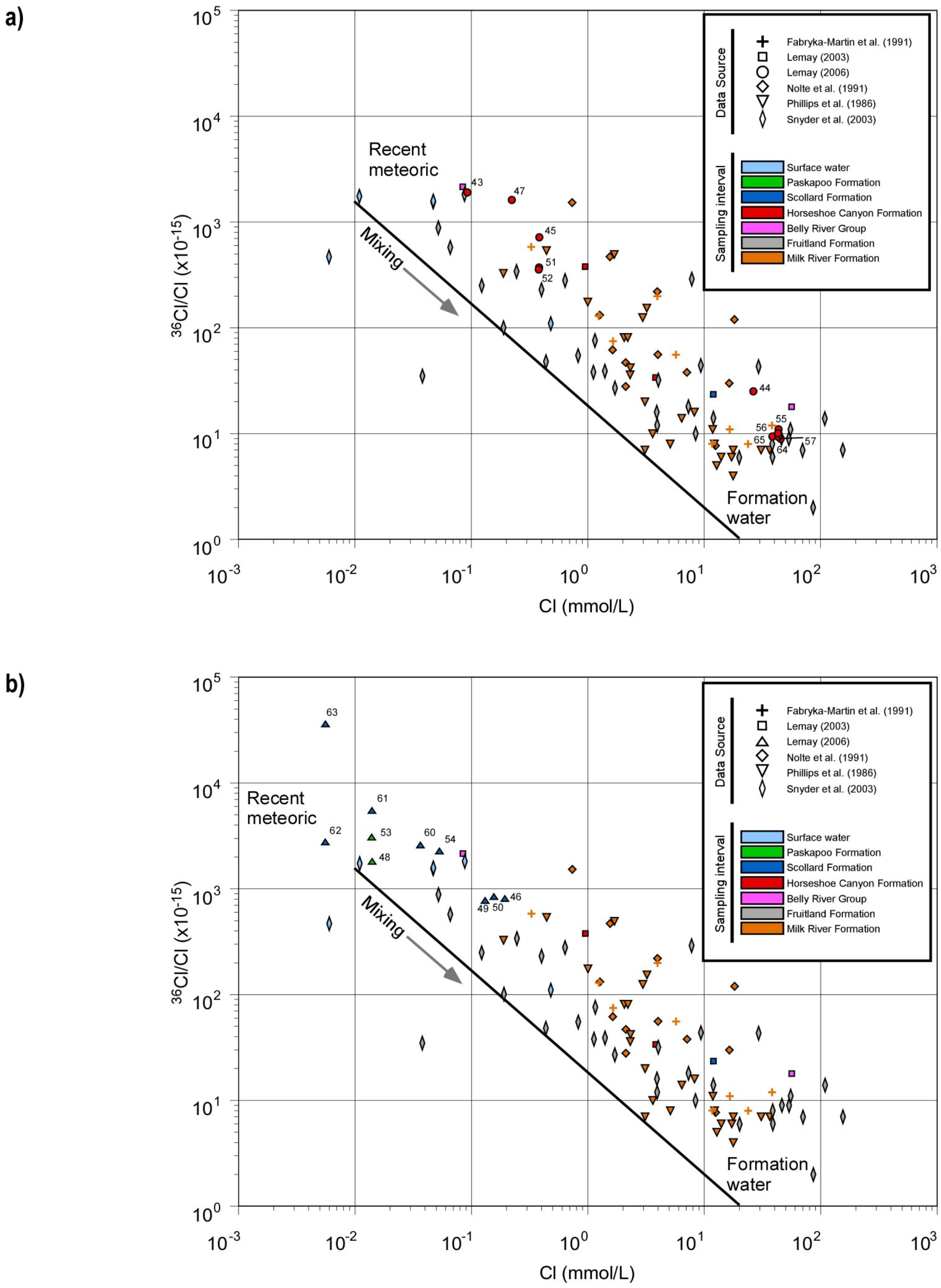


Figure 37. ^{36}Cl/Cl vs.chloride concentrations: a) Horseshoe Canyon Formation; and b) Scollard and Paskapoo formations. Note: Linework and proposed mechanisms reprinted from Geochimica et Cosmochimica Acta, Vol. 67, No. 23, Snyder, G.T., Riese, W.C., Franks, S., Fehn, U., Pelzmann, W.L., Gorody, A.W., and Moran, J.E., Origin and history of waters associated with coal-bed methane: ^{129}I, ^{36}Cl, and stable isotope results from the Fruitland Formation, CO and NM, p. 4529-4544, Copyright (2003), with permission from Elsevier. Additional data from Fabryka-Martin et al. (1991), Lemay (2003), Nolte et al. (1991), Phillips et al. (1986) and Snyder et al. (2003).

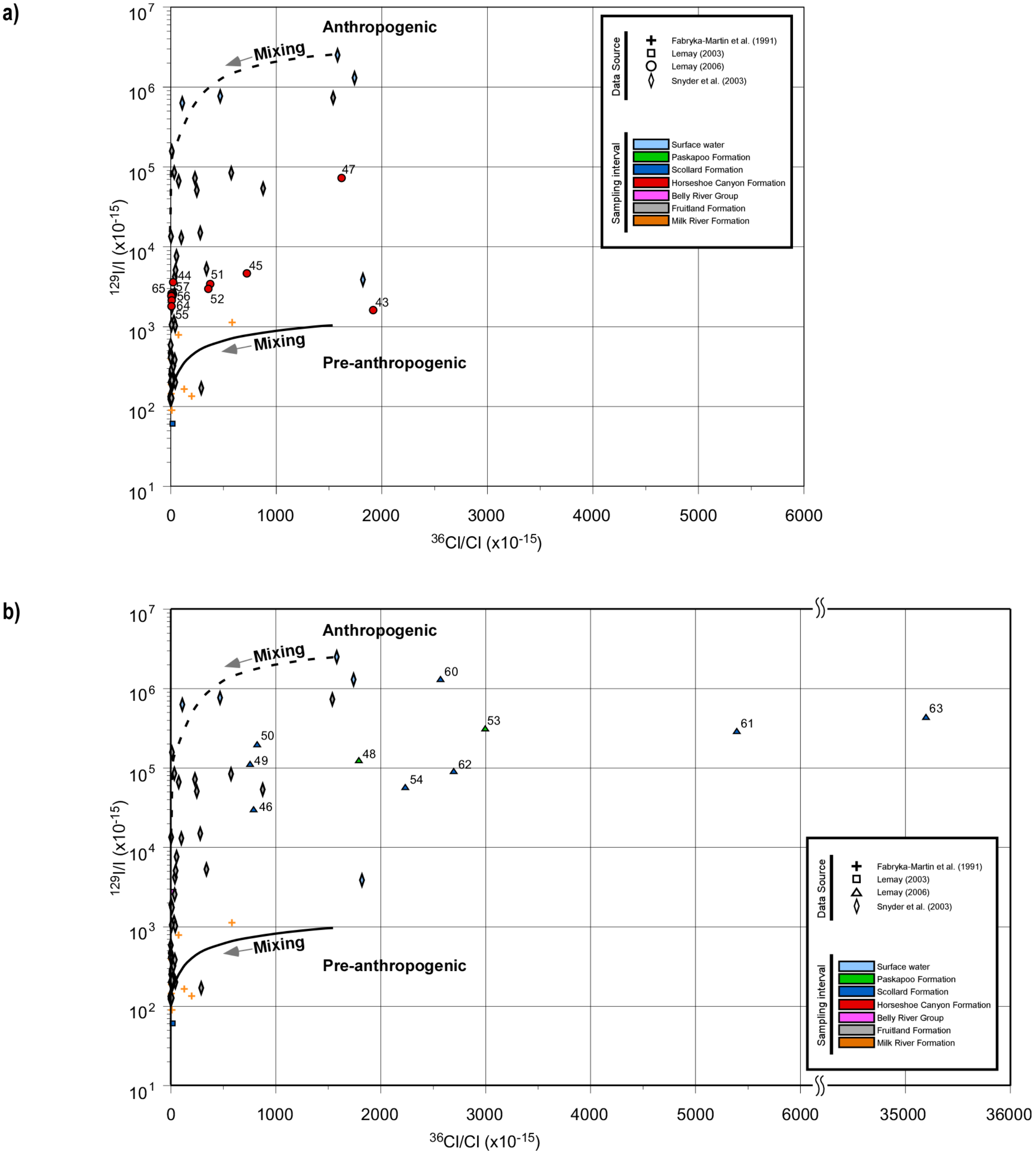


Figure 38. ^{129}I/I vs ^{36}Cl/Cl: a) Horseshoe Canyon Formation; and b) Scollard and Paskapoo formations. Note: Linework and proposed mechanisms reprinted from Geochimica et Cosmochimica Acta, Vol. 67, No. 23, Snyder, G.T., Riese, W.C., Franks, S., Fehn, U., Pelzmann, W.L., Gorody, A.W., and Moran, J.E., Origin and history of waters associated with coal-bed methane: 129I, 36Cl, and stable isotope results from the Fruitland Formation, CO and NM, p. 4529-4544, Copyright (2003), with permission from Elsevier. Additional data from Fabryka-Martian et al. (1991), Lemay (2003) and Snyder et al. (2003).

Table 22. Summary table of groundwater age dates for the Horseshoe Canyon Formation.

Age calculations using the Phillips et al. (1986) values for C_o, R_o and R_{se} and the Equation 1 age calculation method						
Sample	**C (mmol/L)**	**C_o (mmol/L)**	**R (x10^{-15})**	**R_o (x10^{-15})**	**R_{se} (x10^{-15})**	**Age (years)**
AERI 0501	0.09	0.19	1,920±100	500	4	A
AERI 0502	26.32	0.19	25±3	500	4	A
AERI 0503	0.39	0.19	723±13	500	4	A
AERI 0506	0.22	0.19	1,620±44	500	4	A
AERI 0510	0.38	0.19	374±13	500	4	A
AERI 0511	0.38	0.19	356±28	500	4	A
AERI 0516	43.44	0.19	10.9±3.3	500	4	A
AERI 0517	43.16	0.19	10.5±4.8	500	4	A
AERI 0518	43.72	0.19	9.3±1.9	500	4	A
AERI 0525	45.13	0.19	9.2±4.2	500	4	A
AERI 0526	38.36	0.19	9.4±2.5	500	4	A

Age calculations using the Phillips et al. (1986) values for R_o and R_{se} and the Equation 2 age calculation method						
Sample	**C (mmol/L)**	**C_o (mmol/L)**	**R (x10^{-15})**	**R_o (x10^{-15})**	**R_{se} (x10^{-15})**	**Age (years)**
AERI 0501	-	-	1,920±100	500	4	A
AERI 0502	-	-	25±3	500	4	1,377,170
AERI 0503	-	-	723±13	500	4	A
AERI 0506	-	-	1,620±44	500	4	A
AERI 0510	-	-	374±13	500	4	127,257
AERI 0511	-	-	356±28	500	4	148,912
AERI 0516	-	-	10.9±3.3	500	4	1,856,298
AERI 0517	-	-	10.5±4.8	500	4	1,882,229
AERI 0518	-	-	9.3±1.9	500	4	1,970,851
AERI 0525	-	-	9.2±4.2	500	4	1,979,122
AERI 0526	-	-	9.4±2.5	500	4	1,962,734

Age calculations using the Phillips et al. (1986) values for C_o and R_{se}, R_o from Moysey et al. (2003), and the Equation 1 age calculation method						
Sample	**C (mmol/L)**	**C_o (mmol/L)**	**R (x10^{-15})**	**R_o (x10^{-15})**	**R_{se} (x10^{-15})**	**Age (years)**
AERI 0501	0.09	0.19	1,920±100	1,000	4	25,754
AERI 0502	26.32	0.19	25±3	1,000	4	A
AERI 0503	0.39	0.19	723±13	1,000	4	A
AERI 0506	0.22	0.19	1,620±44	1,000	4	A
AERI 0510	0.38	0.19	374±13	1,000	4	128,110
AERI 0511	0.38	0.19	356±28	1,000	4	149,765
AERI 0516	43.44	0.19	10.9±3.3	1,000	4	A
AERI 0517	43.16	0.19	10.5±4.8	1,000	4	A
AERI 0518	43.72	0.19	9.3±1.9	1,000	4	A
AERI 0525	45.13	0.19	9.2±4.2	1,000	4	A
AERI 0526	38.36	0.19	9.4±2.5	1,000	4	A

Age calculations using the Phillips et al. (1986) value for R_{se}, R_o from Moysey et al. (2003), and the Equation 2 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R ($x10^{-15}$)	R_o ($x10^{-15}$)	R_{se} ($x10^{-15}$)	Age (years)
AERI 0501	-	-	1,920±100	1,000	4	A
AERI 0502	-	-	25±3	1,000	4	1,679,893
AERI 0503	-	-	723±13	1,000	4	141,505
AERI 0506	-	-	1,620±44	1,000	4	A
AERI 0510	-	-	374±13	1,000	4	429,980
AERI 0511	-	-	356±28	1,000	4	451,635
AERI 0516	-	-	10.9±3.3	1,000	4	2,159,021
AERI 0517	-	-	10.5±4.8	1,000	4	2,184,952
AERI 0518	-	-	9.3±1.9	1,000	4	2,273,574
AERI 0525	-	-	9.2±4.2	1,000	4	2,281,845
AERI 0526	-	-	9.4±2.5	1,000	4	2,265,457

Age calculations using the Phillips et al. (1986) values for C_o and R_{se}, R_o from Snyder et al. (2003), and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R ($x10^{-15}$)	R_o ($x10^{-15}$)	R_{se} ($x10^{-15}$)	Age (years)
AERI 0501	0.09	0.19	1,920±100	1,600	4	230,491
AERI 0502	26.32	0.19	25±3	1,600	4	A
AERI 0503	0.39	0.19	723±13	1,600	4	37,986
AERI 0506	0.22	0.19	1,620±44	1,600	4	A
AERI 0510	0.38	0.19	374±13	1,600	4	332,846
AERI 0511	0.38	0.19	356±28	1,600	4	354,502
AERI 0516	43.44	0.19	10.9±3.3	1,600	4	5,071
AERI 0517	43.16	0.19	10.5±4.8	1,600	4	33,831
AERI 0518	43.72	0.19	9.3±1.9	1,600	4	116,813
AERI 0525	45.13	0.19	9.2±4.2	1,600	4	A
AERI 0526	38.36	0.19	9.4±2.5	1,600	4	A

Age calculations using the Phillips et al. (1986) value for R_{se}, R_o from Snyder et al. (2003), and the Equation 2 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R ($x10^{-15}$)	R_o ($x10^{-15}$)	R_{se} ($x10^{-15}$)	Age (years)
AERI 0501	-	-	1,920±100	1,600	4	A
AERI 0502	-	-	25±3	1,600	4	1,884,630
AERI 0503	-	-	723±13	1,600	4	346,242
AERI 0506	-	-	1,620±44	1,600	4	A
AERI 0510	-	-	374±13	1,600	4	634,717
AERI 0511	-	-	356±28	1,600	4	656,372
AERI 0516	-	-	10.9±3.3	1,600	4	2,363,758
AERI 0517	-	-	10.5±4.8	1,600	4	2,389,689
AERI 0518	-	-	9.3±1.9	1,600	4	2,478,310
AERI 0525	-	-	9.2±4.2	1,600	4	2,486,581
AERI 0526	-	-	9.4±2.5	1,600	4	2,470,194

Age calculations using the Phillips et al. (1986) values for R_{se}, R_o from Moysey et al. (2003), C_o from Snyder et al. (2003), and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0501	0.09	0.01	1920±100	1000	4	A
AERI 0502	26.32	0.01	25±3	1000	4	A
AERI 0503	0.39	0.01	723±13	1000	4	A
AERI 0506	0.22	0.01	1,620±44	1,000	4	A
AERI 0510	0.38	0.01	374±13	1,000	4	A
AERI 0511	0.38	0.01	356±28	1,000	4	A
AERI 0516	43.44	0.01	10.9±3.3	1,000	4	A
AERI 0517	43.16	0.01	10.5±4.8	1,000	4	A
AERI 0518	43.72	0.01	9.3±1.9	1,000	4	A
AERI 0525	45.13	0.01	9.2±4.2	1,000	4	A
AERI 0526	38.36	0.01	9.4±2.5	1,000	4	A

Age calculations using the Phillips et al. (1986) values for R_{se} and R_o, C_o from this study and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0501	0.09	0.014	1,920±100	500	4	A
AERI 0502	26.32	0.014	25±3	500	4	A
AERI 0503	0.39	0.014	723±13	500	4	A
AERI 0506	0.22	0.014	1,620±44	500	4	A
AERI 0510	0.38	0.014	374±13	500	4	A
AERI 0511	0.38	0.014	356±28	500	4	A
AERI 0516	43.44	0.014	10.9±3.3	500	4	A
AERI 0517	43.16	0.014	10.5±4.8	500	4	A
AERI 0518	43.72	0.014	9.3±1.9	500	4	A
AERI 0525	45.13	0.014	9.2±4.2	500	4	A
AERI 0526	38.36	0.014	9.4±2.5	500	4	A

Age calculations using the Phillips et al. (1986) value for R_{se}, R_o from Moysey et al. (2003), C_o from this study and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0501	0.09	0.014	1,920±100	1,000	4	A
AERI 0502	26.32	0.014	25±3	1,000	4	A
AERI 0503	0.39	0.014	723±13	1,000	4	A
AERI 0506	0.22	0.014	1,620±44	1,000	4	A
AERI 0510	0.38	0.014	374±13	1,000	4	A
AERI 0511	0.38	0.014	356±28	1,000	4	A
AERI 0516	43.44	0.014	10.9±3.3	1,000	4	A
AERI 0517	43.16	0.014	10.5±4.8	1,000	4	A
AERI 0518	43.72	0.014	9.3±1.9	1,000	4	A
AERI 0525	45.13	0.014	9.2±4.2	1,000	4	A
AERI 0526	38.36	0.014	9.4±2.5	1,000	4	A

Age calculations using the Phillips et al. (1986) value for R_{se}, R_o from Snyder et al. (2003), C_o from this study and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0501	0.09	0.014	1,920±100	1,600	4	A
AERI 0502	26.32	0.014	25±3	1,600	4	A
AERI 0503	0.39	0.014	723±13	1,600	4	A
AERI 0506	0.22	0.014	1,620±44	1,600	4	A
AERI 0510	0.38	0.014	374±13	1,600	4	A
AERI 0511	0.38	0.014	356±28	1,600	4	A
AERI 0516	43.44	0.014	10.9±3.3	1,600	4	A
AERI 0517	43.16	0.014	10.5±4.8	1,600	4	A
AERI 0518	43.72	0.014	9.3±1.9	1,600	4	A
AERI 0525	45.13	0.014	9.2±4.2	1,600	4	A
AERI 0526	38.36	0.014	9.4±2.5	1,600	4	A

Age calculations using the Phillips et al. (1986) values for R_{se} and R_o, C_o from Snyder et al. (2003) and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0501	0.09	0.01	1,920±100	500	4	A
AERI 0502	26.32	0.01	25±3	500	4	A
AERI 0503	0.39	0.01	723±13	500	4	A
AERI 0506	0.22	0.01	1,620±44	500	4	A
AERI 0510	0.38	0.01	374±13	500	4	A
AERI 0511	0.38	0.01	356±28	500	4	A
AERI 0516	43.44	0.01	10.9±3.3	500	4	A
AERI 0517	43.16	0.01	10.5±4.8	500	4	A
AERI 0518	43.72	0.01	9.3±1.9	500	4	A
AERI 0525	45.13	0.01	9.2±4.2	500	4	A
AERI 0526	38.36	0.01	9.4±2.5	500	4	A

Age calculations using the Phillips et al. (1986) value for R_{se}, R_o and C_o from Snyder et al. (2003) and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0501	0.09	0.01	1,920±100	1,600	4	A
AERI 0502	26.32	0.01	25±3	1,600	4	A
AERI 0503	0.39	0.01	723±13	1,600	4	A
AERI 0506	0.22	0.01	1,620±44	1,600	4	A
AERI 0510	0.38	0.01	374±13	1,600	4	A
AERI 0511	0.38	0.01	356±28	1,600	4	A
AERI 0516	43.44	0.01	10.9±3.3	1,600	4	A
AERI 0517	43.16	0.01	10.5±4.8	1,600	4	A
AERI 0518	43.72	0.01	9.3±1.9	1,600	4	A
AERI 0525	45.13	0.01	9.2±4.2	1,600	4	A
AERI 0526	38.36	0.01	9.4±2.5	1,600	4	A

NOTE: A= age could not be calculated

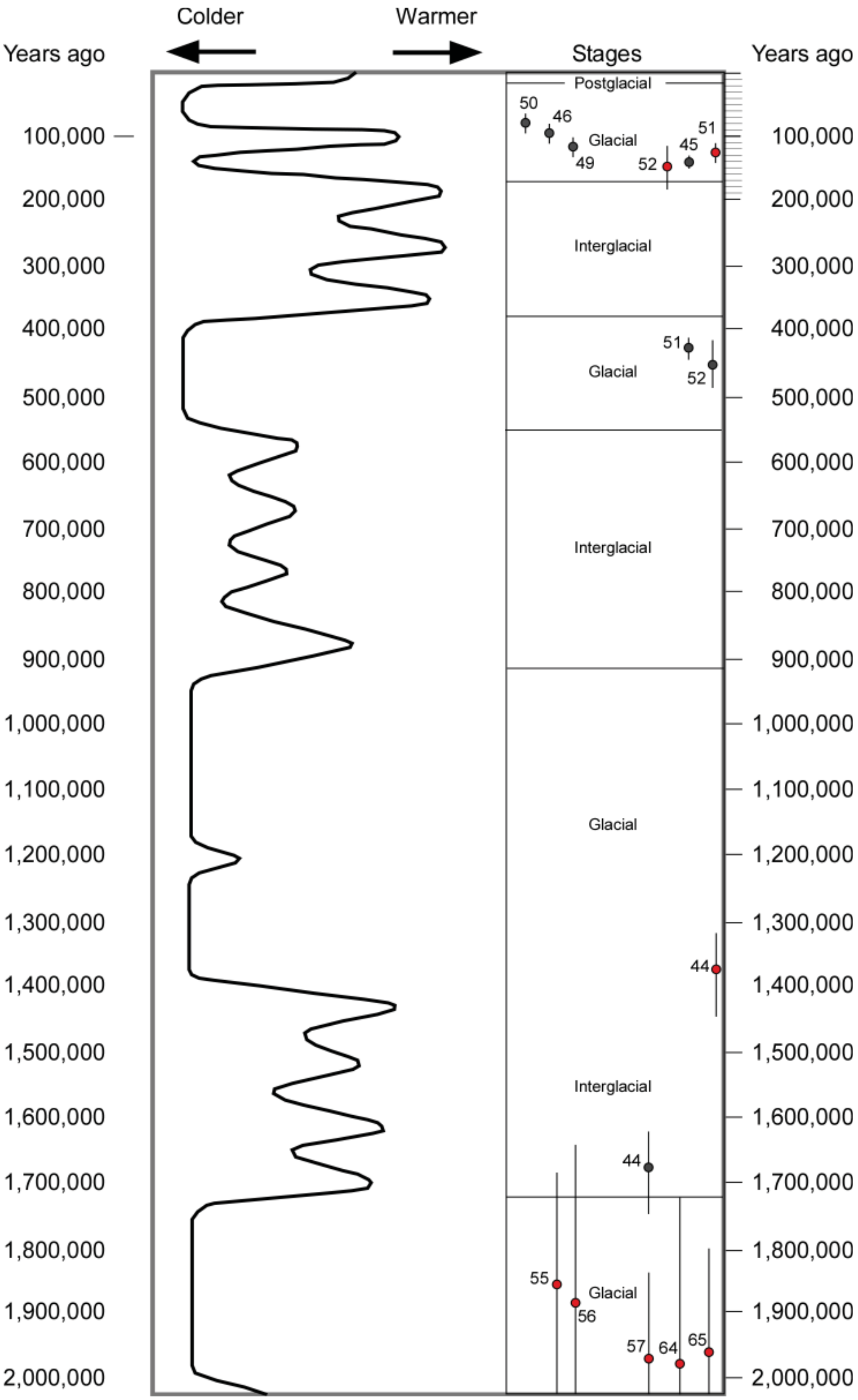


Figure 39. Glaciation and climatic patterns for North America during the Pleistocene and Pliocene. Notes: 1) Solid red dots represent ages calculated using the ion filtration model (Phillips et al., 1986) with R_o=500x10^{-15} and R_{se}=4x10^{-15}; 2) Solid grey dots represent ages calculated using the ion filtration model with R_o=1,000x10^{-15} and R_{se}=4x10^{-15}; and 3) Ages calculated using these last values for samples 55, 56, 57, 64 and 65 are greater than 2,000,000 years and so are not plotted. Source: http://www.calstatela.edu/faculty/acolvil/glaciation.html, April, 2006.

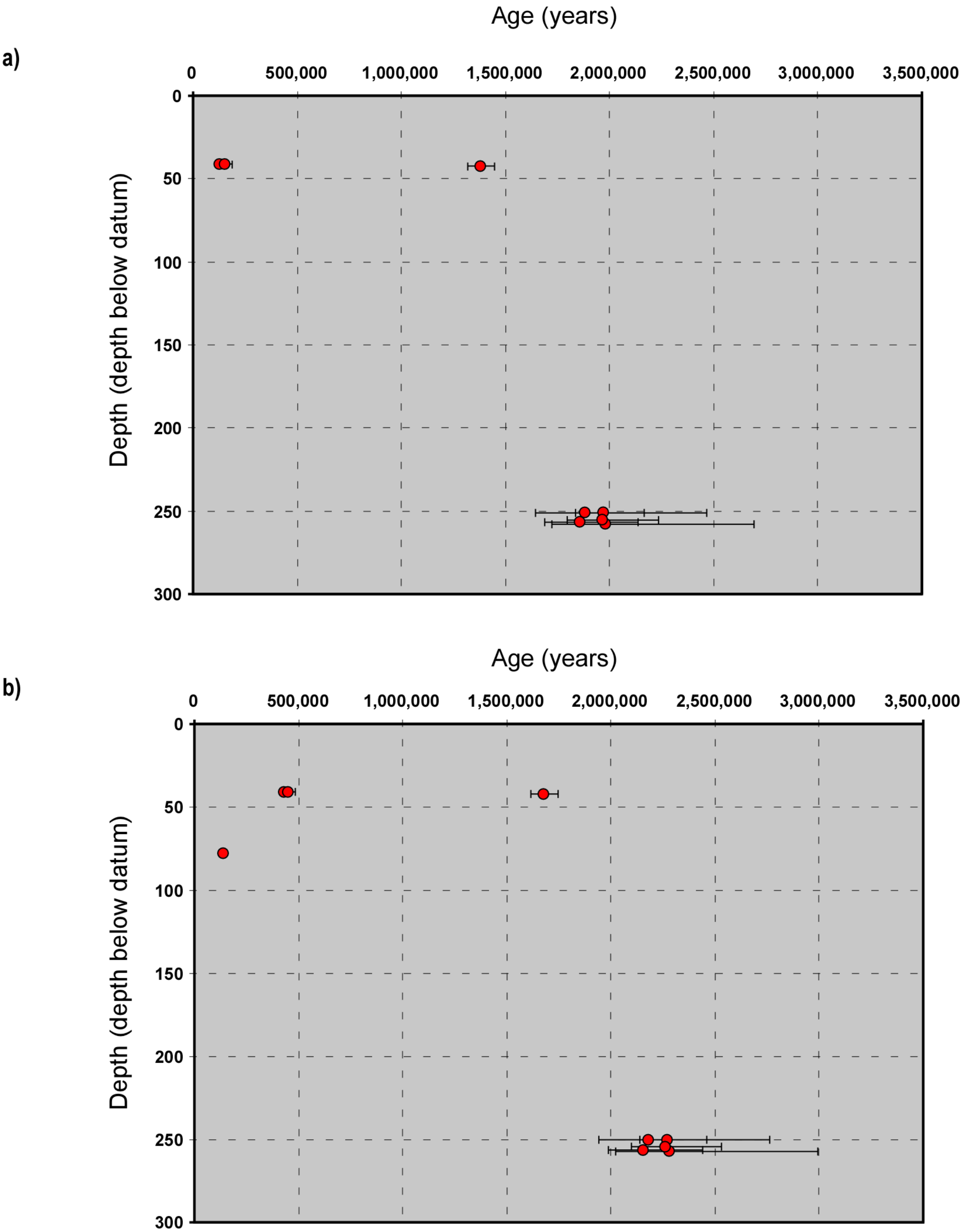


Figure 40. ^{36}Cl/Cl age vs.depth in the Horseshoe Canyon Formation using the ion filtration model with: a) R_o=500x10^{-15} and Rse=4x10^{-15}; and b) with R_o=1,000x10^{-15} and R_{se}=4x10^{-15}. Notes: Bars on either side of the data point represent the range in values based on the error in the ^{36}Cl/Cl values. Datum for water wells ground level and for CBM wells KB.

Age = 6547 x depth + 275552 $R^2 = 0.7810$ (using R_o=500x10^{-15} and R_{se}=4x10^{-15})

Age = 7369 x depth + 333375 $R^2 = 0.7416$ (using R_o=1,000x10^{-15} and R_{se}=4x10^{-15})

This model suggests that the CBM well formation water ages are between approximately 4 to 12 times greater than the groundwater ages determined for the water wells with 1 exception. One of the water wells (Sample 44) appears to have a groundwater age that is similar to those of the CBM wells. On many of the geochemical plots this sample plots near the compositions of the CBM wells suggesting a similarity with deeper formation water (Figure 17 and Figure 21). The $\delta^{18}O$ vs. δ^2H plot suggests something slightly different, as the sample point plots closer to the water well data points (Figure 23). This could suggest: 1) the interception of formation water at a shallow depth, 2) potential contamination by a source of Cl with a lower ^{36}Cl/Cl ratio; or 3) perhaps a complex mixing relationship exists between end members with distinct ^{36}Cl/Cl and stable isotope ratios.

All of ^{36}Cl/Cl ratios could have been affected by another factor. The in situ production of ^{36}Cl is a possibility given the distribution of data in Figure 38. The addition of any in situ production of ^{36}Cl, although not quantified, would suggest that the calculated ages could be minimum ages. Depending on the potential rate of production of in situ ^{36}Cl, the impact of this mechanism could significantly affect the calculated ages. If the rate of production is relatively stable however, the age relationships between the different water sample types could remain more or less constant. As such, the differences in ages between these different sample types could suggest that the connections between the shallower and deeper portions of the Horseshoe Canyon Formation are limited or take place over long time periods.

4.8.1.3 Scollard and Paskapoo Formations

Samples were collected from water wells and mine dewatering wells for the purpose of determining ages of groundwater in the general areas of active CBM exploration and development. The results are presented in the table below (Table 23).

Table 23. ^{36}Cl/Cl and ^{129}I/I analytical results for the Scollard and Paskapoo formations

Sample Name	Well Type	Sample ID	Cl^- (mmol/L)	^{36}Cl/Cl(x10^{-15})	I(µmol/L)	^{129}I/I(x10^{-15})	Formation
AERI 0505	Water	46	0.195	797±14	0.191	29,607	Scollard
AERI 0507	Water	48	0.014	1,760±460	0.028	122,928	Paskapoo
AERI 0508	Water	49	0.133	763±22	0.030	110,912	Scollard
AERI 0509	Water	50	0.155	832±26	0.029	193,647	Scollard
AERI 0512	Water	53	0.014	3,000±700	0.020	307,995	Paskapoo
AERI 0513	Water	54	0.054	2,240±80	0.083	56,196	Scollard
AERI 0521	Dewatering	60	0.037	2,570±120	0.041	1,284,662	Scollard
AERI 0522	Dewatering	61	0.014	5,350±300	0.039	286,597	Scollard
AERI 0523	Dewatering	62	0.006*	2,700±300	0.035	88,976	Scollard
AERI 0524	Dewatering	63	0.006*	35,200±1,700	0.021	437,076	Scollard

Note: *Cl concentration <0.4mg/L

The Scollard and Paskapoo formations ^{36}Cl/Cl values tend to be higher than the Horseshoe Canyon Formation values. Certain samples, such as samples 46, 48, 49 and 50 have similar values however. It is interesting to note that these samples are located close to the boundary between the Scollard and Paskapoo formations.

The majority of the wells plot towards the meteoric end member composition as described by Snyder et al. (2003) for the Fruitland Formation in the San Juan Basin (Figure 37) as well as to the right of the proposed mixing line. The plotting position for many of these data points is beyond the Snyder et al. (2003) meteoric end member range of values. Three of the samples (samples 46, 49 and 50) plot towards the upper range of values measured in the Horseshoe Canyon Formation ^{36}Cl/Cl samples. Some of the higher values (samples 61 and 63) could indicate the incorporation of ^{36}Cl from nuclear weapons testing or some other anthropogenic input. As mentioned above, the majority of the samples plot to the right of the mixing curve proposed by Snyder et al. (2003). This suggest that, as was the case with the Horseshoe Canyon Formation water samples, in situ production of ^{36}Cl could be occurring and affecting the ^{36}Cl/Cl ratios of the Scollard and Paskapoo formations water samples. The relationship between ^{129}I/I and ^{36}Cl/Cl in Figure 38 seems to support this possibility, as the Scollard and Paskapoo data points plot between the two proposed mixing curves. The points tend to plot closer to the anthropogenic end member-formation water mixing curve than the Horseshoe Canyon Formation water samples do however.

Despite the potential complication of in situ production of ^{36}Cl in the Scollard and Paskapoo formations, approximate groundwater age dates can be calculated using the equations described above using the same approach as for the Horseshoe Canyon Formation. The table below summarizes the results (Table 24) and highlights the importance of selecting an appropriate model as well as representative initial and reference values.

Table 24. Scollard and Paskapoo formations groundwater age date summary table

Age calculations using the Phillips et al. (1986) values for C_o, R_o and R_{se} and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R ($x10^{-15}$)	R_o ($x10^{-15}$)	R_{se} ($x10^{-15}$)	Age (years)
AERI 0505	0.195	0.19	797±14	500	4	A
AERI 0507	0.014	0.19	1,760±460	500	4	580,292
AERI 0508	0.133	0.19	763±22	500	4	A
AERI 0509	0.155	0.19	832±26	500	4	A
AERI 0512	0.014	0.19	3,000±700	500	4	348,316
AERI 0513	0.054	0.19	2,240±80	500	4	A
AERI 0521	0.037	0.19	2,570±120	500	4	691
AERI 0522	0.014	0.19	5,350±300	500	4	96,874
AERI 0523	0.006*	0.19	2,700±300	500	4	791,998
AERI 0524	0.006*	0.19	35,200±1,700	500	4	A

Age calculations using the Phillips et al. (1986) values for R_o and R_{se} and the Equation 2 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R ($x10^{-15}$)	R_o ($x10^{-15}$)	R_{se} ($x10^{-15}$)	Age (years)
AERI 0505	-	-	797±14	500	4	A
AERI 0507	-	-	1,760±460	500	4	A
AERI 0508	-	-	763±22	500	4	A
AERI 0509	-	-	832±26	500	4	A
AERI 0512	-	-	3,000±700	500	4	A
AERI 0513	-	-	2,240±80	500	4	A
AERI 0521	-	-	2,570±120	500	4	A
AERI 0522	-	-	5,350±300	500	4	A
AERI 0523	-	-	2,700±300	500	4	A
AERI 0524	-	-	35,200±1,700	500	4	A

Age calculations using the Phillips et al. (1986) values for C_o and R_{se}, R_o from Moysey et al. (2003), and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0505	0.195	0.19	797±14	1,000	4	88,530
AERI 0507	0.014	0.19	1,760±460	1,000	4	883,015
AERI 0508	0.133	0.19	763±22	1,000	4	274,279
AERI 0509	0.155	0.19	832±26	1,000	4	168,245
AERI 0512	0.014	0.19	3,000±700	1,000	4	651,039
AERI 0513	0.054	0.19	2,240±80	1,000	4	198,407
AERI 0521	0.037	0.19	2,570±120	1,000	4	303,414
AERI 0522	0.014	0.19	5,350±300	1,000	4	399,597
AERI 0523	0.006*	0.19	2,700±300	1,000	4	1,094,721
AERI 0524	0.006*	0.19	35,200±1,700	1,000	4	A

Age calculations using the Phillips et al. (1986) value for R_{se}, R_o from Moysey et al. (2003), and the Equation 2 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0505	-	-	797±14	1,000	4	98,968
AERI 0507	-	-	1,760±460	1,000	4	A
AERI 0508	-	-	763±22	1,000	4	117,996
AERI 0509	-	-	832±26	1,000	4	80,215
AERI 0512	-	-	3,000±700	1,000	4	A
AERI 0513	-	-	2,240±80	1,000	4	A
AERI 0521	-	-	2,570±120	1,000	4	A
AERI 0522	-	-	5,350±300	1,000	4	A
AERI 0523	-	-	2,700±300	1,000	4	A
AERI 0524	-	-	35,200±1,700	1,000	4	A

Age calculations using the Phillips et al. (1986) values for C_o and R_{se},R_o from Snyder et al. (2003), and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0505	0.195	0.19	797±14	1,600	4	293,267
AERI 0507	0.014	0.19	1,760±460	1,600	4	1,087,751
AERI 0508	0.133	0.19	763±22	1,600	4	479,016
AERI 0509	0.155	0.19	832±26	1,600	4	372,982
AERI 0512	0.014	0.19	3,000±700	1,600	4	855,776
AERI 0513	0.054	0.19	2,240±80	1,600	4	403,144
AERI 0521	0.037	0.19	2,570±120	1,600	4	508,150
AERI 0522	0.014	0.19	5,350±300	1,600	4	604,334
AERI 0523	0.006*	0.19	2,700±300	1,600	4	1,299,458
AERI 0524	0.006*	0.19	35,200±1,700	1,600	4	A

Age calculations using the Phillips et al. (1986) values for R_{se} and R_o from Snyder et al. (2003) and the Equation 2 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0505	-	-	797±14	1,600	4	303,705
AERI 0507	-	-	1,760±460	1,600	4	A
AERI 0508	-	-	763±22	1,600	4	322,733
AERI 0509	-	-	832±26	1,600	4	284,951
AERI 0512	-	-	3,000±700	1,600	4	A
AERI 0513	-	-	2,240±80	1,600	4	A
AERI 0521	-	-	2,570±120	1,600	4	A
AERI 0522	-	-	5,350±300	1,600	4	A
AERI 0523	-	-	2,700±300	1,600	4	A
AERI 0524	-	-	35,200±1,700	1,600	4	A

Age calculations using the Phillips et al. (1986) values for R_{se}, R_o from Moysey et al. (2003), C_o from Snyder et al. (2003), and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0505	0.195	0.01	797±14	1000	4	A
AERI 0507	0.014	0.01	1,760±460	1000	4	A
AERI 0508	0.133	0.01	763±22	1000	4	A
AERI 0509	0.155	0.01	832±26	1000	4	A
AERI 0512	0.014	0.01	3,000±700	1000	4	A
AERI 0513	0.054	0.01	2,240±80	1000	4	A
AERI 0521	0.037	0.01	2,570±120	1000	4	A
AERI 0522	0.014	0.01	5,350±300	1000	4	A
AERI 0523	0.006*	0.01	2,700±300	1000	4	A
AERI 0524	0.006*	0.01	35,200±1,700	1000	4	A

Age calculations using the Phillips et al. (1986) values for R_{se} and R_o, C_o from this study, and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0505	0.195	0.014	797±14	500	4	A
AERI 0507	0.014	0.014	1,760±460	500	4	A
AERI 0508	0.133	0.014	763±22	500	4	A
AERI 0509	0.155	0.014	832±26	500	4	A
AERI 0512	0.014	0.014	3,000±700	500	4	A
AERI 0513	0.054	0.014	2,240±80	500	4	A
AERI 0521	0.037	0.014	2,570±120	500	4	A
AERI 0522	0.014	0.014	5,350±300	500	4	A
AERI 0523	0.006*	0.014	2,700±300	500	4	A
AERI 0524	0.006*	0.014	35,200±1,700	500	4	A

Age calculations using the Phillips et al. (1986) value for R_{se}, R_o from Moysey et al. (2003), C_o from this study, and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0505	0.195	0.014	797±14	1,000	4	A
AERI 0507	0.014	0.014	1,760±460	1,000	4	A
AERI 0508	0.133	0.014	763±22	1,000	4	A
AERI 0509	0.155	0.014	832±26	1,000	4	A
AERI 0512	0.014	0.014	3,000±700	1,000	4	A
AERI 0513	0.054	0.014	2,240±80	1,000	4	A
AERI 0521	0.037	0.014	2,570±120	1,000	4	A
AERI 0522	0.014	0.014	5,350±300	1,000	4	A
AERI 0523	0.006*	0.014	2,700±300	1,000	4	A
AERI 0524	0.006*	0.014	35,200±1,700	1,000	4	A

Age calculations using the Phillips et al. (1986) value for R_{se}, R_o from Snyder et al. (2003), C_o from this study and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0505	0.195	0.014	797±14	1,600	4	A
AERI 0507	0.014	0.014	1,760±460	1,600	4	A
AERI 0508	0.133	0.014	763±22	1,600	4	A
AERI 0509	0.155	0.014	832±26	1,600	4	A
AERI 0512	0.014	0.014	3,000±700	1,600	4	A
AERI 0513	0.054	0.014	2,240±80	1,600	4	A
AERI 0521	0.037	0.014	2,570±120	1,600	4	A
AERI 0522	0.014	0.014	5,350±300	1,600	4	A
AERI 0523	0.006*	0.014	2,700±300	1,600	4	167,036
AERI 0524	0.006*	0.014	35,200±1,700	1,600	4	A

Age calculations using the Phillips et al. (1986) values for R_{se} and R_o, C_o from Snyder et al. (2003), and the Equation 1 age calculation method

Sample	C (mmol/L)	C_o (mmol/L)	R (x10^{-15})	R_o (x10^{-15})	R_{se} (x10^{-15})	Age (years)
AERI 0505	0.195	0.01	797±14	500	4	A
AERI 0507	0.014	0.01	1,760±460	500	4	A
AERI 0508	0.133	0.01	763±22	500	4	A
AERI 0509	0.155	0.01	832±26	500	4	A
AERI 0512	0.014	0.01	3,000±700	500	4	A
AERI 0513	0.054	0.01	2,240±80	500	4	A
AERI 0521	0.037	0.01	2,570±120	500	4	A
AERI 0522	0.014	0.01	5,350±300	500	4	A
AERI 0523	0.006*	0.01	2,700±300	500	4	167,036
AERI 0524	0.006*	0.01	35,200±1,700	500	4	A

Age calculations using the Phillips et al. (1986) values for R_{se}, R_o and C_o from Snyder et al. (2003), and the Equation 1 age calculation method						
Sample	**C (mmol/L)**	**C_o (mmol/L)**	**R ($x10^{-15}$)**	**R_o ($x10^{-15}$)**	**R_{se} ($x10^{-15}$)**	**Age (years)**
AERI 0505	0.195	0.01	797±14	1,600	4	A
AERI 0507	0.014	0.01	1,760±460	1,600	4	A
AERI 0508	0.133	0.01	763±22	1,600	4	A
AERI 0509	0.155	0.01	832±26	1,600	4	A
AERI 0512	0.014	0.01	3,000±700	1,600	4	A
AERI 0513	0.054	0.01	2,240±80	1,600	4	A
AERI 0521	0.037	0.01	2,570±120	1,600	4	A
AERI 0522	0.014	0.01	5,350±300	1,600	4	A
AERI 0523	0.006*	0.01	2,700±300	1,600	4	20,935
AERI 0524	0.006*	0.01	35,200±1,700	1,600	4	A

Note: A= Age could not be calculated

The most likely age dates are those calculated using the R_o values of Phillips et al. (1986) or Moysey et al. (2003) since they reflect possible values for Alberta rather than U.S. examples. Upon examination of the age dating results, the most appropriate model may be the ion filtration model using the R_o value proposed by Moysey et al. (2003). The age dates calculated using this model and initial value are 98,968, 117,996 and 80,215 years for samples 46, 49 and 50 respectively. Age dates could not be calculated for the remaining samples using this model with other initial values. These ages are generally consistent with warmer climatic periods in North America when the errors in the $^{36}Cl/Cl$ ratios are taken into account (Figure 39). The same relationship is not as obvious with depth as was noted for the Horseshoe Canyon Formation water samples (Figure 41).

Figure 41. $^{36}Cl/Cl$ age vs. depth in the Scollard Formation using the ion filtration model with R_o=1,000x10^{-15} and RSE=4x10^{-15}.

4.8.2 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 Ma (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). This ratio has been set at $1500 \times 10^{-15} \pm 10\%$ by Moran et al. (1998). 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).

4.8.2.1 Horseshoe Canyon Formation

The AGS collected samples from 9 sites in order to determine the ages of water in the Horseshoe Canyon Formation. All of the samples had measurable ^{129}I concentrations, with most of the water well samples having ^{129}I concentrations close to the process blank (Kieser, pers. comm.). The ^{129}I data along with some additional information used in the interpretation of the ^{129}I data is presented in the table below (Table 25).

Table 25. Horseshoe Canyon Formation ^{129}I age dating summary table.

Sample ID	Sample Name	Well Type	^{129}I (atoms/µL)	I (µmol/L)	Cl (mmol/L)	^{129}I/I ($\times 10^{-15}$)	δ^2H (‰ VSMOW)
43	AERI 0501	Water	0.8 ± 0.5	0.827	0.0931	1,606	-135
44	AERI 0502	Water	4.6 ± 3.4	2.13	26.3	3,590	-129
45	AERI 0503	Water	2.0 ± 0.4	0.712	0.386	4,662	-163
47	AERI 0506	Water	3.1 ± 0.6	0.0709	0.222	72,590	-148
51	AERI 0510	Water	2.3 ± 0.4	1.12	0.381	3,413	-158
52	AERI 0511*	Water	2.0 ± 0.4	1.12	0.381	2,968	-160
55	AERI 0516	CBM	43.7 ± 1.7	40.0	43.4	1,814	-107
56	AERI 0517	CBM	33.4 ± 1.4	22.7	43.2	2,448	-109
57	AERI 0518**	CBM	33.3 ± 2.3	23.2	43.7	2,386	-110
64	AERI 0525	CBM	40.9 ± 1.3	31.9	45.1	2,130	-108
65	AERI 0526	CBM	37.2 ± 1.5	24.0	38.4	2,571	-107

Notes: *duplicate analysis of AERI 0510; **duplicate analysis of AERI 0517

Age dates using ^{129}I are calculated using the standard radiometric age dating equation:

$$a_t = a_0 e^{-\lambda t}$$

where: a_t is the calculated ^{129}I/I ratio
a_0 is the reference ^{129}I/I ratio of 1500×10^{-15}
λ = the decay constant of 4.41×10^{-8} years^{-1}
t = time

In this case, all of the calculated ^{129}I/I ratio values are greater than 1500×10^{-15} and as such the direct calculation of groundwater ages using ^{129}I is not possible unless the possible contribution from other ^{129}I sources is taken into account. These could include mixing with an anthropogenic source, input from the host formation or fissiogenic addition of ^{129}I. The calculation of such correction factors requires some detailed knowledge of radiogenic element concentrations in, and properties of, the host rocks. Since this information is not readily available, the corrected ages have not been calculated because of the uncertainties associated with these calculations. Possible mechanisms for ^{129}I/I ratio modification can be better understood however using the information available on the concentrations of iodine, ^{129}I, Cl and ^{2}H/^{1}H ratios in the water samples.

Snyder et al. (2003) suggested that the combination of halide and stable isotope systematics points towards the modification of water in the Fruitland Formation of the San Juan Basin both during ongoing coal diagenesis and through subsequent involvement of water of a meteoric origin. Based on a comparison with their results, water from the Horseshoe Canyon Formation appears to have undergone similar processes.

Snyder et al. (2003) suggest that since most of the iodine concentrations in water from the Fruitland Formation exceed iodine concentrations in river water (0.045 µM), seawater (0.45 µM) and peat deposit interstitial waters (0.045 µM), the iodine was derived from diagenetic reactions with the organic material in the Formation without substantially changing the total chloride content. Final iodine concentrations would have reached approximately 10 µM. Where preserved, these waters would have undergone dilution from meteorically-derived groundwater. Subsequent basin processes would have initiated further diagenetic alteration in certain portions of the Basin and would have increased the iodine concentrations of the water samples without appreciably altering the chloride concentrations and therefore increasing the I/Cl ratio by approximately one order of magnitude compared to the water in unaffected portions of the Basin. Subsequent dilution by meteoric water has decreased the iodine and chloride concentrations, but has maintained the original I/Cl ratios.

All of the Horseshoe Canyon Formation water samples have iodine concentrations greater than river water, seawater and peat deposit interstitial waters. This suggests that the iodine concentrations in the samples are the result of diagenetic reactions with the organic matter within the rock units. When superimposed over the results presented in Snyder et al. (2003), samples 55, 56, 57, 64 and 65 seem to plot near the end member compositions they describe for water that has undergone two episodes of diagenesis, with the remaining samples plotting along possible dilution lines (Figure 42). This interpretation is consistent with those put forward in the sections on Cl/Br ratios and on stable isotopes of O and H in water. In addition, water well samples, with the exception of sample 44, are classified as Na-HCO_3 type waters, suggesting that they have evolved significantly from their original recharge compositions. The CBM wells and sample 44 are classified as either Na-Cl or Na-Cl-HCO_3 type waters indicating that they have an even more significant evolution history than the water wells and likely have much longer residence times. These samples in fact plot closer to the proposed formation water end member composition put forward in Snyder et al. (2003).

Snyder et al. (2003) indicate that a large portion of their samples had ^{129}I/I ratios below pre-anthropogenic values suggesting that a major portion of the Fruitland Formation has preserved its original isotopic signature, but that anthropogenic signatures are present within samples collected from the margins of the Basin. The construction of, and comparison to, mixing lines between samples with anthropogenic signatures and formation water samples revealed that most of the samples with anthropogenic signatures plotted below the mixing curve reflecting the variation in the anthropogenic signature over time. None of the samples plotted on a mixing curve constructed between pre-anthropogenic water and formation waters suggesting that either pre-anthropogenic water contributed little to the overall ^{129}I/I ratios, or that in-situ production has affected initial ratios.

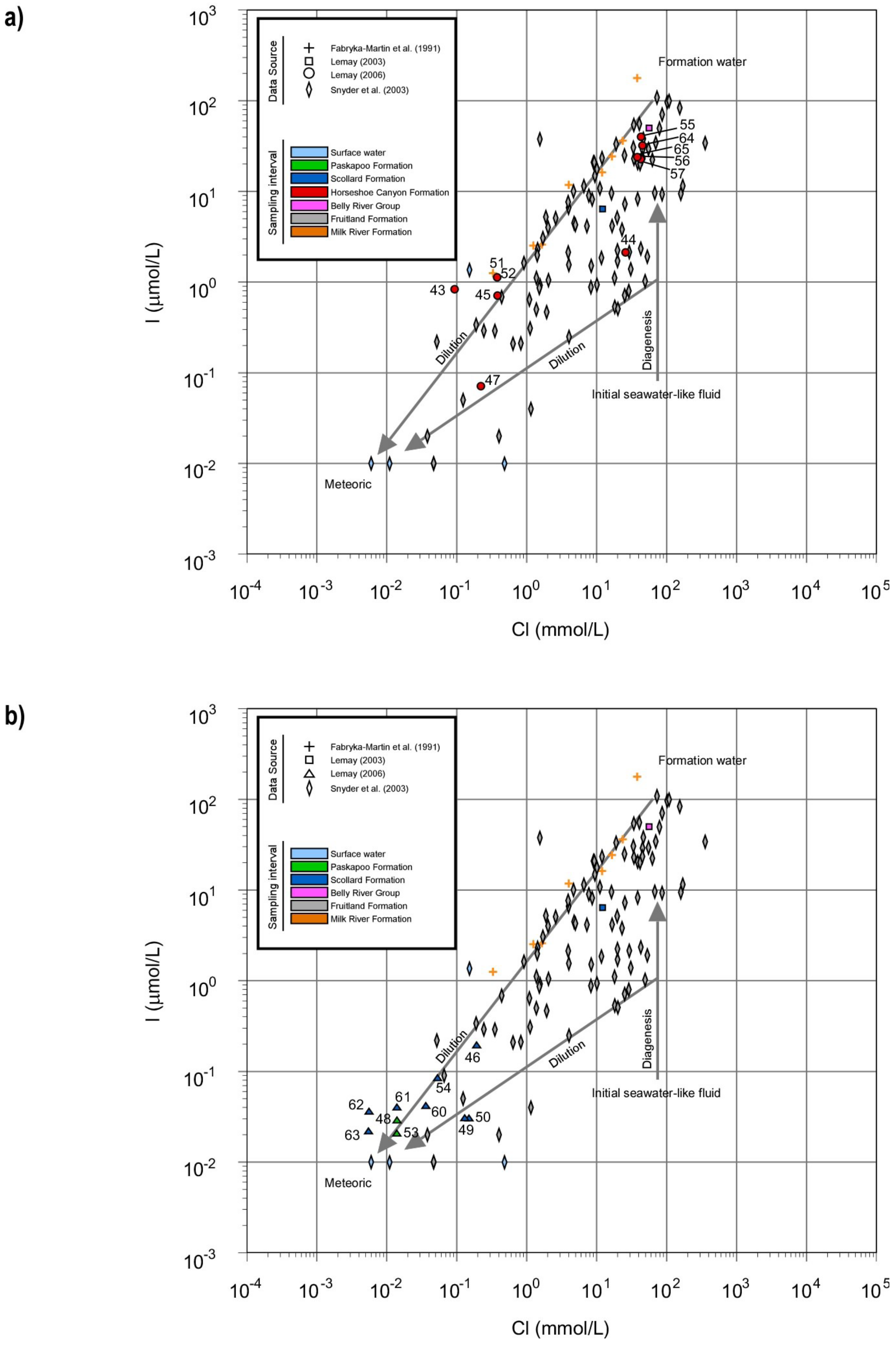


Figure 42. Iodine vs. chloride concentrations: a) Horseshoe Canyon Formation; and b) Scollard and Paskapoo formations. Note: Linework and proposed mechanisms reprinted from Geochimica et Cosmochimica Acta, Vol. 67, No. 23, Snyder, G.T., Riese, W.C., Franks, S., Fehn, U., Pelzmann, W.L., Gorody, A.W., and Moran, J.E., Origin and history of waters associated with coal-bed methane: ^{129}I, ^{36}Cl, and stable isotope results from the Fruitland Formation, CO and NM, p. 4529-4544, Copyright (2003), with permission from Elsevier. Additional data from Fabryka-Martin et al. (1991), Lemay (2003) and Snyder et al. (2003).

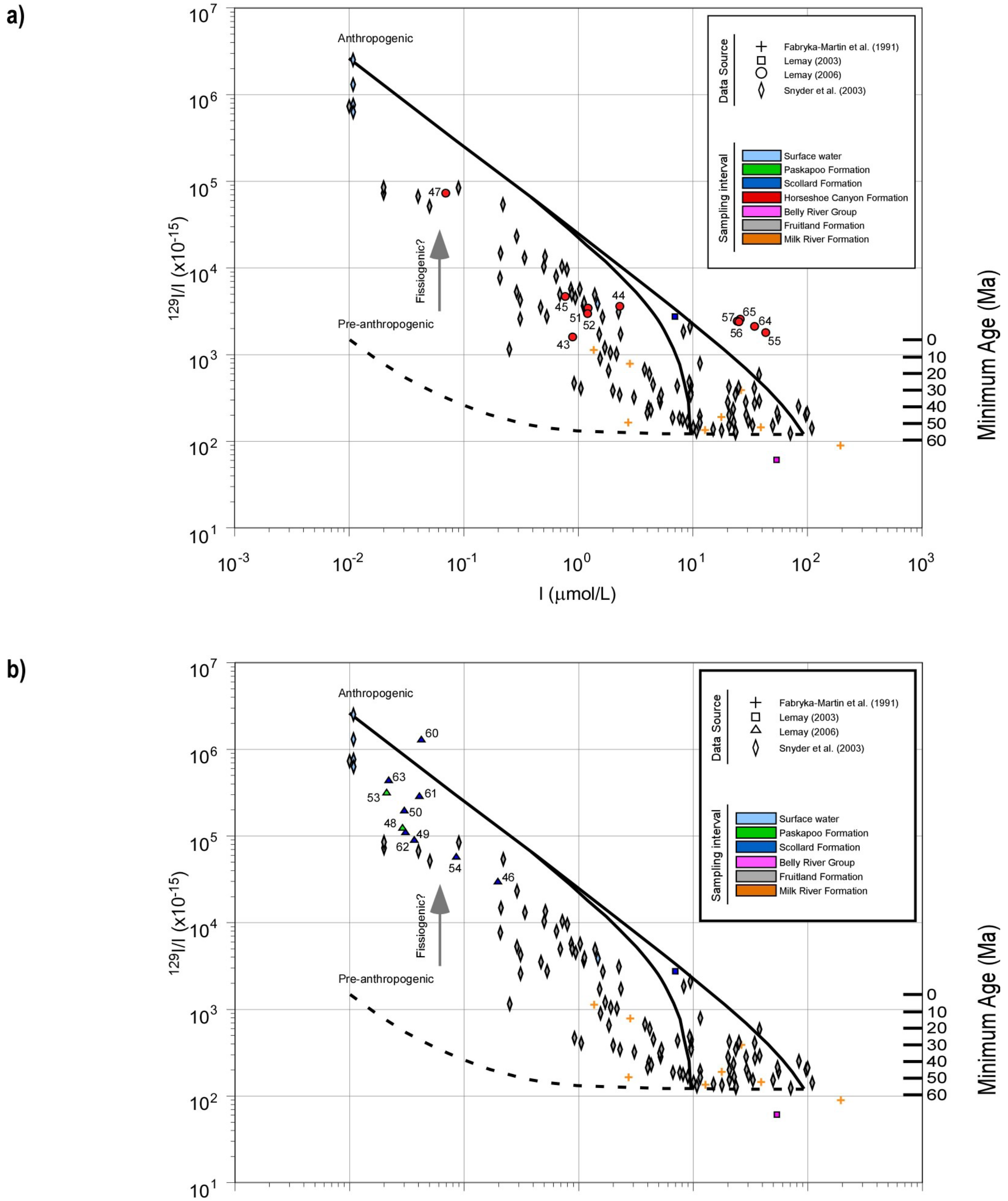


Figure 43. ^{129}I/I vs. iodine concentrations: a) Horseshoe Canyon Formation; and b) Scollard and Paskapoo formations. Note: Linework and proposed mechanisms reprinted from Geochimica et Cosmochimica Acta, Vol. 67, No. 23, Snyder, G.T., Riese, W.C., Franks, S., Fehn, U., Pelzmann, W.L., Gorody, A.W., and Moran, J.E., Origin and history of waters associated with coal-bed methane: ^{129}I, ^{36}Cl, and stable isotope results from the Fruitland Formation, CO and NM, p. 4529-4544, Copyright (2003), with permission from Elsevier. Additional data from Fabryka-Martian et al. (1991), Lemay (2003) and Snyder et al. (2003).

A comparison with the data presented in Snyder et al. (2003) shows that the Horseshoe Canyon Formation water samples all plot above pre-anthropogenic values, suggesting that these samples do not represent the formation's original isotopic signature (Figure 43). However, none of the samples plot towards the anthropogenic end member either. CBM water samples plot to the right of the anthropogenic water-formation water mixing curves, while the water well samples plot to the left of these lines. CBM water samples are tightly clustered and do appear to exhibit a trend. However, it is difficult to speculate on whether or not this may indicate a mixing line exists that passes through these points towards anthropogenic and formation water end members. If a trend does exist, the end member compositions would appear to be substantially different from those of the Fruitland Formation, or perhaps fissiogenic processes have introduced additional ^{129}I pushing the data points above the mixing curve. Despite the fact that no uranium was detected in the water samples, uranium has been detected in coal zones within the Horseshoe Canyon Formation suggesting that the in situ production of ^{129}I is possible. The water well samples are much less clustered, but, with the exception of sample 47, fall within the cluster of data points from the Fruitland Formation. This suggests that similar mixing processes that are occurring between meteoric and formation water within the Fruitland Formation may be occurring within the Horseshoe Canyon Formation generating the observed water well ^{129}I/I ratios.

4.8.2.2 Scollard and Paskapoo Formations

Samples were collected from 9 sites completed in either the Scollard or Paskapoo formations. Five of the samples were collected from water wells, while 4 of the samples were collected from dewatering wells. As with the Horseshoe Canyon Formation water samples, all of the Scollard and Paskapoo formations water samples had measurable ^{129}I concentrations, with most of the water well samples having ^{129}I concentrations close to the process blank (Kieser, pers. comm.). The ^{129}I data along with some additional information used in the interpretation of the ^{129}I data is presented in the table below (Table 26).

Table 26. Scollard and Paskapoo formations ^{129}I age dating summary table.

Sample ID	Sample Name	Formation	Well Type	^{129}I (atoms/ µL)	I (µmol/L)	Cl (mmol/L)	^{129}I/I (x10^{-15})	δ^2H (‰ VSMOW)
46	AERI 0505	Scollard	Water	3.4 ± 0.6	0.191	0.195	29,610	-148
48	AERI 0507	Paskapoo	Water	2.1 ± 0.4	0.0284	0.0141	122,900	-148
49	AERI 0508	Scollard	Water	2.0 ± 0.4	0.0299	0.133	110,900	-143
50	AERI 0509[†]	Scollard	Water	3.4 ± 0.6	0.0292	0.155	193,600	-144
53	AERI 0512	Paskapoo	Water	3.8 ± 0.6	0.0205	0.0141	308,000	-142
54	AERI 0513	Scollard	Water	2.8 ± 0.5	0.0827	0.0536	56,200	-145
60	AERI 0521	Scollard	Dewatering	31.7 ± 1.2	0.0410	0.0367	1,285,000	-135
61	AERI 0522	Scollard	Dewatering	6.8 ± 0.7	0.0394	0.0141	286,600	-134
62	AERI 0523	Scollard	Dewatering	1.9 ± 0.4	0.0355	<0.01	88,980	-129
63	AERI 0524*	Scollard	Dewatering	5.6 ± 0.6	0.0213	<0.01	437,100	-130

Notes: [†]duplicate analysis of AERI 0508

All of the Scollard and Paskapoo formation ^{129}I/I ratios substantially exceed the initial pre-anthropogenic ^{129}I/I value of 1500x10^{-15}. Sample AERI 0521 in fact is approximately half the value put forward by Snyder et al. (2003) as being characteristic of meteoric water that is less than 50 years old (^{129}I/I = 2 550 000 x 10^{-15}). Given the ^{129}I/I ratio values of the Scollard and Paskapoo formations water samples, direct calculation of groundwater ages cannot be completed. However, an interpretation of the origin of water within, and on geochemical processes occurring within the rock units can be examined based on the available information.

Iodine concentrations, with the exception of samples 46 and 54, are below those put forward by Snyder et al. (2003) as being representative of river water and interstitial waters in peat deposits (0.045 µM), but are less than the value these others put forward for seawater (0.45µM). Given the terrestrial depositional history of the Scollard and Paskapoo formations, seawater is an unlikely possible source of iodine and as such diagenetic processes are the likely cause of the increase in the iodine concentrations in these two samples as compared to interstitial peat water. In comparison to the Fruitland Formation, the Scollard and Paskapoo formations water samples have iodine and chloride concentrations that place them towards the meteoric end member composition as well as along some possible dilution trends with formation water as the other end member (Figure 42). Samples 60, 61, 62 and 63 have a $Ca\text{-}Na\text{-}HCO_3$ water type suggesting they are immature hydrochemically, consistent with a recent recharge history. Samples 46, 48, 49, 50, 53 have $Na\text{-}HCO_3$ water types and sample 54 has a $Na\text{-}HCO_3\text{-}SO_4$ water type suggesting that water within these portions of the rock units have undergone geochemical evolution processes that would have modified them from their original recharge compositions. In addition, samples 46 and 54 have the highest TDS concentrations of any of the Scollard or Paskapoo formation samples indicating that these sample waters would have undergone the greatest degree of geochemical evolution of any of these more evolved samples perhaps explaining why among these more evolved samples, they appear to stand out. The presence of two somewhat distinct groups within this subset of the data, suggests that some were derived from a meteoric source and that some were derived from mixing between a meteoric and formation water end member. Given the proximity of this second group to the meteoric water composition, the mixing reaction appears dominated by the meteoric end member.

At first glance, the $^{129}I/I$ ratios of these water samples suggest that the water within these portions of the Scollard and Paskapoo formations has been strongly affected by anthropogenic input of ^{129}I and/or in situ fissiogenesis. Samples 50, 53, 60, 61 and 63 plot towards the anthropogenic end of the plot (Figure 43), whereas the remaining samples (46, 48, 49, 54 and 62) plot within the cloud of data from the Fruitland Formation interpreted to be the result of mixing between a meteoric end member and a formation water end member. The similarity of the plotting positions of the isotopic data with respect to potential end member compositions appears to mirror the plotting positions of the halide data possibly confirming the iodine and chloride plot interpretation.

Despite the potential agreement between the halide and isotope plots as to the origin of the ^{129}I and stable iodine in the water, fissiogenic input can not be discounted as a possible source of ^{129}I. Dissolved uranium was detected in samples 46, 53 and 63. Uranium has also been detected in samples from the Ardley coal zone of the Scollard Formation (Appendix 6). The possible input is difficult to characterize without assuming a number of parameters and as such has not been attempted. Given the presence of uranium in water samples and coal samples fissiogenic input of ^{129}I is a distinct possibility.

5 Geomicrobiology

Micro organisms are integral to elemental cycling on the Earth's surface and near subsurface. Arguably one of the most important of these cycles involves the transfer of carbon between the atmosphere-hydrosphere-biosphere and the sedimentary environment. In this regard, micro organisms fulfill both the role of primary producers, through the fixation of inorganic carbon into biomass during photosynthesis and chemolithoautotrophy, and as the major degraders of that biomass (as heterotrophs), gaining energy and carbon for growth from its transformation to CO_2 or CH_4. A fraction of that organic carbon also becomes incorporated into the sedimentary record as coal, kerogen or fossil fuel, where it is either degraded *in situ* by indigenous microbial communities or ultimately returned to the Earth's atmosphere through long-term geological processes or human activity. Intimately tied to the carbon cycle is the fate of an entire suite of redox-active elements that make up part of the cell and/or function as electron donors or acceptors in metabolic pathways. The complete geomicrobiological data set is available in Appendix 8.

5.1 Microbial Metabolic Processes

Within an aquifer, microbial activity plays an important role in modifying the chemical composition of the groundwaters and some solid-phase constituents of the host sediment or rock. It is widely recognized that through their various chemoheterotrophic pathways, micro organisms are ultimately responsible for the conversion of organic carbon to CO_2 and CH_4 at temperatures <100°C. Some bacteria use hydrolytic enzymes to break down complex molecules into simple monomers such as sugars, amino acids and fatty acids that they can then utilize, while others are restricted to simple fermentation products, of which acetate and H_2 are probably the most utilized (Lovley et al., 1994; Lovley and Chapelle, 1995). The source of the organics may either be primary, i.e., deposited along with the original sediment as particulate organic carbon (POC), or secondary, having migrated in from adjacent organic-rich soils or sediment as dissolved organic carbon (DOC).

Groundwater and mineralogical changes during metabolic processing of organic compounds is directly related to bacterial reduction of dissolved gases and solutes (e.g., O_2, NO_3^-, SO_4^{2-}, CO_2) or solid-phase components (e.g., manganese and ferric oxyhydroxides) in the aquifer. The terminal electron accepting process that occurs at any given location along the flow path depends on what oxidants are available and, in the situation when multiple electron acceptors are present, on the free energy yield of the specific reaction (Postma and Jakobsen, 1996). Thus, the decomposition of complex organic material proceeds in a continuous sequence of redox reactions, with the most electropositive oxidants being consumed near the point of recharge, and progressively poorer oxidants being consumed at greater distances along the flow path of confined aquifers or at greater depth in unconfined aquifers, until the labile organic fraction is exhausted and the groundwater is left with a composition potentially very different from that at its source. Inorganic by-products of chemoheterotrophy (e.g., HCO_3^-, Mn^{2+}, Fe^{2+}, NH_4^+, NO_2^-, HS^-, HPO_3^{2-} and CH_4) seldom accumulate because chemolithoautotrophic bacteria may use them as metabolic reactants, or alternatively, their presence may trigger important abiotic reactions between the solid and dissolved phases leading to secondary mineral formation.

This sequence of redox reactions is manifest in a biogeochemically zoned groundwater regime, with characteristic aqueous and mineralogical patterns that reflect the dominant microbial communities growing at a particular location in the aquifer, although in many cases they may overlap. Indeed, the changes in organic and inorganic chemistry are complex, transient and involve numerous recycling reactions that can complicate our full understanding of what microbial processes are taking place in the subsurface.

5.1.1 Aquifer Geochemistry

Trends in groundwater geochemistry serve as useful indicators of the dominant microbial chemoheterotrophic pathways dominating any given location in the subsurface (Figure 44). Those species which maximize the potential energy yield (by using terminal electron acceptors, TEA's, that promote a higher yield of biomass per mole of substrate oxidized) may then be in a position to monopolize that substrate to the detriment of species using less energetic reaction pathways. The form of microbial respiration that yields the most energy to support microbial growth is oxidation of organic carbon coupled to the reduction of O_2. This process is called aerobic respiration, and the environment in which the bacteria reside is referred to as the oxic zone. Metabolism in the absence of O_2 is less energetically favourable, and is called anaerobic respiration. Facultative anaerobes are unique in that they are capable

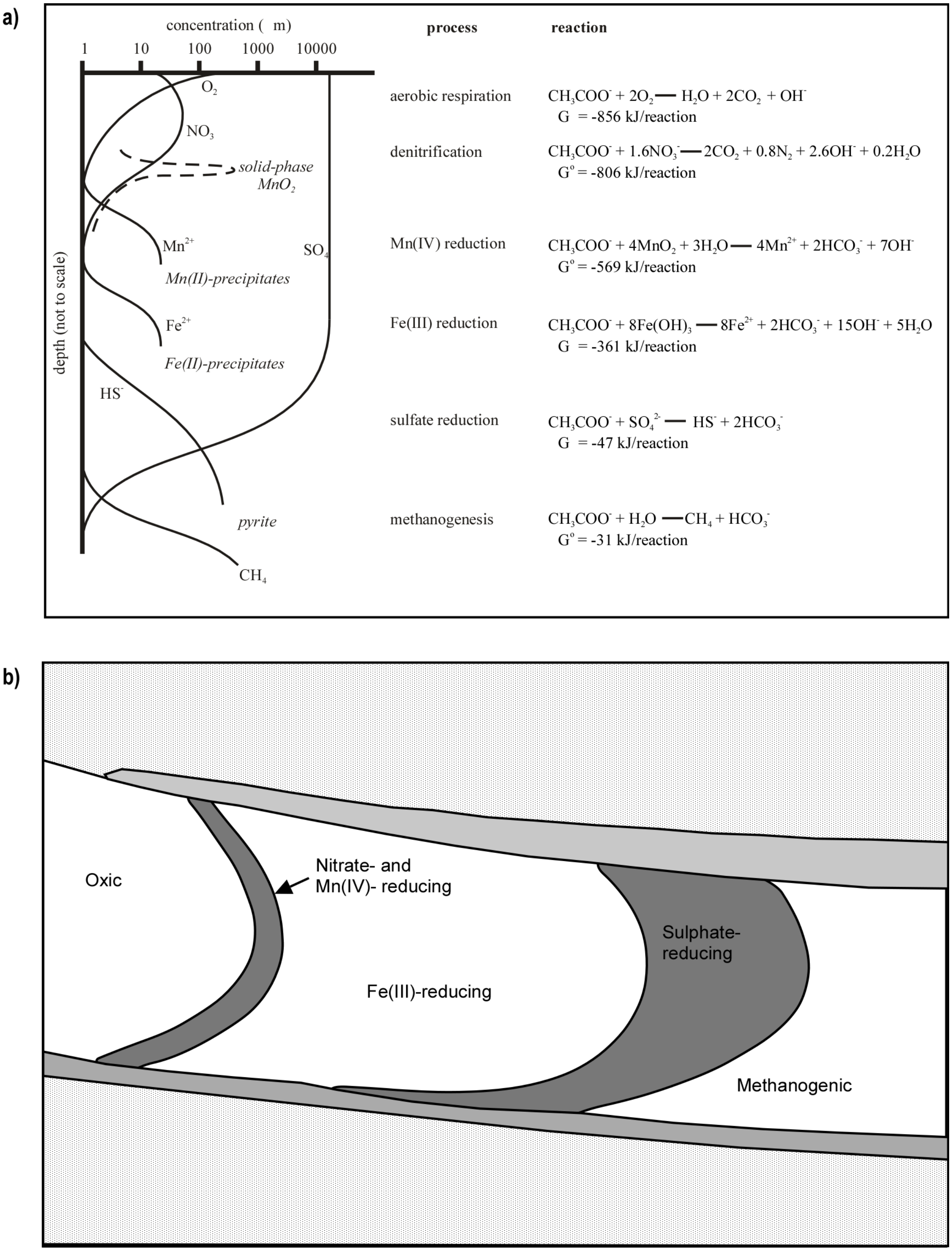


Figure 44. Dominant microbial chemoheterotrophic pathways in: a) sediment (adapted from Konhauser, K., 2006, Figure 6.20, Introduction to Geomicrobiology, Blackwell Publishing); and b) groundwater (Reprinted with permission from (Lovley, D.R., Chapelle, F.H. and Woodward, J.C. (1994): Use of dissolved H_2 concentrations to determine distribution of microbially catalyzed redox reactions in anoxic groundwater; Environmental Science and Technology, v. 28, p. 1205-1210) Copyright (1994) American Chemical Society).

of aerobic respiration but can switch to anaerobic processes (i.e., fermentation or using an alternative TEA) when O_2 is unavailable. They grow in what is referred to as the suboxic zone, where O_2 is depleted, yet redox potential is kept positive due to availability of NO_3^-, NO_2^-, Mn(IV) and Fe(III). Anaerobic micro organisms that cannot use O_2 as an electron acceptor are generally inhibited in the presence of O_2. These micro organisms are called obligate anaerobes, and the most used TEA's in the anoxic zone are SO_4^{2-} and CO_2.

The most important chemoheterotrophic pathway in terms of oxidizing potential is aerobic respiration (Lovley and Chapelle, 1995). Because of the lack of photosynthesis, the only source of O_2 in the subsurface is that dissolved in recharge water. Consequently, intermediate and regional flow systems are generally depleted of O_2.

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

Nitrogen cycling in aquifers is relatively complex, with nitrate concentrations governed by the balance between nitrification and denitrification. Denitrifiers closely resemble aerobic respirers in that they are capable of completely degrading complex organic matter to carbon dioxide.

$2.5C_6H_{12}O_6 + 12NO_3^- \rightarrow 6N_2 + 15CO_2 + 12OH^- + 9H_2O$

The pathways for organic matter oxidation by most other anaerobic processes are much different from those of aerobic respiration and denitrification. Whereas aerobes and denitrifiers can by themselves completely oxidize a wide variety of organic compounds to carbon dioxide, most anaerobes are limited to a few types of simple organic compounds. Therefore, under suboxic to anoxic conditions, organic matter released from hydrolysis of complex polymers must first be metabolized by fermentative micro organisms. These micro organisms convert the larger polymers into smaller degradation products, the most common ones being H_2, pyruvate, lactate, acetate and formate. In turn, those simpler compounds are utilized by various acetogenic bacteria and anaerobic respirers, that growing syntrophically, bring about the complete oxidation of the organic matter to CO_2 or CH_4. In addition, their metabolism releases bicarbonate into the groundwater, thus contributing to the accumulation of dissolved inorganic carbon (DIC) in the flow path.

In aquifers where MnO_2 forms part of the solid-phase, the concentration of Mn^{2+} is negligible near the recharge zone, but at some distance between the NO_3^- maximum and zero NO_3^-, it begins to increase towards its maximum values:

$CH_3COO^- + 4MnO_2 + 3H_2O \rightarrow 4Mn^{2+} + 2HCO_3^- + 7OH^-$

In sediments/sedimentary rocks where ferric oxyhydroxides, e.g., $Fe(OH)_3$ or Fe_2O_3, are abundant, those minerals can be reduced when coupled to the oxidation of organic matter (e.g., Lovley et al., 1990).

$CH_3COO^- + 8Fe(OH)_3 \rightarrow 8Fe^{2+} + 2HCO_3^- + 15OH^- + 5H_2O$

In most freshwater systems, the concentration of dissolved sulphate precludes it from being a significant TEA. However, in evaporite-hosted aquifers (with gypsum/anhydrite), sulphate-reducing bacteria (SRB) have been found in abundance within the anoxic zones (e.g., Plummer et al., 1990).

$CH_3COO^- + SO_4^{2-} \rightarrow HS^- + 2HCO_3^-$

In many instances, the terminal step in the anaerobic degradation of organic material is methanogenesis (see below). In fact, it has been estimated that nearly half of the organic carbon degraded globally by anaerobically-respiring bacteria is eventually converted to methane (Higgins et al., 1981).

5.1.1.1 Horseshoe Canyon Formation

The loss of Ca^{2+} and Mg^{2+} from the groundwater flow path in non-CBM formation waters suggests that either secondary carbonate formation or cation exchange reactions is contributing to that pattern. If active carbonate precipitation is occurring, then the continued presence of HCO_3^- (with values as high as 1000 mg/L) further suggests that some form of anaerobic metabolic pathway is mineralizing organic carbon and concomitantly generating secondary alkalinity (Figure 45 and Figure 46); aerobic respiration could only generate that much bicarbonate if pCO_2 values were several orders of magnitude higher than atmospheric pCO_2. The anaerobic processes might include Mn(IV) reduction, Fe(III) reduction or sulphate reduction. Which of these three processes is unresolved given the lack of information on solid-phase metal oxyhydroxides in the bedrock, the paucity of data on primary electron donors, such as acetate and H_2 (the latter not reported to nM concentrations), and detailed groundwater profiles of Mn^{2+}, Fe^{2+}, SO_4^{2-} and H_2S/HS (speciation depending on pH). The only inferences of active sulphate reduction comes from Figure 47 and Figure 45, which show well waters with sulphate concentrations between 10 - 150 mg/L, high bicarbonate, but low Mn^{2+} (between 0.007 - 0.017 mg/L) and Fe^{2+} (between 0.03 - 0.09 mg/L), and data on oxidation-reduction potential (ORP) in some wells between -50 mV to -350 mV, the natural range for sulphate-reducing bacteria. However, as will be discussed below, the DNA results for those wells shows no clear evidence for the presence of actively metabolizing SRB's (each of the wells, samples 43, 45, 47, and 51 have less than 9,000 SRB cells/mL), and none of the well waters report the presence of H_2S (although field notes do mention a slight H_2S odour in Sample 45). Low dissolved metal concentrations (Figure 47) might suggest minimal metal oxyhydroxide reductive dissolution, yet this observation may also be a result of an absence of solid TEA's on aquifer sediments due either to not being present initially or having been subjected to sustained reductive dissolution. Unfortunately, trends between well sites cannot be adequately determined due to the spatial distances, i.e., nearly 120 km, separating samples 43 and 51.

By contrast, groundwater from a CBM aquifer show a chemical composition dominated by Na-Cl. These waters are from deeper depths and downgradient from the HCO_3^- portion of the flowpath, suggesting that the well waters are more biogeochemically mature, i.e., most of the TEA's are likely depleted, including sulphate (which makes up 0% of the well water). Consequently, the only likely metabolic pathways remaining are fermentation, acetogenesis and methanogenesis, which as discussed below, are found in abundance in some of the well waters (e.g., Sample 56).

5.1.1.2 Scollard and Paskapoo Formations

Similar to the groundwater flow path in the Horseshoe Canyon Formation, the loss of Ca^{2+} and Mg^{2+}, and the presence of abundant HCO_3^- in both formations (recall Figure 19) points to either the precipitation of a carbonate phase or cation exchange: the bicarbonate concentrations cluster according to formation waters, with Scollard Formation waters having values between 830 – 1030 mg/L, while the Paskapoo Formation waters are between 550 – 600 mg/L (Figure 48). As expected, alkalinity follows the same pattern (Figure 48). The Whitewood Mine dewatering wells also fall within the bicarbonate-rich waters, although one sample shows nearly 50% sulphate (Figure 19). These waters have the lowest bicarbonate concentrations, between 450 – 550 mg/L.

Dissolved Fe concentrations are low (0.01 – 0.02 mg/L) for both formations, suggesting that Fe(III) reduction is not a significant metabolic process in the aquifer (Figure 49). Conversely, dissolved Mn concentrations in the Scollard and Paskapoo Formations are higher than Fe, and much more variable (0 – 1.25 mg/L). Interestingly, Mn^{2+} is significantly higher in the Whitewood Mine wells, possibly suggestive of active Mn(IV) reduction taking place. The high Mn^{2+} concentrations will have implications for its extraction and subsequent oxidation to Mn(IV), which can lead to biofouling, and ultimately, a

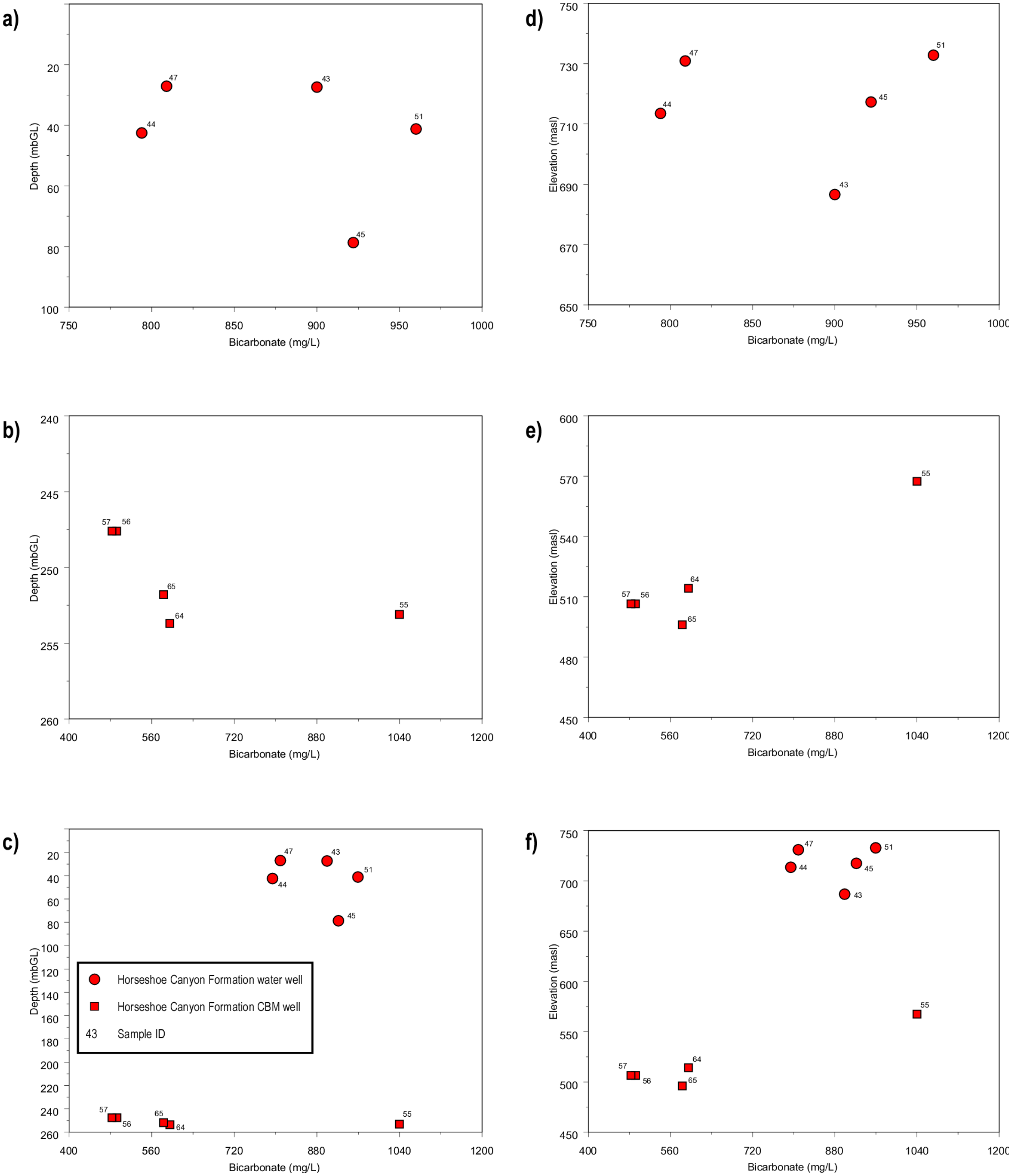


Figure 45. Well water bicarbonate concentrations in the Horseshoe Canyon Formation: a) water well bicarbonate concentrations vs. depth; b) CBM well bicarbonate concentration vs. depth; c) all well bicarbonate concentrations vs. depth; d) water well bicarbonate concentrations vs. elevation; e) CBM well bicarbonate concentrations vs. elevation; and f) all well bicarbonate concentrations vs. elevation.

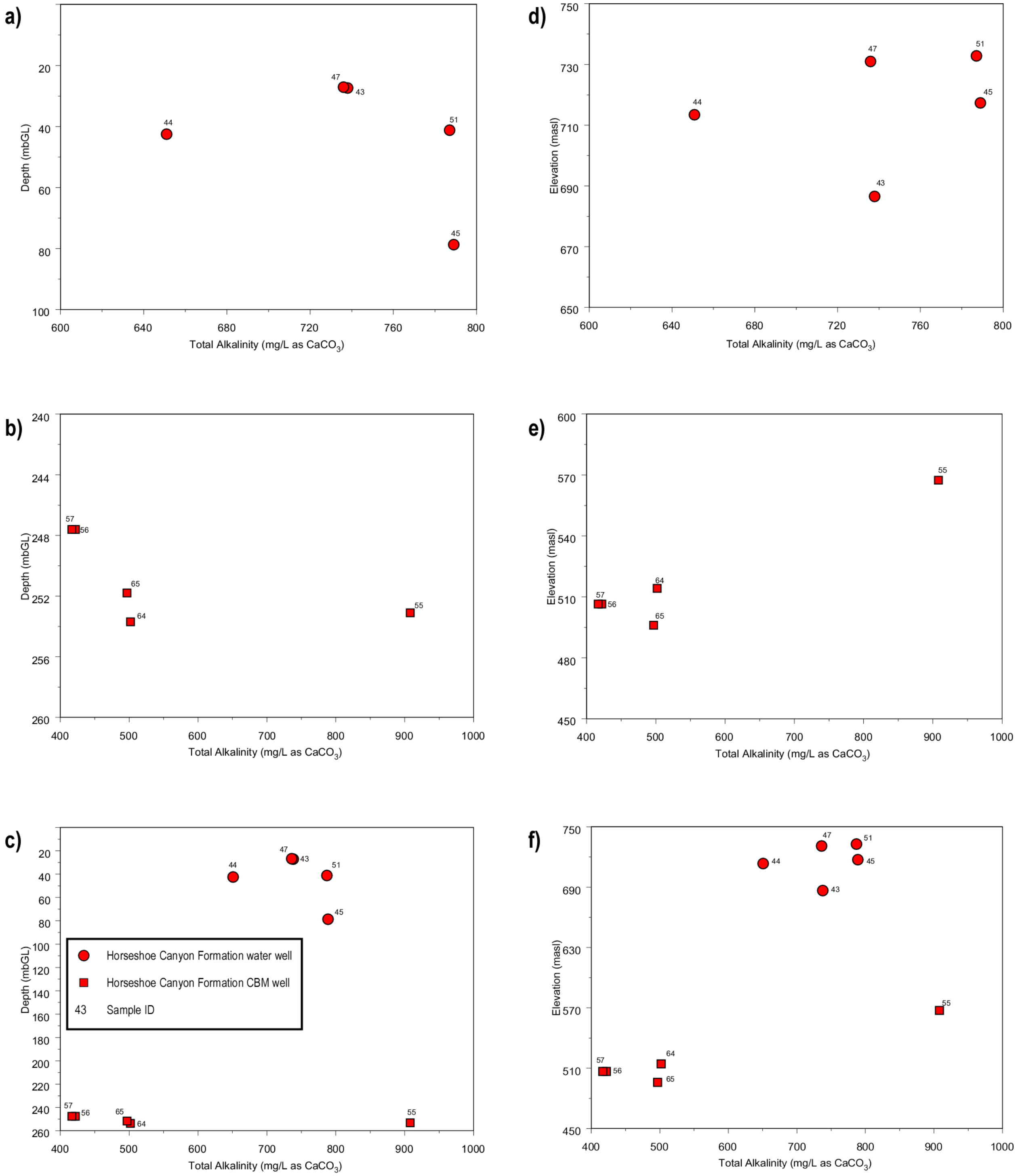


Figure 46. Well water alkalinity in the Horseshoe Canyon Formation: a) water well alkalinity vs. depth; b) CBM well alkalinity vs. depth; c) all well alkalinity vs. depth; d) water well alkalinity vs. elevation; e) CBM well alkalinity vs. elevation; and f) all well alkalinity vs. elevation.

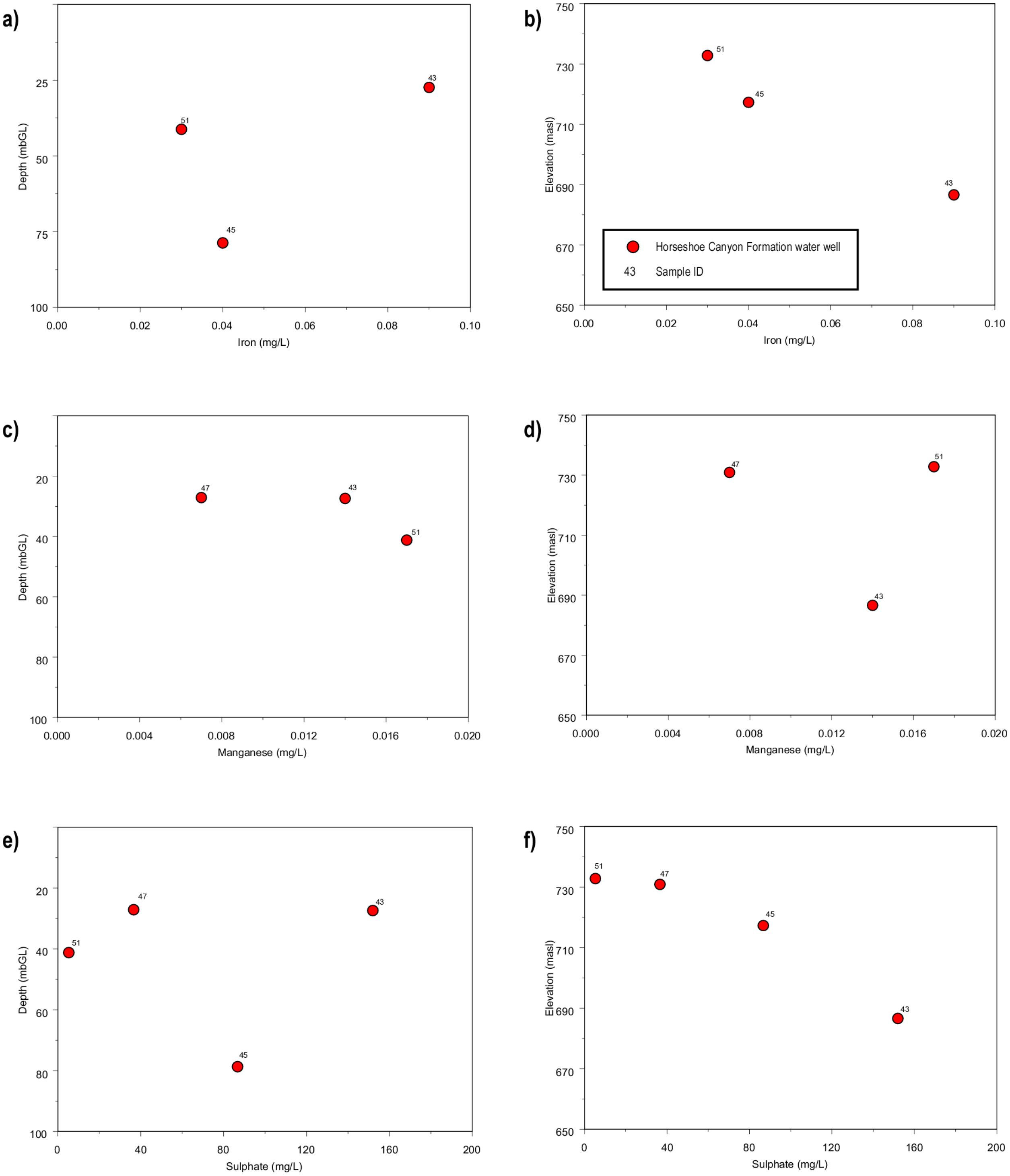


Figure 47. Well water Fe, Mn and SO$_4$ cocentrations in the Horseshoe Canyon Formation: a) Fe vs. depth; b) Fe vs. elevation; c) Mn vs depth; d) Mn vs. elevation; e) SO$_4$ vs. depth; and f) SO$_4$ vs. elevation.

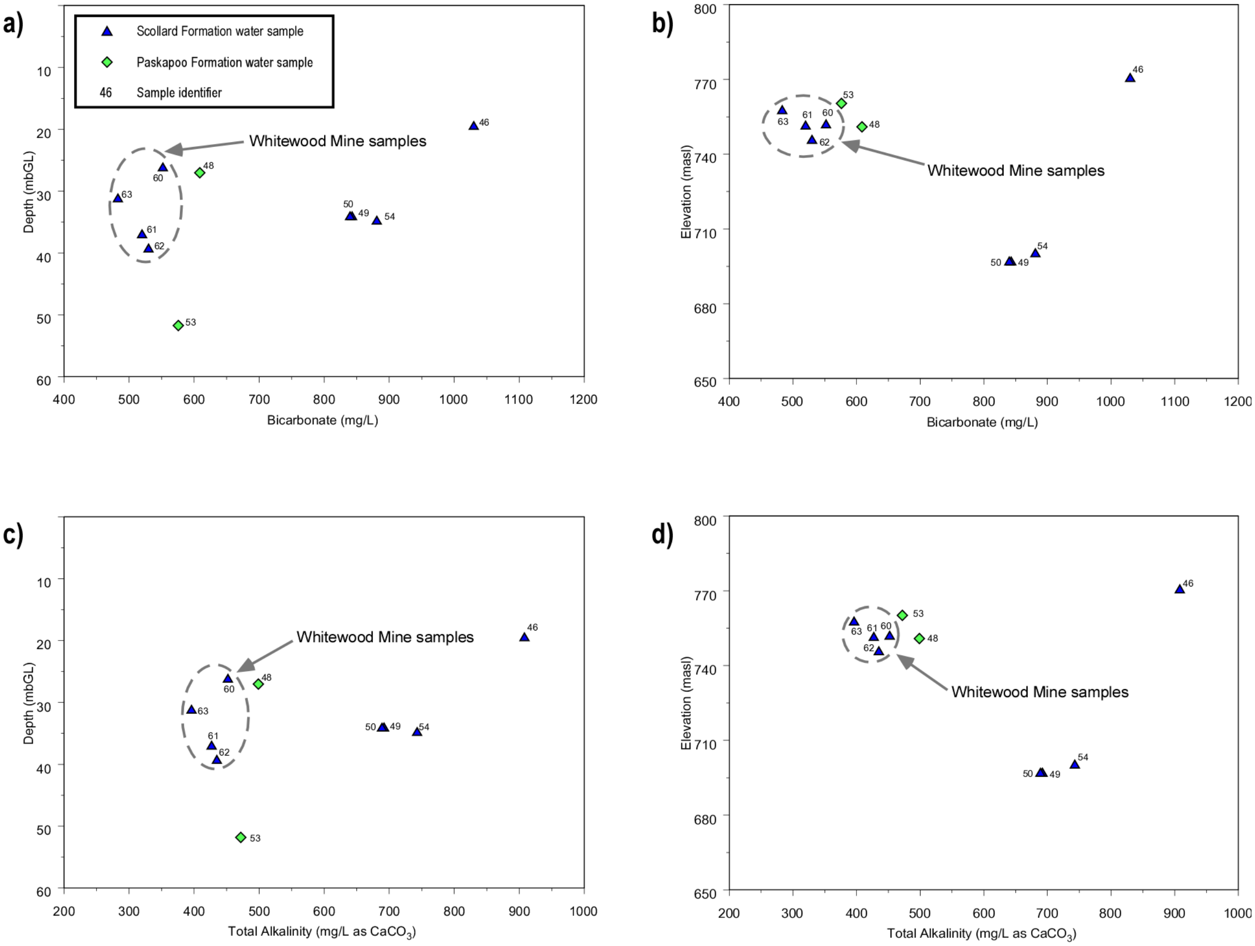


Figure 48. Water well bicarbonate and alkalinity in the Scollard and Paskapoo formations: a) bicarbonate vs. depth; b) bicarbonate vs. elevation; c) Alkalinity vs. depth; and d) alkalinity vs. elevation.

decrease in the efficiency of well abstraction. Most dissolved sulphate values are <100 mg/L, but with one well in the Scollard Formation (Sample 54) having concentrations approaching 550 mg/L. Analyses for dissolved sulphide (H_2S) would indicate whether active sulphate reduction is occurring in that portion of the aquifer.

5.1.2 Mineralogical Trends

The mineral components of an aquifer's sediment/bedrock are for the most part unreactive. The oxides and hydroxides of iron and manganese are the exceptions. These phases are stable within an aquifer's oxic zone, but they quickly become unstable after the groundwater becomes anoxic.

There are a number of Mn(IV) oxides in sediments, principally those with an average composition of MnO_2. These phases are readily reduced by dissimilatory Mn(IV)–reducing bacteria almost as soon as the groundwaters become depleted in O_2. The subsequent release of Mn^{2+}, and its reaction with HCO_3^-, most commonly results in the formation of pure manganous carbonates, such as rhodochrosite, or mixed Mn- and- Ca-carbonates (Aller and Rude, 1988). Unlike their carbonate counterparts, manganese sulphides are rather soluble and only precipitate at very high concentrations.

$$Mn^{2+} + Ca^{2+} + 4HCO_3^- \rightarrow MnCa(CO_3)_2 + 2CO_2 + 2H_2O$$

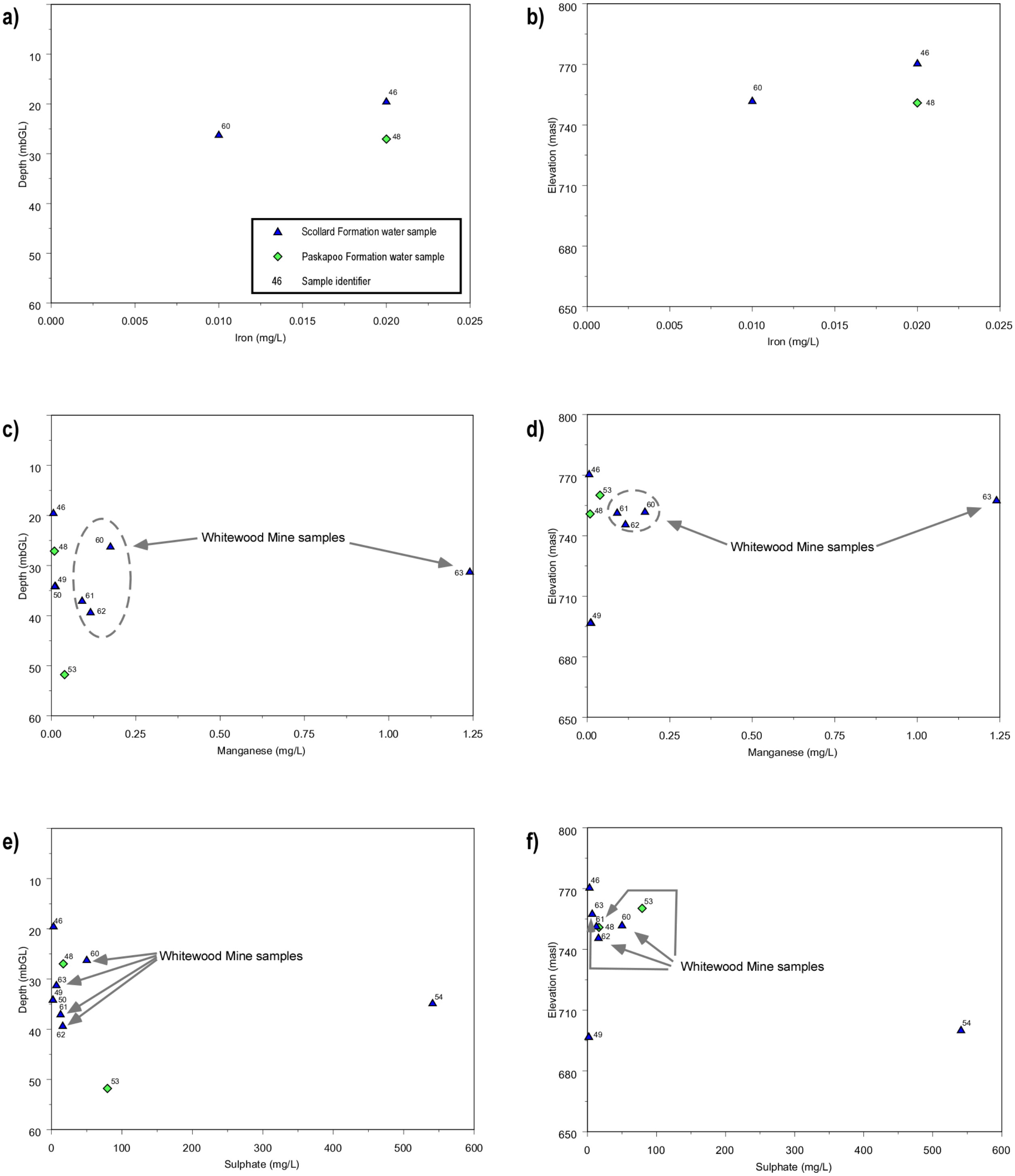


Figure 49. Well water Fe, Mn and SO$_4$ concentrations in the Scollard and Paskapoo formations: a) Fe vs. depth; b) Fe vs. elevation; c) Mn vs. depth; c) Mn vs. elevation; e) SO$_4$ vs. depth; and f) SO$_4$ vs. elevation.

The reduction of ferric iron minerals produces an increase in the concentration of Fe^{2+} in suboxic waters, with a peak in concentration at the boundary between the Fe(III) and sulphate reduction zones. Some of this ferrous iron may diffuse upwards to be re-oxidized to ferric hydroxide inorganically by either NO_3^- or MnO_2 (e.g., Myers and Nealson, 1988; Postma, 1985). In aquifers with abundant pore water sulphate, ferrous iron is instead removed from solution by reaction with hydrogen sulphide, produced by sulphate reducing bacteria (Thamdrup et al., 1994). This forms metastable iron monosulphide minerals, such as mackinawite, that are a precursor to pyrite, provided that adequate supplies of intermediate sulphur species are present. Typically, abundant reactive iron is present, and the concentration of Fe^{2+} exceeds the solubility product of a number of other minerals (Zachara et al., 2002). In particular, the high reactivity of Fe^{2+} and the general availability of HCO_3^- in suboxic and anoxic groundwaters tend to cause ferrous iron to precipitate quickly as a sideritic cement (e.g., Coleman, 1985). The formation of vivianite requires that soluble phosphate is made available through oxidation of organic matter, the dissolution of phosphorous-bearing solid phases or through reduction of phosphorous-adsorbing Fe(III) oxides (Krom and Berner, 1980).

The saturation state of an aquifer, with respect to various carbonate minerals, is directly related to the metabolic process responsible for organic matter oxidation. Aerobic respiration typically results in the complete oxidation of organic carbon to CO_2, thereby promoting the dissolution of biogenic carbonate both above and below the calcite saturation horizon (Archer et al., 1989):

$$CO_2 + H_2O + CaCO_3 \leftarrow\rightarrow Ca^{2+} + 2HCO_3^-$$

Anaerobic respiration, on the other hand, releases bicarbonate into the groundwater. Increased alkalinity can cause the equilibrium ion activity product for calcium carbonate to be exceeded, leading to the precipitation of authigenic carbonate minerals that are relatively stable once formed and not subject to rapid recycling by redox reactions in the same way as sulphides and oxides (Irwin et al., 1977). Such processes become most predominant within the sulphate reduction zone, because that metabolic process increases alkalinity. In many aquifers, the balance between porosity enhancement via CO_2 production and porosity diminishment via carbonate precipitation is complex. Furthermore, water moving through unconsolidated sediment may carry dissolved ions capable of reacting with $CaCO_3$ grains. One such solute is Mg^{2+}, which under some conditions can react with calcite to form dolomite.

5.1.2.1 Horseshoe Canyon Formation

No mineralogical data is provided for this formation and as such a detailed analysis could not be performed.

5.1.2.2 Scollard and Paskapoo Formations

As above, no mineralogical data is provided for this formation and as such a detailed analysis could not be performed.

5.1.3 Isotopic Trends

A characteristic sequence of different terminal electron accepting processes can be distinguished on both mineralogical and stable isotopic grounds in environments where precipitation of carbonate minerals is possible (Figure 50). Although aerobic respiration induces calcite dissolution, other aerobic processes can actually facilitate the precipitation of non-ferroan calcite (no dissolved iron is present under oxic conditions), with a stable carbon isotopic composition ($\delta^{13}C$) of 0‰. For instance, chemolithoautotrophic oxidation of NH_4^+ and H_2S, in the receding portions of the oxic zone, actually leads to a rise in pH because these reactions effectively remove protolytic species from solution, resulting in a pH higher

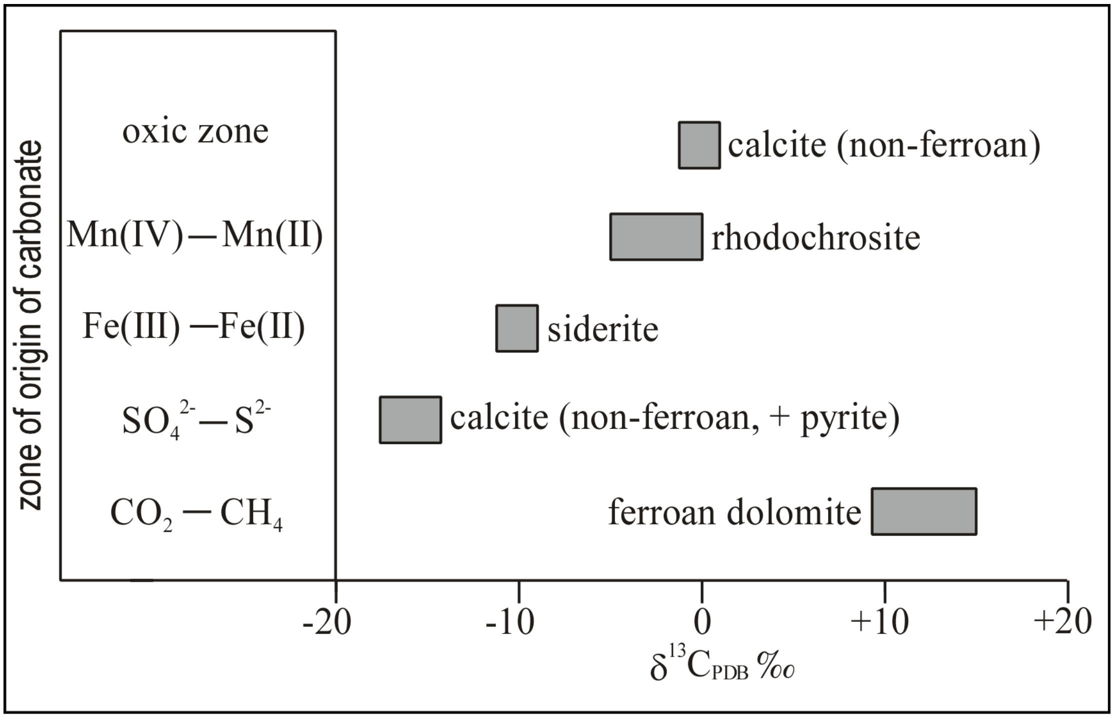


Figure 50. Diagenetic isotopic signatures (adapted from Konhauser, K., 2006, Figure 6.20, Introduction to Geomicrobiology, Blackwell Publishing).

than predicted from the reaction stoichiometries (Boudreau and Canfield, 1993). Nitrate reduction does not produce carbonate minerals with characteristic chemistry. Manganese (IV) and Fe(III) reduction produce rhodochrosite and siderite, with increasingly negative $\delta^{13}C$ (typically -2 and -10‰, respectively) due to the incorporation of a larger proportion of biogenic carbonate that has a $\delta^{13}C$ signature of -20 to -30‰. Sulphate reduction produces non-ferroan calcite because any available iron reacts preferentially with sulphide. These calcites have an even more negative $\delta^{13}C$ signature (typically -15‰). Finally, downgradient of the sulphate reduction zone, methanogenesis leads to the production of ferroan carbonates (siderite) with a characteristic positive $\delta^{13}C$ signature due to coupling of methane oxidation with reduction of residual iron minerals (Curtis et al., 1986).

5.1.3.1 Horseshoe Canyon Formation

The formation well waters all possess negative carbon isotopic fractionations, with a mean $\delta^{13}C$ value of -11.8‰ (Figure 25). Such patterns can be indicative of dissolution of secondary carbonate minerals that formed in association with sulphate reduction or mixing of DIC formed via methane oxidation (see below) with DIC from dissolution of atmospheric CO_2. By contrast, the CBM waters have uniquely positive fractionations, with a mean value of 18.3‰. Positive fractionations are most commonly observed to result from methanogenic activity in the groundwaters. However, the isotopic signatures of the gases obtained do not provide unequivocal evidence for the source of methane. In fact, for many samples it lies between $\delta^{13}C$ values commonly found associated with dry bacterial and wet thermogenic sources (Hunt, 1995). It has commonly been observed that bacteria tend to form methane that has $\delta^{13}C$ depleted by -70‰, relative to the initial source of C (Rosenfeld and Silverman, 1959). Depending on which is the most representative value of for initial $\delta^{13}C$ (i.e., 18.3‰ from DIC in water, or 3.4‰ from $\delta^{13}C$ in CO_2), the $\delta^{13}C$ of methane may suggest either origin. Interpretation is further complicated by the presence of methanotrophic bacteria (see below), which may lead to isotopically heavier residual methane. In any case, initial evaluation of $\delta^{13}C$ isotopic values suggests a biogenic or mixed (i.e. some component wet thermogenic) methane that is being oxidized.

5.1.3.2 Scollard and Paskapoo Formations

The formation well waters have a mean $\delta^{13}C$ value of -13.7‰. None of the formations water samples have positive fractionations. As discussed above, dissolved gas was detected in sample 46 and the analysis of the gas indicated that methane was present with a $\delta^{13}C$ value of -74 and $\delta^{2}H$ value of -374, both suggestive of biogenesis. Indeed, microbial analyses (see below) indicate the presence of an active methanogen population in that well water.

5.1.4 Aquifer Microbiology

Determining the indigenous microbiology community structure for any given location within an aquifer is very important for understanding the biogeochemical cycling that takes place in the subsurface. In particular, it explains the partitioning of organic carbon and the main TEA's in the groundwater flow path. However, caution must be applied in the attribution of microbial processes to specific microbial communities identified only at the phylum level; indeed, many micro organisms are capable of utilizing more than one metabolic pathway for growth, and a single species may be found regulating different chemical transformations at different locations within an aquifer, depending on local geochemical conditions and symbiotic relationships with other microbial species.

In the following section, potential microbial processes are described within the constraints provided by the geochemical and genetic data provided. However, in natural environments it is estimated that up to 90% of micro organisms grow attached to solid substrata, where they remain fixed to that location as long as favourable geochemical and nutritional conditions persist (van Loosdretch et al., 1989). As a result, both vertical and lateral stratification occurs in terms of the microbial species constituting a mixed community at any given location, and correspondingly, chemical gradients are established by their diverse metabolic activities. While well water chemistry is influenced by microbial activities that occur at a variety of locations along a flow path, the analysis of solid-phase samples permits the localization of microbial activities to specific locations within the aquifer. Therefore, it must be noted at the outset that information obtained by the analysis of well water alone cannot provide a complete understanding of the *in situ* geomicrobiological processes.

5.1.4.1 Horseshoe Canyon Formation

The microbial population breakdown in the Horseshoe Canyon Formation indicates that the two most significant groupings are (1) those species which fall under the heading ‘general’ (i.e., undetermined) and (2) the *Proteobacteria* (Figure 51). Some of the former may represent methanogenic species (e.g., Sample 45 and Sample 65, see Figure 52) and some are methanotrophic, i.e., those species that oxidize methane (e.g., samples 43 and 56; Figure 53 and Figure 54). The second group, also known as the purple bacteria, are the largest and most physiologically diverse of all bacterial phyla. They comprise five major classes, alpha, beta, gamma, delta and epsilon, all of which may have diversified from one ancestral phototroph. The alpha (including the purple non-sulphur bacteria), gamma (purple sulphur bacteria) and some of the beta subdivisions have members that are still phototrophic. Other genera within those subdivisions, as well those from the delta and epsilon subdivisions, are entirely non-phototrophic, utilizing other energy-yielding strategies, including the chemolithoautotrophs that oxidize Fe(II), Mn(II), H_2S, NH_4^+ and NO_2^-, as well as the chemoheterotrophic Mn(IV)-reducers, Fe(III)-reducers, and sulphate-reducing bacteria (Figure 55). The third most abundant grouping are the ‘metal-reducers’. It is unclear, if this grouping represents non-proteobacterial metal-reducing species, or whether it simply refers to all metal-reducing

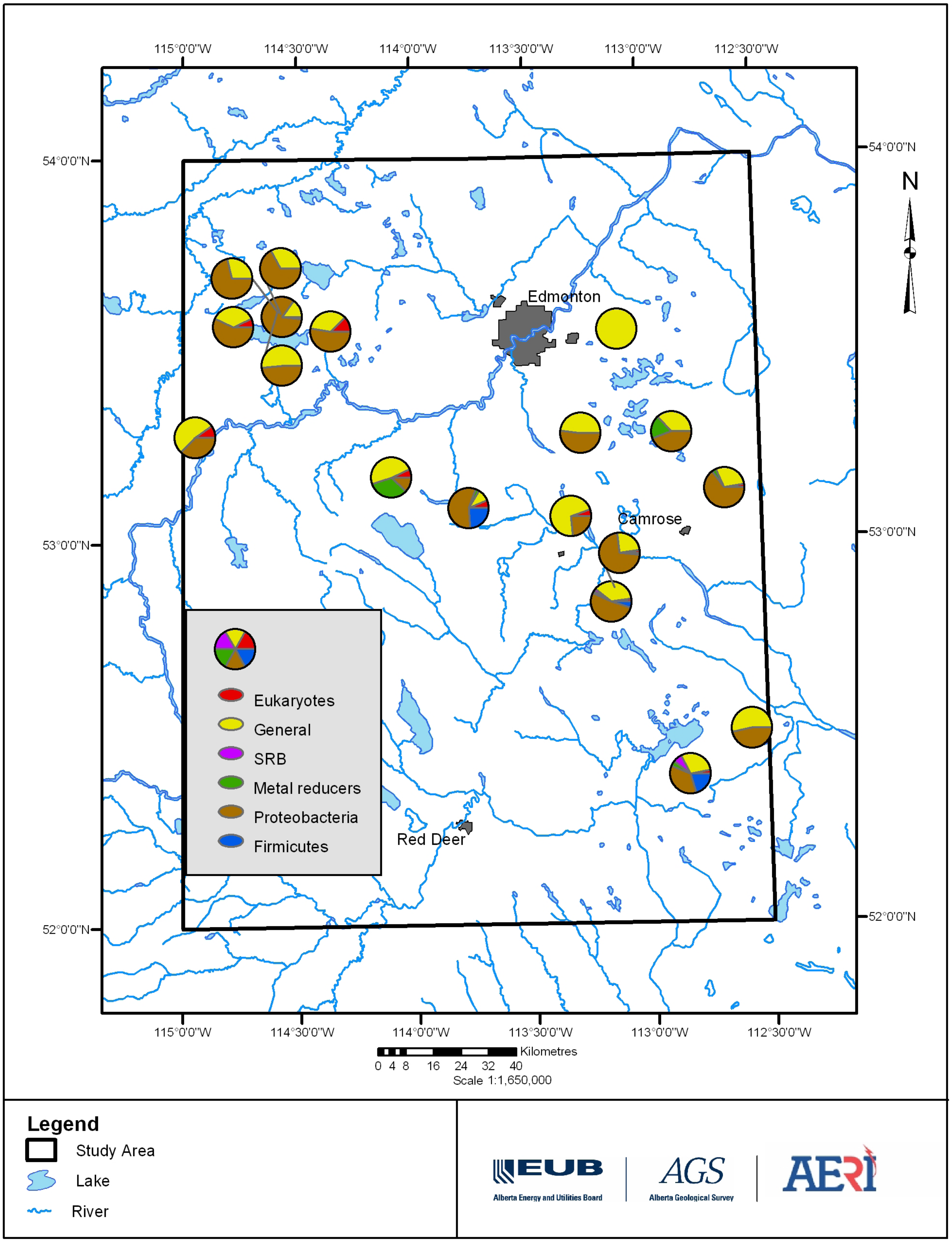


Figure 51. Microbial population breakdown by PLFA (phospholipid fatty acid).

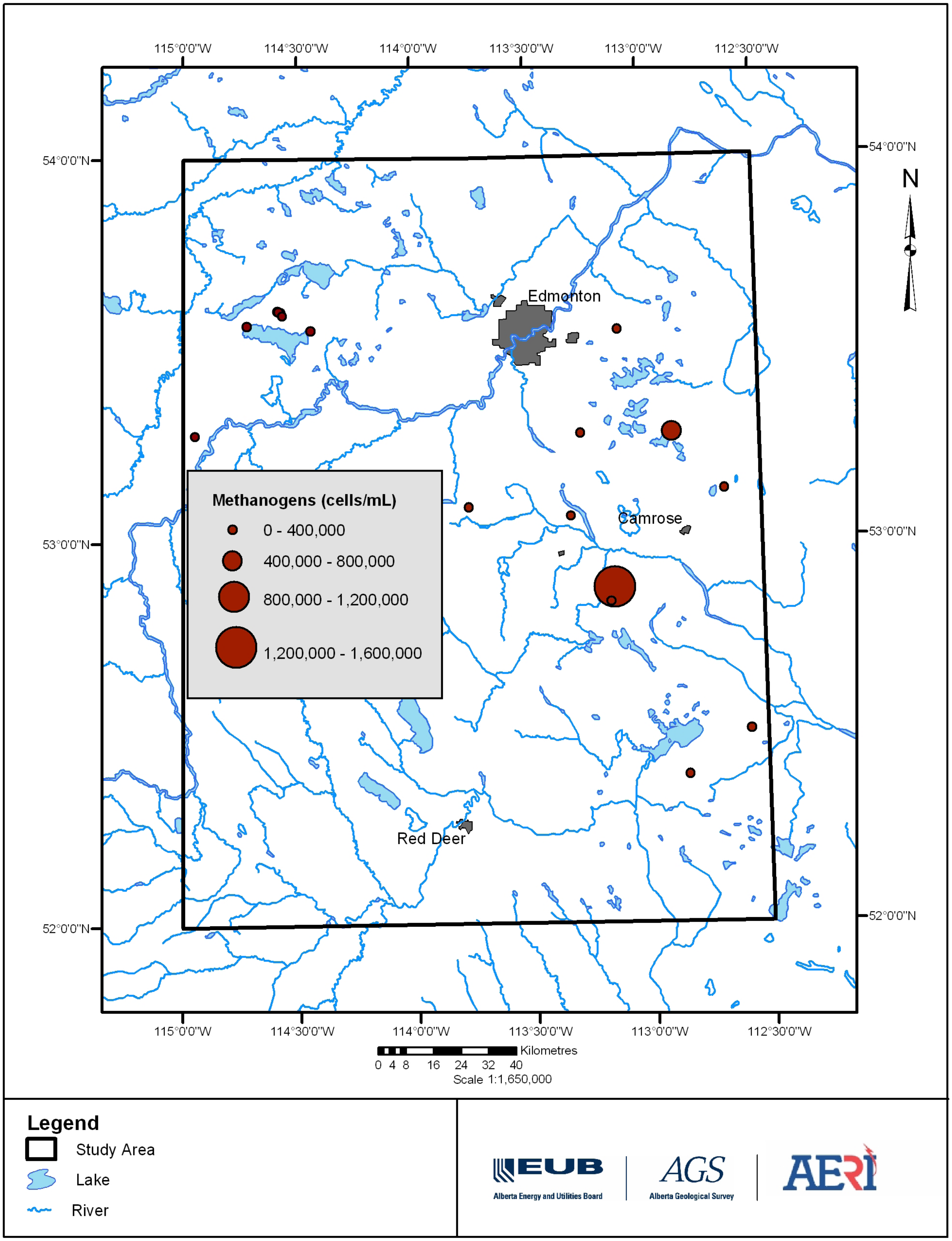


Figure 52. Methanogen cell densities.

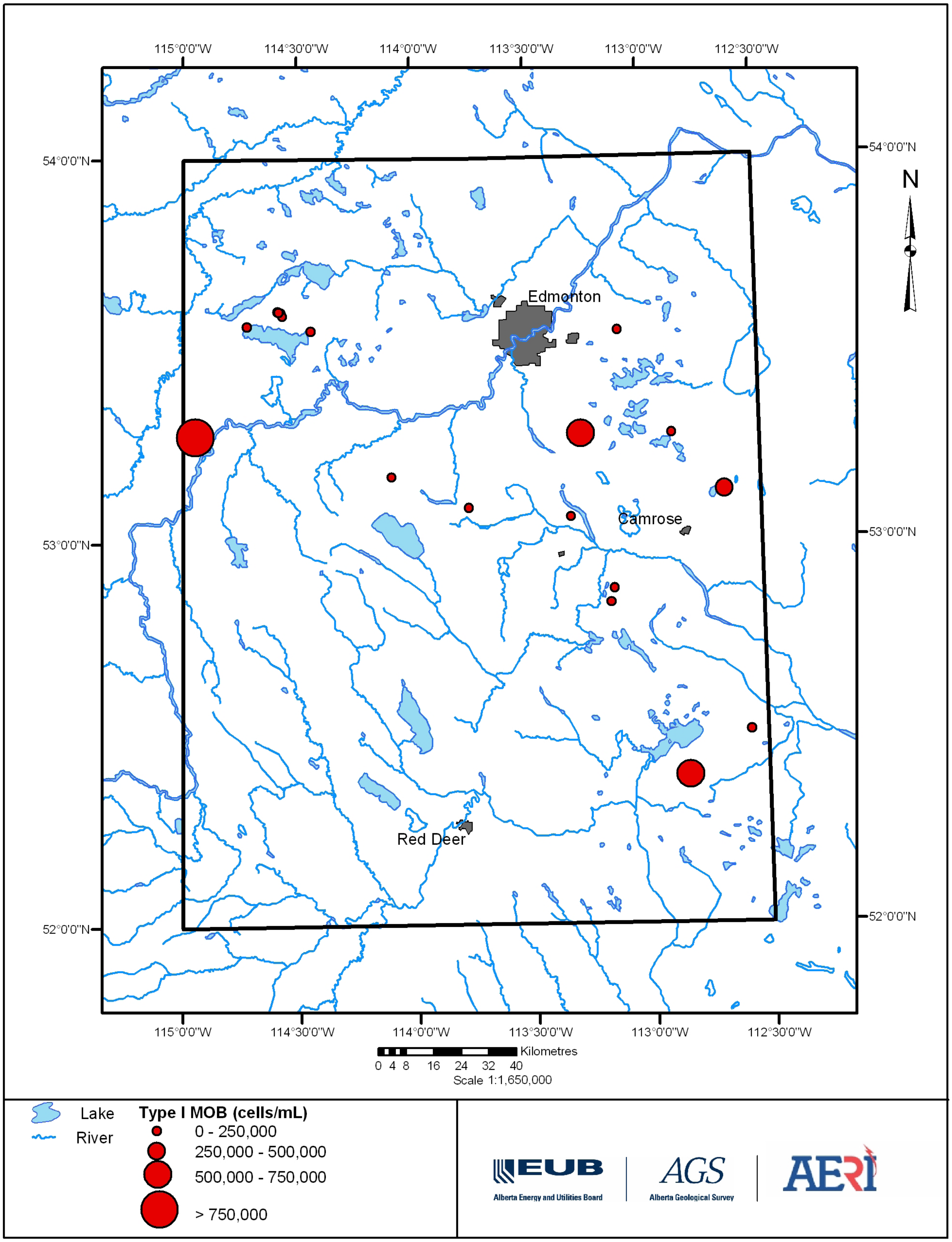


Figure 53. Type I Methane-oxidizing bacteria cell densities.

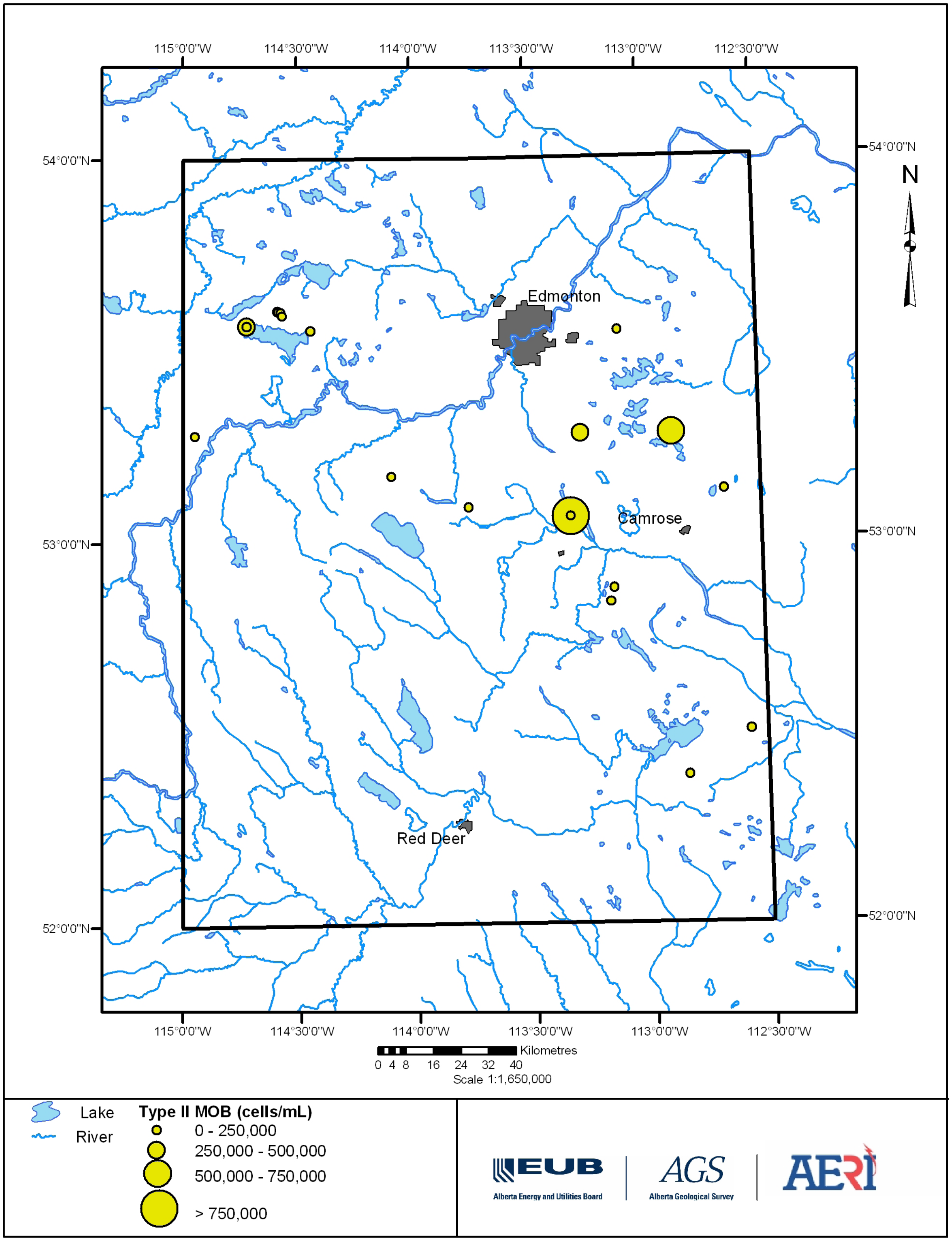


Figure 54. Type II Methane-oxidizing bacteria cell densities

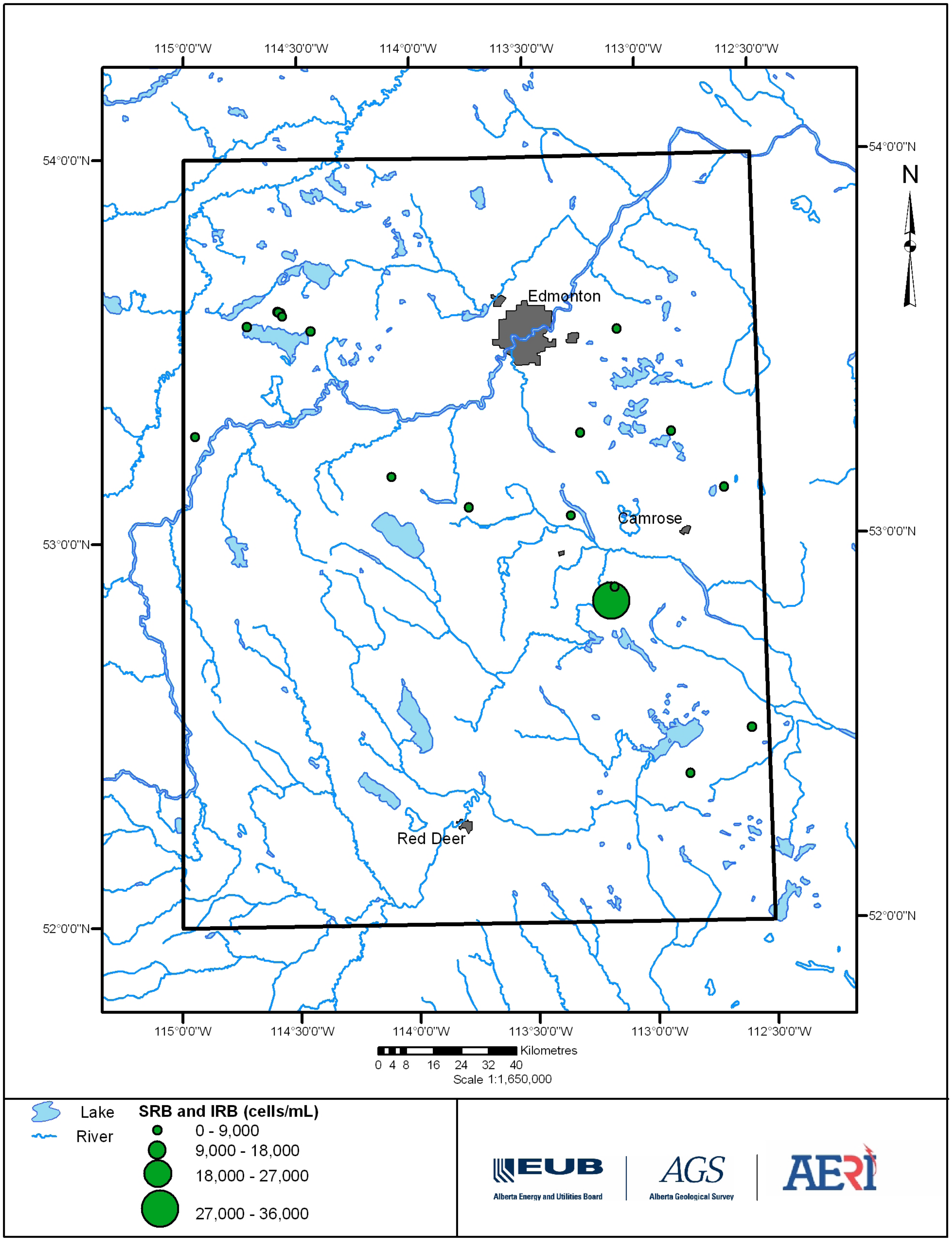


Figure 55. SRB and IRB microbial population cell densities.

species, inclusive of the *Proteobacteria*, because the analytical method does not distinguish between them. It is also ambiguous whether the lack of 'SRB' really means just that, because the vast majority of SRB are *Proteobacteria*, and only the thermophilic varieties belong to different phyla. Nevertheless, the high dissolved sulphate concentrations in many of the well waters (recall Figure 47), and the lack of dissolved H_2S (where reported), coupled with the lack of DNA evidence of active populations of SRB's, is suggestive of a lack of bacterial sulphate reduction. DGGE results (Appendix 10) suggest that some of the samples (samples 45, 52 and 65) have microorganisms present that could participate in sulphate reduction such as bacteria from the *Desulfobubaceae* family, and from the *Desulfatibacillum* and *Desulfovibrio* genera respectively. Without additional information however, the data would therefore, imply that CBM well waters, such as Sample 65, are dominated by either Mn(IV) or Fe(III)-reducing *Proteobacteria*.

5.1.4.2 Scollard and Paskapoo Formations

Microbial populations are similar in the Scollard Formation well waters and Whitewood Mine wells, i.e., dominated by unidentified species (general grouping) and *Proteobacteria* (Figure 51). Of the former, once again, many appear to be comprised of methanogens (e.g., Sample 46) and methane-oxidizing bacteria (the Whitewood Mine wells) (Figure 53 and Figure 54). As above, it is unclear what types of *Proteobacteria* are included, and thus, some may represent Mn(IV)-reducing bacteria, as alluded to above. What is different, at least in the formation water in Sample 46 is that a significant fraction of the microbial community consists of *Firmicutes*. These are a Gram-Positive phyla made up of aerobic respiring and fermentative species. Given that the dissolved O_2 concentration in that well is 0.15 mg/L, with an ORP value of -173 mV, one can only assume that the well waters would be more conducive to fermentative bacteria. Moreover, comparison to Figure 52, which shows the presence of methanogens (<90,000 cells/mL), further suggesting that the waters are anoxic, and thus the *Firmicutes* are fermentative. It is also noteworthy that the largest viable cell counts come from Sample 46 (Figure 56), perhaps suggesting that sufficient organic substrate is available within that portion of the aquifer.

The microbial community from the Paskapoo Formation are also largely undetermined, although once again, Figure 52 shows that some are methanogenic, while Figure 53 and Figure 54 show a significant number are methanotrophic. Indeed, cell count data shows that methanotrophs are found in densities in excess of 4 million cells/L in Sample 53. There is also a greater eukaryotic component. The importance of this finding is that the well waters must contain dissolved O_2 to support those species, yet in apparent contradiction, field measurements indicate dissolved O_2 concentrations of only 0.06 mg/L.

5.2 Organic Geochemistry

5.2.1 Source of Methane in Aquifer

The organic matter that supports microbial metabolism in subsurface environments largely originates from sediment burial. The amount of POC can be extremely variable, with sandy sediments containing relatively little metabolizable carbon (0.1%) compared to clayey sediment (1-50%) (Lovley and Chapelle, 1995). In fact, it has been documented that the fermentation products produced in C-rich beds may diffuse into adjacent beds (McMahon and Chapelle, 1991). Meanwhile, the amount of DOC that enters with recharge varies depending on the properties of the overlying sediments, such as organic matter cover and infiltration rates.

As described above, sedimentary organic carbon undergoes a series of biologically-mediated oxidative events, with the terminal step being methanogenesis. As the least exergonic process of organic degradation, the reaction product, methane, actually stores a major part of the energy available for aerobically respiring species, i.e., methanotrophs (see below). Some methane is also generated thermally

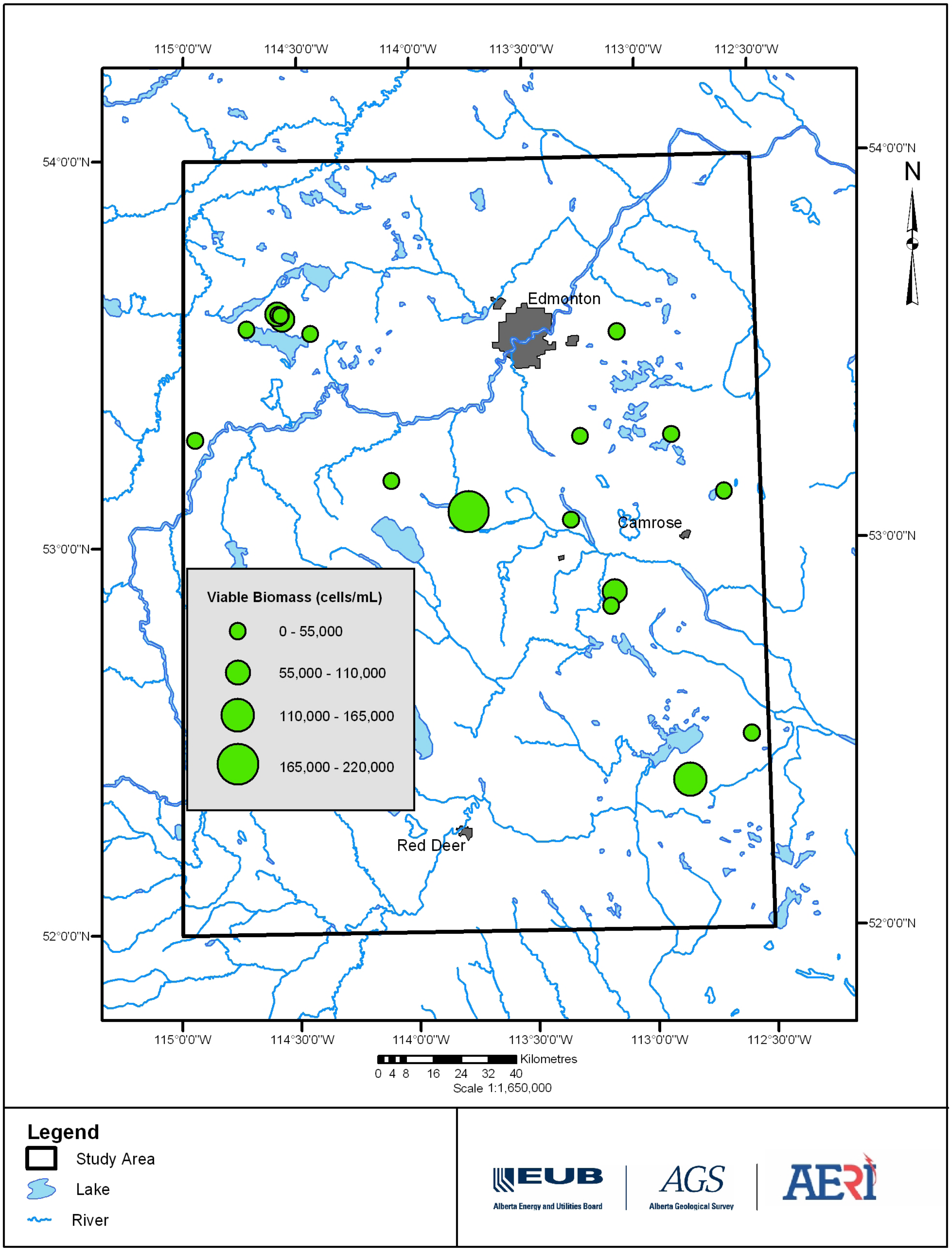


Figure 56. Viable biomass numbers.

from all types of kerogen in the "oil window" (i.e., catagenetically), which for methane, peaks at approximately 150°C. Biogenic versus thermogenic methane can be distinguished on the basis of their carbon isotopic signatures (Schoell, 1983) and relative content of propane and butane (Hunt, 1995).

Typically, methane does not accumulate in sediments until more than 90% of the dissolved sulphate has been reduced (Martens and Berner, 1974). This is unsurprising given that the growth of methanogens are inhibited by SRB because the latter have a higher affinity for the oxidizable substrates than do the former (Lovley et al., 1982). This implies that methanogenic activity is usually limited to groundwaters where the accumulation of labile organic material (e.g., fermentation products) exceeds decay by conventional terminal electron acceptors, particularly sulphate. In other words, methanogens prosper when subsurface activity of SRB is high and dissolved SO_4^{2-} becomes diminished.

Three classes of methanogens are known, one of which is chemolithoautotrophic and the other two are heterotrophic. The autotrophic methanogens produce methane from HCO_3^- and H_2. Quantitatively, this reaction is the most important process involving H_2 in non-sulphate environments, and it accounts for some 40% of the methane produced in sediments.

$4H_2 + HCO_3^- + H^+ \rightarrow CH_4 + 3H_2O$

Of the chemoheterotrophic varieties, one of the classes disproportionate compounds containing the methyl functional group ($-CH_3$) to methane. Some species, such as *Methanococcus*, grow on methanol or methylamine (CH_3NH_2), while others, such as *Methanospirillum*, oxidize propanol, ethanol and butanol (Lovley and Klug, 1983). Importantly, the methylated compounds do not stimulate sulphate reducing bacteria which means the two types of species can co-exist where the compounds are abundant (Oremland et al., 1982).

$4CH_3OH$ (methanol) $\rightarrow 3CH_4 + CO_2 + 2H_2O$

Another class disproportionate acetate to give methane and bicarbonate. Only two genera of methanogens, *Methanosarcina* and *Methanothrix*, have species that are acetotrophic (Mah et al., 1976).

$CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3^-$

Methanogens cannot use long chain fatty acids (with more than two carbons) or aromatic compounds, so they depend on the activity of other micro organisms to break down complex organic compounds into more suitable and simple substrates. In reality, the simple conversion of cellulose into methane may require as many as five major physiological groups of bacteria. One such group are the homoacetogenic bacteria, such as *Acetobacterium woodii* and *Clostridium aceticum* (Drake, 1994). These bacteria ferment sugars, fatty acids and aromatics to acetate and H_2 via a pyruvate intermediate.

$2C_3H_3O_3^-$ (pyruvate) $+ 2H_2O \rightarrow 2CH_3COO^- + 2CO_2 + 2H_2$

Despite the presence of chemoheterotrophic communities, some complex and refractory materials (e.g., lignin, resin and waxes) remain relatively intact. Unlike other polymers, lignins have no regular structure to serve as a target for hydrolytic enzymes, and its degradation requires the collective efforts of a variety of non-specific enzymes. Importantly, most of those enzymes require oxic conditions, and in their absence, anaerobic degradation rates of cellulose and lignins is only about 1-30% of aerobic respiration rates (Benner et al., 1984). As a result, these compounds may persist for many thousands of years, particularly if they are associated with clay minerals that protect them from microbial decay. Rapid burial into anoxic layers (i.e., water-logged soils, swamps etc.) can also lead to very inefficient mineralization rates: in oxic sediment the decay rate is 2-4% per year versus 0.1-0.000001% in the anoxic zone (Swift et al., 1979). These poorly degradable residues are collectively known as humic substances. In environments with high rates of cellulose and lignin burial, and where the environment quickly becomes anoxic, refractory organic materials can accumulate to great thicknesses, resulting initially in peat formation, and if subjected to increased temperatures and pressure that tend to concentrate carbon, they may ultimately be converted into coal through the process of coalification. Some buried organic matter may instead be transformed into bitumen or kerogen at higher temperatures. The former applies to organic material that is largely soluble in organic solvents, and the latter to material that is insoluble. Kerogen can be either labile (sapropelic) or refractory (humic), depending on the nature of the original organic matter contributions. The most labile kerogens break down to form heavy hydrocarbons (e.g., oils), while more resistant kerogens break down to form light hydrocarbons (e.g., gases).

5.2.1.1 Horseshoe Canyon Formation

Methanogens have been identified in a number of wells from the Horseshoe Formation, with densities on average between 0 – 400,000 cells/mL. Similar methanogen densities are observed in a number of the CBM wells, the exception being Sample 65, which has between 1,200,000 – 1,600,000 cells/ml (Figure 52). It is, however, interesting that only between 55,000 – 110,000 of those cells were reported as being viable (Figure 56). The presence of methanogens in CBM wells would seem to suggest that some fraction of the gas phase in the aquifer is microbially generated.

5.2.1.2 Scollard and Paskapoo Formations

The Whitewood Mine dewatering wells have methanogen densities between 0 – 400,000 cells/ml. Similar cell densities exist for the formation waters of the Scollard and Paskapoo Formations. Similar to above, the presence of methanogens in coalbed gas-bearing wells suggests that some of the methane is biogenic.

5.2.2 Hydrocarbon Oxidation

Bacteria that are indigenous to hydrocarbon reservoirs, through deposition with the original sediment and that have survived ever since (predominantly aerobes, fermenters, SRB's and methanogens), as well as those imported with groundwaters, can induce changes in hydrocarbon composition if circumstances favour their growth (Machel and Foght, 2000). For instance, a variety of bacteria, the methylotrophs, make a living from oxidizing 1-carbon compounds, ranging from those highly reduced, such as methane (C^{-4}), to progressively more oxidized carbon compounds, like methanol (C^{-2}) and methylamine (C^{-2}), through to formaldehyde (C^{0}) and formate (C^{+2}) (Ribbons et al., 1970). Those that oxidize methane are known as methanotrophs, and all are obligate aerobes (i.e., they require O_2). This includes the ‘Type I’ methanotrophs (*Methylomonas*, *Methylmicrobium*, *Methylobacter* and *Methylococcus* species) that use the ribulose monophosphate path to assimilate carbon entirely from formaldehyde, and the ‘Type II’ methanotrophs (*Methylosinus*, *Methylocystis*, and *Methylocella* species) that utilize the serine pathway to assimilate carbon from both formaldehyde and CO_2.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Methane can also be oxidized under anoxic conditions, in association with dissolved sulphate. Indications for such anaerobic methane oxidation were for many years presumed based on the observations that methane diffusing upwards from deep sediments often disappeared long before any contact with oxygen was possible. Moreover, the presence of ^{13}C-enriched methane in anoxic sediments is consistent with kinetic fractionation that would result from bacterial conversion of a proportion of that methane into carbon dioxide. Subsequently, the site of maximum anaerobic methane oxidation (AOM) was shown to exist at the methane-sulphate reduction interface, where the supplies of both oxidant and reductant are concurrently available (Reeburgh, 1980). For many years ago it was presumed that some sulphate reducers were capable of directly coupling the oxidation of methane to sulphate reduction, albeit slowly, as long as they had access to another carbon source (e.g., Davis and Yarborough, 1966). However, it is now recognized that this reaction probably involves a syntrophic relationship between methanogens and SRB, with the former reversing their normal metabolism, and oxidizing methane under anoxic conditions, rather than producing it from H_2 and HCO_3^-. Such “reverse methanogenesis” is energetically favourable only so long as the H_2 end product is maintained at a low concentration by another group of micro organisms, e.g., the H_2-oxidizing sulphate reducers (Hoehler et al., 1994). Evidence for such syntrophy comes from methane-rich marine sediments, where lipid biomarkers and fluorescently labelled rRNA-targeted probes have identified methanotrophs growing in tight clusters, closely surrounded by their sulphate-reducing bacterial partners, *Desulfosarcina* and *Desulfocococcus* (e.g., Boetius et al., 2000).

$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$

The oxidation of methane (and other hydrocarbon gases) under anoxic conditions leads to an increase in alkalinity and the subsequent precipitation of aragonite and Mg-calcites as (1) isopachous cements that line cavities formed by bedding expansion and (2) as carbonate nodules that tend to show repeated zonation with framboidal pyrite. Methane oxidation coupled to sulphate reduction further generates H_2S/HS^- that provides an inorganic energy source for sulphur-oxidizing bacteria, such as *Beggiatoa*, *Thiothrix* and *Thioploca* that form elemental sulphur as a metabolic by product. Sometimes oxygen consumption rates are lower than rates for sulphide oxidation, pointing also to the importance of nitrate as an alternative electron acceptor for sulphide oxidation. Any excess sulphide reacts with iron to precipitate as iron monosulphide, and it is not uncommon to observe pyritized remains of bacteria (Sassen et al., 2004). The diagenetic carbonate phases associated with hydrocarbon oxidation are typified by negative $\delta^{13}C$ values, reportedly as low as -60‰ (see Peckmann and Thiel, 2004). The variable isotopic signatures reflect the mixing ratio between groundwater DIC , highly negative DIC generated by the various metabolic pathways that preferentially oxidize ^{12}C from ^{13}C-depleted biogenic gases (as low as -110‰) and DIC from the thermogenic pool (-30 to -50‰).

5.2.2.1 Horseshoe Canyon Formation

All information on methanotrophic activity in the Horseshoe Canyon Formation comes from DNA data (Figure 53 and Figure 54). Methanotrophic cell densities appear equivalent between the formation well waters and the CBM wells, on average between 90,000-270,000 cell/mL, although some formation waters (samples 45 and 47) and CBM wells (samples 55 and 56) show densities as high as 860,000-4,400,000 cells/mL. It is interesting to note that of those high cell densities, <10% of the population are viable (Figure 48). DGGE analysis (Appendix 10) suggested the presence of methanotrophs as well. These results suggested that the following genera are present, *Methylobacter/Methylobacterium* and *Methylobacillus*. The *Methylobacter/Methylobacterium* are present in samples 44, 51 and 52, while *Methylobacillus* is found in samples 44 and 45.

Although methanotrophs are obligate aerobes, it is interesting to note that the well waters have very low dissolved O_2 concentrations (between 0.12 to 0.25 mg/L). Thus, it is unclear as to what their TEA is because even dissolved nitrate concentrations are below detection. The only clue at present is the DNA data which suggests the presence of methanogens in the same well waters, and thus would imply the use of sulphate as a TEA. However, methanogen densities are low in each of those wells, with the exception of sample 45.

5.2.2.2 Scollard and Paskapoo Formations

The Paskapoo Formation also has a number of wells with abundant methanotrophs, with sample 53 having between 860,000-4,400,000 cells/mL. Similar to the Horseshoe Formation, those wells also have minor methanogen populations (<90,000 cells/mL). DGGE results (Appendix 10) suggest that *Methylobacillus* is present in Sample 62, while both *Methylobacter/Methylobacterium* and *Methylobacillus* are present in Sample 63.

5.2.3 Organic Pollutant Oxidation

Micro organisms are also implicated in the modification of various groundwater organic anthropogenic pollutants. Most hydrocarbon degrading bacteria tend to be aerobic respirers since the aliphatic fraction is not fermentable, and hence, cannot be directly attacked by the majority of anaerobes (Atlas, 1981). Volatile hydrocarbons are similarly oxidized under oxic conditions, although as discussed above, anaerobic oxidation of methane and other gaseous hydrocarbons occurs profusely in anoxic environments. In other instances, the ability to attack hydrocarbons stems not so much from the micro organisms being able to directly use such a compound as a sole source of carbon and energy, but instead, the hydrocarbons are oxidized in a process known as co-metabolism. It necessitates that another compound, which may be quite unrelated, is the carbon and energy source, but its presence in some way permits the simultaneous oxidation of the hydrocarbon (Horvath, 1972).

One important fossil fuel-related issue is groundwater contamination by compounds such as benzene. Benzene is a major environmental concern due to its toxicity and high solubility, thus significant attention has focused on micro organisms that can attenuate its dispersion into drinking water supplies. Fortunately, a number of benzene-degrading aerobes have been identified, notably *Pseudomonas* species, which can account for the majority of gasoline-degrading bacteria in contaminated aquifers (Ridgway et al., 1990). Similarly, benzene degradation has been demonstrated in sediments with nitrate, ferric iron, sulphate and CO_2 as alternate electron acceptors (e.g., Lovley et al., 1994), thus extending the possibility for remediation over a broad range of Eh conditions.

5.2.3.1 Horseshoe Canyon Formation

It is promising that the most of the non-halogenated aromatic compounds are below analytical detection, however, it should be noted that these results were based on only a few samples, and in one case the analyses detected toluene. The biodegradation of non-halogenated aromatic compounds will be controlled, in part, by the presence of viable *Pseudomonas* and their presence in aquifer or soil is favourable. DGGE results (Appendix 10) suggest that *Pseudomonas* is present in samples 64 and 65. Their role in controlling concentrations of such pollutants is unclear however.

5.2.3.2 Scollard and Paskapoo Formations

The concentrations of non-halogenated compounds are below analytical detection limits, however, it should be noted that these results were based on only a few samples. The biodegradation of non-halogenated aromatic compounds will be controlled, in part, by the presence of viable *Pseudomonas*, and DGGE results (Appendix 10) do indeed suggest that *Pseudomonas* is present in Sample 60. Their role in controlling any possible concentrations of such pollutants in these formations is unclear however.

6 CBM Exploration Potential Within the Study Area

Most current CBM exploration tools assess the characteristics, the extent and the potential gas content of the coal. The most common considerations taken into account during the exploration for CBM resources include the following items discussed in an interview with D. Marchioni of the Geological Survey of Canada compiled by Finch (2006):

1) Coal seam thickness – thicker, laterally continuous coal zones generally make better targets
2) Gas content – coal with higher gas contents are considered better targets and helps to understand the resource potential
3) Maturity level of the coal – the maturity level of the coal reveals the nature of the coal chemistry which is significant when assessing gas content and type within coal beds
4) Permeability – permeability values must be high enough to allow the flow of gas
5) Water content – the nature and volume of water within the coal zone affects disposal decisions of any produced water

Typical exploration tools such as drilling, seismic information gathering and well testing, followed by mapping are used to assess the nature and extent of the various parameters listed above. The information is then used to select areas where gas accumulations are more likely. The sites are subsequently explored and the information is used to improve knowledge of a particular area.

Other methods may also exist to help define zones of higher CBM-potential. According to Van Voast (2003):

> "Formation waters associated with coalbed methane have a common chemical character that can be an exploration tool, regardless of formation lithology or age. Effectively devoid of sulphate, calcium and magnesium, the waters contain primarily sodium and bicarbonate and, where influenced by water of marine association, also contain chloride."

Van Voast (2003) continues:

> "The waters are typified not so much by their dissolved constituents but by the specific absence of some of these constituents. It is proposed here that coalbed methane will be found exclusively with formation waters of this specific chemical type. It does not follow, however, that methane will be found wherever these waters occur."

An approximate limit of 10 meq/L of dissolved sulphate is suggested by Van Voast (2003) as a maximum concentration associated with coalbed methane. Van Voast (2003) also suggests that a low (<3 mg/L per mg/L) sulphate/bicarbonate ratios characterizes most water produced in association with coalbed methane development.

Extensive data sets exist for wells within the study area that can be tested to assess CBM exploration-potential using this geochemical method. Formation-water datasets include the data used in a basin-wide CBM study conducted by Bachu and Michael (2002), data provided by Penn West Resources for 2 Scollard Formation CBM wells and the data collected in this study for Horseshoe Canyon Formation CBM wells. Information on the shallower portions of the coal-bearing formations within the study area is provided by data from the water wells collected as part of this study, data from water wells collected by Lemay (2003), water well data compiled by Bachu and Michael (2002) and from water well analyses compiled from government sources.

In the assessment of major ion chemistry as an exploration tool, Van Voast (2003) generated plots of what he determined to be the chemical signature of CBM-related water. An examination of these plots and the text suggests that water associated with CBM has the following characteristics:

- Sodium ≥10 meq/L
- Calcium ≤ 3 meq/L
- Magnesium ≤ 3 meq/L
- Sodium (meq/L)/Calcium (meq/L) ≥ ~90
- Sodium (meq/L)/Magnesium (meq/L) ≥ ~90
- Sulphate < 10 meq/L
- Bicarbonate ≥ 10 meq/L
- Sulphate (mg/L)/Bicarbonate (mg/L) < 3

By querying the available data according to these chemical characteristics, it was possible to highlight areas where the water chemistry, according to Van Voast, is associated with possible CBM accumulations. Comparison of these areas to areas where CBM is produced or is of interest to explorers suggests to us that these criteria need modification to be successful in the Alberta Basin.

6.1 CBM Potential in the Horseshoe Canyon Formation

Data within the study area was compiled from the work of Lemay (2003), Bachu and Michael (2002), from oil and gas wells and from government sources of information on water well water chemistry. The appropriate calculations were carried out on these water chemistry results and compared to the criteria discussed above. The table below summarizes the results of these comparisons (Table 27).

Table 27. Horseshoe Canyon Formation water chemistry comparison to ideal CBM water characteristics

		Number of Points passing the various criteria								
Dataset	**# of Points**	**Na**	**Ca**	**Mg**	**Na/Ca**	**Na/Mg**	**SO_4**	**HCO_3**	**SO_4/HCO_3**	**All**
Current study	11	11	11	11	1	9	11	9	11	1
Lemay (2003)	15	14	13	14	1	12	8	14	15	1
Bachu and Michael (2002)	128	96	82	95	13	48	79	103	126	10
Government data sources	3713	2550	2335	3354	103	1071	2918	2778	3670	84
Totals	3867	2671	2441	3474	118	1140	3016	2904	3821	96

As can be seen in the table above, 96 of the 3867 water analyses, or 2.5%, have a signature consistent with the criteria as established in Van Voast (2003). It should be noted that some duplication between the Bachu and Michael (2002) and government source datasets might exist. As such the above percentage is only approximate, but is likely a close approximation. When these data points are plotted on a map of the study area (Figure 57) some clusters of data points are apparent.

The first cluster of data points appears to be located close to the subcrop boundary between the Scollard and Horseshoe Canyon Formations, to the southwest of the City of Camrose. It is interesting to note that these points fall within the area of the Drumheller coal zone defined in Beaton et al. (2002) as having

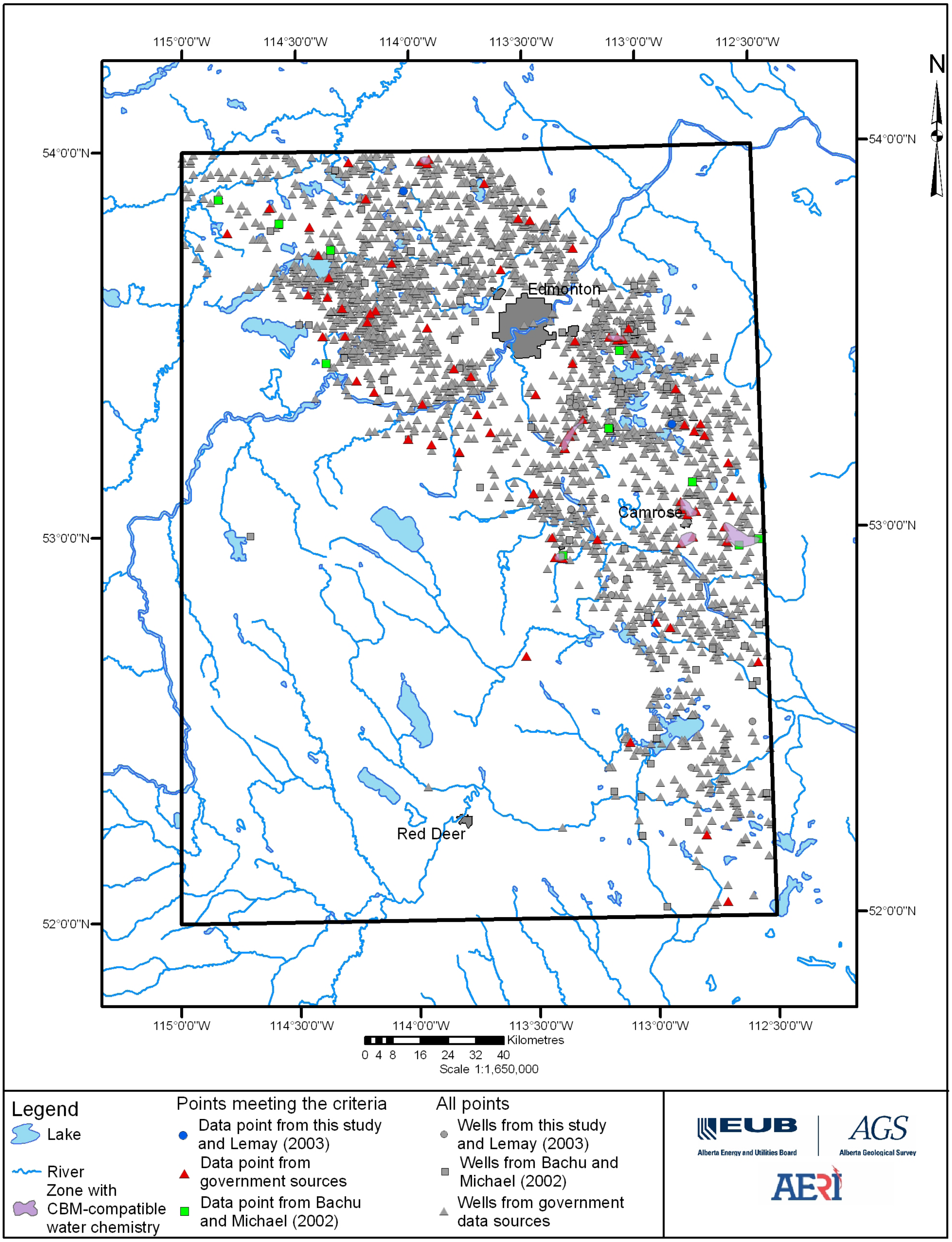


Figure 57. Location of water wells completed in the Horseshoe Canyon Formation with CBM-compatible water chemistry values - criteria as approximated from Van Voast (2003).

a gas content of approximately 2 bcf/section. The second concentration of data points is located to the east and northeast of the City of Camrose. The third cluster of data appears to be to the northwest of the City of Camrose and west of the Miquelon Lakes. The fourth cluster of data points is located north and northwest of Cooking Lake near the City of Edmonton. Gas content in the Drumheller coal zone in the areas of these last three clusters is between 0 and 1 bcf/section. These areas are in a zone where active exploration and development of CBM is occurring and so the presence of water types compatible with CBM accumulations seems to suggest that the current exploration focus in these areas is justified. The fifth cluster of locations with a CBM-compatible water composition is located west of the City of Edmonton, to the east of Wabamun Lake and south of Lac Ste Anne, in the vicinity of the Scollard and Horseshoe Canyon formations subcrop boundary. Gas content in the Drumheller coal zone in this area is between 0 and ≥ 1 bcf/section, but < 2 bcf/section. The remaining locations with a CBM-compatible composition appear generally scattered throughout the study area.

None of the CBM wells sampled had water chemistry signatures consistent with the general criteria put forward by Van Voast (2003). The CBM wells were excluded based on the Na/Ca ratios that were all below 90, and by the bicarbonate concentrations in 2 of the samples (samples 56 and 57) being below 10 meq/L. Methane was collected from each of these wells and is the dominant gas within the gas samples with a mole fraction of between 0.7546 and 0.9673. This suggests that either the signature of water associated with CBM in the Alberta Plains is somewhat different from that observed in the CBM basins in the USA, or that the water samples collected from these wells are not entirely representative of the actual formation water and may have been diluted by fresher water. An obvious mechanism for dilution is not apparent however since most of these wells have had the water removed from the well bore previous to this sampling event and the oxygen and hydrogen isotope plot suggests that the water composition is consistent with a formation water source. Although the possibility can't be ruled out, contamination does not appear to be the likely cause of the observed differences between Alberta and US CBM water. If the criteria are modified to use the Alberta CBM values then a different picture emerges as to potential zones.

The criteria in this case are similar to those used by Van Voast (2003), but have a different Na/Ca ratio value. In this case, the lowest ratio for the CBM wells with methane as the dominant gas in the gas analysis was 47.5. Both the Na/Ca and Na/Mg ratios were set to 47 and the water chemistry data was again queried. The following table summarizes the effect this change has on the overall number of wells with CBM-compatible water signatures (Table 28).

Table 28. Horseshoe Canyon Formation water chemistry comparison to possible Alberta CBM water characteristics.

		Number of Points passing the various criteria								
Dataset	**# of Points**	**Na**	**Ca**	**Mg**	**Na/Ca**	**Na/Mg**	**SO_4**	**HCO_3**	**SO_4/HCO_3**	**All**
Current study	11	11	11	11	8	10	11	9	11	6
Lemay (2003)	15	14	13	14	6	12	8	14	15	4
Bachu and Michael (2002)	128	96	82	95	41	54	79	103	126	33
Government data sources	3713	2550	2335	3354	471	1478	2918	2778	3670	369
Totals	3867	2671	2441	3474	526	1554	3016	2904	3821	412

In this case, approximately 11% of the wells have a water chemistry signature that might be compatible with the occurrence of CBM. The following figure shows the spatial distribution of these points along with a series of polygons that groups some of the concentrations of points (Figure 58). For the most part, the clusters of CBM-compatible water chemistries are in the same locations as the clusters noted using the earlier more exclusive criteria. The more inclusive criteria reveal some clusters of data to the north of Lac Ste Anne and to the north and northwest of the City of Edmonton however.

Alberta Environment maintains a database of information on water wells within the Province. Included within this database is information on whether or not gas was noted during or after drilling. The data are somewhat subjective since gas present observations are not quantified, the composition of the gas is not known, and the interval the gas is coming from is not identified. Nevertheless, the data can help to further evaluate the water chemistry criteria used to assess the potential presence of CBM. The figure below (Figure 59) shows the locations where gas was noted and also shows the locations where CBM-compatible waters were identified. Although the areas do not overlap precisely, there are a number of clusters of data that coincide with wells identified as having gas present. Additional clusters could also be drawn using the available data.

Regardless of which set of criteria is used to assess CBM compatibility of water within the Horseshoe Canyon Formation, the question of whether or not these clusters represent possible accumulations of CBM remains. On the con side of the argument: 1) the CBM wells sampled as a part of this study were only included within the selected wells after the criteria were modified so that they were included; 2) the remaining wells are wells that are not necessarily completed in coal, are generally less than 100 m deep and may or may not be well connected to deeper gas charged portions of the Formation; and 3) even though the 1 water well sampled as part of this study completed in the Horseshoe Canyon Formation where gas was collected met the second set of compatibility criteria, the gas collected was predominantly CO_2 and not methane. On the pro side of the argument: 1) the formations and hence pathways for groundwater flow in the Alberta Basin are different from those in the CBM basins of the USA and as such, perhaps it is to be expected that CBM-compatibility criteria are different as well; 2) the stable isotopic composition of water in the study area and the Cl/Br ratios indicate that water within the Horseshoe Canyon Formation is likely the result of mixing between a meteoric end member and a formation water end member and as such a connection between deeper and shallower portions of the Formation appears likely, although the time frame for mixing is still unclear; 3) regional groundwater flow in the area is towards the northeast, but given the shallow nature of most of the wells, groundwater flow will also be affected by topography and regional drainage features; 4) Cui et al. (2004) found that preferential transport of CO_2 over CH_4 by groundwater can substantially accumulate more gas rich in CO_2 upgradient of CH_4 accumulations, suggesting that CO_2 in a water well could be an indication of a deeper CH_4 source; and 5) A number of the clusters of data points are in close proximity to or include locations where gas was noted during or after drilling of wells as documented in Alberta Environment's water well database.

Additionally the following can also be said: 1) gas is present within the Horseshoe Canyon Formation; 2) wells completed in the Horseshoe Canyon Formation were encountered during this and previous sampling events or through the consultation of government records where gas was noted in water wells; 3) current exploration within the study area is focused in many of the areas highlighted by this analysis, 4) the wells that meet the criteria generally have higher concentrations of methanogens present in the water samples than those that fail to meet the criteria, suggesting that gas generation is a distinct possibility in these wells or other portions of this Formation; and 5) the CBM wells that meet the water chemistry criteria, where methane gas was noted appear to have a distinctly different microbial makeup compared to the wells that do not have methane gas accumulations or that do not meet the water chemistry criteria.

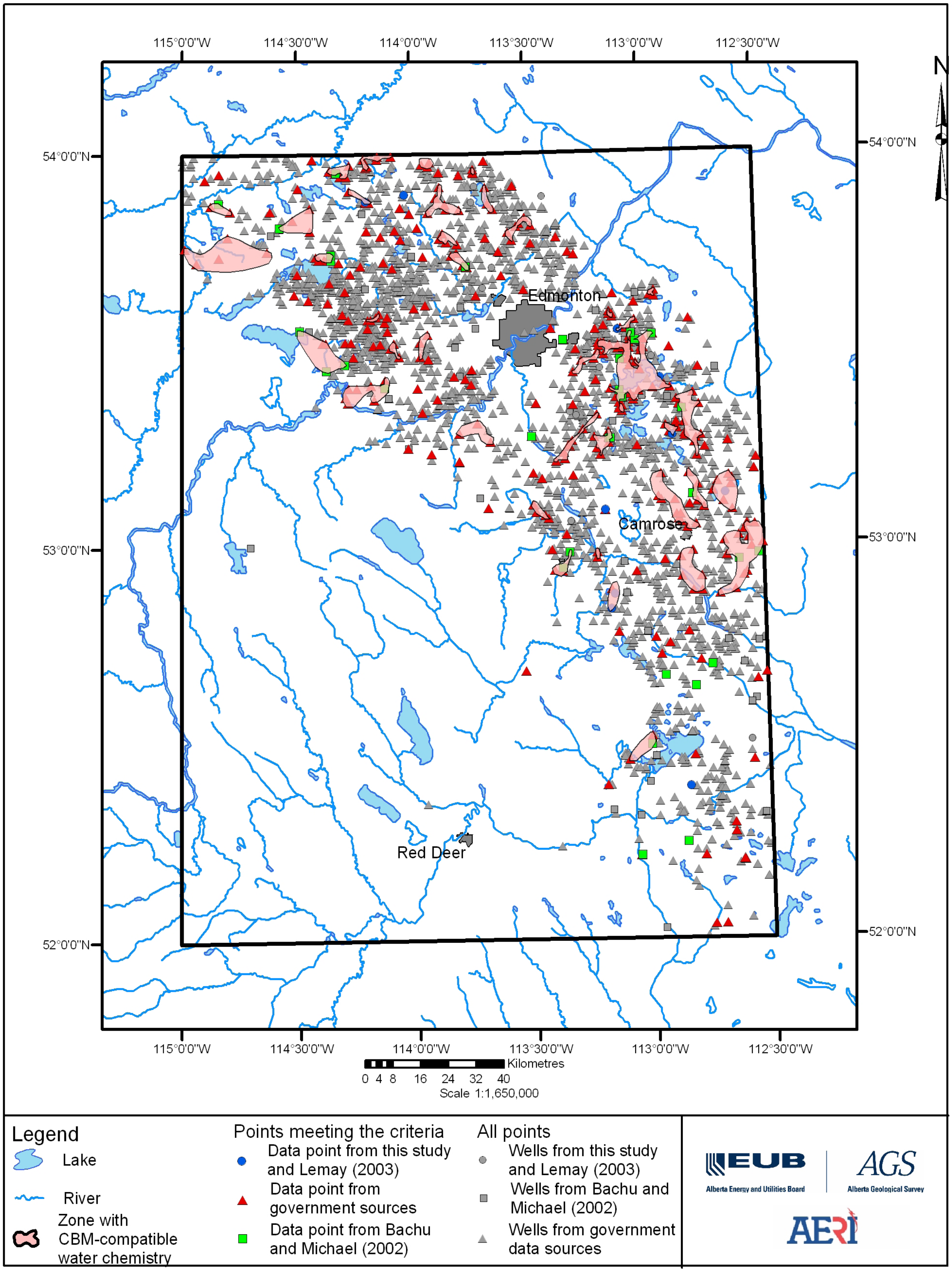


Figure 58. Location of water wells completed in the Horseshoe Canyon Formation with CBM-compatible water chemistry values - modified criteria.

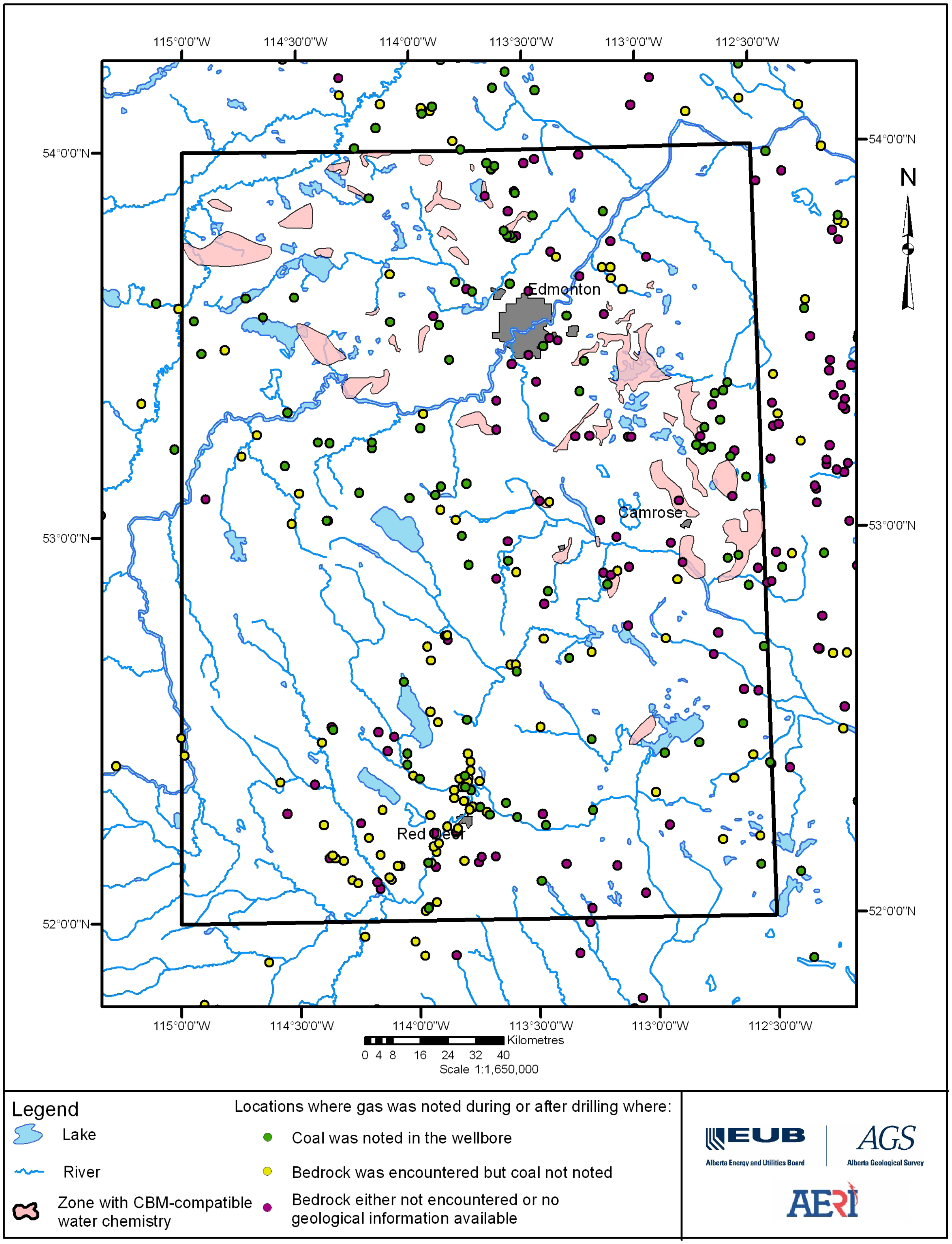


Figure 59. Locations where gas was noted compared to locations that meet CBM-water compatibility criteria in the Horseshoe Canyon Formation.

The use of standard water chemistry along with gas sampling, stable isotope ratios and microbiological parameters appears to confirm current exploration areas for CBM. The interpretation of the data also seems to suggest the possibility that through a knowledge of the groundwater flow characteristics of an area, methane accumulations could be discovered by moving either downwards in, or downgradient from areas where CBM-compatible water chemistries have been encountered. Therefore by comparing the major ion chemistry to the CBM-compatibility criteria, assessing the microbial population for the presence of certain microorganisms, and mapping out coal thickness, gas potential values and groundwater flow characteristics, potential exploration areas could be further highlighted.Care must be exercised during such an attempt at locating resources however. As Van Voast (2003) states (referring to his proposed compatibility criteria): "It is proposed here that coalbed methane will be found exclusively with formation waters of this specific chemical type. It does not follow, however, that methane will be found wherever these waters occur."

6.2 CBM Potential in the Scollard and Paskapoo Formations

The same sources used to compile data for the Horseshoe Canyon Formation were used to compile data for the Scollard and Paskapoo formations. The same types of calculations were performed on the data and the same criteria (developed by Van Voast (2003)) were applied to the results. The table below summarizes the results of these comparisons (Table 29).

Table 29. Scollard and Paskapoo formations water chemistry comparison to ideal CBM water characteristics.

		Number of Points passing the various criteria								
Dataset	**# of Points**	**Na**	**Ca**	**Mg**	**Na/Ca**	**Na/Mg**	**SO_4**	**HCO_3**	**SO_4/HCO_3**	**All**
Current study	10	6	6	10	1	3	9	5	10	0
Lemay (2003)	8	5	5	8	2	5	8	4	8	1
Bachu and Michael (2002)	231	124	193	204	35	70	223	102	231	18
Government data sources	4647	1448	2935	4034	54	303	4388	1671	4644	29
Totals	4896	1583	3139	4256	92	381	4628	1782	4893	31

In this case 0.6 % of the wells completed within the Scollard and Paskapoo formations within the study area have a water chemistry consistent with the criteria established by Van Voast for CBM potential. As with the Horseshoe Canyon Formation, certain clusters of data points can be seen on a map of the study area (Figure 60).

Fewer clusters of data points are present than on the Horseshoe Canyon Formation plot however. The most prominent cluster is located southeast of the City of Red Deer. Other less obvious clusters may exist to the southeast and to the north of Pigeon Lake. All of these clusters fall in areas of the Ardley coal zone that have gas contents >2 bcf/section based on the work of Beaton et al. (2002).

If the selection criteria are modified and instead of reflecting those developed by Van Voast (2003), reflect those developed for the Horseshoe Canyon Formation in this study, the number of data points passing the test increases and the extent and the number of clusters changes. The following table provides a summary of the effect this change in the criteria has (Table 30).

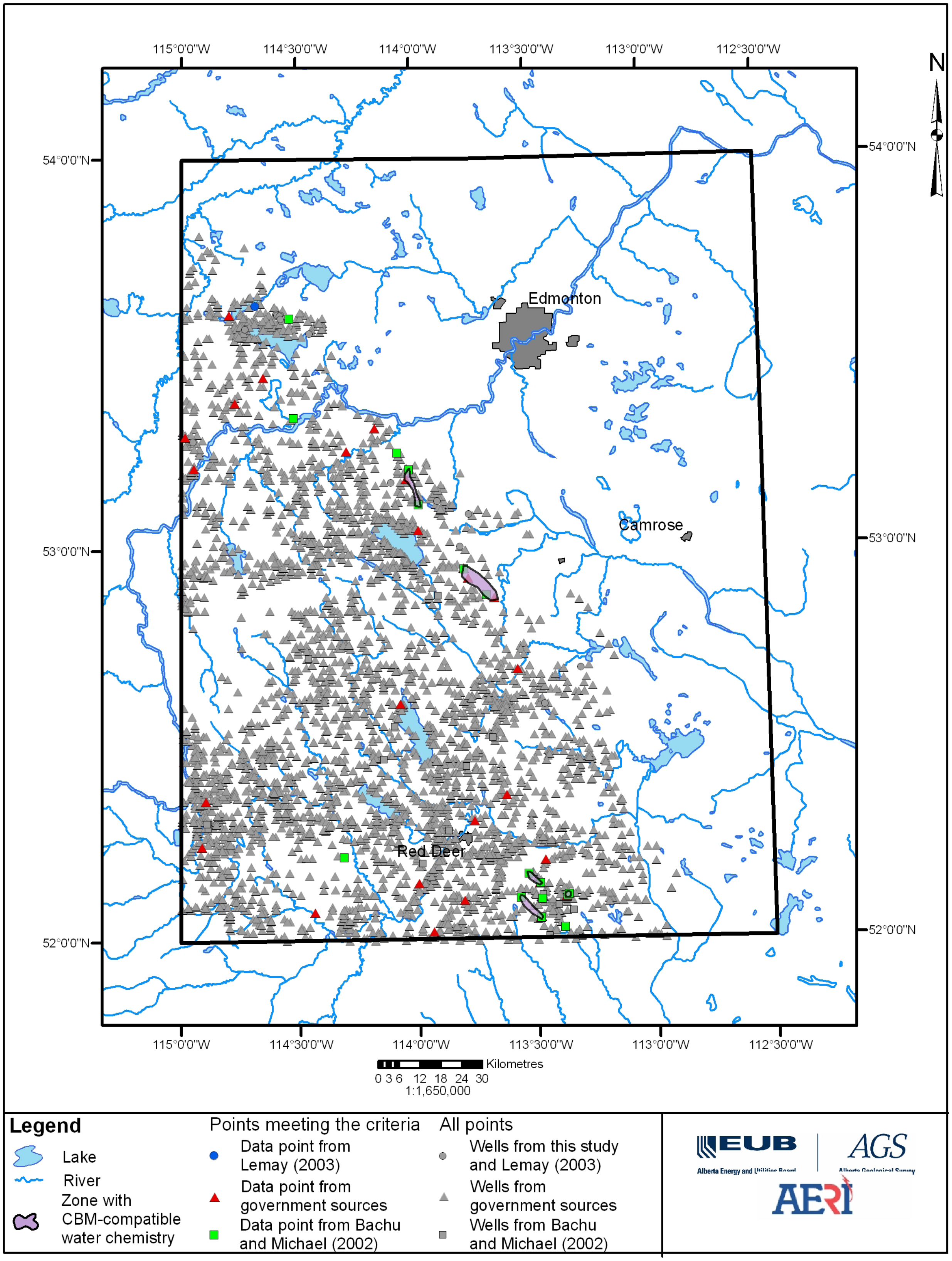


Figure 60. Location of water wells completed in the Scollard or Paskapoo formations with CBM-compatible water chemistry values - criteria as approximated from Van Voast (2003).

Table 30. Scollard and Paskapoo formations water chemistry comparison to possible Alberta CBM water characteristics.

			Number of Points passing the various criteria							
Dataset	**# of Points**	**Na**	**Ca**	**Mg**	**Na/Ca**	**Na/Mg**	**SO_4**	**HCO_3**	**SO_4/HCO_3**	**All**
Current study	10	6	6	10	2	3	9	5	10	1
Lemay (2003)	8	5	5	8	5	5	8	4	8	4
Bachu and Michael (2002)	231	124	193	204	65	87	223	102	231	35
Government data sources	4647	1448	2935	4034	165	568	4388	1671	4644	121
Totals	4896	1583	3139	4256	237	663	4628	1782	4893	161

The number of wells with a CBM-compatible water chemistry increases to 3.3% with a change in the selection criteria. Two additional clusters of data are revealed through this process, but the locations of the original clusters remain consistent. The number of data points associated with these original clusters has increased however. The new clusters are located to the west of Buffalo Lake and to the west northwest of Wabamun Lake. The following figure shows the locations of the points that meet these new criteria as well as the outlines of the clusters of data (Figure 61).

The one water well completed in the Scollard Formation (Sample 46) that was sampled as part of this program with sufficient dissolved gas for gas sampling has a CBM-compatible water signature when the modified set of criteria is used. In addition, field notes collected during sampling of this well indicated that there was abundant gas present. The gas isotope results suggest that the gas has a possible biogenic source and methanogens were detected in the water sample. Field notes made during the collection of the 4 samples from the work conducted by Lemay (2003) that met all of the CBM-compatibility criteria indicated that dissolved gas was present at each of the sites. One of these points along with the point from the current study are located in a cluster to the northeast of Pigeon Lake, while the others are found either at the east end of Isle Lake or towards the south end of Samson Lake. If these clusters of water well locations with CBM-compatible water chemistry are related to CBM accumulations, then a similar strategy as proposed for exploration in the Horseshoe Canyon might be applicable. Regional groundwater flow appears to be towards the northeast with some control by topography and hydrology apparent. By using this knowledge, the downgradient portions of the Formation, or deeper portions of the Formation might contain potential accumulations of CBM. Once again, the words of Van Voast (2003) should be heeded when applying any technique that uses major ion chemistry as an exploration tool, "It is proposed here that coalbed methane will be found exclusively with formation waters of this specific chemical type. It does not follow, however, that methane will be found wherever these waters occur."

Several clusters of data points are present around Pine Lake in the south-central portion of the study area. A discussion with a colleague involved in the sampling of wells in this area in the past, indicated that gas was encountered during sampling of these wells in this area. A cursory examination of well information in the area also shows the presence of coal in the subsurface. These wells are most likely completed in the Paskapoo Formation however and as such, the relationship between the CBM compatibility of the water chemistry and these locations is more difficult to assess in terms of CBM exploration. Rumours of exploration activity in the general area suggests some oil and gas industry interest in the prospects of gas in the vicinity of Pine Lake, and as such perhaps the presence of CBM-compatible water validates this interest.

When the locations of these clusters are compared to the locations of wells from AENV's groundwater

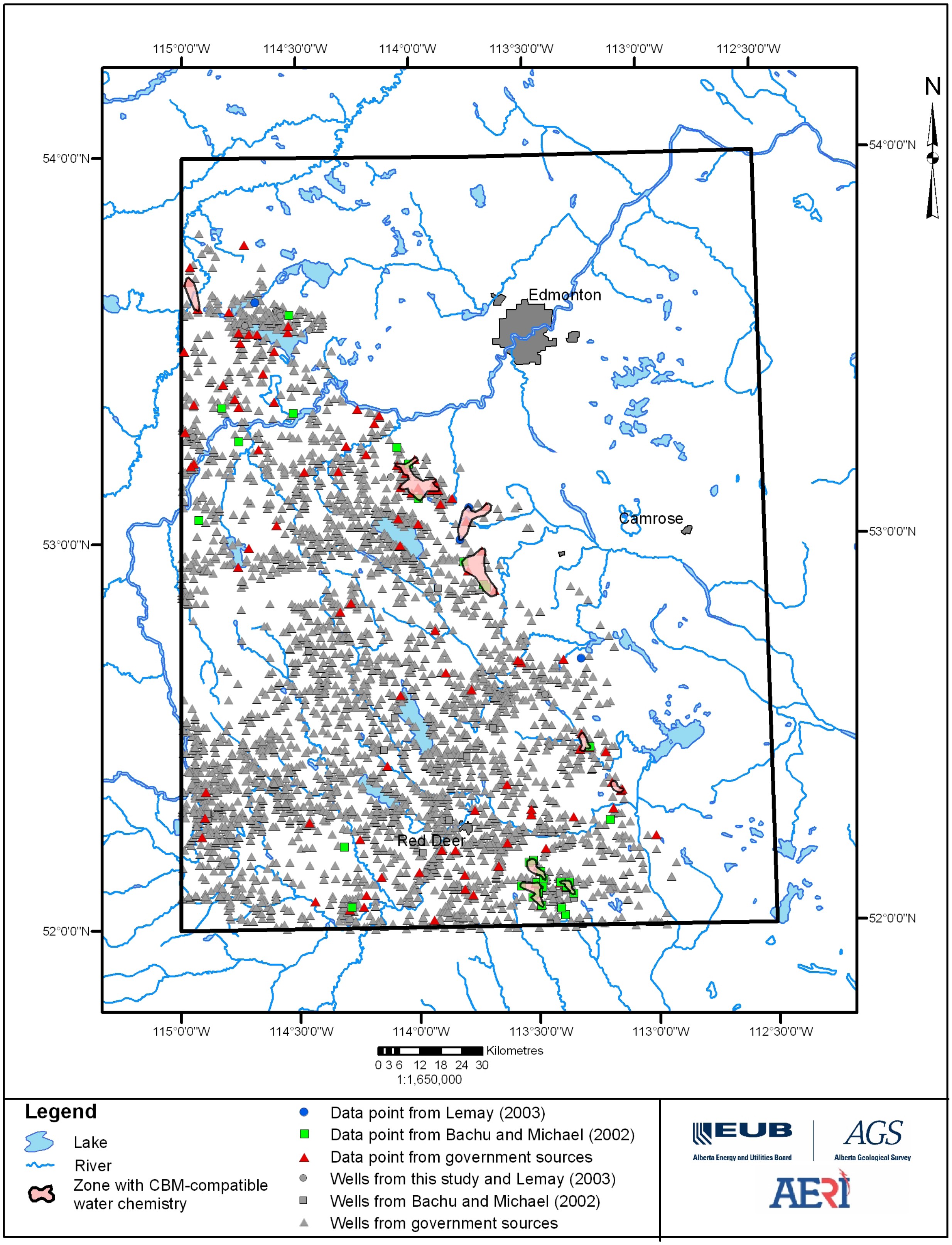


Figure 61. Location of water wells completed in the Scollard or Paskapoo formations with CBM-compatible water chemistry values - modified criteria.

database where gas was noted (Figure 62), a number of correspondences can be observed between the locations. The locations of gas noted observations also suggest that additional clusters could exist. The CBM-compatibility criteria appear to be supported to a certain degree by this independent data set.

In addition, as discussed in Section 6.1, the Horseshoe Canyon Formation CBM wells (samples 55, 64 and 65) that met the CBM-water compatibility criteria where methane was measured have a distinct microbial makeup. The sole Scollard/Paskapoo formation water well (Sample 46) with measured methane concentrations that met the CBM-water compatibility criteria has a very similar microbial composition. This may indicate that CBM accumulations have a distinct chemical and microbial signature regardless of coal-bearing formation and that the combination of geochemical and geomicrobiological mapping could assist in their discovery. Therefore by comparing the major ion chemistry to the CBM-compatibility criteria, assessing the microbial population for the presence of certain microorganisms, and mapping out coal thickness and gas potential values, potential exploration areas could be further highlighted. Care must be exercised during such an attempt at locating resources however. As Van Voast (2003) states (referring to his proposed compatibility criteria): "It is proposed here that coalbed methane will be found exclusively with formation waters of this specific chemical type. It does not follow, however, that methane will be found wherever these waters occur."

7 Conclusions

The water sampling program undertaken as part of this project has yielded a number of interesting conclusions. The following is a list of the various generalized conclusions from the various sections of the report ordered by the major goals listed in the introduction. The goals included: 1) the development of a better understanding of coalbed methane generation and its resource potential in Alberta; 2) the development of potentially new exploration strategies based on water chemistry and geomicrobiology; 3) the assessment of the connection between gas-producing and domestic or agricultural water use zones of coalbeds; 4) the development of water handling and disposal strategies consistent with the goals of regulators, stakeholders and developers and the compilation of baseline datasets for future reference.

Goal 1 – The development of a better understanding of coalbed methane generation and its resource potential in Alberta

- Some of the water-well carbon stable isotope values indicate that biological methane oxidation has occurred. (Section 5.1.3.1)
- Certain of the sulphur stable isotopic compositions indicate that processes such as sulphide oxidation or sulphate reduction have occurred and are likely biologically mediated (Section 4.6.3.1 and Section 4.6.3.2).
- The stable isotopic composition of the gas samples suggests that the majority of the methane present in the gas samples is likely made up of both biogenic and abiogenic components while certain samples are clearly biogenic (Section 4.6.4.1, Figure 27, Figure 28, Section 4.6.4.2, Figure 29, Section 5.1.3.1 and Section 5.1.3.2).
- Certain important pieces of information are lacking in order to assess the microbial activity within coal-bearing formations within the study area, but certain parameters suggest that micro organisms are generating methane in some of the wells (Section 5.1.3.1 and Section 5.1.3.2).

Goal 2 – The development of a better understanding of potentially new exploration strategies based on water chemistry and geomicrobiology

- The application of major ion chemistry values identified certain areas as having CBM-compatible water (Section 6.1 and Section 6.2).

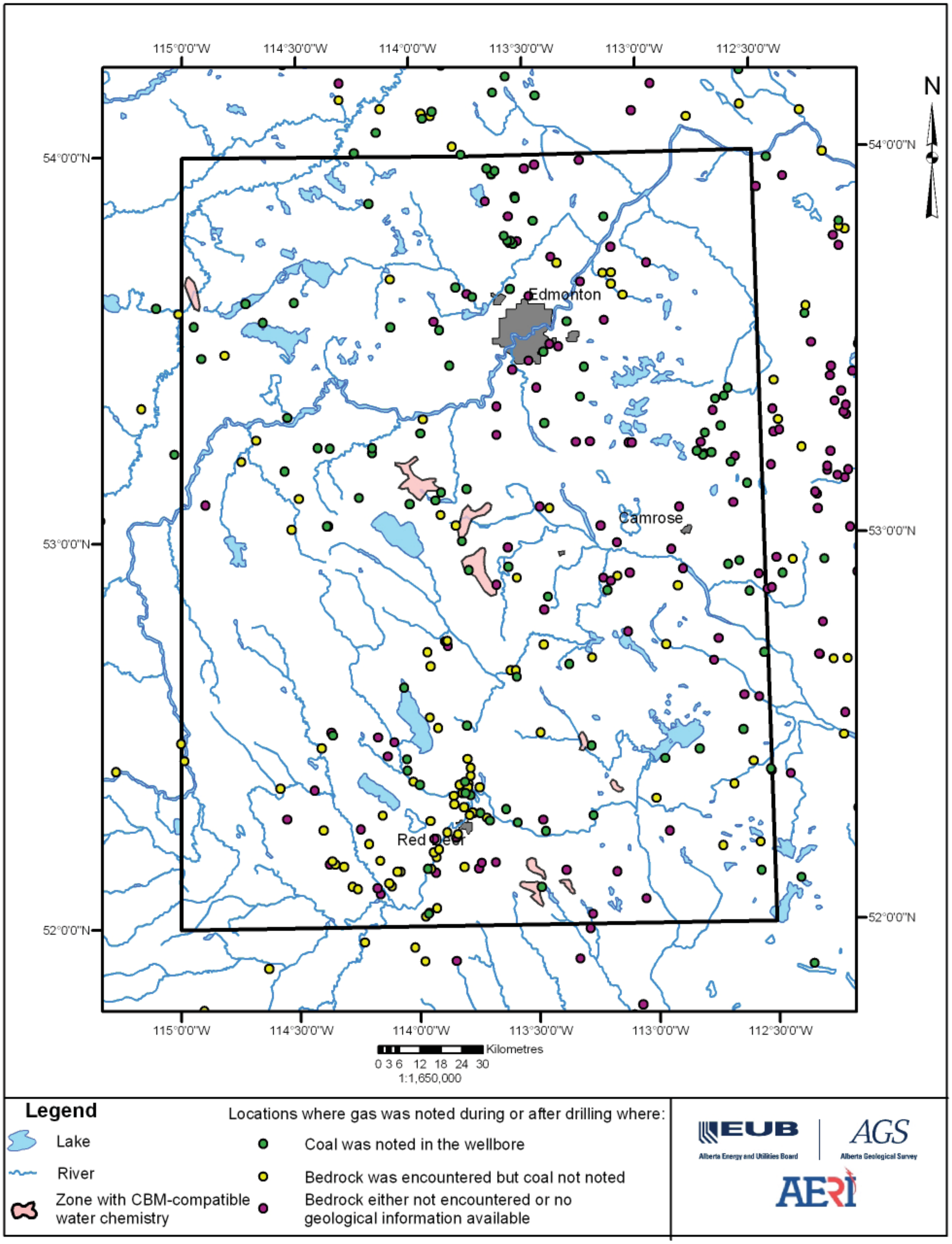


Figure 62. Locations where gas was notede compared to locations in the Scollard and Paskapoo formations that meet CBM-water compatibility criteria.

- Comparison of the locations of samples with areas where current CBM exploration is occurring and where gas was noted in water wells shows a number of areas where overlaps occur (Figure 57, Figure 58, Figure 60 and Figure 61).
- Field evidence along with laboratory analyses show that gas was encountered at certain sites visited as part of this sampling event and past AERI-funded sampling events.
- There is an apparent biological signature in the water samples collected as part of this program that have a CBM-compatible water signature and where a gas sample was collected.
- All of these samples have the six major types of micro organisms identified by the PLFA analysis whereas the others do not (Figure 51).
- By using information on regional groundwater flow and the locations of wells with CBM-compatible water chemistry, CBM accumulations might possibly be located deeper in the Formation below these wells or downgradient of these wells.

Goal 3 – The assessment of the connection between gas-producing and domestic or agricultural water use zones of coalbeds

- Major ion chemistry suggests that the water samples collected from most of the water wells have been influenced by standard geochemical processes perhaps in conjunction with biological processes to give the water wells an almost consistent Na-HCO_3 water type (Section 4.4.1.1, Figure 17, Section 4.4.1.2 and Figure 19).
- CBM-well major ion chemistry suggests that these water samples have undergone a greater degree of geochemical evolution and are generally characterized by a Na-Cl water type (Figure 17).
- The major ion chemistry of the water samples collected from the vicinity of the Whitewood Mine near Wabamun Lake indicates a rather immature water in terms of its geochemistry (Figure 19).
- Chloride/Bromide ratios suggest that the water within the shallower portions of the formations is the result of mixing between a formation-water end-member and a meteoric-water end-member and appear to be consistent with values determined for water samples collected during previous studies (Section 4.4.2.1, Figure 21, Section 4.4.2.2 and Figure 22).
- Stable isotope values of oxygen and hydrogen of the water samples appear consistent with values collected from previous sampling events and suggest that the isotopic composition is the result of mixing between a formation water end member and one or more meteoric end members (Section 4.6.1.1, Figure 23, Section 4.6.1.2 and Figure 24).
- A trend in Sr composition and isotope values was noted in the Whitewood Mine dewatering wells suggesting that certain hydrogeological processes at this site could be modelled through the use of Sr isotope ratios (Section 4.7.1.2 and Figure 34).
- Groundwater age dating using $^{36}Cl/Cl$ suggests that when compared to recent glacial cycles for North America, there is an interesting relationship between the ages and warmer and colder climatic periods (Section 4.8.1.2, Figure 39 and Section 4.8.1.3).
- The age calculation using $^{36}Cl/Cl$ ratios suggested that the CBM well formation water ages are between approximately 4 to 12 times greater than the groundwater ages determined for the water wells (with 1 exception) indicating the possibility that the hydraulic connections between the shallower and deeper portions of the Horseshoe Canyon Formation could be limited or take place over long time periods (Section 4.8.1.2).

- There were indications that in situ fissiogenesis could be contributing ^{36}Cl to groundwater and therefore could be affecting the calculation of groundwater ages (Section 4.8.1.2, Section 4.8.1.3 and Figure 37).
- Groundwater dating using ^{129}I/I ratios could not confirm the age dates calculated using the ^{36}Cl/Cl values, but instead suggest that the water samples are relatively young and that some could be preserving traces of anthropogenic input. The presence of radiogenic elements in the coal and certain water samples indicates that in situ fissiogenic input of ^{129}I could be occurring and could affect the calculation of some of these ages however (Section 4.8.2.1, Section 4.8.2.2, Figure 42 and Figure 43).

Goal 4 - The development of water handling and disposal strategies consistent with the goals of regulators, stakeholders and developers and the compilation of baseline datasets for future reference.

- A number of major, minor and trace element inorganic element or compound concentrations and organic compound concentrations in the water samples exceeded established environmental water quality guideline values and as such any water management plans will have to take this into account (Section 4.4.3.1, Section 4.4.3.2, Section 4.5.1.1 and Section 4.5.1.2)
- Stable isotope values of carbon and oxygen of dissolved inorganic carbon (DIC) show that the majority of the DIC incorporated into the water was introduced through the dissolution of soil CO_2, through the dissolution of carbonate minerals, or some combination of the two (Section 4.6.4.1 and Section 4.6.4.2).
- Strontium isotopes in the water samples are consistent with values determined from previous sampling events and suggest that the majority of the Sr is introduced through the dissolution of Sr-bearing minerals (Section 4.7.1.1, Figure 30, Section 4.7.1.2 and Figure 34).

Based on these specific conclusions some more general conclusions can be made. These include:

- There is evidence that micro organisms are affecting the composition of water in coal-bearing aquifers in the study area and may be responsible for the generation of some or all of the observed methane. (**Goal 1**)
- A potential method for screening sites with CBM potential was attempted based on work conducted in the USA and it revealed a number of areas where CBM-compatible water chemistries could be found. It was found that this screening method needs to be adapted for Alberta. (**Goal 2**)
- A distinctive microbiological assemblage was noted in the wells where gas was noted and that had a CBM-compatible water chemistry signature. (**Goal 2**)
- These last two items suggest that the combined major ion chemistry analysis and microbiological analysis might serve as a tool to further highlight areas for exploration and development of CBM resources. (**Goal 2**)
- Water samples from shallower portions of the Horseshoe Canyon Formation have geochemical signatures that suggest their compositions are the result of mixing between a formation water end member and a meteoric water end member(s). (**Goal 3**)
- The age dates calculated from currently available radiogenic isotope data provided inconclusive results. The ^{129}I/I results suggest that the water samples are relatively young, but that some could be preserving the signature of anthropogenic input while others could have been affected by fissiogenic input of radiogenic isotopes thereby skewing the ages towards younger ones. The ^{36}Cl/Cl results also suggest the possibility of anthropogenic or in situ fissiogenic input of radionuclides in some of the samples. The calculated ages suggest that with one exception, the groundwater ages from the CBM

wells are much older than the groundwater ages from the water wells with the ages corresponding to interglacial periods for the most part. (**Goal 3**)

- The comparison of the water chemistry to existing environmental water quality guidelines indicates that a number of inorganic and organic parameters exceed the established guidelines and as such any water management plans will have to carefully consider these parameters during its design. (**Goal 4**)

8 Recommendations

The study has provided insight into a number of processes and answered a number of questions, there are however some areas that could benefit from additional clarification. The recommendations are organized by the original project goal they support and include a summary of approximate costs associated with implementing them. In many cases costs overlap and as such if multiple recommendations were implemented costs would be shared between them. These include:

1) Understanding the aquifer redox environment and its affect on micro organisms and microbiological processes occurring in coal-bearing formations (**Goal 1**)

In order to determine the dominant terminal electron accepting process (TEAP) occurring in an aquifer, aqueous samples from along a groundwater flow path are necessary. As outlined by Chapelle et al., (1995) there are different levels of confidence that can be applied when trying to ascertain the dominant redox process. These levels of confidence are based on the number of lines of evidence that lead to the interpretation of the occurrence of a particular redox process (Figure 63). For example, when O_2-reduction is the dominant TEAP, a decrease in O_2 is predicted as one moves along a groundwater flowpath. Despite the analyses of dissolved O_2 in some wells, which show low levels (<1 mg/L), it is impossible to ascertain the pattern of O_2 removal in the aquifer. Similarly, the accumulation of dissolved Mn(II) or Fe(II) suggests the reductive dissolution of Fe and Mn oxyhydroxides is occurring, although it is difficult to measure the concentrations of solids. The greatest confidence can be assigned when the consumption of reactants (e.g., fermentation products) and accumulation of products (e.g., H_2S and HCO_3^-) are measured.

Chapelle and Lovley (1992) and Lovley et al. (1994) have shown that there is a clear correlation between acetate and H_2 concentrations in groundwater and the dominant TEA's. In other words, groundwater has distinct electron donor concentration gradients for each particular metabolism and a threshold level below which, for example H_2, cannot be further metabolized. Therefore, when nitrate and/or Mn(IV) reduction are the dominant terminal electron accepting pathways, hydrogen concentrations are extremely low (<0.05 nM), with increasing levels through Fe(III) reduction (0.2 nM), sulphate reduction (1-1.5 nM) and methanogenesis (7-10 nM). The use of H_2 concentrations for assigning confidence to the dominant redox process is demonstrated by Chapelle et al., (1995), who examined numerous different geochemical systems. In addition to measurable changes in product/reactant concentration and H_2 concentration, there may be a segregation in the micro organisms responsible for individual redox reactions, that is, increased populations of Mn(IV)-reducers may be expected in zones of active Mn(IV)-reduction (e.g. Chapelle, 1993). Ascertaining aquifer microbial communities is described below. The costs associated with this recommendation include those related to sample analysis and field sample collection.

Analytical costs:	
Major, minor and trace element analysis	~$150/sample
Gas sampling	~$200/sample
Total of approximate costs	~$350/sample

The analytical costs associated with collecting 25 samples of each type could total approximately $8,750.

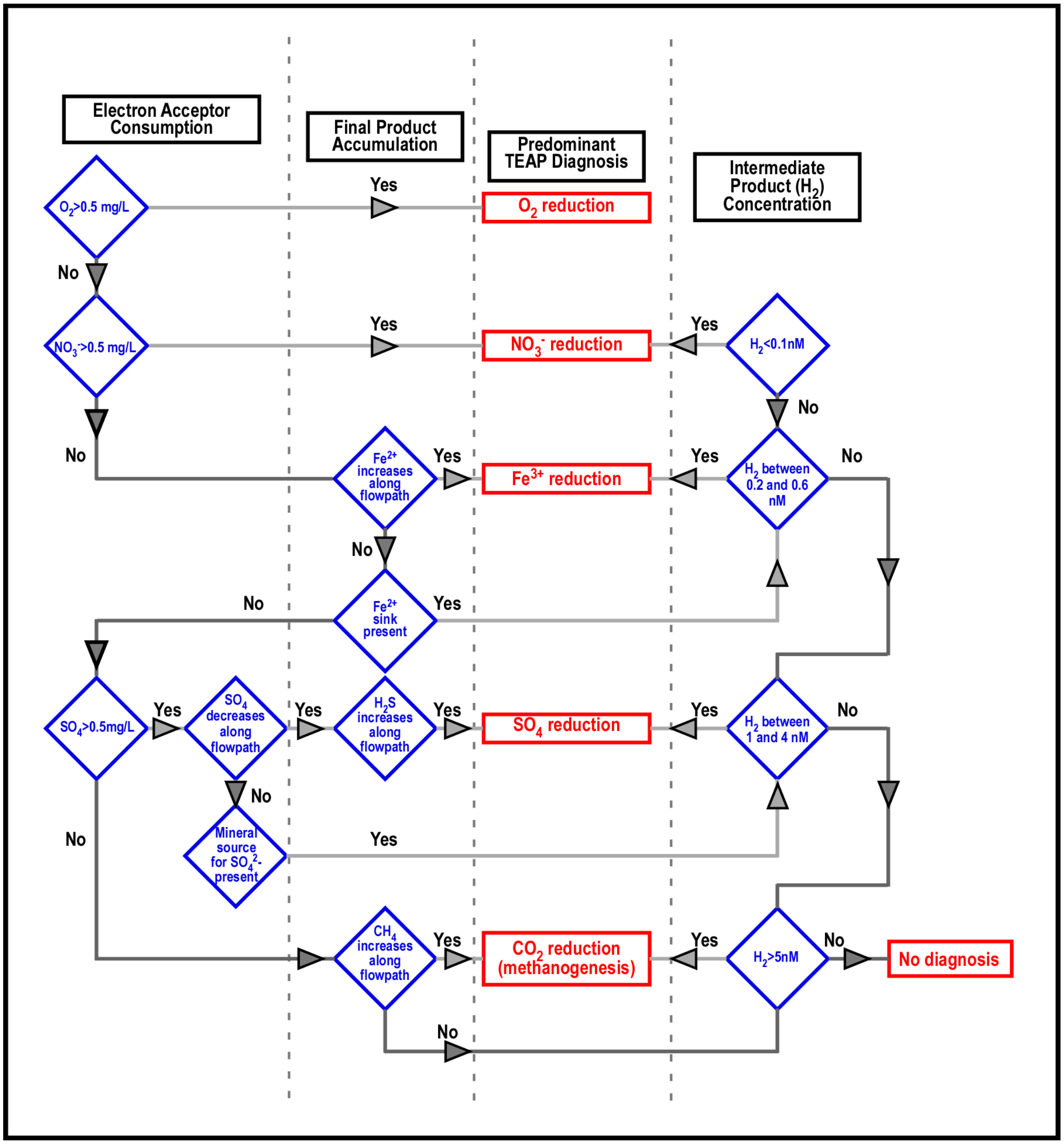


Figure 63. Dominant TEAPs in aquifers (Chapelle, F.H., McMahon, P.B., Dubrovsky, N.M., Fujii, R.F., Oaksford, E.T., and Vroblesky, D.A. (1995): Deducing the distribution of terminal electron-accepting processes in hydrologically diverse groundwater systems; Water Resources Research, v. 31, p. 359-371. Copyright [1995] American Geophysical Union. Reproduced/modified by permission of American Geophysical Union.)

Field sample collection costs are difficult to estimate. The determination of groundwater flow directions and the location of suitable sample sites could make the use of existing water wells difficult perhaps necessitating the installation of piezometers to complete the necessary assessment. The following general categories should be taken into account during the planning stages:

- Equipment rental if required (including vehicle rental)
- Meals and accommodation

- Fuel
- Piezometer installation if necessary
- Equipment purchases

2) Understanding the aquifer mineralogy and its affect on micro organisms and microbiological processes occurring in coal-bearing formations (**Goal 1**)

In order to differentiate amongst some of the dominant terminal electron accepting processes, solid-phase samples are required specifically Fe and Mn phases. Despite water analyses yielding information on Fe^{2+} and Mn^{2+}, without mineralogical data, it is not possible to identify whether metal reductive processes are taking place within the aquifer, and furthermore, where along the flowpath the reductive dissolution of Mn and Fe oxyhydroxides is occurring. This will prove important from the point of view of extraction as well. For example, Mn has been measured in some waters in the Horseshoe Canyon formation (Figure 37), suggesting reductive dissolution of Mn(IV) phases at the sampled location, or somewhere upgradient. The reductive dissolution of ferric oxyhydroxides is not predicted to occur in the presence of Mn(IV)-oxide, until the Mn(IV) solid-phase source is depleted (Postma, 1985). Thus, despite Fe^{2+} concentrations being below detection limits, a source of Fe(III) may still exist within the flow path. Furthermore, the oxidation of Fe(II) is kinetically much faster than the oxidation of Mn(II) (e.g. Langmuir, 1997), so its rapid loss may mask whether Fe(III) reduction has even taken place. Therefore, future studies should focus on more detailed groundwater sampling along a known flow path, with the view of simultaneously collecting solution and solid-phase samples.

To further elucidate on the potential mineralogical sinks, equilibrium modeling should also be undertaken using USGS modeling software PHREEQC (Parkhurst and Appello, 1999). The assumption of local equilibrium is often met, that is the residence time of the water is greater than the reaction ½ time (Langmuir, 1997). The use of an equilibrium model will allow for the dissolving and precipitating mineral phases to be predicted. For example, one could infer whether the sink for Ca^{2+} down the flowpath is sorption or mineral precipitation based on the saturation indices for carbonate minerals.

The costs associated with this recommendation include those related to sample analysis, field sample collection and modeling.

Analytical costs:

Major, minor and trace element analysis of water samples	~\$150/sample
Total of approximate costs	~\$150/sample

Whole rock analysis	~\$45/sample
Sample preparation for mineral identification	~\$75/sample
Total of approximate costs	~\$115/sample

The collection of information on water and coal zone chemistry and mineralogy in such a program could necessitate the installation of approximately 25 piezometers installed at various depths. The analytical costs associated with collecting 25 water samples could total approximately \$3,750. The analysis of rock samples from the various coal zones, if on average 5 coal zones/site were encountered could total \$5,625. If samples for mineral identification are prepared the cost could total \$9,375. The total analytical costs could therefore reach approximately \$18,750.

Field sample collection costs are difficult to estimate, but the following general categories should be taken into account during the planning stages:

- Equipment rental if required (including vehicle rental)
- Meals and accommodation
- Fuel
- Piezometer installation (for 25 sites could cost approximately $1,000,000)
- Equipment purchases

Modeling costs are also difficult to estimate, but the following categories should be taken into account during the planning stages:

- Software costs
- Calibration and verification requirements
- Auditing needs

3) Understanding the impact of micro organisms and microbiological processes on stable isotope compositions of dissolved gases and inorganic carbon occurring in coal-bearing formations (**Goal 1**)

In order to further constrain the source, either wet thermogenic or diagenetic, as well as the potential use of CH_4 as an electron donor for methanotrophic bacteria, additional samples should be obtained from the coal-bearing units, as well as from units directly above and below to constrain the effects of mixing. Ideally, the collection of further values of the inorganic $\delta^{13}C$, as CO_2 or DIC, would decrease the uncertainty of the present inorganic pool. The costs associated with this recommendation include those related to sample analysis and field sample collection.

Analytical costs:

Gas sample analysis	~$200/sample
Stable isotope determinations of gases	~$400/sample
Total of approximate costs	~$600/sample

The total analytical costs depending on the sampling requirements will vary. For instance, a sampling program designed to collect 25 samples could cost $15,000.

Field sample collection costs are difficult to estimate, but the following general categories should be taken into account during the planning stages:

- Equipment rental if required (including vehicle rental)
- Meals and accommodation
- Fuel
- Piezometer installation (if necessary)
- Equipment purchases

4) Understanding the microbiological structure within coal-bearing formations (**Goal 1**)

One of the major difficulties in defining the microbiological processes taking place in the various well waters has been trying to elucidate species structures from the DNA data provided. It is impossible to discern the relative proportion of different metabolic groups based simply on the different pie charts. Instead, a total tabulation of all the different types of metabolic groupings would be needed to better constrain just how relatively important one group is over another. Moreover, an assessment of viable biomass for each grouping would provide a better understanding of what metabolic pathway is most important in each well.

As discussed above, it is also impossible to extrapolate subsurface microbial community dynamics from well water analyses only because most micro organisms grow attached to solid surfaces. Therefore, the DNA recovered represents only a fraction of the total microbial community living in the subsurface. Along similar lines, some compounds generated as the result of microbial metabolism may be consumed by adjacent species, or may nucleate to form solid-phase precipitates, and hence, are not detectable by analysis of well waters alone. For these reasons, detailed inferences of microbial activity in the subsurface largely rely on the collection and analysis of aquifer sediment or the lining of fractures in bedrock (Phelps and Fredrickson, 2002). Accordingly, future examination of microbial communities and processes indigenous to the aforementioned formations should employ methods strongly focused on the analysis of solid-phase samples.

Investigations of the dynamics of subsurface microbial populations are broadly categorized according to the nature of techniques employed: (1) culture dependent methods, in which attempts are made to grow indigenous micro organisms under a variety of conditions, and (2) culture independent methods, which employ techniques in molecular biology to characterize microbial populations directly from solid-phase aquifer samples (i.e., by DNA extraction). Culture-dependent methods, although unable to provide relative abundances of microbial species, allow for microbial processes to be directly inferred. For example, incubation of sediment samples in growth media of varying chemistry, and monitoring the consumption of nutrients and the generation of metabolic by-products, allows for the characterization of microbial metabolisms that may be occurring within the aquifer (e.g., Kasai et al., 2005). This can include an understanding of the prevalent electron donors or terminal electron acceptors. The ultimate goal of such techniques is to reveal which micro organisms in the aquifer are responsible for specific chemical transformations (Connon et al., 2005). In addition to laboratory cultivation, culture-dependent methods include *in-situ* microcosm studies, where chemical conditions within a carefully selected section of the aquifer are modified by the injection of groundwater spiked with one or more compounds of relevance to specific micro organisms. By the monitoring of groundwater and solid-phase chemical transformations resulting from the injection, microbial processes may be directly identified and their importance in determining aquifer geochemistry may be confidently assessed (Mandelbaum et al., 1997). Also, laboratory cultures of micro organisms may be similarly injected directly into the aquifer flowpath in order to ascertain the role of those particular species in determining aquifer geochemistry. *In-situ* microcosm studies are advantaged over traditional laboratory culture-dependent methods by the fact that they closely mimic natural conditions, a difficult feat to achieve in laboratory settings. Furthermore, *in-situ* microcosm studies permit specific remediation strategies to be assessed directly in the aquifer system of interest. The shortcoming of culture-dependent methods is that they are unable to provide the identity of microbial populations, and for this reason, they are often accompanied by culture-independent methods (discussed below).

Culture-independent techniques involve sampling of DNA from the solid-phase samples for the identification of microbial species present. There exist multiple DNA extraction procedures that may be applied to soil and sediment samples; Miller et al. (1999) found that bead mill homogenization with sodium dodecyl sulphate, followed by DNA extraction into either chloroform or phenol, optimized the amount and fragment size of DNA isolated from a variety of soils and sediments. Isolated DNA is then amplified using traditional polymerase chain reaction (PCR) technology with universal 16S and 18S rRNA primers; microbial sequence databases focus on these genes for the identification of diverse microbiota. DNA-receptive (i.e., “competent”) laboratory strains of the bacterium *E. coli* are then incubated with the amplified 16S/18S DNA conjugated to a marker, and those that incorporate the DNA are selected for by expression of the marker. The resulting “clone library” serves to represent each 16S/18S sequence isolated from the natural sample by a corresponding laboratory culture that provides amply supply of the natural DNA of interest. Natural micro organisms are subsequently identified by 16S/18S rRNA homology to previously identified micro organisms, and may be enumerated by their relative importance within the overall subsurface microbial community. While costly DNA sequencing is required to obtain absolute identification by 16S/18S sequence homology, alternative techniques that compare banding patterns on agarose gels, such as denaturing gradient gel electrophoresis (DGGE) and/or terminal restriction fragment length polymorphism (T-RFLP), permit the comparison between samples by band presence/absence, and serve as effective tools for the selection of DNA bands to be sequenced for absolute identification. These techniques have become routine for many environmental microbiology laboratories, and in the case of DGGE, are capable of identifying species by DNA gel banding patterns, even if they comprise as little as 10% of the *in-situ* microbial community (Torsvik et al., 2002). Beyond simple identification, the above-mentioned culture-independent methods have been employed to reveal temporal and spatial variability in microbial community structure as a function of time, depth, recharge condition, and geochemical environment (Haack et al., 1985). Culture-independent methods benefit from quantitative estimates of *in-situ* biomass obtained by microscope cell counting, or more recently and cost-effectively, by flow cytometry (DeLeo and Baveye, 1996). Finally, as a complement or follow up to the above culture-independent methods, fluorescent *in-situ* hybridization (FISH) may be applied directly to sediment samples without DNA extraction; fluorescently-labelled DNA probes that have affinity for 16S/18S DNA sequences specific to the species or phylum level may be incubated with natural samples, and directly imaged using an epi-fluorescent light microscope. Micro organisms with DNA sequences corresponding to the selected probes fluoresce and may then be enumerated by cell counting. FISH enables quantification of specific microbial populations directly from natural samples without DNA extraction and sequencing, and while generic probes are commercially available for a wide variety of species, customized probes may be ordered that are tailored for the indigenous micro organisms of the aquifer of interest.

Costs associated with the implementation of this recommendation are difficult to propose given the different methodologies and the uncertainty surrounding the success of each. Such a program could have costs in the $10,000+ range and depending on the need for piezometer installation could be quite higher.

5) Understanding the process of methane generation by micro organisms in coal-bearing formations (**Goal 1**)

Although DNA analyses have shown the presence of methanogenic communities within a number of formation and CBM wells, as well as Whitewood Mine dewatering wells, those same analyses have not provided sufficient detail to clarify speciation. As discussed above, this has an important bearing on the types of substrates utilized, and thus, the biogeochemical cycling that is taking place within the aquifer.

It would also be extremely useful if more information was available on the concentration of DOC in the well waters and its chemical breakdown, i.e., what compounds comprise the DOC. This would corroborate the DNA data in that one could obtain a better understanding of what organic substrates are available to the various chemoheterotrophic communities, including the methanogens. The costs associated with this recommendation include those related to sample analysis and field sample collection.

Analytical costs:

DNA analysis	~$500/sample
DOC analysis	~$350/sample
Total of approximate costs	~$850/sample

The total analytical costs depending on the sampling requirements will vary. For instance, a sampling program designed to collect 25 samples could cost $21,250.

Field sample collection costs are difficult to estimate, but the following general categories should be taken into account during the planning stages:

- Equipment rental if required (including vehicle rental)
- Meals and accommodation
- Fuel
- Equipment purchases

6) Understanding the process of methane use by micro organisms in coal-bearing formations (**Goal 1**)

The recommendations mirror those from in Recommendation 5, in that better described DNA data, and more complete aquifer groundwater chemistry is required to better understand the methane-related processes taking place in both the formation waters and the CBM wells. The costs associated with this recommendation include those related to sample analysis and field sample collection.

Analytical costs:

DNA analysis	~$500/sample
DOC analysis	~$350/sample
Total of approximate costs	~$850/sample

The total analytical costs depending on the sampling requirements will vary. For instance, a sampling program designed to collect 25 samples could cost $21,250.

Field sample collection costs are difficult to estimate, but the following general categories should be taken into account during the planning stages:

- Equipment rental if required (including vehicle rental)
- Meals and accommodation
- Fuel
- Equipment purchases

7) Understanding the presence of organic pollutants in coal-bearing formations and the role of micro organisms in organic pollutant oxidation (**Goal 1**)

It is promising that the most of the non-halogenated aromatic compounds are below analytical detection, however, it should be noted that these results were based on only a few samples, and in one case the analyses detected toluene. Given the BTEX compounds high vapour pressure, solubility in water and toxicity, it is recommended to obtain a few more representative samples. Furthermore, the biodegradation will be controlled, in part, by the presence of viable *Pseudomonas* and their presence in aquifer or soil is favourable. Consequently, it would be extremely useful to know in greater detail whether they are indeed present in the aquifer, and if so, are they active. The costs associated with this recommendation include those related to sample analysis and field sample collection.

Analytical costs:

DNA analysis	~$500/sample
Total of approximate costs	~$500/sample

The total analytical costs depending on the sampling requirements will vary. For instance, a sampling program designed to collect 25 samples could cost $12,500.

Field sample collection costs are difficult to estimate, but the following general categories should be taken into account during the planning stages:

- Equipment rental if required (including vehicle rental)
- Meals and accommodation
- Fuel
- Equipment purchases

8) Understanding the chemical and biological signatures of water associated with methane from coal-bearing formations and its use as an exploration tool (**Goal 2**)

The study utilized and modified an approach develop by Van Voast (2003) to determine the CBM compatibility of water samples compiled from a number of AGS and other government sources. Based on this analysis, a number of clusters of data points were identified throughout the study area. It was noted that a number of wells that had such a CBM-compatible signature were also locations where dissolved gas was observed or in the case of this study sampled. In addition, the biological profile of the samples collected as part of this study where gas was collected and that met the CBM-compatibility criteria was unique compared to those sites that didn't meet the criteria or that didn't have any associated gas. This analysis focused on the available datasets that were made up of primarily water well data and was limited to the CBM wells sampled as part of this program. Additional confirmation of the relationships between CBM water compatibility and microbial community structure should be expanded to include additional CBM wells. Such a confirmation could provide a valuable tool in determining the locations of other potential CBM accumulations. The cost to complete this work would include expenses related to field collection and analyses of the samples. A general breakdown is provided below.

Analytical costs:

Phospholipid Fatty Acid analysis	~$330/sample
Chemical analysis of water samples	~$100/sample
Gas composition analysis	~$125/sample
Total of approximate costs	~$555/sample

The analytical costs associated with a sampling program looking at 25 samples could therefore cost approximately $13,875.

Field collection costs are difficult to estimate but the following general categories should be taken into account during the planning stages:

- Equipment rental if required (including vehicle rental)
- Meals and accommodation
- Fuel
- Equipment purchases

9) The connection of shallower and deeper portions of coal-bearing formations (**Goal 3**)

The results of this study confirmed some of the ideas presented in previous work conducted in the Alberta Basin that water in the shallower portions of coal-bearing formations is composed of two end-member compositions. The first is a formation water end member while the other is a meteoric water end member. This suggests that these different portions of the formations are linked in some manner. What it does not do is specifically quantify this connection. The quantification of this connection could be achieved through the simulation of water withdrawals from the deeper portions of coal-bearing formations to see what occurs in the shallower portions while utilizing the chemical and age date information provided by this and other studies, and available information on the formation hydrogeology as constraints. Additional data on end member radiogenic isotope compositions, such as rain water and deep formation water, and in situ radiogenic isotope production rates would also assist in the calculation of groundwater age dates by providing starting point compositions and correction factors. The costs associated with this recommendation include those related to sample analysis, field sample collection and modeling.

Analytical costs:

Radiogenic isotope analysis of water for ^{36}Cl	~$1,000/sample
Radiogenic isotope analysis of water for ^{129}I	~$600/sample
Total of approximate costs	~$1,600/sample

Whole rock analysis for the presence of U and Th to calculate neutron fluxes	~$45/sample
Determininination of rock density and porosity	~$100/sample
Total of approximate costs	~$145/sample

The analytical costs associated with collecting 25 samples of each type could total approximately $43,625.

Field sample collection costs are difficult to estimate, but the following general categories should be taken into account during the planning stages:

- Equipment rental if required (including vehicle rental)
- Meals and accommodation
- Fuel
- Equipment purchases

Modeling costs are also difficult to estimate, but the following categories should be taken into account during the planning stages:

- Software costs
- Calibration and verification requirements
- Auditing needs

10) Water management of produced water at CBM sites (**Goal 4**)

The majority of CBM developers in the Province have not encountered situations where water management has become a significant issue as much of the production has been termed “dry”. As exploration continues and new areas are developed, such issues could arise and will have to be dealt with. This study has shown that many of the water samples have concentrations of dissolved parameters that exceed certain environmental water quality guideline values and TDS values that categorize them as non-saline. Alberta Environment released a document in April, 2004 entitled “Alberta Environment Guidelines for Groundwater Diversion for Coalbed Methane/Natural Gas in Coal Development” that outlines the process for obtaining a groundwater diversion in such a case. Additional work to map out areas where such authorizations are required as well as categorizing the areas where water quality guideline values are exceeded could assist in the development of water management plans as well as guide some exploration decisions. The costs associated with this recommendation include those related to sample analysis and field sample collection.

Analytical costs:

Major, minor and trace element analysis	~$100/sample
BTEX and hydrocarbons analysis	~$205/sample
PAH analysis	~$200/sample
Phenols analysis	~$39/sample
Total of approximate costs	~$544/sample

The costs associated with collecting 25 samples is therefore approximately $13,600.

Field sample collection costs are difficult to estimate, but the following general categories should be taken into account during the planning stages:

- Equipment rental if required (including vehicle rental)
- Meals and accommodation
- Fuel
- Equipment purchases

9 References

Abraham, C. (1999): Evaporation and evapotranspiration in Alberta: report 1912-1985 data 1912-1996; Alberta Environmental Protection, Water Management Division, Water Sciences Branch, 82 p.

Adams, J.J., Rostron, B.J. and Mendoza, C.A. (2000): Regional fluid flow and the Athabasca oil sands: numerical simulations using a fully-coupled heat, solute and groundwater flow model; Geological Association of Canada– Mineralogical Association of Canada, Joint Annual Meeting, GeoCanada 2000, Program and Abstracts (CD-ROM), Abstract 476.

Ahrens, L.H. (1968a): Bismuth behaviour in natural waters; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, Pt. 17, p. 83-H-1.

Ahrens, L.H. (1968b): Bismuth Abundance in Common Igneous Rock Types; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, Pt. 17, p. 83-E-1–83-E-3.

Ahrens, L.H. (1968c): Bismuth abundance in common sedimentary rock types; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, Pt. 17, p. 83-K-1–83-K-2.

Ahrens, L.H. (1968d): Bismuth abundance in ocean and lake water; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, Pt. 17, p. 83-I-1.

Alberta Environment (1999): Surface water quality guidelines for use in Alberta; Alberta Environment, 20 p.

Alberta Environment (2004): Alberta Environment guidelines for groundwater diversion for coalbed methane/natural gas in coal development; Alberta Environment, 12 p.

de Albuquerque, C.A.R. and Shaw, D.M. (1970a): Thallium behaviour during weathering and alteration of rocks; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, Pt. 25, p. 81-G-1–81-G-2.

de Albuquerque, C.A.R. and Shaw, D.M. (1970b): Solubilities of compounds which control concentrations in natural waters; adsorption processes; valence states in natural environments; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, Pt. 25, p. 81-H-1.

de Albuquerque, C.A.R. and Shaw, D.M. (1970c): Thallium abundance in common igneous rock types; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, Pt. 25, p. 81-E-1–81-E-10.

de Albuquerque, C.A.R. and Shaw, D.M. (1970d): Thallium abundance in common sediments and sedimentary rock types; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, Pt. 25, p. 81-K-1–81-K-5.

de Albuquerque, C.A.R. and Shaw, D.M. (1970e): Thallium abundance in natural water; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, Pt. 25, p. 81-I-1.

Aller, R.C. and Rude, P.D. (1988): Complete oxidation of solid phase sulphides by manganese and bacteria in anoxic marine sediments; Geochimica et Cosmochimica Acta, v. 52, p. 751-765.

Allman, R. (1974): Fluorine Crystal Chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, Part 9, p. 9-A-1 to 9-A-6.

Anfort, S.J., Bachu, S. and Bentley. L.R. (2001): Regional-scale hydrogeology of the Upper Devonian–Lower Cretaceous sedimentary succession, south-central Alberta Basin, Canada; AAPG Bulletin, v. 85, no. 4, p. 637-660.

Appelo, C.A.J. and Postma D. (1994): Geochemistry, Groundwater and Pollution; A.A. Balkema, Rotterdam, Netherlands, 536 p.

Aravena, R., Warner, B.G., Charman, D.J., Belyea, L.R., Mathur, S.P. and Dinel, H. (1993): Carbon isotopic composition of deep carbon gases in an ombrogenous peatland, northwestern Ontario, Canada; Radiocarbon, v. 35, no. 2, p. 271-276.

Aravena, R., Wassenaar, L.I. and Plummer, L.N. (1995): Estimating ^{14}C groundwater ages in a methanogenic aquifer; Water Resources Research, v. 31, p. 2307-2317.

Archer, D.E., Emerson, S., and Reimers, C. (1989): Dissolution of calcite in deep-sea sediments: pH and O_2 microelectrode results; Geochimica et Cosmochimica Acta, v. 53, p. 2831-2845.

Atlas, R.M. (1981): Microbial degradation of petroleum hydrocarbons: An environmental perspective; Microbiology Reviews, v. 45, p. 180-209.

Bachu, S. (1995): Synthesis and model of formation water flow in the Alberta Basin, Canada; AAPG Bulletin, v. 79, no. 4, p. 1159-1178.

Bachu, S. (1999): Flow systems in the Alberta Basin: Patterns, types and driving mechanisms; Bulletin of Canadian Petroleum Geology, v. 47, p. 455-474.

Bachu, S. and Michael, K. (2002): Hydrogeology and stress regime of the upper Cretaceous – Tertiary coal-bearing strata in Alberta; unpublished report, Alberta Science and Research Authority, 73 p.

Bachu, S. and Underschultz, J.R. (1995): Large-scale underpressuring in the Mississippian-Cretaceous succession, southwestern Alberta Basin; AAPG Bulletin, v. 79, p. 989-1004.

Back, W. (1966): Hydrochemical facies and ground-water flow patterns in the northern part of the Coastal Plain; United States Geological Survey, Professional Paper 498-A, 42 p.

Back, W. (1961): Techniques for mapping of hydrochemical facies; United States Geological Survey, Professional Paper 424-D, p. 380-382.

Barker, J.F. and Fritz, P. (1981): The occurrence and origin of methane in some groundwater flow systems; Canadian Journal of Earth Sciences, v. 18, p. 1802-1816.

Barker, J.F. and Pollock, S.J. (1984): The geochemistry and origin of natural gases in southern Ontario; Bulletin of Canadian Petroleum Geology, v. 32, no. 3, p. 313-326.

Baur, W.H. (1972): Nitrogen crystal chemistry; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 7, p. 7-A-1 - 7-A-6.

Baur, W.H. (1974): Arsenic crystal chemistry; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 10, p. 33-A-1 - 33-A-8.

Beaton, A., Paňa, C., Chen, D, Wynne, D. and Langenberg, C.W. (2002): Coal and coalbed-methane potential of upper Cretaceous – Tertiary strata, Alberta Plains; Alberta Energy and Utilities Board, Alberta Geological Survey, Earth Sciences Report 2002-06.

Bekele, E.B., Person, M.A. and Rostron, B.J. (2000): Anomalous pressure generation within the Alberta Basin: implications for oil charge to the Viking Formation; Journal of Geochemical Exploration, v.69-70, p. 601-605.

Benner, R., Maccubbin, A.E., and Hodson, R.E. (1984): Anaerobic biodegradation of the lignin and polysaccharide components of lignocellulose and synthetic lignin by sediment microflora; Applied and Environmental Microbiology, v. 47, p. 998-1004.

Berner, R. (1969): Iron behaviour during weathering, sedimentation, and diagenesis; *in* Handbook of Geochemistry, Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 3, p. 26-G-1 - 26-G-8.

Bethke, C.M. and Johnson, T.M. (2002a): Paradox of groundwater age: correction; Geology, v. 30, no. 4, p. 385-388.

Bethke, C.M. and Johnson, T.M. (2002b): Ground water age; Ground Water, v. 40, no. 4, p. 337-339.

Bibby, R. (1974): Hydrogeology of the Edmonton area (northwest segment), Alberta; Alberta Research Council, Report 74-10, 10 p.

Billings, G.K., Hitchon, B. and Shaw, D.R. (1969): Geochemistry and origin of formation waters in the Western Canada Sedimentary Basin, 2. Alkali Metals; Chemical Geology, v. 4, p. 211-223.

Boetius, A., Ravenschlag, K., Schubert, C.J., Rickert, D., Widdel, F., Gleseke, A., Amann, R., Jørgensen, B.B., Witte, U., and Pfannkuche, O. (2000): A marine microbial consortium apparently mediating anaerobic oxidation of methane; Nature, v. 407, p. 623-626.

Borneuf, D. (1972): Hydrogeology of the Drumheller area, Alberta; Research Council of Alberta, Report 72-1, 15 p.

Borneuf, D. (1973): Hydrogeology of the Tawatinaw area, Alberta; Research Council of Alberta, Report 72-11, 15 p.

Borneuf, D. (1979): Hydrogeology of the Oyen area, Alberta; Alberta Research Council, Report 78-2, 35 p.

Boudreau, B.P. and Canfield, D.E. (1993): A comparison of closed-and-open system models of porewater pH and calcite-saturation state; Geochimica et Cosmochimica Acta, v. 57, p. 317-334.

Brehler, S. (1968): Zinc crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 7, p. 30-A-1 - 30-A-10.

Brehler, B. (1972): Cadmium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 13, p. 48-A-1 - 48-A-7.

Brehler, B. (1973a): Chlorine crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 4, p. 17-A-1 - 17-A-7.

Brehler, B. (1973b): Bromine crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 12, p. 35-A-1 - 35-A-3.

Brehler, B. (1973c): Iodine crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 18, p. 53-A-1 - 53-A-5.

Brookins, D.G., Chaudhuri, S. and Dowling, P.L. (1969): The isotopic composition of strontium in Permian limestones, eastern Kansas; Chemical Geology, v. 4, p. 439-444.

Burns, R.G. and Burns, V.M. (1973a): Magnesium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 12, p. 12-A-1 - 12-A-17.

Burns, R.G. and Burns, V.M. (1973b): Cobalt crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 4, p. 27-A-1 - 27-A-4.

Burns, R.G. and Burns, V.M. (1977): Nickel crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 5, p. 28-A-1 - 28-A-6.

Canadian Council of Ministers of the Environment (2003): Summary of existing Canadian environmental quality guidelines; Canadian Council of Ministers of the Environment, 12 p.

Ceroici, W. (1979): Hydrogeology of the Southwest Segment, Edmonton area, Alberta; Alberta Research Council, Report 78-5, 13 p.

Chapelle F. H. (1993): Ground-water Microbiology and Geochemistry; John Wiley and Sons, Inc., New York, NY.

Chapelle, F.H. and Lovley, D.R. (1992): Competitive exclusion of sulphate reduction by Fe(III)-reducing bacteria: A mechanism for producing discrete zones of high-iron ground water; Ground Water, v. 30, p. 29-36.

Chapelle, F.H., McMahon, P.B., Dubrovsky, N.M., Fujii, R.F., Oaksford, E.T., and Vroblesky, D.A. (1995): Deducing the distribution of terminal electron-accepting processes in hydrologically diverse groundwater systems; Water Resources Research, v. 31, p. 359-371.

Chaudhuri, S. (1978): Strontium isotopic composition of several oilfield brines from Kansas and Colorado; Geochimica et Cosmochimica Acta, v. 42, p. 329-331.

Chebotarev, I.I. (1955): Metamorphism of natural waters in the crust of weathering; Geochimica et Cosmochimica Acta, v. 8, p. 22-48, 137-170, 198-212.

Cherry, J.A., Shaikh, A.U., Tallman, D.E. and Nicholson, R.V. (1979): Arsenic species as an indicator of redox conditions in groundwater; Journal of Hydrology, v. 43, no 1-4, p. 373-392.

Christ, C.L. (1968): Boron crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 5, p. 5-A-1 - 5-A-6.

Clark, I.D. and Fritz, P. (1997): Environmental isotopes in hydrogeology; Lewis Publishers, Boca Raton, FL, 328 p.

Cocco, G., Fanzani, L. and Fanzani, P.F. (1970a): Sodium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 11, p. 11-A-1 - 11-A-10.

Cocco, G., Fanzani, L. and Fanzani, P.F. (1970b): Potassium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 6, p. 19-A-1 - 19-A-9.

Cocco, G., Fanzani, L. and Fanzani, P.F. (1970c): Lithium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 3, p. 3-A-1 - 3-A-7.

Cocco, G., Fanzani, L. and Fanzani, P.F. (1970d): Rubidium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 2, p. 37-A-1 - 37-A-3.

Coleman, M.L. (1985): Geochemistry of diagenetic non-silicate minerals. Kinetic considerations; Philosophical Transactions of the Royal Society of London, v. 315, p. 39-56.

Connolly, C.A., Walter, L.M., Baadsgaard, H. and Longstaffe, F.J. (1990a): Origin and evolution of formation waters, Alberta Basin, Western Canada Sedimentary Basin. I. Chemistry; Applied Geochemistry, v. 5, p. 375-395.

Connolly, C.A., Walter, L.M., Baadsgaard, H. and Longstaffe, F.J. (1990b): Origin and evolution of formation waters, Alberta Basin, Western Canada Sedimentary Basin. I. Isotope systematics and water mixing; Applied Geochemistry, v. 5, p. 397-413.

Connon, S.A., Tovanabootr, A., Dolan, M., Vergin, K., Giovannoni, S.J., and Semprini, L. (2005): Bacterial community composition determined by culture-independent and –dependent methods during propane-stimulated bioremediation in trichloroethene-contaminated groundwater; Environmental Microbiology, v. 7, p. 165-178.

Corbet, T.F. and Bethke, C.M. (1992): Disequilibrium fluid pressures and groundwater flow in the Western Canada Sedimentary Basin; Journal of Geophysical Research, v. 97(B5), p. 7203-7217.

Correns, C.W. (1976a): Titanium behavior during weathering and rock alteration; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 9, p. 22-G-1 - 22-G-3.

Correns, C.W. (1976b): Titanium abundance in common igneous rock types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 9, p. 22-E-1 - 22-E-14.

Correns, C.W. (1976c): Titanium abundance in common sediments and sedimentary rocks; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 9, p. 22-K-1 - 22-K-7.

Correns, C.W. (1976d): Titanium abundance in natural waters; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 9, p. 22-I-1.

Craig, H. (1961): Isotopic variations in meteoric waters; Science, v. 133, p. 1702-1703.

Curtis, C.D., Coleman, M.L., and Love, L.G. (1986): Pore water evolution during sediment burial from isotopic and mineral chemistry of calcite, dolomite and siderite concretions; Geochimica et Cosmochimica Acta, v. 50, p. 2321-2334.

Dasch, E.J. (1969): Strontium isotopes in weathering profiles, deep-sea sediments, and sedimentary rocks; Geochimica et Cosmochimica Acta, v. 33, p. 1521-1552.

Davis, S.N. and De Wiest, R.J.M. (1966): Hydrogeology; John Wiley & Sons, New York, NY, 463 p.

Davis, J.B. and Yarborough, H.E. (1966): Anaerobic oxidation of hydrocarbons by *Desulfovibrio desulfuricans*; Chemical Geology, v. 1, p. 137-144.

Dawson, F.M., Kalkreuth, W.D. and Sweet, A.R. (1994): Stratigraphy and coal resource potential of the upper Cretaceous to Tertiary strata of northwestern Alberta; Geological Survey of Canada, Bulletin 466, 59 p.

Decker, A.D., Klusman, R. and Horner, D.M. (1987): Geochemical techniques applied to the identification and disposal of connate coal water; Gas Research Institute-University of Alabama-U.S. Department of Labor, Symposium, The 1987 Coalbed Methane Symposium Proceedings, p. 229-242.

DeLeo, P.C., and Baveye, P. (1996): Enumeration and biomass estimation of bacteria in aquifer microcosm studies by flow cytometry; Applied and Environmental Microbiology, v. 62, p. 4580-4586.

Demaiffe, D. and Fieremans, M. (1981): Strontium-isotopic geochemistry of the Mbuji Mayi and Kundelungu kimberlites (Zaire, central Africa); Chemical Geology, v. 31, p. 311-323.

Deming, D. and Nunn, J.A. (1991): Numerical simulations of brine migration by topographically driven recharge; Journal of Geophysical Research, v. 96(B2), p. 2485-2499.

Denison, R.E., Koepnick, R.B., Burke, W.H., Hetherington, E.A. and Fletcher, A. (1997): Construction of the Silurian and Devonian seawater $^{87}Sr/^{86}Sr$ curve; Chemical Geology, v. 140, p. 109-121.

Drake, H.L. (1994): Acetogenesis; Chapman and Hall, New York, NY.

Drever, J.I. (1997): The geochemistry of natural waters: surface and groundwater environments (3rd Edition); Prentice Hall, Upper Saddle River, NJ, 436 p.

Elderfield, H. and Greaves, M.J. (1981): Strontium isotope geochemistry of Icelandic geothermal systems and implications for sea water chemistry; Geochimica et Cosmochimica, v. 45, p. 2201-2212.

Environment Canada (2005): Climate Data Online; Environment Canada, URL <http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html> [November, 2005]

Environmental Protection Agency (1992): Statistical training course for ground-water monitoring data analysis; United States Environmental Protection Agency, EPA530-R-93-003.

Evans, H.T. Jr. (1967): Vanadium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 10, p. 23-A-1 - 23-A-7.

Evans, H.T. Jr. (1973): Molybdenum crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 7, p. 42-A-1 - 42-A-3.

Ewart, A. and Stipp, J.J. (1968): Petrogenesis of the volcanic rocks of the Central North Island, New Zealand, as indicated by a study of Sr^{87}/Sr^{86} ratios, and Sr, Rb, K, U and Th abundances; Geochimica et Cosmochimica Acta, v. 32, p. 699-736.

Fabryka-Martin, J., Bentley, H., Elmore, D. and Airey, P.L. (1985): Natural iodine-129 as an environmental tracer; Geochimica et Cosmochimica Acta, v. 49, p. 337-347.

Fabryka-Martin, J., Whittemore, D.O., Davis, S.N., Kubik, P.W. and Sharma, P. (1991): Geochemistry of halogens in the Milk River aquifer, Alberta, Canada; *in* Dating Very Old Groundwater, Milk River Aquifer, Alberta, Canada, Ivanovich, M., Fröhlich, K. and Hendry, M.J., Editors, Applied Geochemistry, v. 6, n. 4, p. 447-464.

Faure, G., Assereto, R. and Tremba, E.L. (1978): Strontium isotope composition of marine carbonates of middle Triassic to early Jurassic age, Lombardic Alps, Italy; Sedimentology, v. 25, p. 523-543.

Faure, G., Crocket, J.H. and Hurley, P.M. (1967): Some aspects of the geochemistry of strontium and calcium in the Hudson Bay and the Great Lakes; Geochimica et Cosmochimica Acta, v. 31, p. 451-461.

Faure, G. and Hurley, P.M. (1963): The isotopic composition of strontium in oceanic and continental basalts: application to the origin of igneous rocks; Journal of Petrology, v. 4, Part 1, p. 31-50.

Faure, G., Hurley, P.M. and Powell, J.L. (1965): The isotopic composition of strontium in surface water from the North Atlantic Ocean; Geochimica et Cosmochimica Acta, v. 29, p. 209-220.

Finch, J. (2006): Seven things you should know before investing in coalbed methane; Stock Interview.com, URL < http://www.stockinterview.com/cbm-tips.html> [April 2006].

Firestone, R.B. (2000): Exploring the table of isotopes; Ernest O. Lawrence Berkeley National Laboratory, URL <http://ie.lbl.gov/education/> [February 2003].

Fischer, K. (1970a): Barium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 21, p. 56-A-1 - 56-A-6.

Fischer, K. (1970b): Crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Volume II-4, Part 3, p. 38-A-1 to 38-A-3.

Fischer, R. and Zemann, J. (1973): Selenium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 11, p. 34-A-1 - 34-A-9.

Fisher, R.S. and Stueber, A.M. (1976): Strontium isotopes in selected streams within the Susquehanna River Basin; Water Resources Research, v. 12, no. 5, p. 1061-1068.

Friedlander, G., Kennedy, J.W., Macias, E.S. and Miller, J.M. (1981): Nuclear and radiochemistry (3rd Edition); John Wiley and Sons, New York, NY, 684 p.

Friedman, I. (1953): Deuterium content of natural water and other substances; Geochimica et Cosmochimica Acta, v. 4, p. 89-103.

Fritz, P., Frape, S.K. and Miles, M. (1987): Methane in the crystalline rocks of the Canadian Shield; *in* Saline Water and Gases in Crystalline Rocks, Fritz, P. and Frape, S.K., Editors, Geological Association of Canada, GAC Special Paper 33, p. 211-223.

Frondel, C. (1969a): Scandium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 8, p. 21-A-1 - 21-A-5.

Frondel, C. (1969b): Solubilities of Sc compounds which control concentrations in natural waters; complexing; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 8, p. 21-H-1.

Frondel, C. (1969c): Scandium abundance in common igneous rock types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 8, p. 21-E-1 - 21-E-4.

Frondel, C. (1969d): Scandium abundance in common sedimentary rocks and residual deposits; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 8, p. 21-K-1 - 21-K-3.

Frost, C.D., Pearson, B.N., Ogle, K.M., Heffern, E.L. and Lyman, R.M. (2002): Sr isotope tracing of aquifer interactions in an area of accelerating coal-bed methane production, Powder River Basin, Wyoming; Geology, v. 30, no. 10, p. 923-926.

Frueh, A.J. (1967): Cadmium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 12, p. 47-A-1 - 47-A-3.

Gabert, G.M. (1975): Hydrogeology of Red Deer and vicinity, Alberta; Alberta Research Council, Bulletin 31, 100 p.

Garven, G. (1985): The role of regional fluid flow in the genesis of the Pine Point Deposit, Western Canada Sedimentary Basin; Economic Geology, v. 80, p. 307-324.

Garven, G. (1989): A hydrogeological model for the formation of the giant oil sands deposits of the Western Canada Sedimentary Basin; American Journal of Science, v. 289, p. 105-166.

Ge, S. and Garven, G. (1989): Tectonically induced transient groundwater flow in foreland basins; *in* The Origin and Evolution of Sedimentary Basins and Their Energy and Mineral Resources; A.E. Beck, G. Garven and I. Stegena (eds.), American Geophysical Union Geodynamics Series, Monograph 48, p. 9119-9144.

Ge, S. and Garven, G. (1994): A theoretical model of thrust-induced deep groundwater expulsion with application to the Canadian Rocky Mountains; Journal of Geophysical Research, v. 99, p. 13851-13868.

Gentzis, T. and Goodarzi, F. (1995): Geochemistry of subbituminous coals from the Highvale mine, Alberta, Canada; Energy Sources, v. 17, p. 57-91.

Gentzis, T. and Goodarzi, F. (1998): Petrology and geochemistry of subbituminous coals from the Red Deer River Valley, Alberta Plains, Canada; Energy Sources, v. 20, p. 839-855.

Ghose, S. (1968): Iron crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 3, p. 26-A-1 - 26-A-14.

Goodarzi, F. (2002): Concentration of metals and polynuclear aromatics in drinking water in the vicinity of the Lake Wabamun area, Alberta, Canada; Geological Survey of Canada, Open File 3909, 17 p.

Goode, D.J. (1996): Direct simulation of groundwater age; Water Resources Research, v. 32, no. 2, p. 289-296.

Grdenić, D. (1967): Mercury crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, P. 24, p. 80-A-1 - 80-A-6.

Grossman, E.L., Coffman, B.K., Fritz, S.J. and Wada, H. (1989): Bacterial production of methane and its influence on ground-water chemistry in east-central Texas aquifers; Geology, v. 17, p. 495-499.

Haack, S.K., Fogarty, L.R., West, T.G., Alm, E.W., McGuire, J.T., Long, D.T., Hyndman, D.W., and Coleman, M.L. (1985): Geochemistry of diagenetic non-silicate minerals. Kinetic considerations; Philosophical Transactions of the Royal Society of London, v. 315, p. 39-56.

Hackbarth, D.A. (1975): Hydrogeology of the Wainwright area, Alberta; Alberta Research Council, Report 75-1, 16 p.

Hahn, T. and Eysel, W. (1969): Calcium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 7, p. 20-A-1 - 20-A-13.

Hamblin, A.P. and Lee, P.J. (1997): Uppermost Cretaceous, post-Colorado Group gas resources of the Western Canada Sedimentary Basin, Interior Plains; Geological Survey of Canada, Bulletin 518, 88 p.

Harder, H. (1973): Processes controlling boron concentrations in natural water; adsorption processes; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 5, p. 5-H-1 - 5-H-2.

Hecker, F. (2002): Sustainable irrigated agriculture in Alberta; Alberta Agriculture, Food and Rural Development, URL <http://www.agric.gov.ab.ca/irrigate/sustain_irrigate.html> [January 2003].

Heier, K.S. and Billings, G.K. (1970a): Rubidium behavior during weathering and abundance in soils; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 2, p. 37-G-1 - 37-G-2.

Heier, K.S. and Billings, G.K. (1970b): Abundance in common sediments and sedimentary rock types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 2, p. 37-K-1 - 37-K-3.

Heier, K.S. and Billings, G.K. (1970c): Rubidium abundance in natural waters; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 2, p. 37-I-1 - 37-I-2.

Heier, K.S. and Billings, G.K. (1970d): Rubidium abundance in common magmatic rock types; Terrestrial Abundance; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 2, p. 37-E-1 - 37-E-10.

Hem, J.D. (1989): Study and interpretation of the chemical characteristics of natural waters (3rd Edition); United States Geological Survey, Water Supply Paper 2254, 264 p.

Higgins, I.J., Best, D.J., Hammond, R.C., and Scott, D.(1981): Methane-oxidizing micro organisms; Microbiology Reviews, v. 45, p. 556-590.

Hitchon, B. (1969a): Fluid flow in the Western Canada Sedimentary Basin: 1. Effect of topography; Water Resources Research, v. 5, p. 187-195.

Hitchon, B. (1969b): Fluid flow in the Western Canada Sedimentary Basin: 2. Effect of geology; Water Resources Research, v. 5, p. 460-469.

Hitchon, B. (1984): Geothermal gradients, hydrodynamics, and hydrocarbon occurrences, Alberta, Canada; AAPG Bulletin, v. 68, p. 1321-1349.

Hitchon, B., Bachu, S. and Underschultz, J.R. (1990): Regional subsurface hydrogeology, Peace River Arch area, Alberta and British Columbia; Bulletin of Canadian Petroleum Geology, v. 38A, p. 196-217.

Hitchon, B., Billings, G.K. and Klovan, J.E. (1971): Geochemistry and origin of formation waters in the Western Canada Sedimentary Basin – III. Factors controlling chemical composition; Geochimica et Cosmochimica Acta, v. 35, p. 567-598.

Hitchon, B. and Friedman, I. (1969): Geochemistry and origin of formation waters in the Western Canada Sedimentary Basin – I. Stable isotopes of hydrogen and oxygen; Geochimica et Cosmochimica Acta, v. 33, p. 1321-1349.

Hitchon, B., Perkins, E.H. and Gunter, W.D. (1999): Introduction to ground water geochemistry; Geoscience Publishing Ltd., Sherwood Park, AB, 310 p.

Hoehler, T.M., Alperin, M.J., Albert, D.B., and Martens, C.S. (1994): Field and laboratory studies of methane oxidation in an anoxic marine sediment: Evidence for a methanogen-sulphate reducer consortium; Global Biogeochemical Cycles, v. 9, p. 451-463.

Hogan, J.F., Blum, J.D., Siegel, D.I. and Glaser, P.H. (2000): $^{87}Sr/^{86}Sr$ as a tracer of groundwater discharge and precipitation recharge in the Glacial Lake Agassiz Peatlands, northern Minnesota; Water Resources Research, v. 36, no. 12, p. 3701-3710.

Hörmann, P.K. (1972a): Beryllium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 4, p. 4-A-1 - 4-A-8.

Hörmann, P.K. (1972b): Solubilities of beryllium compounds which control concentrations in natural waters; adsorption processes; valence states in natural environments; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 4, p. 4-H-1.

Hörmann, P.K. (1972c): Beryllium abundance in common igneous rock types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 4, p. 4-E-1 - 4-E-8.

Hörmann, P.K. (1972d): Beryllium abundance in common sedimentary rock types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 4, p. 4-A-1 - 4-A-8.

Hörmann, P.K. (1972e): Beryllium abundance in natural waters; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 4, p. 4-A-1 - 4-A-8.

Horvath, R.S. (1972): Microbial co-metabolism and the degradation of organic compounds in nature; Bacteriological Reviews, v. 36, p. 146-155.

Hunt, J.M. (1995): Petroleum Geochemistry and Geology; W.H. Freeman and Co., New York.

Hurley, P.M., Bateman, P.C., Fairbairn, H.W. and Pinson, W.H. Jr. (1965): Investigation of initial Sr^{87}/Sr^{86} ratios in the Sierra Nevada Plutonic Province; Geological Society of America Bulletin, v. 76, p. 165-174.

International Atomic Energy Agency-World Meteorological Organization (2001): Global network for isotopes in precipitation; IAEA, URL <http://isohis.iaea.org/> [January 2002].

Irwin, H., Curtis, C., and Coleman, M. (1977): Isotopic evidence for source of diagenetic carbonates formed during burial of organic-rich sediments; Nature, v. 269, p. 209-213.

Johnson, T.M. and DePaolo, D.J. (1997): Rapid exchange effects on isotopic ratios in groundwater systems 2. Flow investigation using Sr isotope ratios; Water Resources Research, v. 33, no. 1, p. 197-209.

Jones, L.M. and Faure, G. (1978): A study of strontium isotopes in lakes and surficial deposits of the ice-free valleys, southern Victoria Land, Antarctica; Chemical Geology, v. 22, p. 107-120.

Kasai, Y., Takahata, Y., Hoaki, T., and Watanabe, K. (2005): Physiological and molecular characterization of a microbial community established in unsaturated, petroleum-contaminated soil; Environmental Microbiology, v. 7, p. 806-818.

Kistler, R.W. and Peterman, Z.E. (1973): Variations in Sr, Rb, K, Na, and initial Sr^{87}/Sr^{86} in Mesozoic granitic rocks and intruded wall rocks in central California; Geological Society of America Bulletin, v. 84, p. 3489-3512.

Klein, C. and Hurlbut, C.S. Jr. (1985): Manual of mineralogy (20th edition); John Wiley and Sons, New York, NY, 596 p.

Koeppen, W. (1936): Das geographische system der klimate. *in* Handbuch der klimatologie, Koeppen, W. and Geiger, R., Editors, Gebruder Borntraeger, Berlin, Germany.

Krom, M.D. and Berner, R.A. (1980): Adsorption of phosphate in anoxic marine sediments; Limnology and Oceanography, v. 25, p. 797-806.

Kupčík, V. (1974): Antimony crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 16, p. 51-A-1 - 51-A-11.

Kupčík, V. (1972): Bismuth crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, P. 17, p. 83-A-1 - 83-A-7.

Landergren, S. (1974a): Solubilities of compounds which control concentrations of vanadium in natural waters; adsorption processes; valence states in natural environments; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 10, p. 23-H-1.

Landergren, S. (1974b): Vanadium abundance in common igneous rock-types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 10, p. 23-E-1 - 23-E-6.

Landergren, S. (1974c): Vanadium abundance in common sediments and sedimentary rocks; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 10, p. 23-K-1 - 23-K-5.

Landergren, S. (1974d): Vanadium abundance in natural waters; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 10, p. 23-I-1.

Landheer, F., Dibbs, H. and Labuda, J. (1982): Trace elements in Canadian coal; Environment Canada, Report EPS 3-AP-82-6, 41 p.

Langmuir, D. (1997): Aqueous Environmental Geochemistry; Prentice Hall, Upper Saddle River, New Jersey.

Los Alamos National Laboratory (2001): Los Alamos National Laboratory's Chemistry Division presents periodic table of the elements; Los Alamos National Laboratory, URL <http://pearl1.lanl.gov/periodic/default.htm > [January 2003].

Le Breton, E.G. (1971): Hydrogeology of the Red Deer area, Alberta; Research Council of Alberta, Report 71-1, 14 p.

Leeman, W.P. (1970): The isotopic composition of strontium in late-Cenozoic basalts from the Basin-Range province, western United States; Geochimica et Cosmochimica Acta, v. 34, p. 857-872.

Leeman, W.P. (1974): Late Cenozoic alkali-rich basalt from the western Grand Canyon area, Utah and Arizona: isotopic composition of strontium; Geological Society of America Bulletin, v. 85, p. 1691-1696.

Lemay, T.G. (2002a): Sampling of groundwater from wells in the Athabasca Oil Sands (in situ) Area, Alberta, 1999-2001 – compilation of protocols and methods; Alberta Energy and Utilities Board, EUB/AGS, Geo-Note 2002-10.

Lemay, T.G. (2002b): Sampling of formation water from wells in the Athabasca Oil Sands (in situ) Area, Alberta, 1999-2001 – compilation of protocols and methods; Alberta Energy and Utilities Board, EUB/AGS, Geo-Note 2002-11.

Lemay, T.G. (2003): 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, EUB/AGS, Earth Sciences Report 2003-04.

Leutwein, G. (1971): Selenium abundance in common igneous rock types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 11, p. 34-E-1 - 34-E-2.

Liebau, F. (1972): Silicon crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 1, p. 14-A-1 - 14-A-32.

Lovley, D.R. and Chapelle, F.H. (1995): Deep subsurface microbial processes; Reviews of Geophysics, v. 33, p. 365-381.

Lovley, D.R., Chapelle, F.H., and Phillips, E.J.P. (1990): Fe(III)-reducing bacteria in deeply buried sediments of the Atlantic Coastal Plain; Geology, v. 18, p. 954-957.

Lovley, D.R., Chapelle, F.H., and Woodward, J.C. (1994): Use of dissolved H_2 concentrations to determine distribution of microbially catalyzed redox reactions in anoxic groundwater; Environmental Science and Technology, v. 28, p. 1205-1210.

Lovley, D.R., Dwyer, D.F., and Klug, M.J. (1982): Kinetic analysis of competition between sulphate reducers and methanogens for hydrogen in sediments; Applied and Environmental Microbiology, v. 43, p. 1373-1379.

Lovley, D.R. and Klug, M.J. (1983): Methanogenesis from methanol and methylamines and acetogenesis from hydrogen and carbon dioxide in the sediments of a eutrophic lake; Applied and Environmental Microbiology, v. 45, p. 1310-1315.

Lyons, W.B., Tyler, S.W., Gaudette, H.E. and Long, D.T. (1995): The use of strontium isotopes in determining groundwater mixing and brine fingering in a playa spring zone, Lake Tyrrell, Australia; Journal of Hydrology, v. 167, p. 225-239.

McCabe, P.J., Strobl, R.S., Macdonald, D.E., Nurkowski, J.R. and Bosman, A. (1989): An evaluation of the coal resources of the Horseshoe Canyon Formation and laterally equivalent strata, to a depth of 400 m, in the Alberta Plains Area; Alberta Research Council, Open File Report 1989-07A, 75 p.

McMahon, P.B. and Chapelle, F.H. (1991): Microbial production of organic acids in aquitard sediments and its role in aquifer geochemistry; Nature, v. 349, p. 233-235.

McNutt, R.H. (1987): ^{87}Sr/^{86}Sr ratios as indicators of water/rock interactions: application to brines found in Precambrian age rocks from Canada; *in* Saline water and gases in crystalline rocks; P. Fritz and S.K. Frape (eds.), Geological Association of Canada, Special Paper 33, p.81-88.

McNutt, R.H., Frape, S.K., Fritz, P., Jones, M.G. and MacDonald, I.M. (1990): The ^{87}Sr/^{86}Sr values of Canadian Shield brines and fracture minerals with applications to groundwater mixing, fracture history, and geochronology; Geochimica et Cosmochimica Acta, v. 54, p. 205-215.

Machel, H.G. and Cavell, P.A. (1999): Low-flux, tectonically induced squeegee fluid flow (“Hot Flash”) into the Rocky Mountain Foreland Basin; Bulletin of Canadian Petroleum Geology, v. 47, p. 510-533.

Machel, H.G., Cavell, P.A. and Patey, K.S. (1996): Isotopic evidence for carbonate cementation and recrystallization, and for tectonic expulsion of fluids into the Western Canada Sedimentary Basin; Geological Society of America Bulletin, v. 108, p. 1108-1119.

Machel, H.G. and Foght, J. (2000): Products and depth limits of microbial activity in petroliferous subsurface settings; *in* Microbial Sediments, Riding, R.E. and Awramik, S.M., Editors, Springer-Verlag, Berlin, pp. 105-120.

Mah, R.A., Hungate, R.E., and Ohwaki, K. (1976): Acetate, a key intermediate in methanogenesis; *in* Microbial Energy Conservation, Schlegel, H.G. and Barnea, J. (Editors), Erich Glotz KG, Göttingen, pp. 97-106.

Malmström, V.H. (1969): A new approach to the classification of climate; The Journal of Geography, v. 68, no. 6, p. 351-357.

Mandelbaum, R.T., Shati, M.R., Ronen, D. (1997): In situ microcosms in aquifer bioremediation studies: FEMS Microbiology Review, v. 20, p. 489-502.

Manheim, F.T. and Landergren, S. (1978a): Molybdenum behavior during weathering and rock alteration; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 7, p. 42-G-1 - 42-G-4.

Manheim, F.T. and Landergren, S. (1978b): Molybdenum abundance in common igneous rocks and in the Earth’s crust; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 7, p. 42-E-1 - 42-E-7.

Manheim, F.T. and Landergren, S. (1978c): Molybdenum abundance in sediments and sedimentary rocks; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 7, p. 42-K-1 - 42-K-14.

Manheim, F.T. and Landergren, S. (1978d): Natural waters and atmospheric precipitation; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 7, p. 42-I-1 - 42-I-8.

Martens, C.S. and Berner, R.A. (1974): Methane production in the interstitial waters of sulphate-depleted sediments; Science, v. 185, p. 1167-1169.

Martini, A.M., Walter, L.M., Ku, T.C.W., Budai, J.M., McIntosh, J.C. and Schoell, M. (2003): Microbial production and modification of gases in sedimentary basins: a geochemical case study from a Devonian shale gas play, Michigan Basin; AAPG Bulletin, v. 87, no. 8, p. 1355-1375.

Matzat, E. (1970): Chromium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 1, p. 24-A-1 - 24-A-7.

Maulé, C.P., Chanasyk, D.S. and Muehlenbachs, K. (1994): Isotopic determination of snow-water contribution to soil water and groundwater; Journal of Hydrology, v. 155, p. 73-91.

Michael, K. (2002): Flow of formation water in the Alberta Basin adjacent to the Rocky Mountains Thrust and Fold Belt, West-Central Alberta, Canada; Ph.D. thesis, University of Alberta, 332 p.

Miller, D.N., Bryant, J.E., Madsen, E.L. and Ghiorse, W.C. (1999): Evaluation and optimization of DNA extraction and purification for soil and sediment samples; Applied Environmental Microbiology, v. 65, p. 4715-4724.

Moore, P.B. (1971): Aluminum crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 13, p. 13-A-1 - 13-A-24.

Moran, J.E. (1996): Origin of iodine in the Anadarko Basin, Oklahoma: An ^{129}I study; AAPG Bulletin, v. 80, no. 5, p. 685-694.

Moran, J.E., Fehn, U. and Teng, R.T.D. (1998): Variations in ^{129}I/^{127}I ratios in recent marine sediments: evidence for a fossil organic component; Chemical Geology, v. 152, p. 192-203.

Morgan, C.O. and Winner, M.D. Jr. (1962): Hydrochemical facies in the 400 foot and 600 foot sands of the Baton Rouge area, Louisiana; United States Geological Survey, Professional Paper 450-B, p 120-121.

Moysey, S., Davis, S.N., Zreda, M. and Cecil, L.D. (2003): The distribution of meteoric ^{36}Cl/Cl in the United States: a comparison of models; Hydrogeology Journal, v. 11, p. 615-627.

Mukhopadhyay, B. and Brookins, D.G. (1976): Strontium isotopic composition of the Madera Formation (Pennsylvanian) near Albuquerque, New Mexico; Geochimica et Cosmochimica Acta, v. 40, p. 611-616.

Myers, K.H. and Nealson, K.H. (1988): Microbial reduction of manganese oxides: Interactions with iron and sulphur; Geochimica et Cosmochimica Acta, v. 52, p. 2727-2732.

Nadon, G. (1988): Tectonic controls on sedimentation within a foreland basin: the Bearpaw, Blood Reserve and St. Mary River formations, southwestern Alberta; Canadian Society of Petroleum Geologists, Field Guide to Sequences, Stratigraphy, Sedimentology: Surface and Subsurface, September 14-16, CSPG Technical Meeting, Calgary, AB, 85 p.

Neat, P.L., Faure, G. and Pegram, W.J. (1979): The isotopic composition of strontium in non-marine carbonate rocks: the Flagstaff Formation of Utah; Sedimentology, v. 26, p. 271-282.

Nolte, E., Krauthan, P., Korschinek, G., Maloszewski, P., Fritz, P. and Wolk, M. (1991): Measurements and interpretations of ^{36}Cl in groundwater, Milk River aquifer, Alberta, Canada; *in* Dating Very Old Groundwater, Milk River Aquifer, Alberta, Canada, Ivanovich, M., Fröhlich, K. and Hendry, M.J., Editors, Applied Geochemistry, v. 6, n. 4, p. 435-445.

Nordstrom, D.K. (2000): An overview of arsenic mass poisoning in Bangladesh and West Bengal, India; *in* Minor Elements 2000: Processing and Environmental Aspects of As, Sb, Sc, Te and Bi; C. Young (ed.), Society for Mining, Metallurgy and Exploration, p. 21-30.

O'Neil, P.E., Harris, S.C., Drottar, K.R., Mount, D.R., Fillo, J.P. and Mettee, M.F. (1989): Biomonitoring of a produced water discharge from the Cedar Cove degasification field, Alabama; Geological Survey of Alabama, Bulletin 135, 195 p.

Onishi, H. (1967a): Antimony abundance in common igneous rocks; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 16, p. 51-E-1 - 51-E-3.

Onishi, H. (1967b): Antimony abundance in common sedimentary rocks; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 16, p. 51-K-1 - 51-K-2.

Onishi, H. (1967c): Antimony abundance in natural waters; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 16, p. 51-I-1 - 51-I-2.

Oremland, R.S., Marsh, L.M., and Polcin, S. (1982): Marine production and simultaneous sulphate reduction in anoxic, salt marsh sediments; Nature, v. 296, p. 143-145.

Ozoray, G.F. (1972): Hydrogeology of the Wabamun Lake area, Alberta; Research Council of Alberta, Report 72-8, 19 p.

Ozoray, G.F. and Barnes, R. (1978): Hydrogeology of the Calgary-Golden area, Alberta; Alberta Research Council, Report 77-2, 37 p.

Ozoray, G.F. and Lytviak, A.T. (1974): Hydrogeology of the Gleichen area, Alberta; Alberta Research, Report 74-9, 16 p.

Ozoray, G., Wallick, E.I. and Lytviak, A.T. (1980): Hydrogeology of the Sand River area, Alberta; Alberta Research Council, Report 79-1, 11 p.

Park, J. and Bethke, C.M. (2002): Transport modeling applied to the interpretation of groundwater ^{36}Cl age; Water Resources Research, v. 38, no. 5, p. 1-15.

Parkhurst, D.L. and Appelo C.A.J. (1999): User's Guide to PHREEQC (version 2); A Computer Program for Speciation, Batch-reaction, One-dimensional Transport, and Inverse Geochemical Calculations, U. S. Geological Survey.

Parks, K.P. and Tóth, J. (1995): Field evidence of erosion-induced underpressuring in Upper Cretaceous and Tertiary strata, West Central Alberta, Canada; Bulletin of Canadian Petroleum Geology, v. 43, no. 3, p. 281-292.

Peacor, D.R. (1970): Manganese crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 2, p. 25-A-1 - 25-A-12.

Peckmann, J. and Thiel, V. (2004): Carbon cycling at ancient methane-seeps; Chemical Geology, v. 205, p. 443-467.

Peterman, Z.E., Hedge, C.E. and Tourtelot, H.A. (1970): Isotopic composition of strontium in sea water throughout Phanerozoic time; Geochimica et Cosmochimica Acta, v. 34, p. 105-120.

Phelps, T.J., and Fredrickson, J.K. (2002): Drilling, coring and sampling subsurface environments; *in* Manual of Environmental Microbiology, Hurst, C.J., (Editor), American Society for Microbiology Press, Washington, DC., p. 679–695.

Phillips, F.M., Bentley, H.W., Davis, S.N., Elmore, D. and Swanick, G.B. (1986): Chlorine 36 dating of very old groundwater 2. Milk River aquifer, Alberta, Canada; Water Resources Research, v. 22, n. 13, p. 2003-2016.

Plummer, L.N., Busby, J.F., Lee, R.W., and Hanshaw, B.B. (1990): Geochemical modelling of the Madison aquifer in parts of Montana, Wyoming, and South Dakota; Water Resource Research, v. 26, p. 1981-2014.

Pollock, S.M., Goodarzi, F. and Riediger, C.L. (2000): Mineralogical and elemental variation of coal from Alberta, Canada: an example from the No. 2 seam, Genesee Mine; International Journal of Coal Geology, v. 43, p. 259-286.

Porter, J.W., Price, R.A and McCrossan, R.G. (1982): The Western Canada Sedimentary Basin; Transactions of the Royal Society of London, v. A305, p. 2003-2016.

Postma, D. (1985): Concentration of Mn and separation from Fe in Sediments. 1. Kinetics and stoichiometry of the reaction between birnessite and dissolved Fe(II) at 10-degrees-C; Geochimica et Cosmochimica Acta, v. 49, p. 1023-1033.

Postma, D. and Jakobsen, R. (1996) Redox zonation: Equilibrium constraints on the Fe(III)/SO_4-reduction interface; Geochimica et Cosmochimica Acta, v. 60, p. 3169-3175.

Pushkar, P. and Condie, K.C. (1973): Origin of the Quaternary basalts from the Black Rock Desert region, Utah: strontium isotopic evidence; Geological Society of America Bulletin, v. 84, p. 1053-1058.

Rahmani, R.A. (1988) Estuarine tidal channel and nearshore sedimentation of a Late Cretaceous epicontinental sea, Drumheller, Alberta, Canada; *in* Tide-Influenced Sedimentary Environments and Facies; de Boer, P.L., van Gelder, A. and Nio, S.D. Editors, Reidel Publishing Co., Dordrecht, Netherlands, p. 433-471.

Reilly, T.E., Plummer, L.N., Phillips, P.J. and Busenberg, E. (1994): The use of simulation and multiple environmental tracers to quantify flow in a shallow aquifer; Water Resources Research, v. 30, no. 2, p. 421-433.

Reeburgh, W.S. (1980): Anaerobic methane oxidation: Rate depth distributions in Skan Bay sediments; Earth and Planetary Science Letters, v. 47, p. 345-352.

Ribbons, D.W., Harrison, J.E., and Wadinski, A.M. (1970): Metabolism of single carbon compounds. Annual Review of Microbiology, v. 24, p. 135-158.

Rice, C.A., Ellis, M.S. and Bullock, J.H., Jr. (2000): Water co-produced with coalbed methane in the Powder River Basin, Wyoming: preliminary compositional data; United States Geological Survey, Open File Report 00-372, 18 p.

Ridgway, H.F., Safarik, J., Phipps, D., and Clark, D. (1990): Identification and catabolic activity of well-derived gasoline-degrading bacteria from a contaminated aquifer; Applied and Environmental Microbiology, v. 56, p. 3565-3575.

Rosenfeld, W.D. and Silverman, S.R. (1959): Carbon isotope fractionations in bacterial production of methane; Science, v. 130, p. 1658-1659.

Rottenfusser, B., Langenberg, W., Mandryk, G., Richardson, R., Fildes, B., Olic, J., Stewart, S., Eccles, R., Evans, C., Spelrem, M., Sprecher, B., Brulotte, M., Gentzis, T., Wynne, D. and Yuan, L.P. (1991): Regional evaluation of the coalbed methane potential in the Plains and Foothills of Alberta, stratigraphy and rank study; Alberta Research Council, Alberta Geological Survey, Special Publication 7, 95 p.

Rozanski, K., Araguas-Araguas, L. and Gonfiantini, R. (1993): Isotopic patterns in modern global precipitation; *in* Continental Isotope Indicators of Climate, American Geophysical Union Monograph.

Sahl, K. (1968): Lead crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, P. 26, p. 82-A-1 - 82-A-6.

Sahl, K. (1972): Thallium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, P. 25, p. 81-A-1 - 81-A-9.

Sanz, H.G., Burnett, D.S. and Wasserburg, G.J. (1970): A precise ^{87}Rb/^{87}Sr age and initial ^{87}Sr/^{86}Sr for the Colomera iron meteorite; Geochimica et Cosmochimica Acta, v. 34, p. 1227-1239.

Sassen, R., Roberts, H.H., Carney, R., Milkov, A.V., DeFreitas, D.A., Lanoil, B., and Zhang, C. (2004): Free hydrocarbon gas, gas hydrate, and authigenic minerals in chemosynthetic communities of the northern Gulf of Mexico continental slope: Relation to microbial processes; Chemical Geology, v. 205, p. 195-217.

Schoell, M. (1980): The hydrogen and carbon isotopic composition of methane from natural gases of various origins; Geochimica et Cosmochimica Acta, v. 44, p. 649-661.

Schoell, M. (1983): Genetic characterization of natural gases; AAPG Bulletin, v. 67, p. 2225-2238.

Schwartz, F.W., Muehlenbachs, K. and Chorley, D.W. (1981): Flow-system controls of the chemical evolution of groundwater; Journal of Hydrology, v. 54, p. 225-243.

Seaber, P.R. (1962): Cation hydrochemical facies of groundwater in the Englishtown Formation, New Jersey; United States Geological Survey, Professional Paper 450-B, p. 124-126.

Sherwood Lollar, B., Frape, S.K., Weise, S.M., Fritz, P., Macko, S.A. and Welhan, J.A. (1993): Abiogenic methanogenesis in crystalline rocks; Geochimica et Cosmochimica Acta, v. 57, p. 5087-5097.

Shiraki, K. (1975a): Chromium behavior during weathering and alteration of rocks; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 1, p. 24-G-1.

Shiraki, K. (1975b): Solubilities of compounds which control concentrations of chromium in natural waters, valence states in natural environments, adsorption processes; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 1, p. 24-H-1.

Smedley, P.L. and Kinniburgh, D.G. (2002): A review of the source, behaviour and distribution of arsenic in natural waters; Applied Geochemistry, v. 17, p. 517-568.

Snyder, G.T., Riese, W.C., Franks, S., Fehn, U., Pelzmann, W.L., Gorody, A.W. and Moran, J.E. (2003): Origin and history of waters associated with coal-bed methane: ^{129}I, ^{36}Cl, and stable isotope results from the Fruitland Formation, CO and NM; Geochimica et Cosmochimica Acta, v. 67, no. 23, p. 4529-4544.

Starinsky, A., Bielski, M., Lazar, B., Steinitz, G. and Raab, M. (1983): Strontium isotope evidence on the history of oilfield brines, Mediterranean Coastal Plain, Israel; Geochimica et Cosmochimica Acta, v. 47, p. 687-695.

Statistics Canada (2005a): 2001 Census of Canada; Statistics Canada, URL <http://www12.statcan.ca/english/census01/home/index.cfm> [December, 2005].

Statistics Canada (2005b): 1996 Census; Statistics Canada, URL <http://www12.statcan.ca/english/census01/info/census96.cfm> [December, 2005].

Stein, R. (1976): Hydrogeology of the Edmonton area (northeast segment), Alberta; Alberta Research Council, Report 76-1, 21 p.

Stevenson, D.R. and Borneuf, D. (1977): Hydrogeology of the Medicine Hat area, Alberta; Alberta Research Council, Report 75-2, 11 p.

Stueber, A.M., Pushkar, P. and Hetherington, E.A. (1984): A strontium isotopic study of Smackover brines and associated solids, southern Arkansas; Geochimica et Cosmochimica Acta, v. 48, p. 1637-1649.

Sudicky, E.A. and Frind, E.O. (1981): Carbon 14 dating of groundwater in confined aquifers: Implications of aquitard diffusion; Water Resources Research, v. 17, p. 1060-1064.

Sunwall, M.T. and Pushkar, P. (1979): The isotopic composition of strontium in brines from petroleum fields of southeastern Ohio; Chemical Geology, v. 24, p. 189-197.

Sweet, A.R. and Braman, D.R. (1992): The K-T boundary and contiguous strata in western Canada: interactions between paleoenvironments and palynological assemblages; Cretaceous Research, v. 13, p. 31-79.

Swift, M.J., Heal, O.W., and Anderson, J.M. (1979): Decomposition in Terrestrial Ecosystems; University of California Press, Berkeley.

Thamdrup, B., Fossing, H., and Jørgensen, B.B. (1994): Manganese, iron, and sulfur cycling in a coastal marine sediment, Aarhus Bay, Denmark; Geochimica et Cosmochimica Acta, v. 58, p. 5115-5129.

Thompson, M.J. (1989): Gas fields, formation-fluid flow and hydrochemistry in Early Cretaceous formations, Peace River region, N.W. Alberta, Canada; M.Sc. thesis, University of Alberta, 160 p.

Tillmans, E. (1972): Titanium crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 9, p. 22-A-1 - 22-A-5.

Tokarsky, O. (1974): Hydrogeology of the Lethbridge-Fernie Area, Alberta; Alberta Research, Report 74-1, 18 p.

Tokarsky, O. (1977a): Hydrogeology of the Iosegun Lake area, Alberta; Alberta Research Council, Report 76-2, 10 p.

Tokarsky, O. (1977b): Hydrogeology of the Whitecourt area, Alberta; Alberta Research Council, Report 76-3, 10 p.

Torsvik, V., Øverás, L., and Thingstad, T.F. (2002): Prokaryotic diversity – magnitude, dynamics and controlling factors; Science, v. 296, p. 1064-1068.

Tóth, J. (1966): Groundwater geology, movement, chemistry, and resources near Olds, Alberta; Research Council of Alberta, Bulletin 17, 126 p.

Tremba, E.L., Faure, G., Katsikatsos, G.C. and Summerson, C.H. (1975): Strontium-isotope composition in the Tethys Sea, Euboea, Greece; Chemical Geology, v. 16, p. 109-120.

Turekian, K.K. (1976a): Cobalt behavior during weathering; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 4, p. 27-G-1.

Turekian, K.K. (1976b): Solubilities of compounds which control concentrations of cobalt in natural waters and adsorption processes; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 4, p. 27-H-1 - 27-H-2.

Turekian, K.K. (1976c): Cobalt abundance in common igneous rock types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 4, p. 27-E-1 - 27-E-2.

Turekian, K.K. (1976d): Cobalt abundance in common sediments and sedimentary rock types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 4, p. 27-K-1 - 27-K-4.

Turekian, K.K. (1976e): Cobalt abundance in natural water and in the atmosphere; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 4, p. 27-I-1 - 27-I-3.

Turekian, K.K. (1977a): Nickel behavior during weathering; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 5, p. 28-G-1 - 28-G-2.

Turekian, K.K. (1977b): Solubilities of compounds which control concentration of nickel in natural waters; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 5, p. 28-H-1.

Turekian, K.K. (1977c): Nickel abundance in common igneous rock types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 5, p. 28-E-1 - 28-E-4.

Turekian, K.K. (1977d): Nickel abundance in common sediments and sedimentary rock types; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 5, p. 28-K-1 - 28-K-4.

Turekian, K.K. (1977e): Nickel abundance in natural waters; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 5, p. 28-I-1 - 28-I-2.

Underhill, P.T. (1996): Naturally occurring radioactive material, principles and practices; St.Lucie Press, Delray Beach, Florida, 145 pages.

Underschultz, J.R. and Bartlett, R. (1999): Hydrodynamic controls on Foothills gas pools, Mississippian strata; CSPG Reservoir, v. 26, p. 10-11.

Usdowski, H.E. (1975): Calcium abundance in natural waters; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 7, p. 20-I-1 - 20-I-4.

van Loosdretch, M.C.M., Lyklema, J., Norde, W., and Zehnder, A.J.B. (1989): Bacterial adhesion: a physicochemical approach; Microbial Ecology, v. 17, p. 1-15.

Van Voast, W.A. (2003): Geochemical signature of formation waters associated with coalbed methane; AAPG Bulletin, v. 87, no. 4, p. 667-676.

Veizer, J. and Compston, W. (1974): ^{87}Sr/^{86}Sr composition of seawater during the Phanerozoic; Geochimica et Cosmochimica Acta, v. 38, p. 1461-1484.

Veizer, J. and Compston, W. (1976): ^{87}Sr/^{86}Sr in Precambrian carbonates as an index of crustal evolution; Geochimica et Cosmochimica Acta, v. 40, p. 905-914.

Veizer, J., Compston, W., Clauer, N. and Schidlowski, M. (1983): ^{87}Sr/^{86}Sr in Late Proterozoic carbonates: evidence for a “mantle” event at approximately 900 Ma ago; Geochimica et Cosmochimica Acta, v. 47, p. 295-302.

Vincent, E.A. (1974): Compounds controlling silver concentration in natural waters; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 12, p. 47-H-1 - 47-H-2.

Wakita, H. (1969): Solubilities of cadmium compounds in natural waters, and valence state in natural environments; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-4, P. 13, p. 48-H-1.

Warrence, N.J., Bauder, J.W. and Pearson, K.E. (2002): Basics of salinity and sodicity effects on soil physical properties; Montana State University Bozeman, URL <http://waterquality.Montana.edu /docs/methane/basics.shtml> [December 2002].

Wedepohl, K.H. (1972a): Zinc behavior during weathering and rock alteration; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 7, p. 30-G-1 - 30-G-6.

Wedepohl, K.H. (1972b): Solubilities of compounds which control concentrations of zinc in natural waters (I); adsorption processes (II); *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 7, p. 30-H-1 - 30-H-5.

Wedepohl, K.H. (1973a): Copper behavior during weathering and rock alteration; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 6, p. 29-G-1 - 29-G-5.

Wedepohl, K.H. (1973b): Solubilities of compounds which control concentration of copper in natural waters (I); adsorption processes (II); *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 6, p. 29-H-1 - 29-H-4.

Wedepohl, K.H. (1973c): Copper abundance in natural waters and in the atmosphere; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 6, p. 29-I-1 - 29-I-5.

Wedepohl, K.H. (1974): Solubilities of compounds which control concentrations of lead in natural waters; valence states in the natural environment; adsorption processes; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-5, P. 26, p. 82-H-1 - 82-H-4.

Welch, A.H., Lico, M.S. and Hughes, J.L. (1988): Arsenic in groundwater of the western United States; Ground Water, v. 26, no. 3, p. 333-347.

Whitford, D.J. (1975): Strontium isotopic studies of the volcanic rocks of the Saunda arc, Indonesia, and their petrogenetic implications; Geochimica et Cosmochimica Acta, v. 39, p. 1287-1302.

Whiticar, M.J., Faber, E. and Schoell, M. (1986): Biogenic methane formation in marine and freshwater environments: CO_2 reduction vs. acetate fermentation – isotope evidence; Geochimica et Cosmochimica Acta, v. 50, p. 693-709.

Wilkinson, P.K. (1995): Is fluid flow in Paleozoic formations of west central Alberta affected by the Rocky Mountain Thrust Belt?; M.Sc. thesis, University of Alberta, 102 p.

Winter, M. (2003a): Thorium; The University of Sheffield and WebElements Ltd., URL <http://www. webelements.com/webelements/elements/text/Th/key.html> [January 2003].

Winter, M. (2003b): Uranium; The University of Sheffield and WebElements Ltd., URL <http://www webelements.com/webelements/elements/text/U/key.html> [January 2003].

Woods, R.L., Fullagar, P.D., Spruill, R.K. and Sutton, L.C. (2000): Strontium isotopes and major elements as tracers of ground water evolution: example from the Upper Castle Hayne Aquifer of North Carolina; Ground Water, v. 38, no. 5, p. 762-771.

Wuensch, B.J. (1970): Sulfur crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-2, P. 3, p. 16-A-1 - 16-A-19.

Yan, X.-P., Kerrich, R. and Hendry, M.J. (2000): Distribution of arsenic(III), arsenic(V) and total inorganic arsenic in porewaters from a thick till and clay-rich aquitard sequence, Saskatchewan, Canada; Geochimica et Cosmochimica Acta, v. 62, no. 15, p. 2637-2648.

Zachara, J.M., Kukkadapu, R.K., Fredrickson, J.K., Gorby, Y.A., and Smith, S.C. (2002): Biomineralization of poorly crystalline Fe(III) oxides by dissimilatory metal reducing bacteria (DMRB); Geomicrobiology Journal, v. 19, p. 179-207.

Zemann, J. (1968): Crystal chemistry of carbon; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-1, P. 6, p. 6-A-1 - 6-A-3.

Zemann, J. (1971): Copper crystal chemistry; *in* Handbook of Geochemistry; Wedepohl, K.H., Editor, Springer-Verlag, Berlin, Germany, Vol. II-3, P. 6, p. 29-A-1 - 29-A-13.

Appendix 1 – Temperature and Precipitation Figures for the Study Area

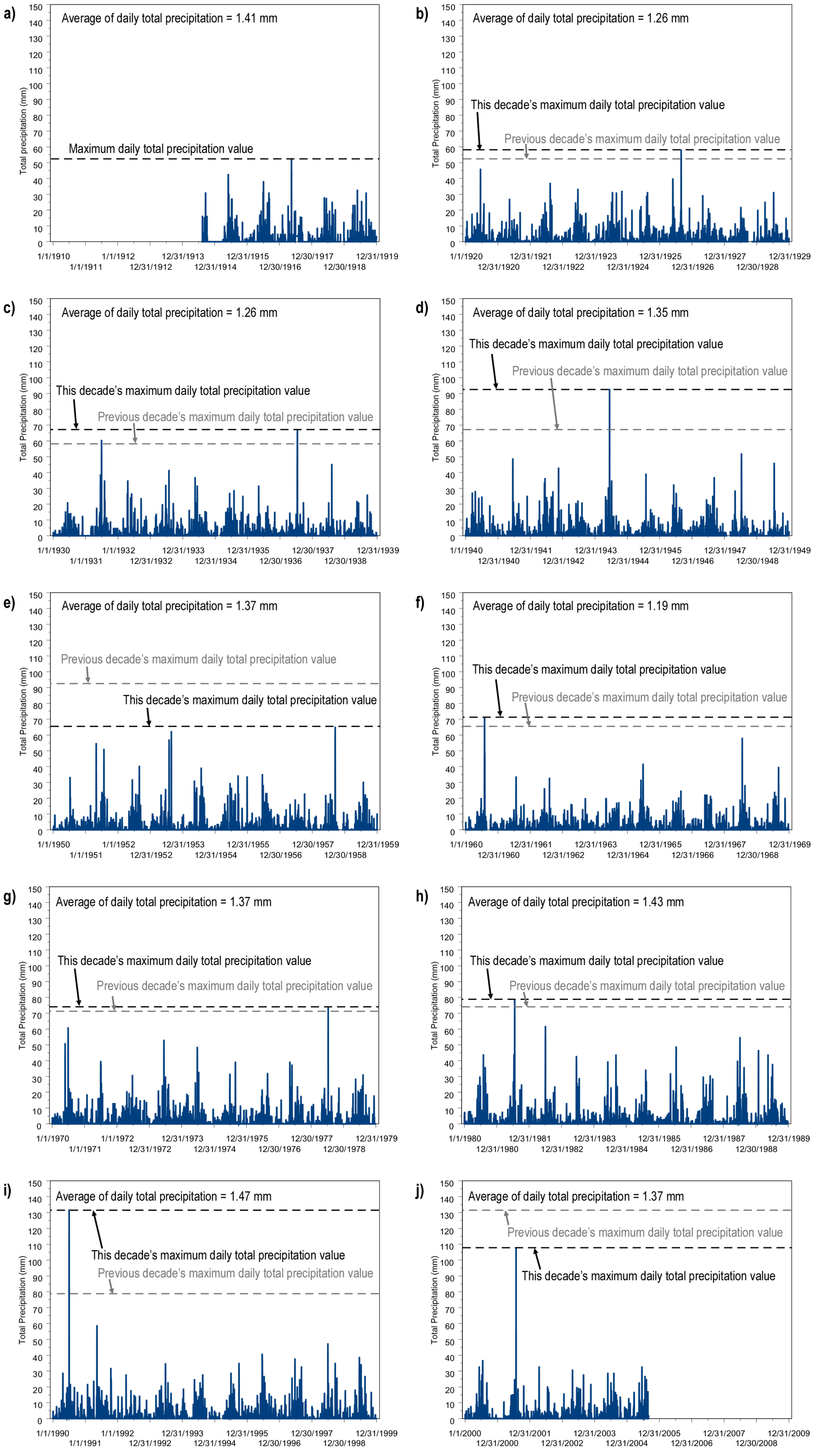


Figure 64. Decadel precipitation summary Calmar climate station 1910-2005.

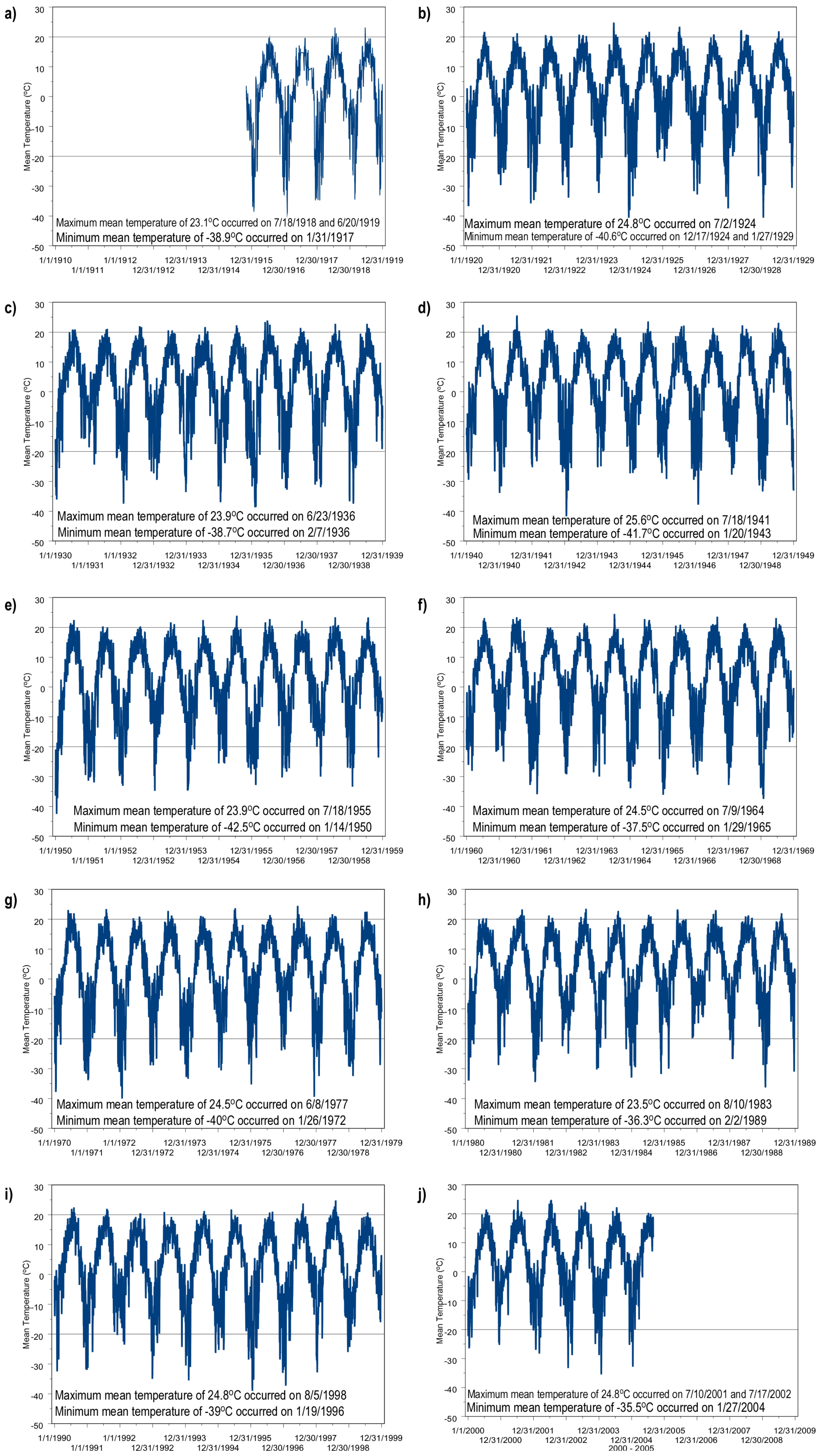


Figure 65. Decadal mean temperature summary Calmar climate station 1910-2005.

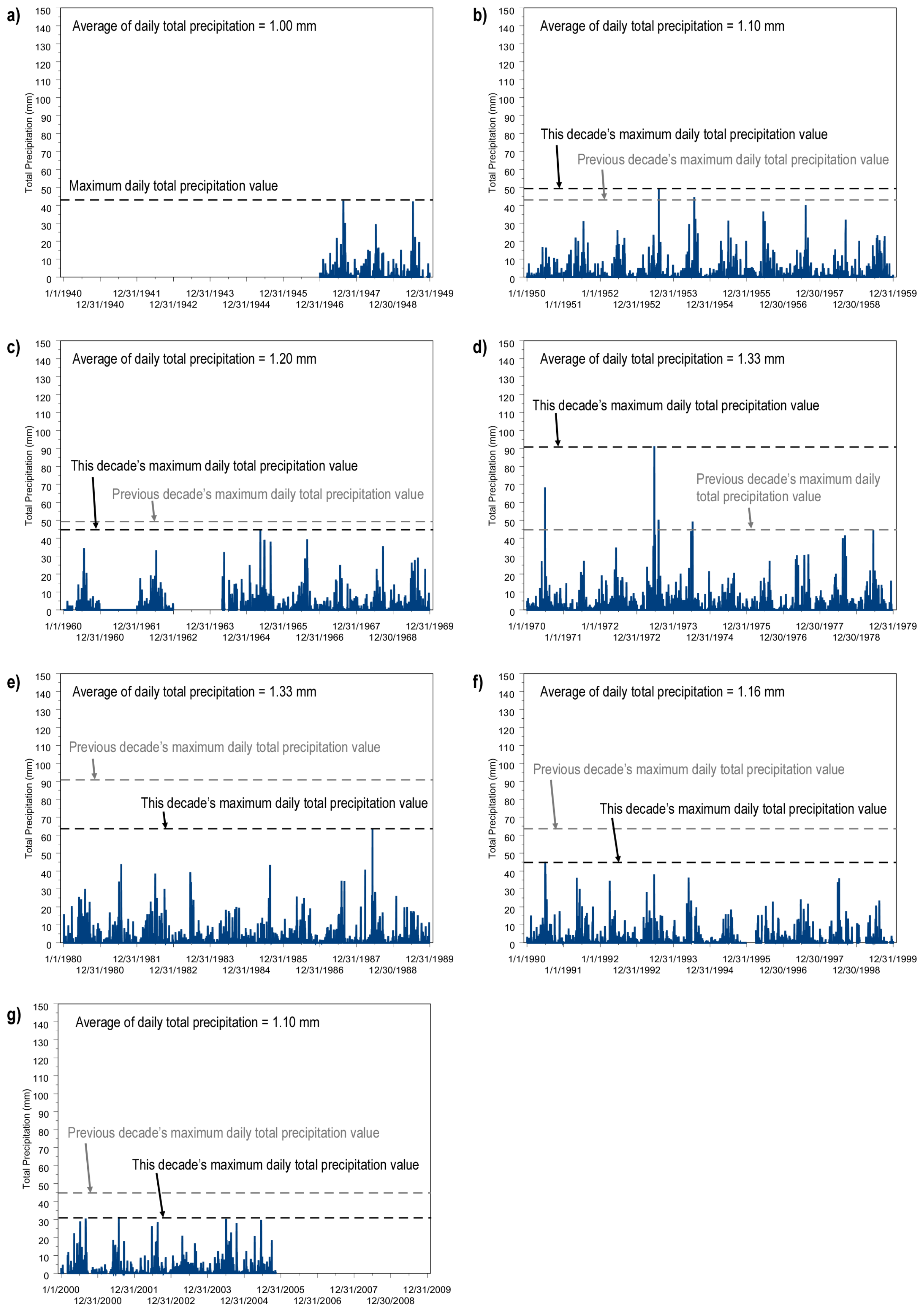
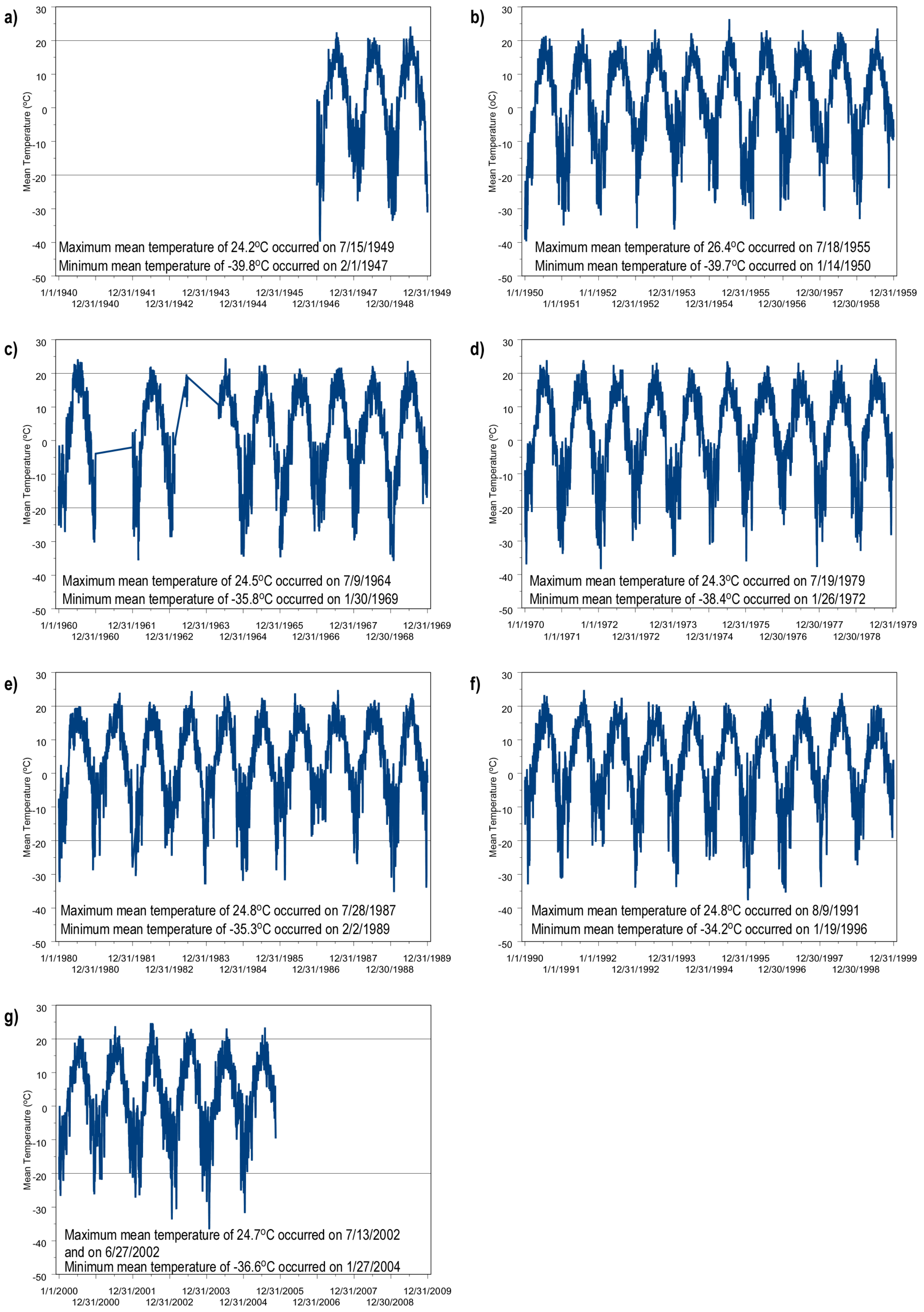


Figure 66. Decadal precipitation summary Camrose climate station 1940-2005.



a) Maximum mean temperature of 24.2^{o}C occurred on 7/15/1949
Minimum mean temperature of -39.8^{o}C occurred on 2/1/1947

b) Maximum mean temperature of 26.4^{o}C occurred on 7/18/1955
Minimum mean temperature of -39.7^{o}C occurred on 1/14/1950

c) Maximum mean temperature of 24.5^{o}C occurred on 7/9/1964
Minimum mean temperature of -35.8^{o}C occurred on 1/30/1969

d) Maximum mean temperature of 24.3^{o}C occurred on 7/19/1979
Minimum mean temperature of -38.4^{o}C occurred on 1/26/1972

e) Maximum mean temperature of 24.8^{o}C occurred on 7/28/1987
Minimum mean temperature of -35.3^{o}C occurred on 2/2/1989

f) Maximum mean temperature of 24.8^{o}C occurred on 8/9/1991
Minimum mean temperature of -34.2^{o}C occurred on 1/19/1996

g) Maximum mean temperature of 24.7^{o}C occurred on 7/13/2002
and on 6/27/2002
Minimum mean temperature of -36.6^{o}C occurred on 1/27/2004

Figure 67. Decadal mean temperature summary Camrose climate station 1940-2005.

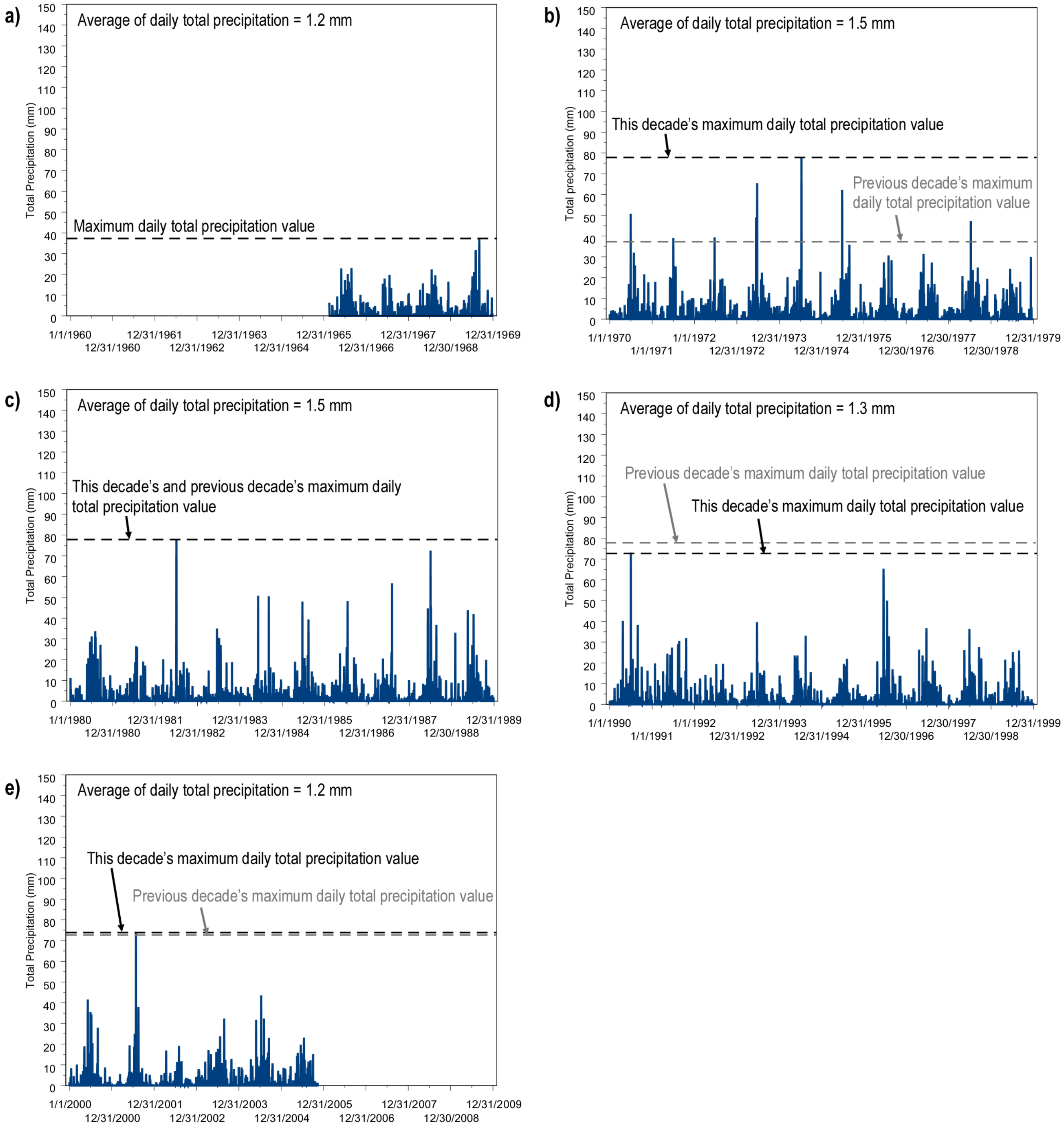
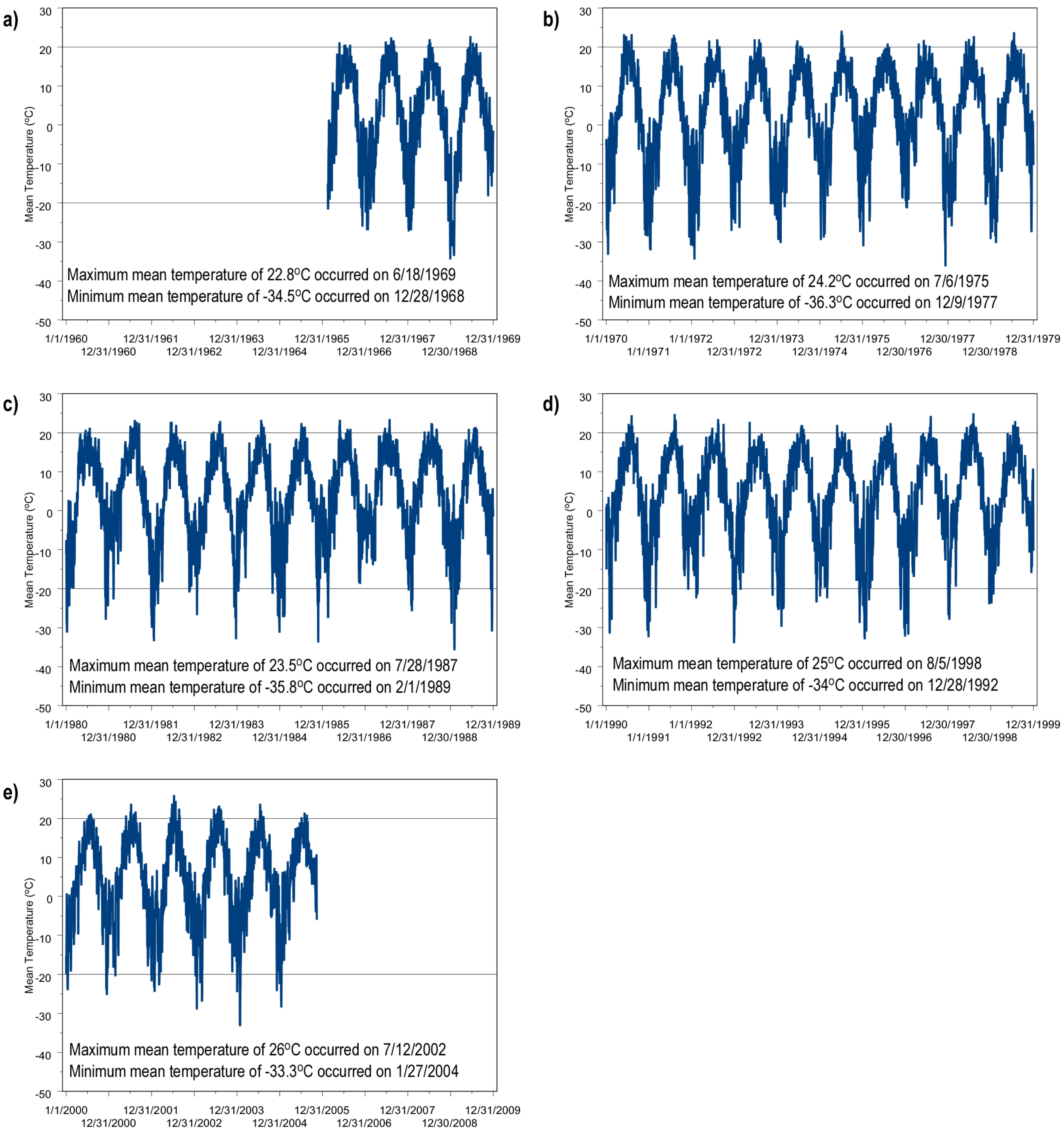


Figure 68. Decadal precipitation summary Edmonton Stony Plain climate station 1960-2005: a) 1960-1969; b) 1970-1979; d) 1980-1989; d) 1990-1999; and e) 2000-2005..



a) Maximum mean temperature of 22.8ºC occurred on 6/18/1969
Minimum mean temperature of -34.5ºC occurred on 12/28/1968

b) Maximum mean temperature of 24.2ºC occurred on 7/6/1975
Minimum mean temperature of -36.3ºC occurred on 12/9/1977

c) Maximum mean temperature of 23.5ºC occurred on 7/28/1987
Minimum mean temperature of -35.8ºC occurred on 2/1/1989

d) Maximum mean temperature of 25ºC occurred on 8/5/1998
Minimum mean temperature of -34ºC occurred on 12/28/1992

e) Maximum mean temperature of 26ºC occurred on 7/12/2002
Minimum mean temperature of -33.3ºC occurred on 1/27/2004

Figure 69. Decadal mean temperature summary Edmonton Stony Plain climate station 1960-2005: a) 1960-1969; b) 1970-1979; d) 1980-1989; d) 1990-1999; and e) 2000-2005..

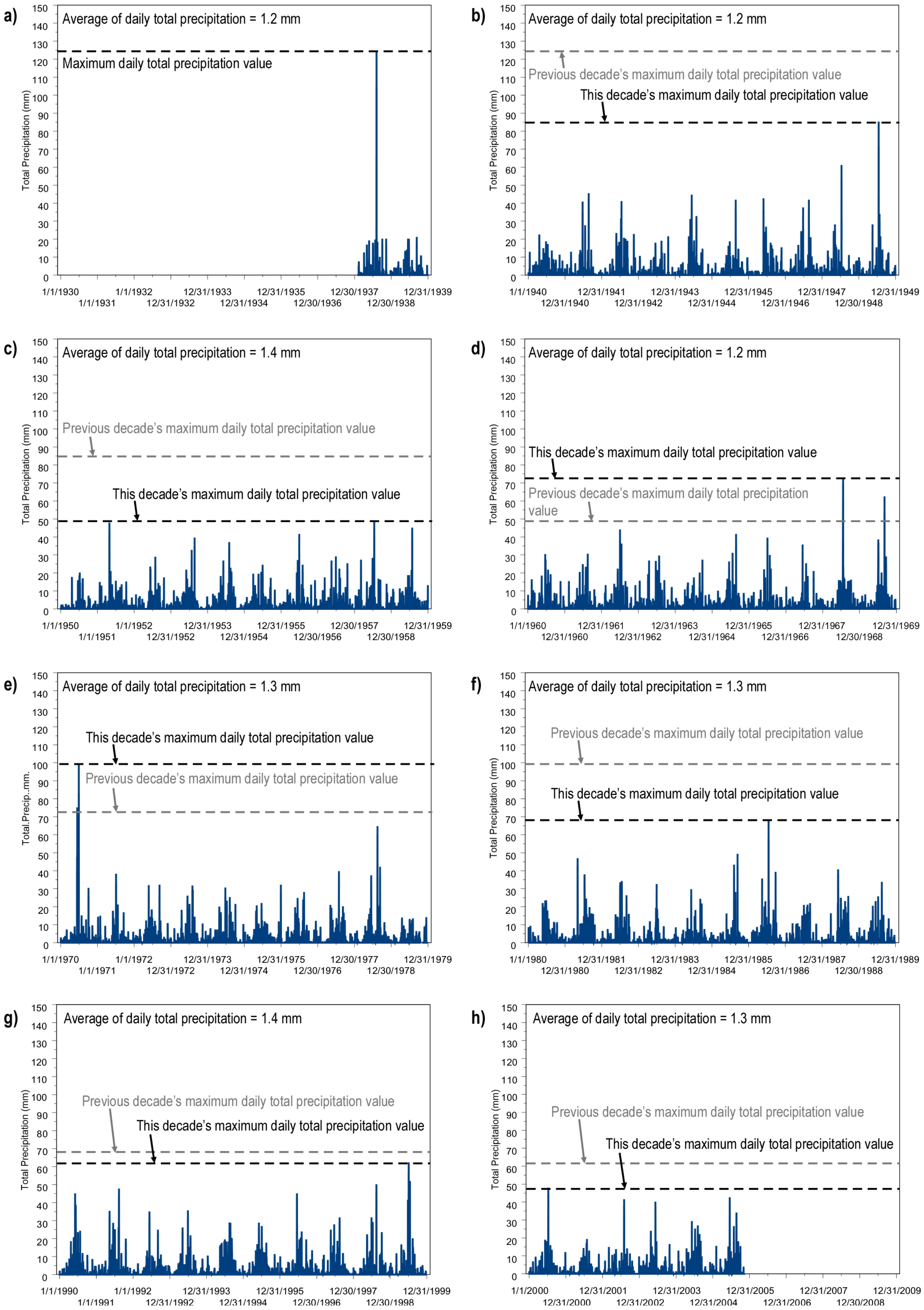


Figure 70. Decadel precipitation summary Red Dear Airport climate station 1930-2005.

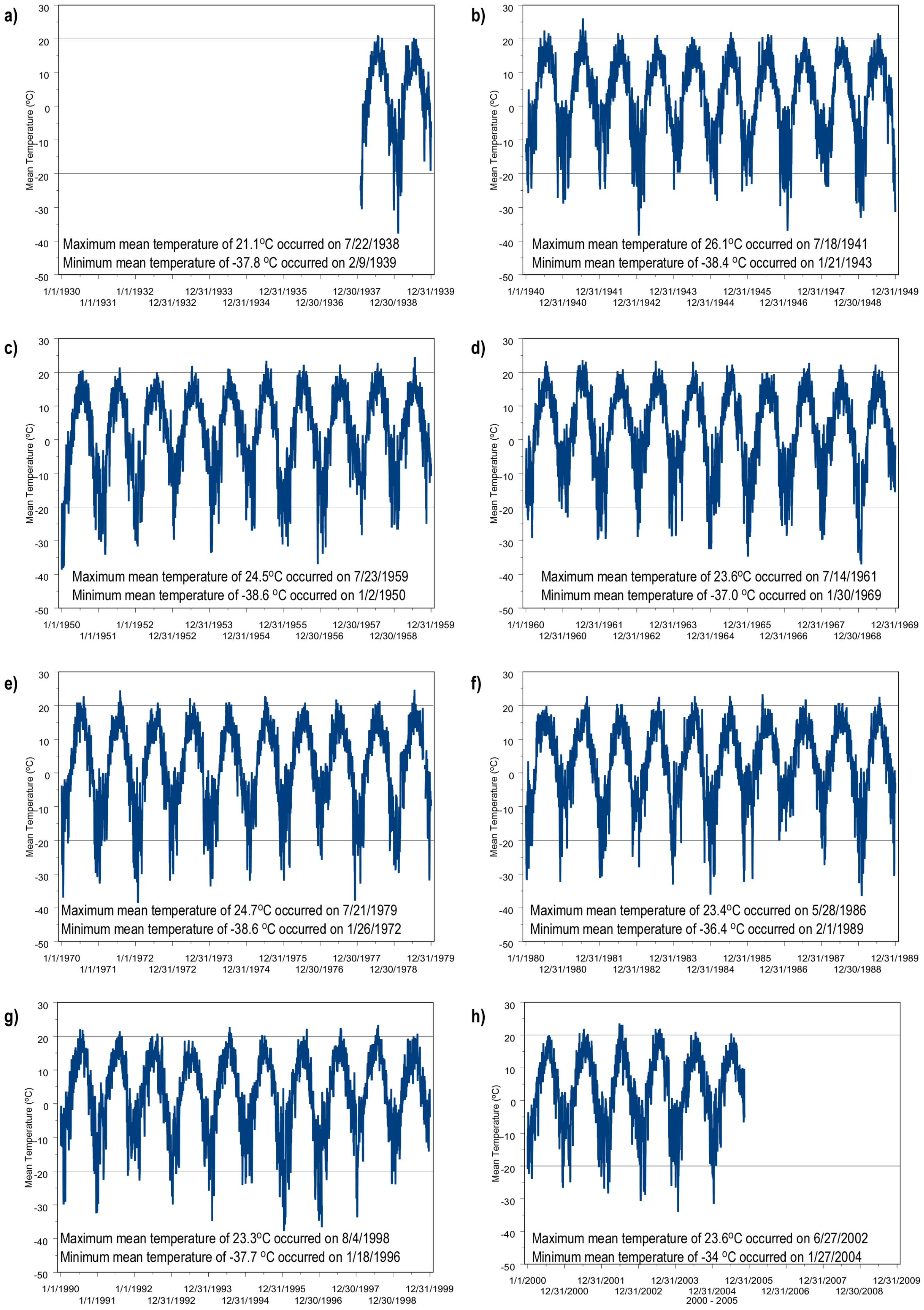


Figure 71. Decadal mean temperature summary Red Deer climate station 1930-2005.

Appendix 2 – Evaporation and Evapotranspiration Data for the Study Area.

Table 31. Yearly evaporation and evapotranspiration values Edmonton City Centre Airport.

Year	Total potential evaporation (mm)	Total potential evapotranspiration (mm)
1912	734	715
1913	760	735
1914	802	775
1915	753	720
1916	755	734
1917	831	805
1918	839	808
1919	790	769
1920	738	709
1921	869	837
1922	831	811
1923	872	844
1924	799	770
1925	819	789
1926	824	797
1927	779	749
1928	817	781
1929	940	922
1930	811	790
1931	-	-
1932	940	926
1933	-	-
1934	975	956
1935	783	756
1936	927	903
1937	845	831
1938	960	930
1939	-	-
1940	758	725
1941	-	-
1942	814	787
1943	835	817
1944	824	797
1945	854	833
1946	844	824

Year	Total potential evaporation (mm)	Total potential evapotranspiration (mm)
1947	765	749
1948	796	777
1949	955	942
1950	908	888
1951	757	736
1952	898	876
1953	809	789
1954	746	725
1955	878	855
1956	919	896
1957	956	939
1958	988	972
1959	933	914
1960	910	889
1961	1012	998
1962	866	846
1963	984	960
1964	939	924
1965	883	858
1966	942	921
1967	1010	993
1968	986	965
1969	996	974
1970	984	965
1971	973	950
1972	924	906
1973	989	972
1974	997	984
1975	936	927
1976	1065	1049
1977	1044	1017
1978	948	923
1979	920	898
1980	921	905
1981	1037	1010
1982	947	925
1983	903	888
1984	977	958

Year	Total potential evaporation (mm)	Total potential evapotranspiration (mm)
1985	1016	993
1986	949	929
1987	1010	987
1988	1090	1068
1989	925	905
1990	1015	991
1991	996	974
1992	992	972
1993	938	914
1994	980	955
1995	864	848
1996	750	729
Average	897	875
Standard deviation	91	93
Maximum	1090	1068
Minimum	734	709
N	81	81

Table 32. Yearly evaporation and evapotranspiration values Edmonton International Airport.

Year	Potential Evaporation (mm)	Potential Evapotranspiration (mm)
1961	1019	1004
1962	832	808
1963	944	919
1964	864	846
1965	731	703
1966	796	772
1967	853	817
1968	863	838
1969	869	849
1970	917	889
1971	861	832
1972	827	794
1973	804	781
1974	778	750
1975	775	751
1976	886	863
1977	849	822
1978	854	829
1979	873	842
1980	818	794
1981	923	891
1982	823	796
1983	802	782
1984	887	869
1985	926	905
1986	870	843
1987	936	920
1988	1016	990
1989	837	813
1990	948	929
1991	927	902
1992	902	875
1993	839	817
1994	920	895
1995	816	793
1996	760	733
Average	865	840
Standard deviation	66	67
Maximum	1019	1004
Minimum	731	703
N	36	36

Table 33. Yearly evaporation and evapotranspiration values Lacombe.

Year	Potential evaporation (mm)	Potential evapotranspiration (mm)
1941	811	779
1942	712	681
1943	-	-
1944	751	721
1945	-	-
1946	736	700
1947	-	-
1948	-	-
1949	-	-
1950	-	-
1951	670	645
1952	754	722
1953	659	629
1954	677	651
1955	813	786
1956	826	801
1957	849	823
1958	942	923
1959	865	846
1960	888	870
1961	996	981
1962	882	863
1963	916	894
1964	858	843
1965	758	742
1966	838	814
1967	-	-
1968	876	856
1969	906	889
1970	949	925
1971	884	869
1972	840	815
1973	968	946
1974	822	804
1975	783	768
1976	934	925
1977	932	918

Year	Potential evaporation (mm)	Potential evapotranspiration (mm)
1978	878	850
1979	-	-
1980	850	825
1981	882	856
1982	811	791
1983	858	833
1984	882	864
1985	912	893
1986	818	789
1987	933	908
1988	1071	1045
1989	841	816
1990	889	864
1991	824	801
1992	922	900
Average	852	829
Standard deviation	86	89
Maximum	1071	1045
Minimum	659	629
N	44	44

Appendix 3 – Demographic Data for the Study Area

Table 34. Population distribution by age for both sexes within the study area.

Community	Population Centre Type	Total Number by Age Group			Percentage by Age Group		
		0-19	20-64	65+	0-19	20-64	65+
Camrose	City (C)	3,850	8,010	2,990	**25.9**	**53.9**	20.1
Edmonton	City (C)	169,430	418,870	77,805	**25.4**	62.9	11.7
Fort Saskatchewan	City (C)	3,940	7,930	1,250	30.0	**60.4**	**9.5**
Leduc	City (C)	4,380	9,005	1,650	29.1	**59.9**	11.0
Red Deer	City (C)	19,075	42,050	6,580	28.2	62.1	**9.7**
Spruce Grove	City (C)	5,100	9,850	1,030	31.9	61.6	**6.4**
St. Albert	City (C)	16,195	32.850	4,030	30.5	61.9	**7.6**
Wetaskiwin	City (C)	3,050	6,115	2,030	27.0	**54.8**	18.2
Camrose County No. 22	County (CM)	2,245	4,215	835	30.8	**57.8**	11.4
Lacombe County	County (CM)	3,370	5,855	930	33.2	**57.7**	**9.2**
Leduc County	County (CM)	3,830	7,505	1,195	30.6	**59.9**	**9.5**
Parkland County	County (CM)	8,490	16,700	2,070	31.1	**61.3**	**7.6**
Ponoka County	County (CM)	2,810	5,045	995	31.8	**57.0**	11.2
Red Deer County	County (CM)	5,495	11,345	1,800	29.5	**60.9**	**9.7**
Stettler County No. 6	County (CM)	1,745	3,030	585	32.6	**56.5**	10.9
Wetaskiwin County No. 10	County (CM)	3,150	6,365	1,180	29.5	**59.5**	11.0
Lac Ste. Anne County	Municipal District (MD)	2,520	5,370	1,060	28.2	**60.0**	11.8
Sturgeon County	Municipal District (MD)	5,920	10,930	1,220	32.8	**60.5**	**6.8**
Alexander 134	Indian Reserve (R)	445	370	25	53.0	**44.0**	**3.0**
Stony Plain 135	Indian Reserve (R)	500	656	30	45.7	**51.6**	**2.7**
Wabamun 133A	Indian Reserve (R)	565	415	20	56.5	**41.5**	**2.0**
Strathcona County	Specialized Municipality (SM)	22,255	44,635	5,100	30.9	62.0	**7.1**
Golden Days	Summer Village (SV)	30	75	20	**24.0**	**60.0**	16.0
Seba Beach	Summer Village (SV)	25	65	20	**22.7**	**59.1**	18.2
Beaumont	Town (T)	2,785	3,965	260	39.7	**56.6**	**3.7**
Bon Accord	Town (T)	555	920	60	36.2	**59.9**	**3.9**
Bruderheim	Town (T)	380	710	110	31.7	**59.2**	**9.2**
Calmar	Town (T)	640	1,095	165	33.7	**57.6**	**8.7**
Devon	Town (T)	1,610	2,960	405	32.4	**59.5**	**8.1**
Drayton Valley	Town (T)	1,840	3,350	615	31.7	**57.7**	10.6
Gibbons	Town (T)	930	1,540	185	35.0	**58.0**	**7.0**
Innisfail	Town (T)	1,910	3,845	1,170	27.6	**55.5**	16.9
Lacombe	Town (T)	2,935	5,080	1,375	31.3	**54.1**	14.6
Legal	Town (T)	340	580	140	32.1	**54.7**	13.2
Morinville	Town (T)	2,380	3,750	415	36.4	**57.3**	**6.3**
Ponoka	Town (T)	1,695	3,440	1,195	26.8	**54.3**	18.9
Redwater	Town (T)	675	1,170	325	31.1	**53.9**	15.0
Rocky Mountain House	Town (T)	1,920	3,585	700	30.9	**57.8**	11.3
Stettler	Town (T)	1,380	2,780	1,055	26.5	**53.3**	20.2
Stony Plain	Town (T)	3,020	5,395	1,175	31.5	**56.3**	12.3
Sylvan Lake	Town (T)	2,480	4,505	505	33.1	**60.1**	**6.7**
New Sarepta	Village (VL)	110	220	45	29.3	**58.7**	12.0
Spring Lake	Village (VL)	135	290	30	29.7	63.7	**6.6**
Thorsby	Village (VL)	220	450	125	27.7	**56.6**	15.7
Wabamun	Village (VL)	155	360	85	**25.8**	**60.0**	14.2
Warburg	Village (VL)	145	265	145	26.1	**47.7**	26.1
Alberta		840,550	1,825,855	308,405	28.3	61.4	10.4
Canada		7,778,865	18,339,680	3,888,550	25.9	61.1	13.0

Table 35. Population distribution by age for females within the study area.

Community	Population Centre Type	Total Number by Age Group			Percentage by Age Group		
		0-19	20-64	65+	0-19	20-64	65+
Camrose	City (C)	1,875	4,165	1,775	**24.0**	**53.3**	22.7
Edmonton	City (C)	83,350	210,155	45,045	**24.6**	62.1	13.3
Fort Saskatchewan	City (C)	1,905	3,950	735	28.9	**59.9**	**11.2**
Leduc	City (C)	2,080	4,560	955	27.4	**60.0**	12.6
Red Deer	City (C)	9,435	20,990	3,895	27.5	61.2	**11.3**
Spruce Grove	City (C)	2,500	4,940	555	31.3	61.8	**6.9**
St. Albert	City (C)	7,915	16,815	2275	29.3	62.3	**8.4**
Wetaskiwin	City (C)	1,440	3,170	1,240	**24.6**	**54.2**	21.2
Camrose County No. 22	County (CM)	1,090	2,040	355	31.3	**58.5**	**10.2**
Lacombe County	County (CM)	1,620	2,880	415	33.0	**58.6**	**8.4**
Leduc County	County (CM)	1,845	3,655	545	30.5	**60.5**	**9.0**
Parkland County	County (CM)	4,025	8,175	940	30.6	62.2	**7.2**
Ponoka County	County (CM)	1,365	2,435	435	32.2	**57.5**	**10.3**
Red Deer County	County (CM)	2,620	5,350	815	29.8	60.9	**9.3**
Stettler County No. 6	County (CM)	835	1,500	270	32.1	**57.6**	**10.4**
Wetaskiwin County No. 10	County (CM)	1,520	3,090	515	29.7	**60.3**	**10.0**
Lac Ste. Anne County	Municipal District (MD)	1,195	2,570	455	28.3	60.9	**10.8**
Sturgeon County	Municipal District (MD)	2,745	5,080	540	32.8	60.7	**6.5**
Alexander 134	Indian Reserve (R)	220	195	10	51.8	**45.9**	**2.4**
Stony Plain 135	Indian Reserve (R)	240	280	15	44.9	**52.3**	**2.8**
Wabamun 133A	Indian Reserve (R)	290	200	15	57.4	**39.6**	**3.0**
Strathcona County	Specialized Municipality (SM)	10,745	22,560	2,675	29.9	62.7	**7.4**
Golden Days	Summer Village (SV)	10	40	10	**16.7**	66.7	16.7
Seba Beach	Summer Village (SV)	10	35	10	**18.2**	63.6	18.2
Beaumont	Town (T)	1,380	1,975	125	39.7	**56.8**	**3.6**
Bon Accord	Town (T)	240	465	30	32.7	63.3	**4.1**
Bruderheim	Town (T)	180	350	55	30.8	**59.8**	**9.4**
Calmar	Town (T)	305	550	85	32.4	**58.5**	**9.0**
Devon	Town (T)	790	1,470	230	31.7	**59.0**	**9.2**
Drayton Valley	Town (T)	915	1,625	360	31.6	**56.0**	12.4
Gibbons	Town (T)	460	760	100	34.8	**57.6**	**7.6**
Innisfail	Town (T)	940	1,965	650	26.4	**55.3**	18.3
Lacombe	Town (T)	1,425	2,570	830	29.5	**53.3**	17.2
Legal	Town (T)	170	280	70	32.7	**53.8**	13.5
Morinville	Town (T)	1,150	1,885	225	35.3	**57.8**	**6.9**
Ponoka	Town (T)	855	1,785	730	25.4	**53.0**	21.7
Redwater	Town (T)	300	580	165	28.7	**55.5**	15.8
Rocky Mountain House	Town (T)	925	1,790	400	29.7	**57.5**	12.8
Stettler	Town (T)	670	1,405	645	**24.6**	**51.7**	23.7
Stony Plain	Town (T)	1,455	2,770	715	29.5	**56.1**	14.5
Sylvan Lake	Town (T)	1,190	2,185	295	32.4	**59.5**	**8.0**
New Sarepta	Village (VL)	50	105	25	27.8	**58.3**	13.9
Spring Lake	Village (VL)	70	150	15	29.8	63.8	**6.4**
Thorsby	Village (VL)	100	220	65	26.0	**57.1**	16.9
Wabamun	Village (VL)	75	165	40	26.8	**58.9**	14.3
Warburg	Village (VL)	75	130	80	26.3	**45.6**	28.1
Alberta		410,275	906,105	171,840	27.6	60.9	11.5
Canada		3,795,725	9,278,620	2,225,900	24.8	60.6	14.5

Table 36. Population distribution by age for males within the study area.

Community	Population Centre Type	Total Number by Age Group			Percentage by Age Group		
		0-19	20-64	65+	0-19	20-64	65+
Camrose	City (C)	1,980	3,845	1,220	28.1	**54.6**	17.3
Edmonton	City (C)	86,080	208,715	32,760	**26.3**	63.7	10.0
Fort Saskatchewan	City (C)	2,035	3.980	520	31.1	**60.9**	**8.0**
Leduc	City (C)	2,300	4,445	690	30.9	**59.8**	9.3
Red Deer	City (C)	9,640	21,065	2,685	28.9	63.1	**8.0**
Spruce Grove	City (C)	2,610	4,915	475	32.6	**61.4**	**5.9**
St. Albert	City (C)	8,280	16,040	1,760	31.7	**61.5**	**6.7**
Wetaskiwin	City (C)	1,560	2,945	790	29.5	**55.6**	14.9
Camrose County No. 22	County (CM)	1,150	2,170	480	30.3	**57.1**	12.6
Lacombe County	County (CM)	1,750	2,980	520	33.3	**56.8**	9.9
Leduc County	County (CM)	1,980	3,850	655	30.5	**59.4**	10.1
Parkland County	County (CM)	4,465	8,520	1,125	31.6	**60.4**	**8.0**
Ponoka County	County (CM)	1,445	2,615	560	31.3	**56.6**	12.1
Red Deer County	County (CM)	2,875	5,995	985	29.2	**60.8**	10.0
Stettler County No. 6	County (CM)	910	1,535	315	33.0	**55.6**	11.4
Wetaskiwin County No. 10	County (CM)	1,630	3,275	665	29.3	**58.8**	11.9
Lac Ste. Anne County	Municipal District (MD)	1,325	2,795	605	28.0	**59.2**	12.8
Sturgeon County	Municipal District (MD)	3,170	5,850	680	32.7	**60.3**	**7.0**
Alexander 134	Indian Reserve (R)	230	175	10	55.4	**42.2**	**2.4**
Stony Plain 135	Indian Reserve (R)	260	285	15	46.4	**50.9**	**2.7**
Wabamun 133A	Indian Reserve (R)	275	210	5	56.1	**42.9**	**1.0**
Strathcona County	Specialized Municipality (SM)	11,510	22,075	2,420	32.0	**61.3**	**6.7**
Golden Days	Summer Village (SV)	15	40	15	**21.4**	**57.1**	21.4
Seba Beach	Summer Village (SV)	15	30	10	27.3	**54.5**	18.2
Beaumont	Town (T)	1,400	1,990	130	39.8	**56.5**	**3.7**
Bon Accord	Town (T)	310	455	25	39.2	**57.6**	**3.2**
Bruderheim	Town (T)	200	360	55	32.5	**58.5**	**8.9**
Calmar	Town (T)	335	545	75	35.1	**57.1**	**7.9**
Devon	Town (T)	815	1,490	175	32.9	**60.1**	**7.1**
Drayton Valley	Town (T)	920	1,725	260	31.7	**59.4**	**9.0**
Gibbons	Town (T)	470	780	85	35.2	**58.4**	**6.4**
Innisfail	Town (T)	970	1,880	515	28.8	**55.9**	15.3
Lacombe	Town (T)	1,510	2,505	545	33.1	**54.9**	12.0
Legal	Town (T)	170	300	70	31.5	**55.6**	13.0
Morinville	Town (T)	1,230	1,865	195	37.4	**56.7**	**5.9**
Ponoka	Town (T)	840	1655	465	28.4	**55.9**	15.7
Redwater	Town (T)	370	590	165	32.9	**52.4**	14.7
Rocky Mountain House	Town (T)	995	1,795	300	32.2	**58.1**	9.7
Stettler	Town (T)	710	1,380	410	28.4	**55.2**	16.4
Stony Plain	Town (T)	1,565	2,630	455	33.7	**56.6**	9.8
Sylvan Lake	Town (T)	1,295	2,320	210	33.9	**60.7**	**5.5**
New Sarepta	Village (VL)	60	115	20	30.8	**59.0**	10.2
Spring Lake	Village (VL)	65	140	15	29.5	63.6	**6.8**
Thorsby	Village (VL)	120	235	60	28.9	**56.6**	14.5
Wabamun	Village (VL)	80	190	40	**25.8**	**61.3**	12.9
Warburg	Village (VL)	70	135	65	**25.9**	**50.0**	24.1
Alberta		430,275	919,750	136,560	28.9	61.9	9.2
Canada		3,983,140	9,061,055	1,662,655	27.1	61.6	11.3

Table 37. Median age for both sexes within the study area.

Community	Population Centre Type	Median Age 2001 Census	Median Age 1996 Census	Median Age Difference
Camrose	City (C)	39.7	37.5	2.2
Edmonton	City (C)	35.3	33.8	**1.5**
Fort Saskatchewan	City (C)	35.6	**33.4**	2.2
Leduc	City (C)	36.0	33.6	2.4
Red Deer	City (C)	**33.1**	**32.2**	**0.9**
Spruce Grove	City (C)	**33.7**	**31.8**	1.9
St. Albert	City (C)	36.3	33.9	2.4
Wetaskiwin	City (C)	38.1	34.7	3.4
Camrose County No. 22	County (CM)	39.4	35.8	3.6
Lacombe County	County (CM)	36.4	na	
Leduc County	County (CM)	38.1	35.2	2.9
Parkland County	County (CM)	37.6	34.9	2.7
Ponoka County	County (CM)	38.3	35.1	3.2
Red Deer County	County (CM)	38.1	35.4	2.7
Stettler County No. 6	County (CM)	37.1	34.5	2.6
Wetaskiwin County No. 10	County (CM)	39.6	36.1	3.5
Lac Ste. Anne County	Municipal District (MD)	39.5	37.4	2.1
Sturgeon County	Municipal District (MD)	**34.2**	**32.8**	**1.4**
Alexander 134	Indian Reserve (R)	**19.0**	**19.6**	**-0.6**
Stony Plain 135	Indian Reserve (R)	**21.9**	**19.7**	2.2
Wabamun 133A	Indian Reserve (R)	**16.7**	**15.6**	**1.1**
Strathcona County	Specialized Municipality (SM)	36.4	34.1	2.3
Golden Days	Summer Village (SV)	47.8	45.0	2.8
Seba Beach	Summer Village (SV)	46.1	44.3	1.8
Beaumont	Town (T)	**30.7**	**28.9**	1.8
Bon Accord	Town (T)	**31.2**	**31.1**	**0.1**
Bruderheim	Town (T)	35.3	**31.8**	3.5
Calmar	Town (T)	**31.3**	**30.7**	**0.6**
Devon	Town (T)	**33.6**	**31.4**	2.2
Drayton Valley	Town (T)	**32.3**	**30.3**	2.0
Gibbons	Town (T)	**33.6**	**30.5**	3.1
Innisfail	Town (T)	38.2	36.0	2.2
Lacombe	Town (T)	35.9	na	
Legal	Town (T)	**34.8**	33.9	**0.9**
Morinville	Town (T)	**31.3**	**30.2**	**1.1**
Ponoka	Town (T)	38.8	36.2	2.6
Redwater	Town (T)	38.1	35.2	2.9
Rocky Mountain House	Town (T)	**33.7**	**31.7**	2.0
Stettler	Town (T)	38.7	36.5	2.2
Stony Plain	Town (T)	35.0	**32.5**	2.5
Sylvan Lake	Town (T)	**31.6**	**32.1**	**-0.5**
New Sarepta	Village (VL)	**32.8**	**32.3**	**0.5**
Spring Lake	Village (VL)	37.3	34.4	2.9
Thorsby	Village (VL)	38.5	38.2	**0.3**
Wabamun	Village (VL)	40.0	34.8	5.2
Warburg	Village (VL)	41.1	36.8	4.3
Median Age – Alberta		35.0	33.4	1.6
Median Age - Canada		37.6	35.3	2.3

Table 38. Median age for females within the study area.

Community	Population Centre Type	Median Age 2001 Census	Median Age 1996 Census	Median Age Difference
Camrose	City (C)	41.7	39.0	2.7
Edmonton	City (C)	36.2	34.5	**1.7**
Fort Saskatchewan	City (C)	36.3	34.2	2.1
Leduc	City (C)	37.1	34.5	2.6
Red Deer	City (C)	**34.3**	**32.9**	**1.4**
Spruce Grove	City (C)	**34.2**	**32.0**	2.2
St. Albert	City (C)	36.9	34.5	2.4
Wetaskiwin	City (C)	40.1	36.6	3.5
Camrose County No. 22	County (CM)	38.8	34.9	3.9
Lacombe County	County (CM)	36.1	na	
Leduc County	County (CM)	37.6	34.7	2.9
Parkland County	County (CM)	37.3	34.5	2.8
Ponoka County	County (CM)	37.7	34.5	3.2
Red Deer County	County (CM)	38.0	35.0	3.0
Stettler County No. 6	County (CM)	37.1	34.8	2.3
Wetaskiwin County No. 10	County (CM)	39.2	35.6	3.6
Lac Ste. Anne County	Municipal District (MD)	39.0	36.6	2.4
Sturgeon County	Municipal District (MD)	**34.9**	**32.9**	2.0
Alexander 134	Indian Reserve (R)	**19.5**	**19.3**	**0.2**
Stony Plain 135	Indian Reserve (R)	**22.0**	**21.3**	**0.7**
Wabamun 133A	Indian Reserve (R)	**16.8**	**15.2**	**1.6**
Strathcona County	Specialized Municipality (SM)	36.7	34.3	2.4
Golden Days	Summer Village (SV)	47.3	44.5	2.8
Seba Beach	Summer Village (SV)	46.7	43.0	3.7
Beaumont	Town (T)	**30.8**	**29.1**	**1.7**
Bon Accord	Town (T)	**32.3**	**30.4**	1.9
Bruderheim	Town (T)	**35.6**	**31.3**	4.3
Calmar	Town (T)	**31.7**	**31.3**	**0.4**
Devon	Town (T)	**34.2**	**31.5**	2.7
Drayton Valley	Town (T)	**32.9**	**30.6**	2.3
Gibbons	Town (T)	**33.6**	**30.4**	3.2
Innisfail	Town (T)	39.2	36.9	2.3
Lacombe	Town (T)	37.2	na	
Legal	Town (T)	**33.7**	**33.3**	**0.4**
Morinville	Town (T)	**31.7**	**30.2**	**1.5**
Ponoka	Town (T)	39.8	37.1	2.7
Redwater	Town (T)	38.3	35.7	2.6
Rocky Mountain House	Town (T)	**34.7**	**31.8**	2.9
Stettler	Town (T)	40.4	38.7	**1.7**
Stony Plain	Town (T)	36.2	**33.2**	3.0
Sylvan Lake	Town (T)	**32.5**	**32.1**	**0.4**
New Sarepta	Village (VL)	**33.5**	35.4	**-1.9**
Spring Lake	Village (VL)	36.7	34.7	2.0
Thorsby	Village (VL)	39.4	40.3	**-0.9**
Wabamun	Village (VL)	40.0	35.7	4.3
Warburg	Village (VL)	41.1	38.0	3.1
Median Age – Alberta		35.6	33.9	1.7
Median Age - Canada		38.4	36.1	2.3

Table 39. Median age for males within the study area.

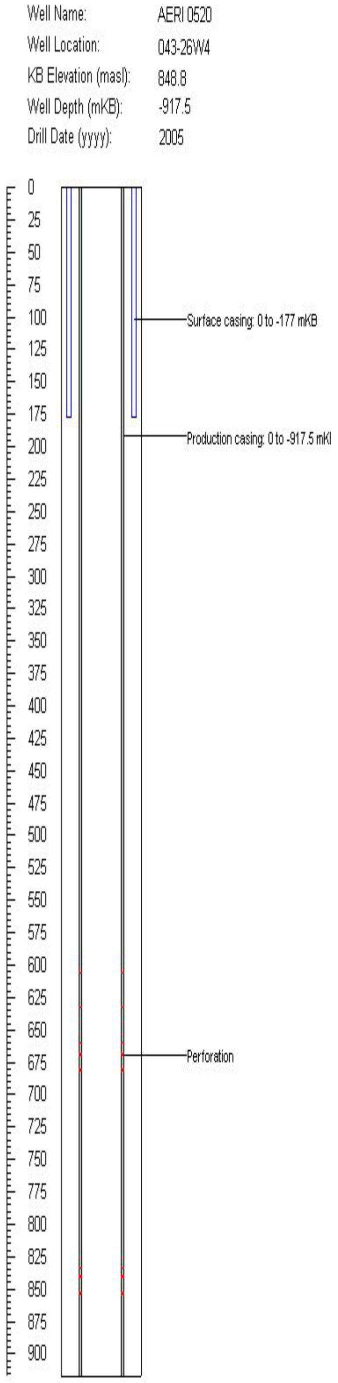
Community	Population Centre Type	Median Age 2001 Census	Median Age 1996 Census	Median Age Difference
Camrose	City (C)	37.7	36.1	1.6
Edmonton	City (C)	**34.4**	33.2	**1.2**
Fort Saskatchewan	City (C)	34.8	**32.7**	2.1
Leduc	City (C)	34.7	**32.8**	1.9
Red Deer	City (C)	**32.1**	**31.4**	**0.7**
Spruce Grove	City (C)	**33.0**	**31.6**	**1.4**
St. Albert	City (C)	35.6	33.3	2.3
Wetaskiwin	City (C)	35.9	**33.0**	2.9
Camrose County No. 22	County (CM)	40.1	36.5	3.6
Lacombe County	County (CM)	36.7	na	
Leduc County	County (CM)	38.5	35.7	2.8
Parkland County	County (CM)	37.8	35.2	2.6
Ponoka County	County (CM)	39.0	35.7	3.3
Red Deer County	County (CM)	38.1	35.8	2.3
Stettler County No. 6	County (CM)	37.2	34.3	2.9
Wetaskiwin County No. 10	County (CM)	40.0	36.6	3.4
Lac Ste. Anne County	Municipal District (MD)	40.0	38.1	1.9
Sturgeon County	Municipal District (MD)	**33.4**	**32.8**	**0.6**
Alexander 134	Indian Reserve (R)	**18.6**	**20.1**	**-1.5**
Stony Plain 135	Indian Reserve (R)	**21.8**	**19**	2.8
Wabamun 133A	Indian Reserve (R)	**16.7**	**15.8**	**0.9**
Strathcona County	Specialized Municipality (SM)	36.1	33.8	2.3
Golden Days	Summer Village (SV)	49.0	45.3	3.7
Seba Beach	Summer Village (SV)	43.5	44.5	**-1.0**
Beaumont	Town (T)	**30.6**	**28.6**	2.0
Bon Accord	Town (T)	**30.1**	**31.9**	**-1.8**
Bruderheim	Town (T)	34.7	**32.2**	2.5
Calmar	Town (T)	**31.0**	**30.3**	**0.7**
Devon	Town (T)	**32.8**	**31.2**	1.6
Drayton Valley	Town (T)	**31.7**	**30.1**	1.6
Gibbons	Town (T)	**33.6**	**30.6**	3.0
Innisfail	Town (T)	37.1	35.3	1.8
Lacombe	Town (T)	**34.3**	na	
Legal	Town (T)	35.4	35.0	**0.4**
Morinville	Town (T)	**30.8**	**30.3**	**0.5**
Ponoka	Town (T)	37.7	35.2	2.5
Redwater	Town (T)	37.8	34.6	3.2
Rocky Mountain House	Town (T)	**32.7**	**31.6**	**1.1**
Stettler	Town (T)	37.0	34.4	2.6
Stony Plain	Town (T)	**33.5**	**31.6**	1.9
Sylvan Lake	Town (T)	**30.8**	**32.1**	**-1.3**
New Sarepta	Village (VL)	**31.9**	**27.0**	4.9
Spring Lake	Village (VL)	38.2	34.1	4.1
Thorsby	Village (VL)	37.1	36.7	**0.4**
Wabamun	Village (VL)	40.1	33.5	6.6
Warburg	Village (VL)	41.0	36.0	5.0
Median Age – Alberta		34.4	33.0	1.4
Median Age - Canada		36.8	34.5	2.3

Appendix 4 – Sample Location Site Descriptions

Belly River Group Sample Site Description

Sample Site 59

This site is located to the northeast of Gull Lake and directly north of the city of Red Deer, within the Paskapoo subcrop area. The sample was collected from a CBM well during swabbing operations.



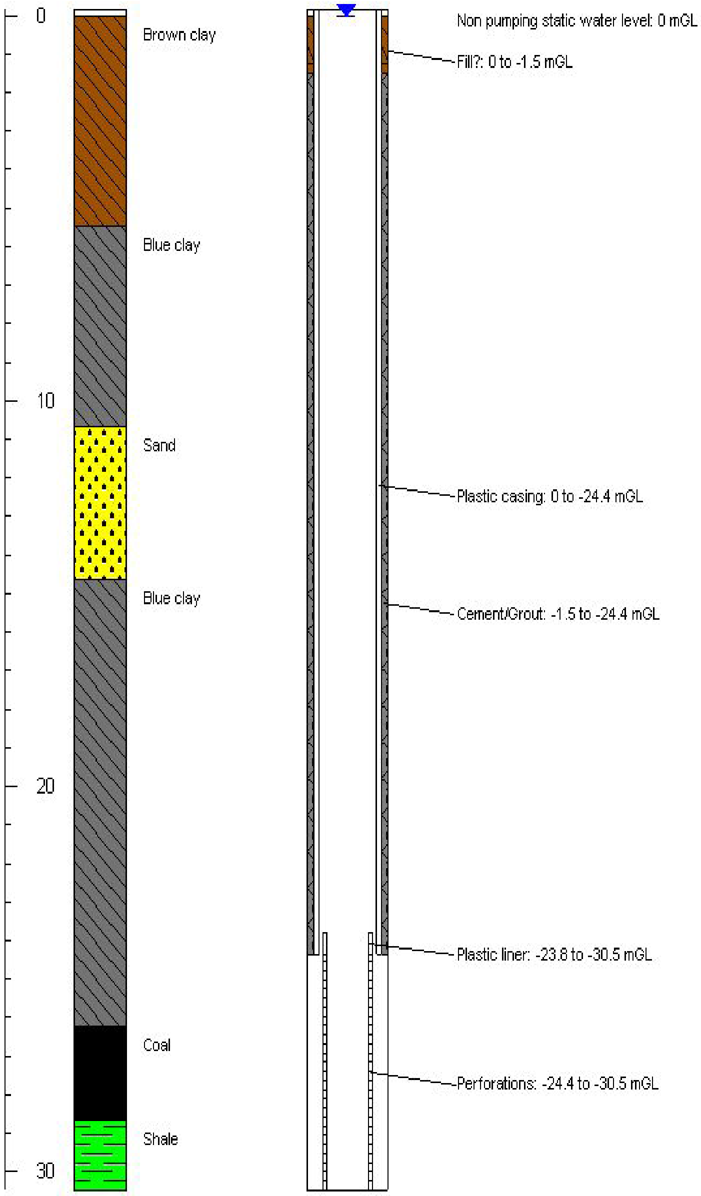
Well Name:	AERI 0520
Well Location:	043-26W4
KB Elevation (masl):	848.8
Well Depth (mKB):	-917.5
Drill Date (yyyy):	2005

Horseshoe Canyon Formation Sample Site Descriptions

Sample Site 43

This site is located east of the city of Edmonton and to the northwest of Cooking Lake. It was collected from a domestic water well. The site is located within the Horseshoe Canyon Formation subcrop. Artesian conditions were observed on site.

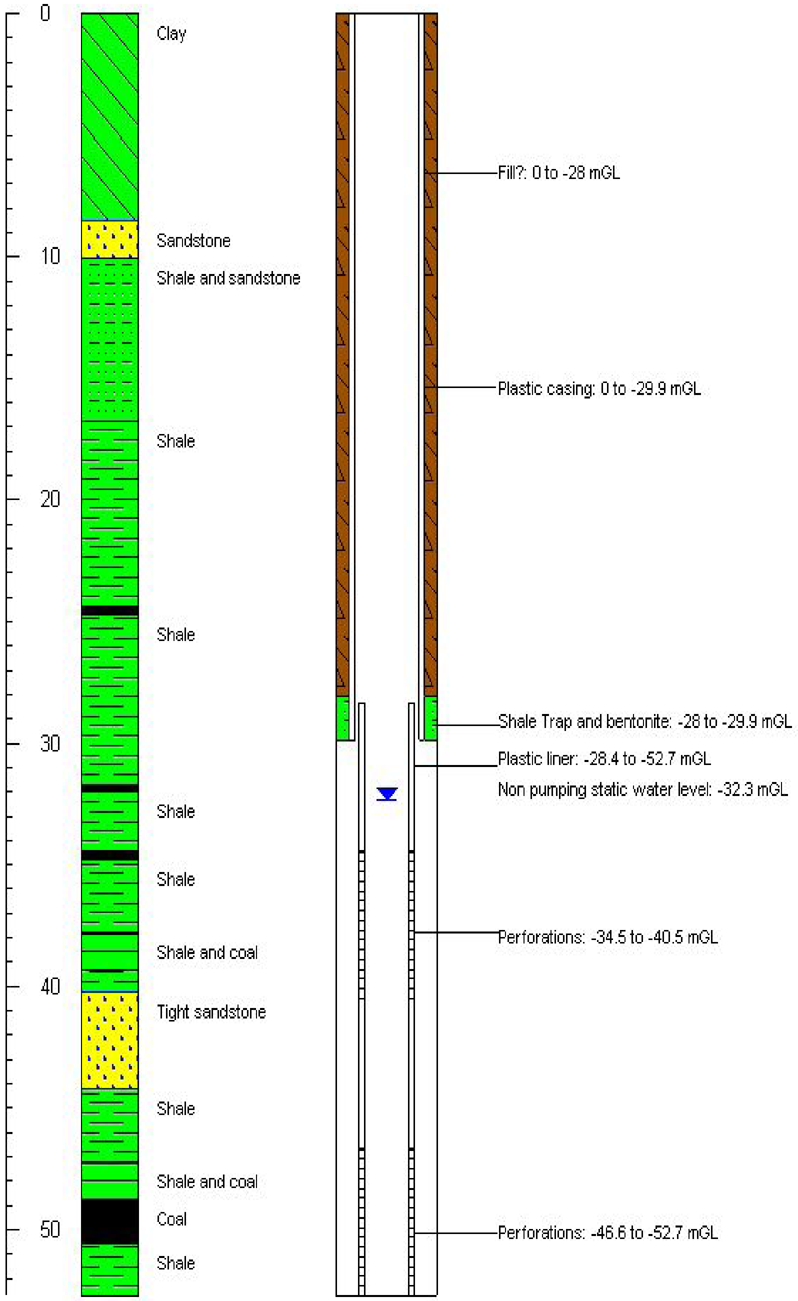
Well Name: AERI 0501
Well Location: 053-22W4
Ground Elevation (masl): 714
Well Depth (mGL): -30.5
Drill Date (yyyy): 1990



Sample Site 44

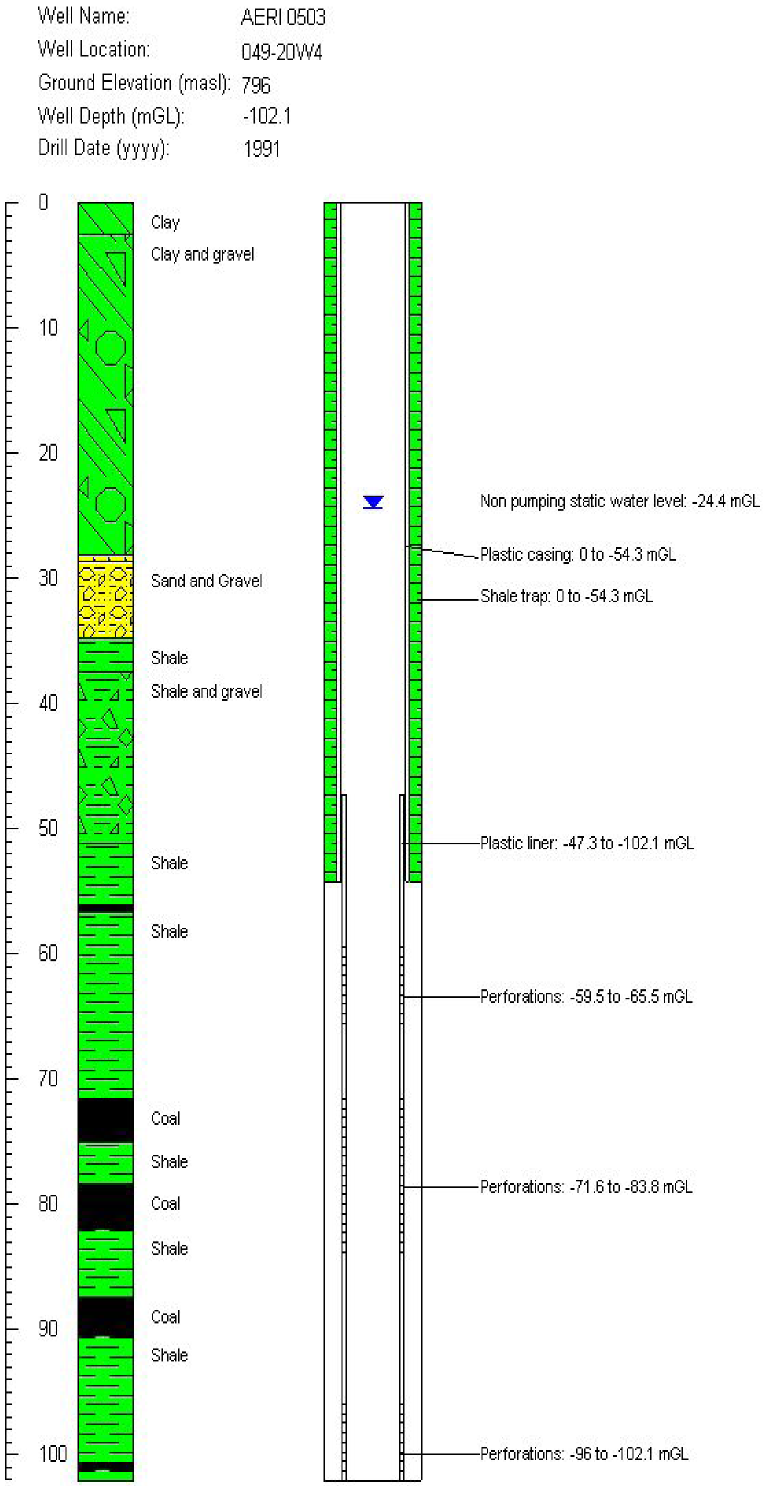
This site is located northeast of the City of Camrose. It is located within the Horseshoe Canyon Formation subcrop and appears to be used for potentially both domestic and agricultural uses.

Well Name:	AERI 0502
Well Location:	048-19W4
Ground Elevation (masl):	756
Well Depth (mGL):	-52.7
Drill Date (yyyy):	1997



Sample Site 45

This site is situated to the north northwest of the City of Camrose, and to the north of Miquelon Lakes. It is located within the Horseshoe Canyon subcrop area. The well appears to be used for domestic purposes.

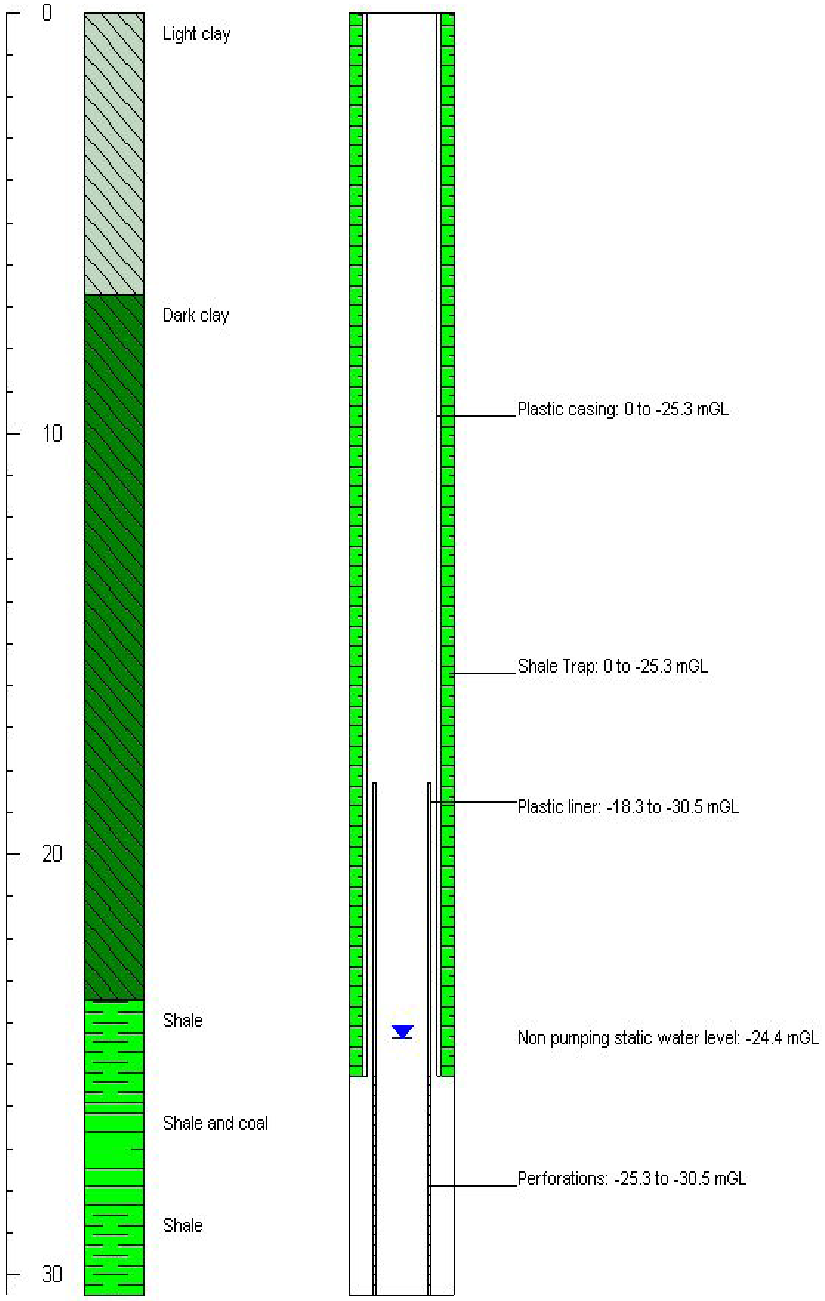


Well Name:	AERI 0503
Well Location:	049-20W4
Ground Elevation (masl):	796
Well Depth (mGL):	-102.1
Drill Date (yyyy):	1991

Sample Site 47

This site is located to the southeast of the City of Edmonton and to the southwest of Cooking Lake. It appears to be used for domestic purposes and is situated within the Horseshoe Canyon subcrop area.

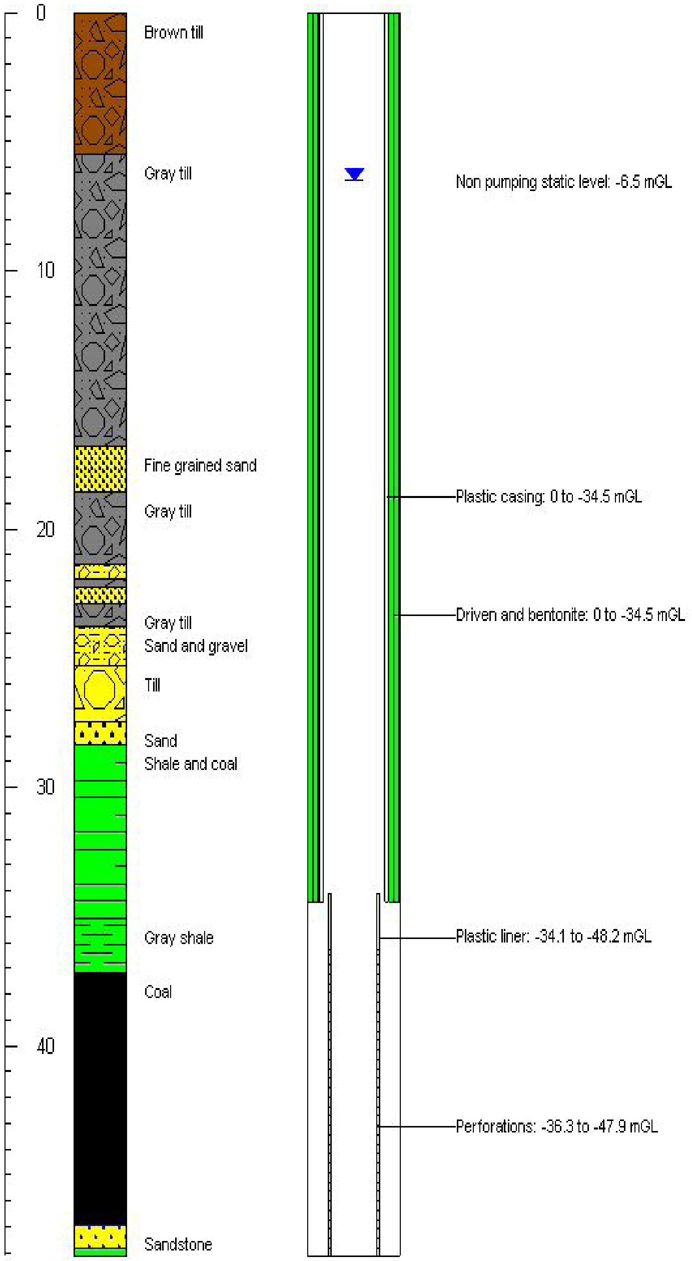
Well Name: AERI 0506
Well Location: 050-23W4
Ground Elevation (masl): 758
Well Depth (mGL): -30.5
Drill Date (yyyy): 1989



Sample Sites 51 and 52

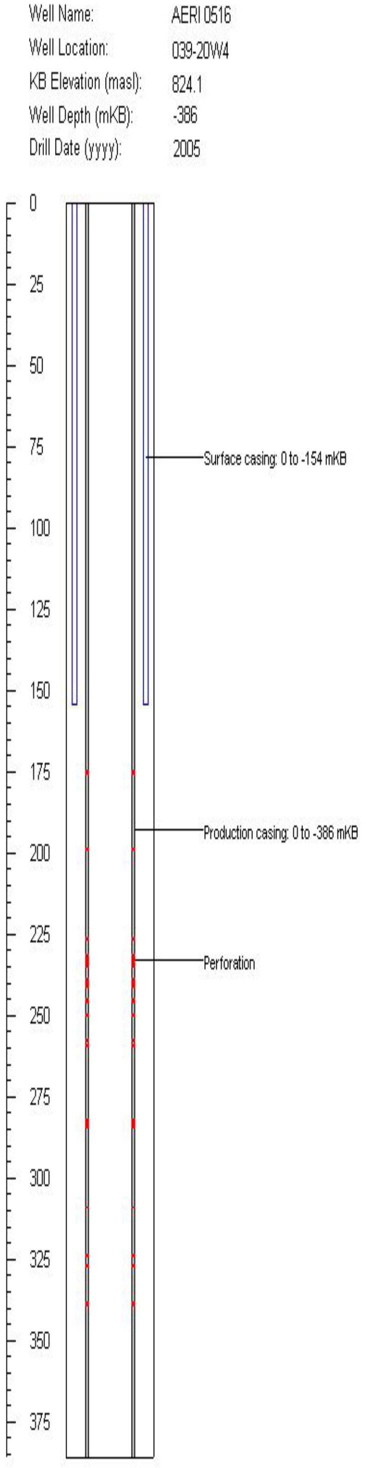
A duplicate sample was collected at this site hence the two site numbers. The site is located east of Buffalo Lake within the Horseshoe Canyon Formation subcrop area. The well appears to be used for domestic purposes.

Well Name:	AERI 0510 and 0511
Well Location:	041-18W4
Ground Elevation (masl):	774
Well Depth (mGL):	-48.2 mGL
Drill Date (yyyy):	1999



Sample Site 55

The site is located to the southeast of Buffalo Lake within the Horseshoe Canyon Formation subcrop area. The water sample was collected during swabbing operations at a CBM well.

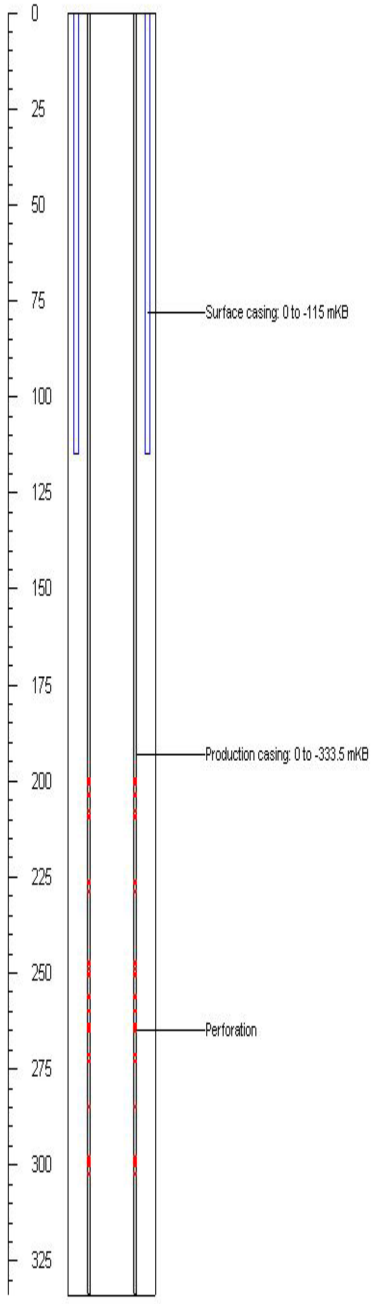


Well Name: AERI 0516
Well Location: 039-20W4
KB Elevation (masl): 824.1
Well Depth (mKB): -386
Drill Date (yyyy): 2005

Sample Sites 56 and 57

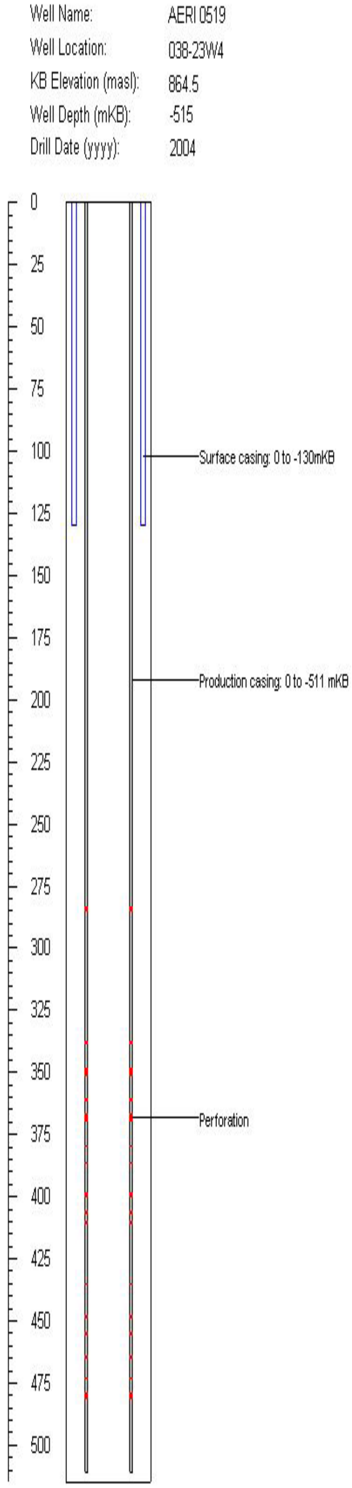
The site is located west of the City of Camrose and directly west of Coal Lake and is within the Horseshoe Canyon subcrop area. The sample was collected during swabbing operations at the CBM well.

Well Name: AERI 0517 and 0518
Well Location: 047-23W4
KB Elevation (masl): 757.4
Well Depth (mKB): -334
Drill Date (yyyy): 2004



Sample Site 58

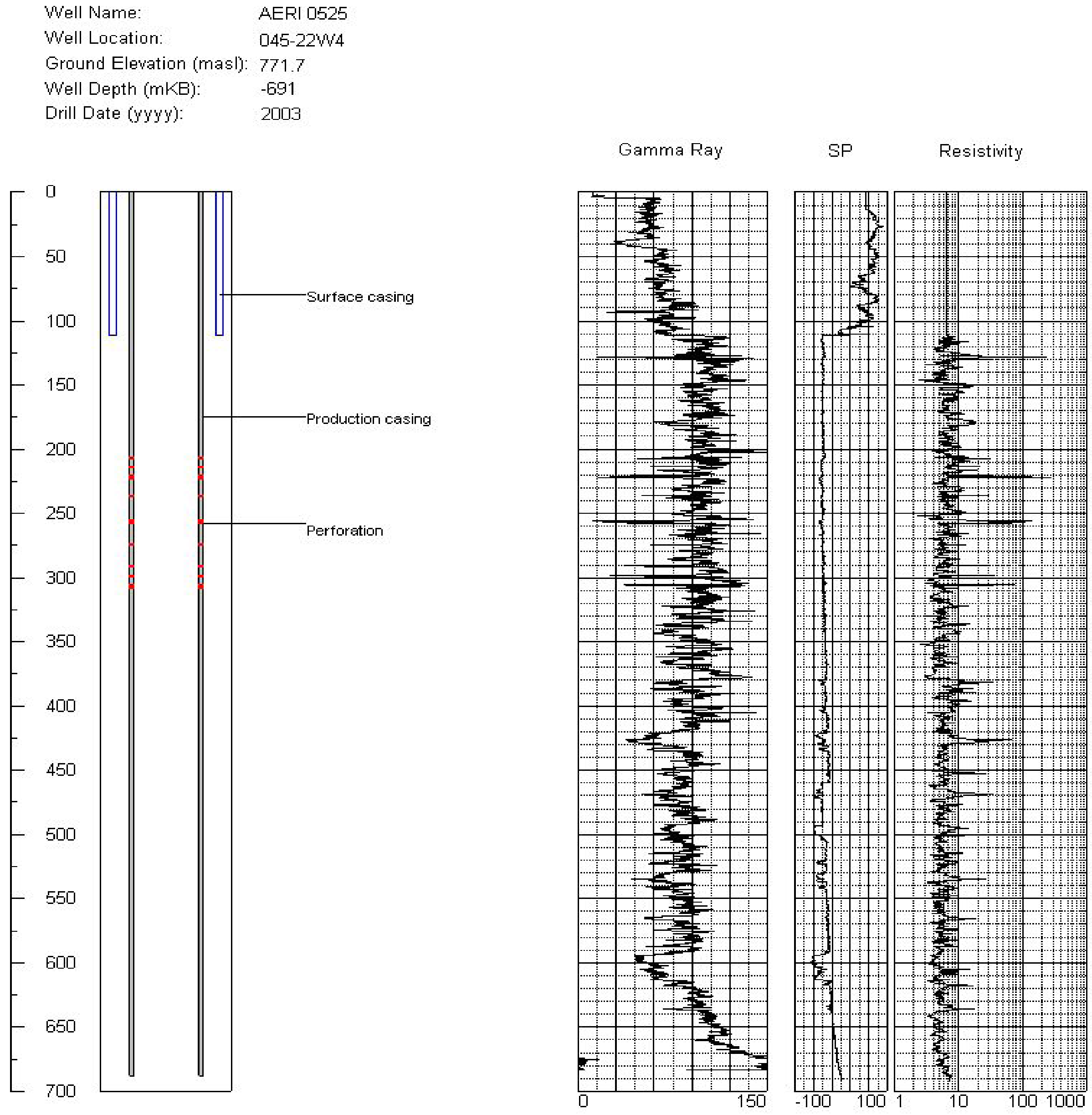
The site is located to the east of the City of Red Deer and southwest of Buffalo Lake within the Paskapoo Formation subcrop area. The sample was collected during swabbing operations on the CBM well.



Well Name: AERI 0519
Well Location: 038-23W4
KB Elevation (masl): 864.5
Well Depth (mKB): -515
Drill Date (yyyy): 2004

Sample Site 64

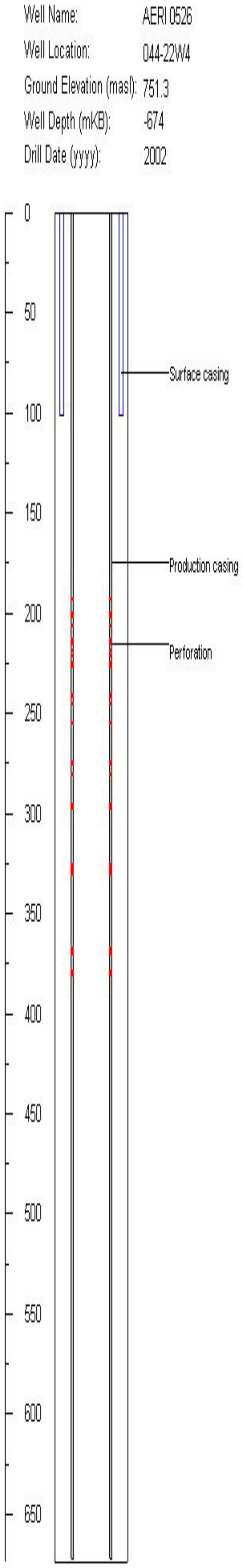
The site is located southwest of the city of Camrose and to the north northwest of Red Deer Lake within the Horseshoe Canyon Formation subcrop area. It was collected during swabbing of the CBM well.



Well Name:	AERI 0525
Well Location:	045-22W4
Ground Elevation (masl):	771.7
Well Depth (mKB):	-691
Drill Date (yyyy):	2003

Sample Site 65

This site is located in the same general location as Site 64 and was similarly collected.

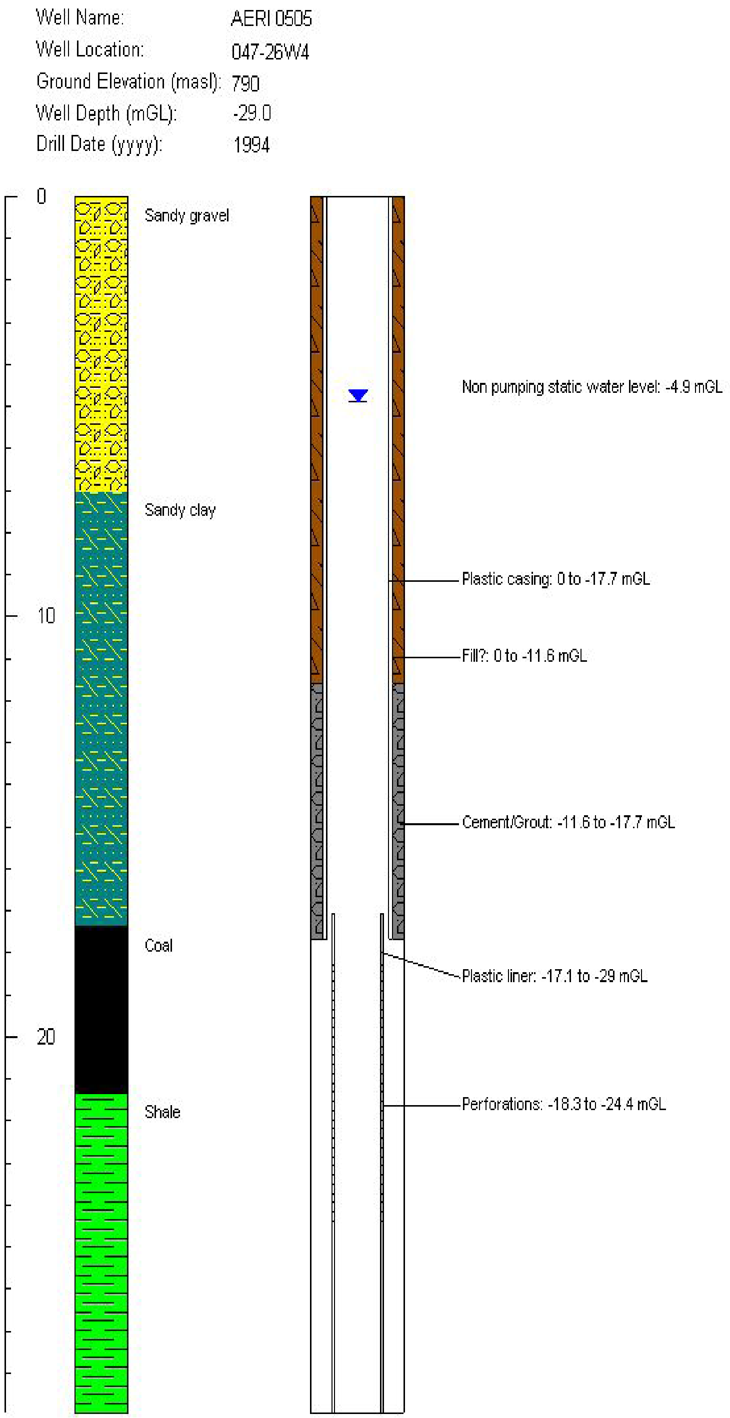


Well Name: AERI 0526
Well Location: 044-22W4
Ground Elevation (masl): 751.3
Well Depth (mKB): -674
Drill Date (yyyy): 2002

Scollard and Paskapoo Formations Sample Site Descriptions

Sample Site 46

This site is located northeast of Pigeon Lake within the Scollard Formation subcrop area. The well appears to be used for domestic purposes.

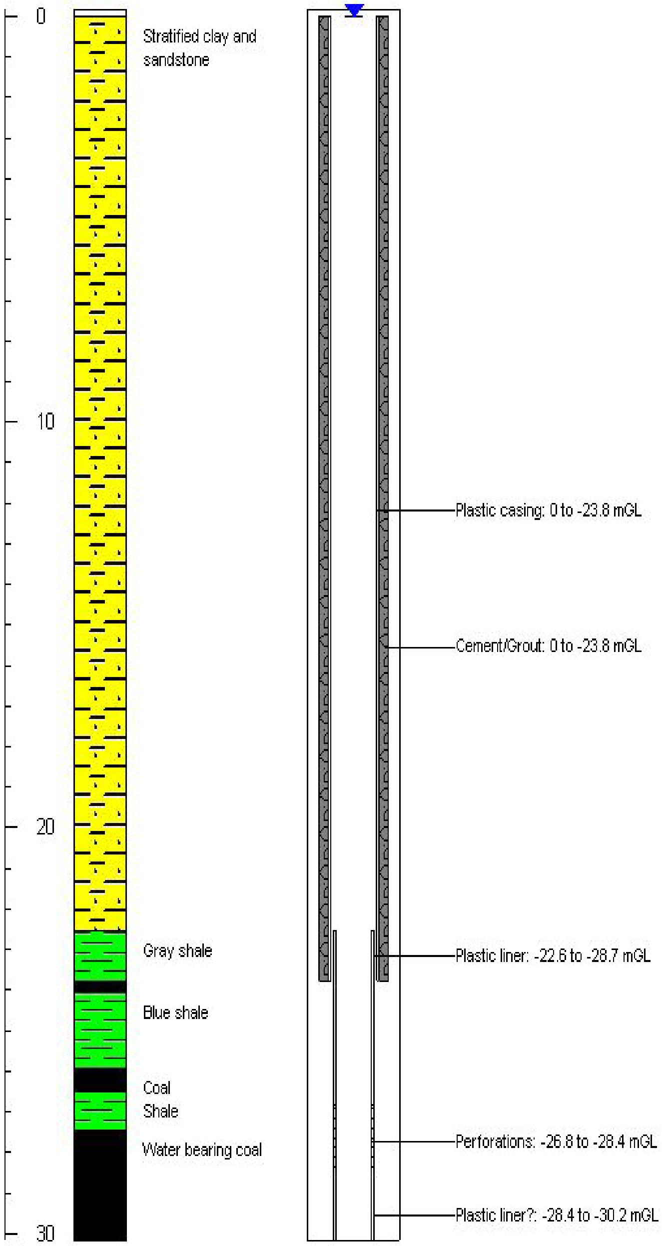


Well Name: AERI 0505
Well Location: 047-26W4
Ground Elevation (masl): 790
Well Depth (mGL): -29.0
Drill Date (yyyy): 1994

Sample Site 48

This site is located north of Pigeon Lake within the Paskapoo subcrop area. The well appears to be used for domestic purposes. Artesian conditions were encountered at this location.

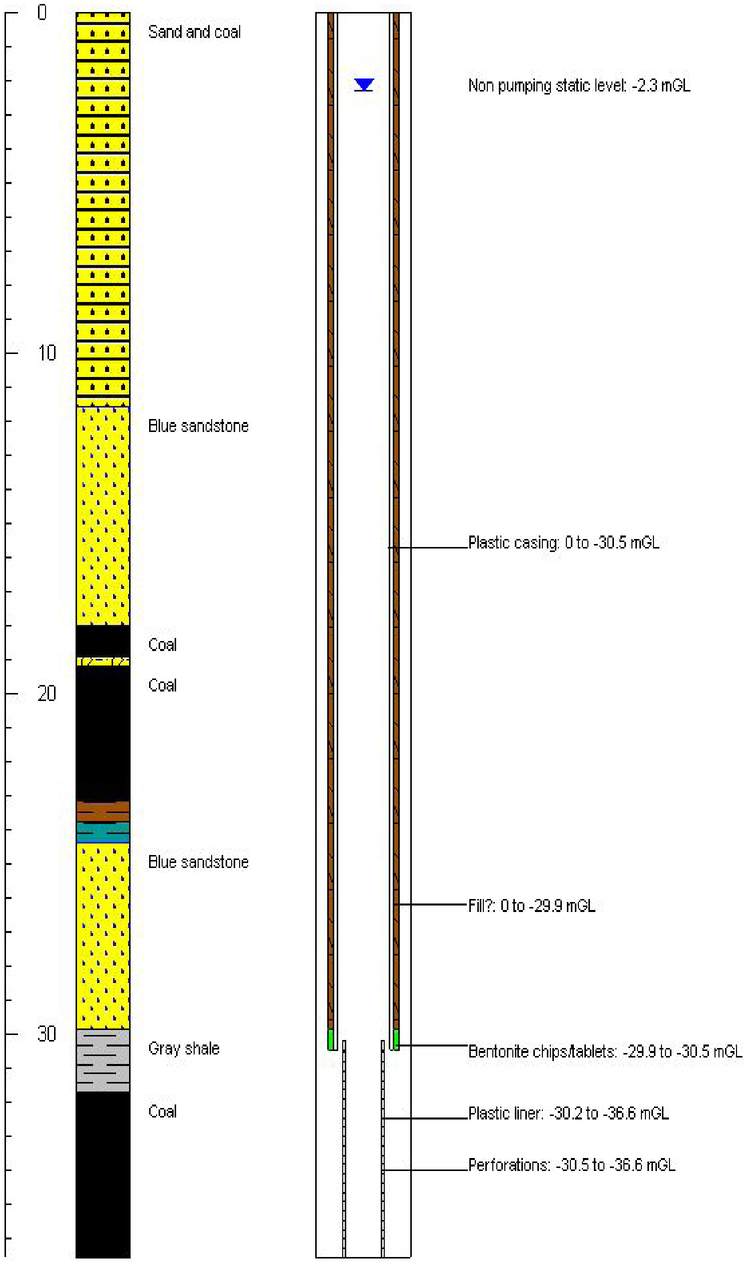
Well Name: AERI 0507
Well Location: 048-01W5
Ground Elevation (masl): 778
Well Depth (mGL): -30.2
Drill Date (yyyy): 1985



Sample Sites 49 and 50

A duplicate sample was collected at this site, hence the two samples. The sample site is located to the west of Wabamun Lake within the Scollard Formation subcrop area. The well appears to be used for domestic purposes.

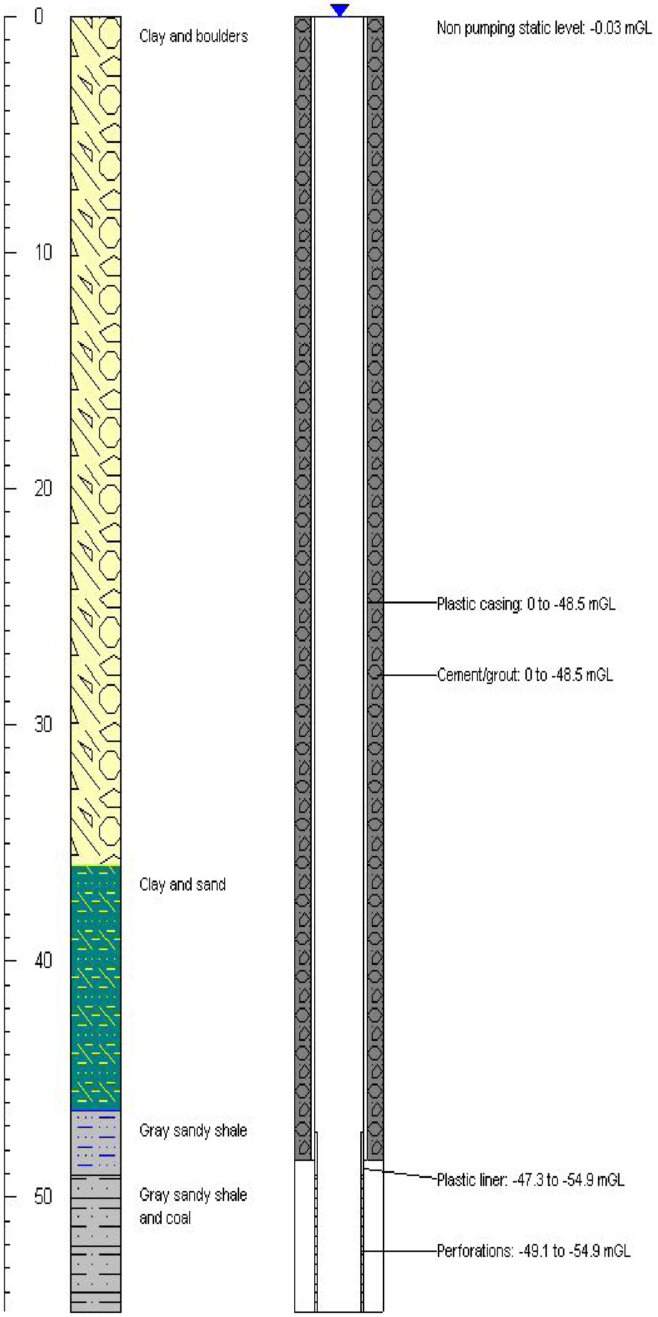
Well Name:	AERI 0508 and 0509
Well Location:	053-05W5
Ground Elevation (masl):	731
Well Depth (mGL):	-36.6
Drill Date (yyyy):	1999



Sample Site 53

This site is located north of the Town of Drayton Valley within the Paskapoo Formation subcrop area. The well appears to be used for domestic purposes. Artesian conditions were present at this site.

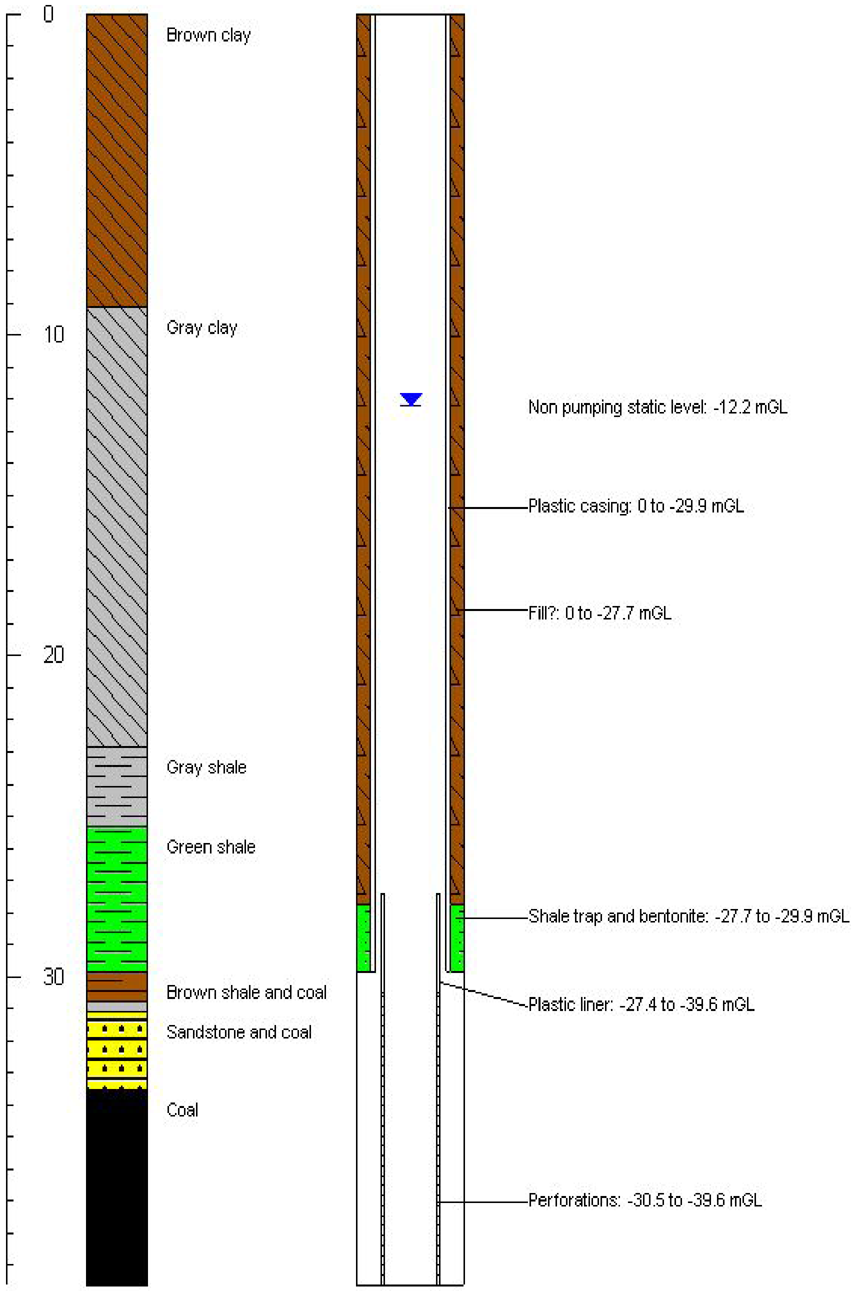
Well Name: AERI 0512
Well Location: 050-07W5
Ground Elevation (masl): 812
Well Depth (mGL): -54.9
Drill Date (yyyy): 1998



Sample Site 54

This site is located to the east of Wabamun Lake within the Scollard Formation subcrop area. The well appears to be used for domestic purposes.

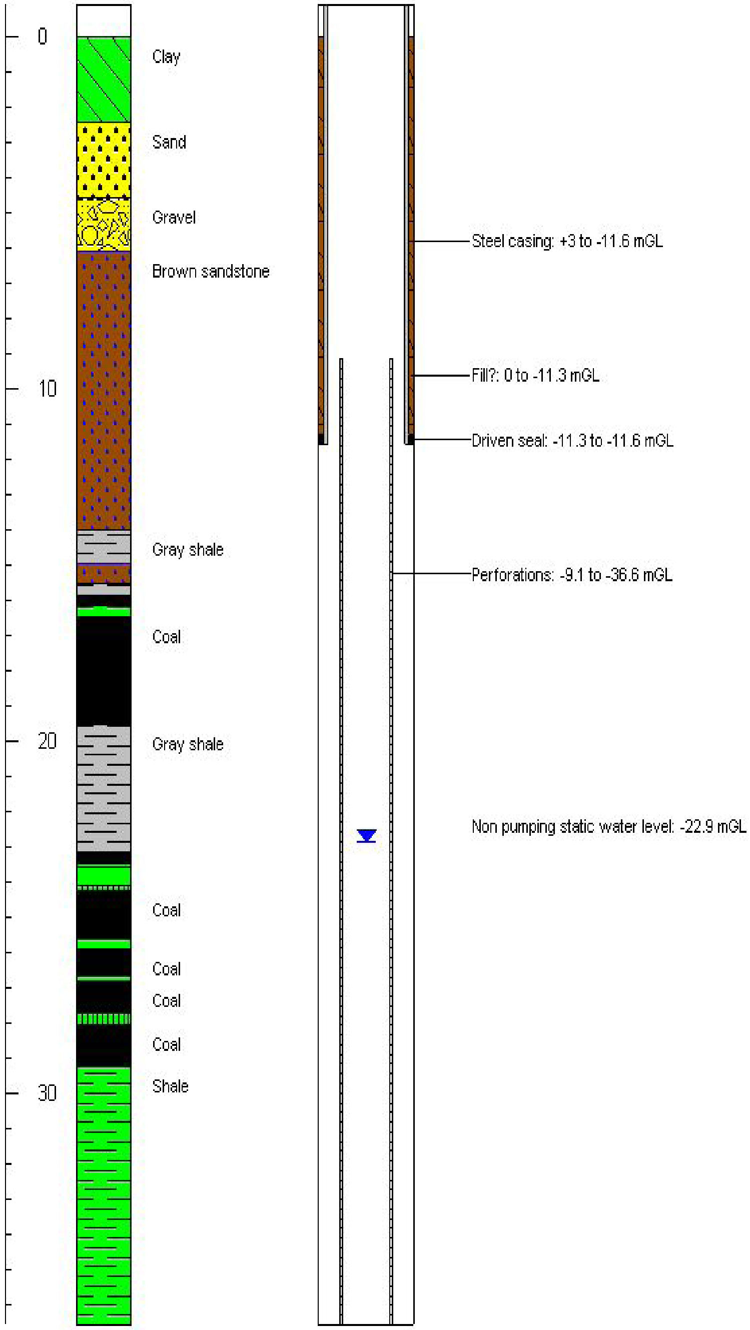
Well Name: AERI 0513
Well Location: 053-04W5
Ground Elevation (masl): 735
Well Depth (mGL): -39.6
Drill Date (yyyy): 1991



Sample Site 60

This well is being used as a dewatering well at the Whitewood Mine. It is located within the Scollard Formation subcrop area.

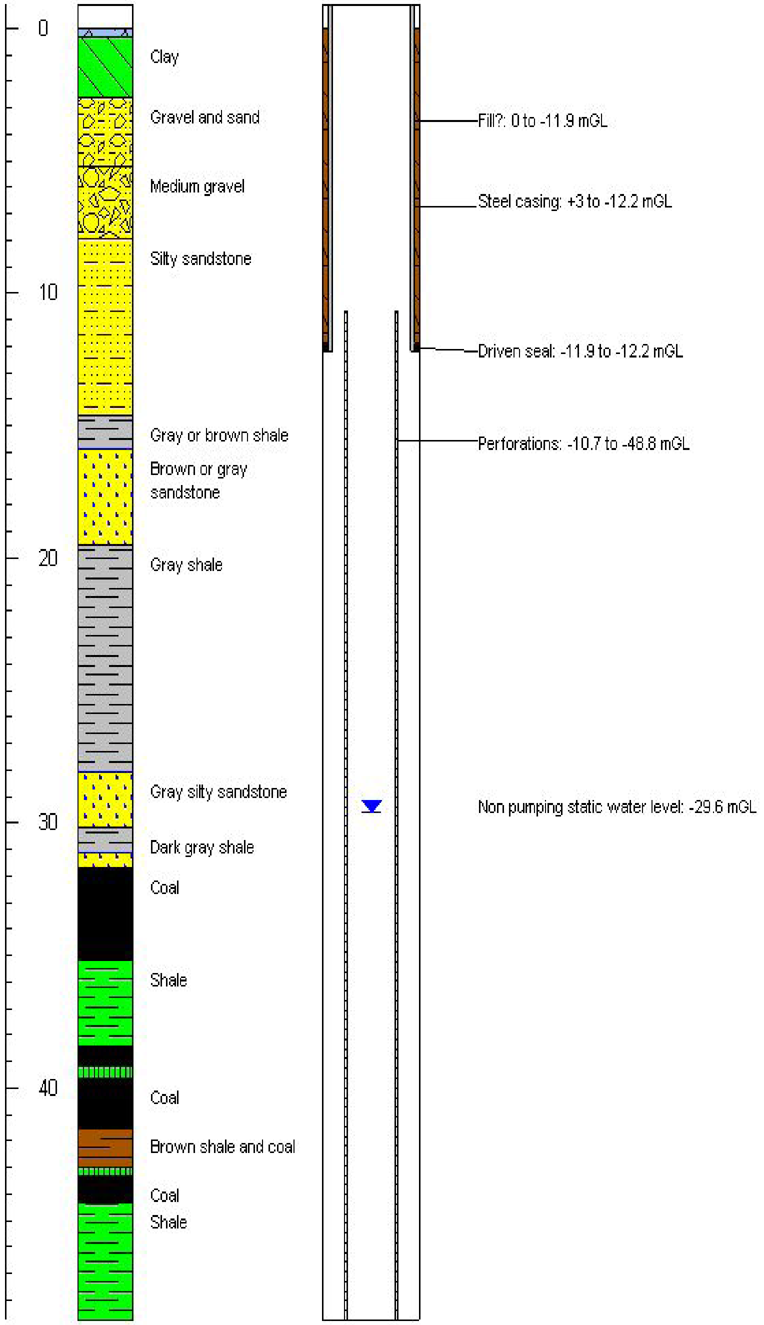
Well Name:	AERI 0521
Well Location:	053-04W5
Ground Elevation (masl):	778.1
Well Depth (mGL):	-36.6
Drill Date (yyyy):	2004



Sample Site 61

This well is being used as a dewatering well at the Whitewood Mine. It is located within the Scollard Formation subcrop area.

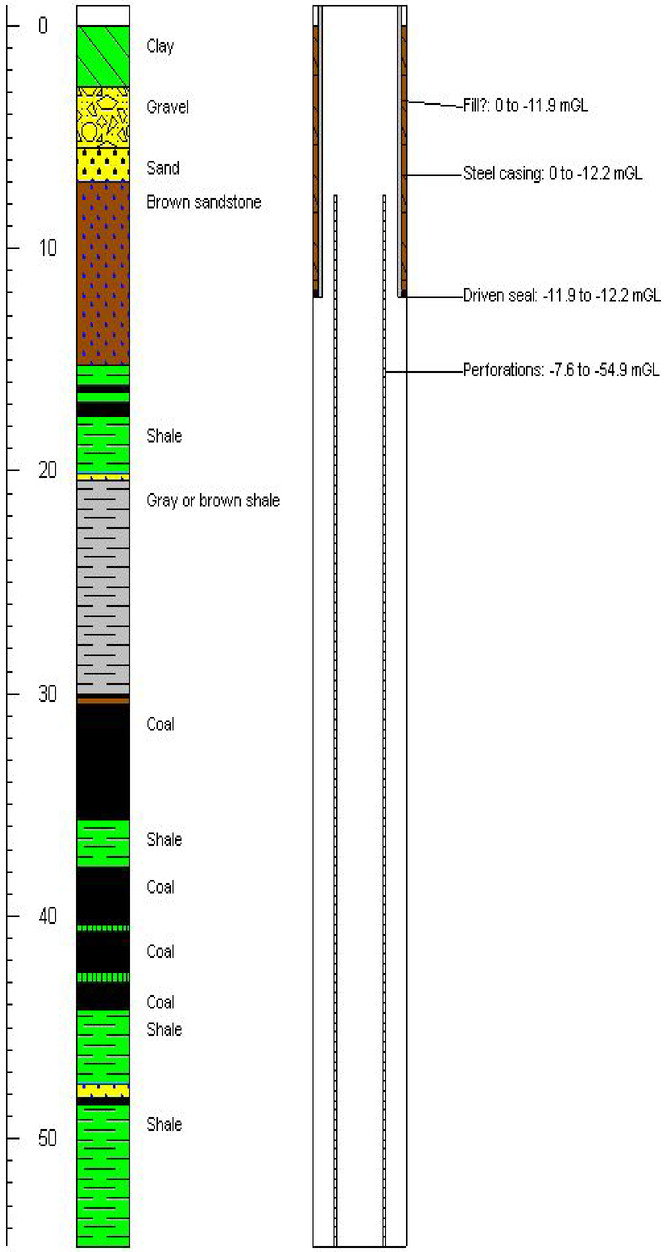
Well Name:	AERI 0522
Well Location:	053-04W5
Ground Elevation (masl):	788.4
Well Depth (mGL):	-48.8
Drill Date (yyyy):	2003



Sample Site 62

This well is being used as a dewatering well at the Whitewood Mine. It is located within the Scollard Formation subcrop area.

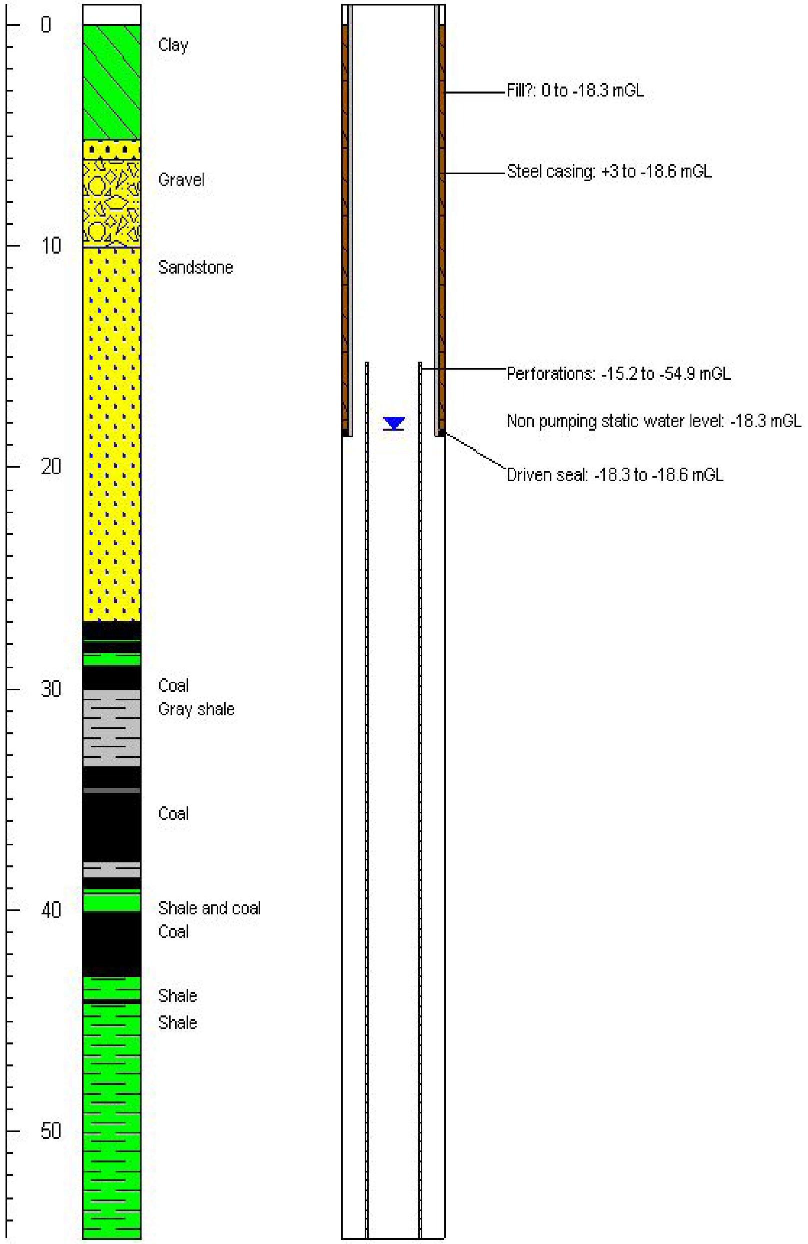
Well Name: AERI 0523
Well Location: 053-04W5
Ground Elevation (masl): 784.97
Well Depth (mGL): -54.9
Drill Date (yyyy): 2004



Sample Site 63

This well is being used as a dewatering well at the Whitewood Mine. It is located within the Scollard Formation subcrop area.

Well Name: AERI 0524
Well Location: 053-04W5
Ground Elevation (masl): 788.8
Well Depth (mGL): -54.9
Drill Date (yyyy): 2004



Appendix 5 – Water Sampling Protocols

EUB/AGS Geo-Note 2002-10 - Sampling of Groundwater from Wells in the Athabasca Oil Sands (In Situ) Area, Alberta, 1999-2001 - A Compilation of Protocols and Methods.

EUB/AGS Geo-Note 2002-11 - Sampling of Formation Water from Wells in the Athabasca Oil Sands (In Situ) Area, Alberta, 1999-2001 - A Compilation of Protocols and Methods.

Appendix 6 – Parameter Specific Concentration Summaries for the Horseshoe Canyon Formation Water Samples

Horseshoe Canyon Formation: Calcium (Ca)

The mean concentration of Ca in Horseshoe Canyon Formation water well samples is 11.0 mg/L, with a standard deviation of 7.4 mg/L (N=5). The mean concentration of Ca in Horseshoe Canyon Formation CBM water samples is 18.7 mg/L, with a standard deviation of 3.6 mg/L (N=4). The complete chemistry dataset is found in Appendix 8 Table 154.

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 1,000 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 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. Horseshoe Canyon Formation: Calcium (Ca).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	11.0	7.4	5	21.4	4.1
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	18.7	3.6	4	22.0	14.0
Horseshoe Canyon water wells[a] (Upper Cretaceous)	18.6	28.2	18	128	2.7
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	62.4	114.3	241	1420	1.7
U.S.A. – Powder River Basin[d] (Tertiary)	32.1	14.9	47	69	5.9
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	16.1	2.9	3	18.9	13.2
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	63.4	37.6	6	118.7	6.5
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	33.4	29.4	13	100	2.5
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	9147	1425	4	11030	7960
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Magnesium (Mg)

The mean Mg concentration from coal aquifer water well samples from within the Horseshoe Canyon Formation is 1.2 mg/L, with a standard deviation of 1.4 mg/L (N=5). The mean Mg concentration from Horseshoe Canyon Formation CBM wells is 2.7 mg/L, with a standard deviation of 0.96 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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 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. Horseshoe Canyon Formation: Magnesium (Mg).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	1.2	1.4	5	3.7	0.2
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	2.7	0.96	4	4.0	2.0
Horseshoe Canyon water wells[a] (Upper Cretaceous)	2.74*	5.42*	18	23.5	<0.2
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	21.4	47.3	240	498	0.1
U.S.A. – Powder River Basin[d] (Tertiary)	16.1	8.13	47	46	1.6
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	6.03	3.89	3	7.77	0
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	16.3	16.3	6	39	2.88
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	12.1	10.2	13	34	1.1
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	885*	726*	3	1690	<500
Drumheller Coal Zone[g] – multiple locations by PES	871	406	4	1440	482
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Sodium (Na)

The mean Na concentration from coal aquifer water well samples from within the Horseshoe Canyon Formation is 472.2 mg/L, with a standard deviation of 224.8 mg/L (N=5). The mean Na concentration from Horseshoe Canyon Formation CBM wells is 1177.5 mg/L, with a standard deviation of 124.5 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

An aesthetic objective concentration value for sodium of 200 mg/L has been established. All 5 water well samples and all 4 CBM well samples have sodium concentrations that exceed the aesthetic objective.

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. Horseshoe Canyon Formation: Sodium (Na).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	472.2	224.8	5	869.0	336.0
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	1177.5	124.5	4	1340	1050
Horseshoe Canyon water wells[a] (Upper Cretaceous)	533.9	186.4	18	861	112
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	647.3	1419	241	16361	1.2
U.S.A. – Powder River Basin[d] (Tertiary)	305.3	175.5	47	800	110
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	2240	378.2	3	2673	1976
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	5339	841.8	6	5939	3674
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	1503	795.8	13	3100	570
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	2375	1320	4	3830	1150
Drumheller Coal Zone[g] – multiple locations by PES	2833.5	-	2	3891	1776
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Potassium (K)

The mean K concentration from coal aquifer water well samples from within the Horseshoe Canyon Formation is 2.4 mg/L, with a standard deviation of 2.0 mg/L (N=5). The mean K concentration from Horseshoe Canyon Formation CBM wells is 5.5 mg/L, with a standard deviation of 1.9 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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 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. Horseshoe Canyon Formation: Potassium (K).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	2.4	2.0	5	6.0	1.1
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	5.5	1.9	4	8.0	4.0
Horseshoe Canyon water wells[a] (Upper Cretaceous)	2.55*	1.93*	18	8.9	<2
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	8.4	3.1	47	18	3.8
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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[g] – multiple locations by NAA	621*	524*	4	1040	<100
Drumheller Coal Zone[g] – multiple locations by PES	511	234	4	756	266
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Chloride (Cl)

The mean Cl concentration from coal aquifer water well samples from within the Horseshoe Canyon Formation is 194.3 mg/L, with a standard deviation of 413.0 mg/L (N=5). The mean Cl concentration from Horseshoe Canyon Formation CBM wells is 1507.5 mg/L, with a standard deviation of 103.1 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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. One of the coal aquifer water well samples (sample 44) and all 4 CBM water samples exceed both the aesthetic objective and irrigation water quality 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. Horseshoe Canyon Formation: Chloride (Cl).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	194.3	413.0	5	933.0	3.3
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	1507.5	103.1	4	1600	1360
Horseshoe Canyon water wells[a] (Upper Cretaceous)	33.7*	57.8*	18	229	<0.5
Horseshoe Canyon water wells[a] (Upper Cretaceous) - NAA	29.5*	52.0*	18	205	<0.7
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group Wells[c] (Upper Cretaceous)	393	2094	239	24202	2
U.S.A. – Powder River Basin[d] (Tertiary)	13.2	12.1	47	64	5.2
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	204.7	343	3	600	4
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	1187	734	6	2499	668
U.S.A. – Black Warrior Basin[f] (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[g] – multiple locations by NAA	-	-	4	-	<100
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	165	19

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Sulphate (SO_4)

The mean SO_4 concentration from coal aquifer water well samples from within the Horseshoe Canyon Formation is approximately 47.1 mg/L, with a standard deviation of approximately 69.4 mg/L (N=5). The mean SO_4 concentration from Horseshoe Canyon Formation CBM wells is 9 mg/L, with a standard deviation of 1 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the samples collected exceeds the aesthetic objective or 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 45. 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 45. Horseshoe Canyon Formation: Sulphate (SO_4).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	47.1*	69.4*	5	152.0	<9
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	9*	1*	4	10	<9
Horseshoe Canyon water wells[a] (Upper Cretaceous)	293	382	18	1320	1
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	401.2	519.5	241	5670	1.2
U.S.A. – Powder River Basin[d] (Tertiary)	2.41	3.63	47	17	0.01
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	56.2	69.2	3	135.5	8.32
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	51.3	66.5	6	166.8	0
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	2.84	0.19

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Bicarbonate (HCO_3)

The mean HCO_3 concentration from coal aquifer water well samples from within the Horseshoe Canyon Formation is 877 mg/L, with a standard deviation of 72.4 mg/L (N=5). The mean HCO_3 concentration from Horseshoe Canyon Formation CBM wells is 677.5 mg/L, with a standard deviation of 246 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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 46. 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 46. Horseshoe Canyon Formation: Bicarbonate (HCO_3).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	877	72.4	5	960	794
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	677.5	246	4	1040	492
Horseshoe Canyon water wells[a] (Upper Cretaceous)	1021	332	18	1720	384
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	773	297	241	2157	63
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	5737	759	3	6612	5250
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	11833	2961	6	14701	6083
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	883	125	13	1120	670

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)

Horseshoe Canyon Formation: Total Dissolved Solids (TDS)

The mean TDS concentration from coal aquifer water well samples from within the Horseshoe Canyon Formation is 1183 mg/L, with a standard deviation of 585 mg/L (N=5). The mean TDS concentration from Horseshoe Canyon Formation CBM wells is 3065 mg/L, with a standard deviation of 312 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

An aesthetic objective of TDS ≤ 500 mg/L has been established for water for domestic use. All of the water samples 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. All of the water samples fall within this range. A recommended maximum TDS value of 3000 mg/L has been established for water to be used for livestock purposes. Two of the TDS values determined from water samples collected from CBM wells (samples 55 and 64) 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 47. 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 47. Horseshoe Canyon Formation: Total Dissolved Solids (TDS).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	1183	585	5	2220	831
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	3065	312	4	3460	2730
Horseshoe Canyon water wells[a] (Upper Cretaceous)	1398	533	18	2620	354
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	1954	3921	241	46435	162
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	6470	1639	5	8328	5230
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	15561	3443	6	19392	10667
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	3971	2073	13	7900	1700

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)

Horseshoe Canyon Formation: Turbidity

The mean turbidity value from coal aquifer water well samples from within the Horseshoe Canyon Formation is 0.3 NTU, with a standard deviation of 0.2 NTU (N=5). The mean turbidity value from Horseshoe Canyon Formation CBM wells is 29.8 NTU, with a standard deviation of 47.1 NTU (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the coal aquifer water well samples exceeds the maximum acceptable value or the aesthetic objective value. Two of the CBM well water samples (samples 55 and 56) 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 48. Horseshoe Canyon Formation: Turbidity.. 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 48. Horseshoe Canyon Formation: Turbidity.

Water samples					
Location	**Mean (NTU)**	**Std. dev. (NTU)**	**N**	**Max. (NTU)**	**Min. (NTU)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.3	0.2	5	0.7	0.1
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	29.8	47.1	4	99.1	0.1
Horseshoe Canyon water wells[a] (Upper Cretaceous)	1.55*	3.13*	18	11.3	<0.1
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Data sources:

[a] Lemay (2003)

[b] Goodarzi (2002)

[c] Bachu and Michael (2002)

[d] Rice et al. (2000)

[e] Decker et al. (1987)

[f] O'Neil et al. (1989)

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 no 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) $ESR = 0.5 \text{ x } 1000/\sqrt{1000} \text{ x } m_{Na+}/(\sqrt{m_{Ca2+}} + m_{Mg2+})$ 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 x 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 aquifer water well samples is 40.5 $(mmol/L)^{0.5}$, with a standard deviation of 16.4 $(mmol/L)^{0.5}$ (N=5). The mean value of SAR in Horseshoe Canyon Formation CBM wells is 67.6 $(mmol/L)^{0.5}$ with a standard deviation of 3 $(mmol/L)^{0.5}$ (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

All of the water samples 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 49. In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes.

Table 49. Horseshoe Canyon Formation: 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. $(mmol/L)^{0.5}$**
Horseshoe Canyon water wells (Upper Cretaceous) this study	40.5	16.4	5	57.0	18.0
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	67.6	3.0	4	70.2	63.7
Horseshoe Canyon water wells[a] (Upper Cretaceous)	42.8	16.1	18	63	5
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	32.1	25.4	240	111	0.04
U.S.A. – Powder River Basin[d] (Tertiary)	11.7	7.3	47	32	5.7
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	131	21	3	144	107
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	149	45	6	199	111
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	64	18	13	108	43

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)

Horseshoe Canyon Formation: Iron (Fe)

The mean Fe concentration from coal aquifer water well samples from within the Horseshoe Canyon Formation is approx. 0.02 mg/L, with a standard deviation of approx. 0.03 mg/L (N=5). The mean Fe concentration from Horseshoe Canyon Formation CBM wells is <0.1 mg/L. The complete chemistry dataset is found in Appendix 8, Table 154.

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 50. 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 50. Horseshoe Canyon Formation: Iron (Fe).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.02*	0.03*	5	0.09	<0.01
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.1		4	<0.1	<0.1
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.16	<0.01
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.78	0.94	47	4.9	0.2
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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[g] – multiple locations by NAA	3412	1024	4	4740	2520
Drumheller Coal Zone[g] – multiple locations by PES	3447	827	4	4347	2438
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Manganese (Mn)

The mean Mn concentration from coal aquifer water well samples from within the Horseshoe Canyon Formation is approximately 0.008 mg/L, with a standard deviation of approximately 0.008 mg/L (N=5). The mean Mn concentration from Horseshoe Canyon Formation CBM wells is <0.05 mg/L. The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the water samples collected as part of this study exceeds the established guideline values.

The summary statistics for water samples collected during this study are presented in Table 51. 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 51. Horseshoe Canyon Formation: Manganese (Mn).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.008*	0.008*	5	0.017	<0.005
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.05	-	4	<0.05	<0.05
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.0017*	0.096*	18	0.295	<0.005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.091*	0.26*	21	1.21	<0.001
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.032	0.026	47	0.101	0.002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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[g] – multiple locations by NAA	63.1	39.6	4	113	26.9
Drumheller Coal Zone[g] – multiple locations by PES	82.2	58.1	3	154	25.1
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	524	15

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Silicon (Si)

The mean Si concentration from coal aquifer water well samples from within the Horseshoe Canyon Formation is 7.43 mg/L, with a standard deviation of 3.49 mg/L (N=5). The mean Si concentration from Horseshoe Canyon Formation CBM wells is 4.70 mg/L, with a standard deviation of 1.36 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

No Canadian environmental quality guidelines have been established for Si.

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: Silicon (Si).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	7.43	3.49	5	13	4
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	4.7	1.36	4	6.7	3.7
Horseshoe Canyon water wells[a] (Upper Cretaceous) by ICP-MS	8.35	4.00	18	15.3	3.89
Horseshoe Canyon water wells[a] (Upper Cretaceous) by ICP	7.55	3.65	18	13.7	3.55
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	4.76	0.62	47	7.1	3.7
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)

Horseshoe Canyon Formation: Mercury (Hg)

The mean Hg concentration from coal aquifer water wells (N=5) and CBM well samples (N=4) from within the Horseshoe Canyon Formation is <0.0001 mg/L. The complete chemistry dataset is found in Appendix 8, Table 154.

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 between 0.000005 and 0.000026 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. None of the water well samples have concentrations that exceed established guidelines.

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: Mercury (Hg).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	<0.0001	-	5	0.0001	<0.0001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.0001	-	4	<0.0001	<0.0001
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	-	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	21	0.000913	<0.000002
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.00025	<0.000005
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Aluminum (Al)

Two of the water well samples had Al concentrations of <0.05 mg/L, two had concentrations of <0.005 and one had a concentration of 0.01 mg/L. As such a mean concentration could not be calculated. Three of the 4 CBM well water samples had Al concentrations <0.05 mg/L, while 1 had a concentration of 0.61 mg/L. The complete chemistry dataset is found in Appendix 8, Table 154.

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. One of the water well samples (sample 45) falls within the range of concentrations of concern to freshwater aquatic life. One of the CBM well samples (sample 56) exceeds the maximum acceptable concentration value for domestic water use as well as the freshwater aquatic life maximum concentration guideline value.

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: Aluminum (Al).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	0.01	<0.005
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	-	-	4	0.61	<0.05
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	-	<0.005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.05
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	10935	2592	4	13200	7640
Drumheller Coal Zone[g] – multiple locations by PES	12412	4457	4	17760	7078
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Antimony (Sb)

The Sb mean concentrations for the water wells and CBM are less than 0.002 mg/L and in the case of the water wells may be <0.0002 mg/L. The complete chemistry dataset is found in Appendix 8, Table 154.

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 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: Antimony (Sb).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	<0.002	<0.0002
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	-	-	4	<0.002	<0.002
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.0004	<0.0002
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Arsenic (As)

The As mean concentration for the water wells is approximately 0.0003 mg/L with a standard deviation of approximately 0.0054 mg/L (N=5). The As mean concentration for the CBM wells is 0.026 mg/L with a standard deviation of 0.005 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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. One of the water well samples (sample 44) and all 4 CBM water samples exceed the value established for the protection of aquatic life. Two of the CBM well samples (samples 55 and 56) exceed the guidelines established for domestic water use and for livestock water use.

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: Arsenic (As).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.0003*	0.0054*	5	0.01	<0.0002
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.026	0.005	4	0.032	0.020
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.0002*	0.0007*	18	0.0022	<0.0002
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	21	0.0249	<0.0004
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.0004*	0.0004*	47	0.0026	<0.0002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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[g] – multiple locations by NAA	-	-	4	1.14	<0.9
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	67	0.5

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Barium (Ba)

The Ba mean concentration for the water wells is 0.22 mg/L with a standard deviation of 0.25 mg/L (N=5). The Ba mean concentration for the CBM wells is 0.92 mg/L with a standard deviation of 0.24 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

A maximum acceptable concentration of 1.0 mg/L has been established for domestic water use. All of the water well samples analyzed have concentrations that fall below these guideline values. Two of the CBM well samples (samples 55 and 64) have Ba concentrations that exceed the guideline values however.

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: Barium (Ba).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.22	0.25	5	0.66	0.017
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.92	0.24	4	1.14	0.62
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.095	0.089	18	0.368	0.007
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.149	0.169	21	0.761	0.007
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.617	0.300	47	1.60	0.14
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	518	171	4	623	264
Drumheller Coal Zone[g] – multiple locations by PES	533	84	4	597	415
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	261	987

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Beryllium (Be)

None of the Be concentrations were above the various analytical detection limits. The complete chemistry dataset is found in Appendix 8, Table 154.

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 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: Beryllium (Be).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	<0.001	<0.0001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.001	-	4	<0.001	<0.001
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	-	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Bismuth (Bi)

None of the Bi concentrations were above the various analytical detection limits. The complete chemistry dataset is found in Appendix 8, Table 154.

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 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: Bismuth (Bi).

Water samples

Location	Mean (mg/L)	Std. dev. (mg/L)	N	Max. (mg/L)	Min. (mg/L)
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	<0.005	<0.0005
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.005	-	4	<0.005	<0.005
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	-	<0.0005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.032	<0.020
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Coal samples Horseshoe Canyon Formation

Location	Mean (ppm)	Std. dev. (ppm)	N	Max. (ppm)	Min. (ppm)
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Boron (B)

The B mean concentration for the water wells is 0.267 mg/L with a standard deviation of 0.120 mg/L (N=5). The B mean concentration for the CBM wells is 0.367 mg/L with a standard deviation of 0.080 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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 water quality guidelines.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 60. Horseshoe Canyon Formation: Boron (B).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.267	0.120	5	0.477	0.190
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.367	0.080	4	0.440	0.280
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.294	0.144	18	0.707	0.099
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.217	<0.100
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	955	183	4	1225	834
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	628	10

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Cadmium (Cd)

The majority of water samples from both the water wells and CBM wells have Cd concentrations below the analytical detection limits. One sample from each sample type does exceed the detection limit however. The complete chemistry dataset is found in Appendix 8, Table 154.

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 coal-aquifer water well sample cadmium concentrations (sample 44) exceeds the guideline values for the protection of freshwater aquatic life, for irrigation purposes and for domestic water use.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 61. Horseshoe Canyon Formation: Cadmium (Cd).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	0.00678	<0.00001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.0001	-	4	0.0001	<0.0001
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.00092	<0.00001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	21	0.00011	<0.00005
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Chromium (Cr)

The water samples from the water wells have a mean Cr concentration of approximately 0.0014 mg/L with a standard deviation of approximately 0.0013 mg/L (N=5). All of the CBM well water samples have Cr concentrations that are below the analytical detection limits. The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the water samples exceed these guideline values.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 62. Horseshoe Canyon Formation: Chromium (Cr).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.0014*	0.0013*	5	0.0027	<0.005
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.005	-	4	<0.005	<0.005
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.0056	0.0025	18	0.0120	0.0012
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	21	-	<0.001
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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[g] – multiple locations by NAA	-	-	4	-	<3
Drumheller Coal Zone[g] – multiple locations by PES	2.85	2.02	4	5.6	0.9
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	254	6

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Cobalt (Co)

Three of the five water well samples and all of the CBM well samples have Co concentrations below the analytical detection limit, making the calculation of a mean and standard deviation impossible. The complete chemistry dataset is found in Appendix 8, Table 154.

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 63. 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 63. Horseshoe Canyon Formation: Cobalt (Co).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	0.0002	<0.00001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.001	-	4	<0.001	<0.001
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.0005	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.0002	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	0.617	0.186	4	0.84	0.42
Drumheller Coal Zone[g] – multiple locations by PES	-	-	1	7.6	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	17	0.6

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Copper (Cu)

Three of the five water well samples and all of the CBM well samples have Cu concentrations below the analytical detection limit, making the calculation of a mean and standard deviation impossible. The complete chemistry dataset is found in Appendix 8, Table 154.

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 2 of the water well samples (samples 47 and 51) 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 64. 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 64. Horseshoe Canyon Formation: Copper (Cu).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	0.13	<0.001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.01	-	4	<0.01	<0.01
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.036	<0.001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.009*	0.0042*	21	0.148	<0.002
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	5.36	4.26	47	28.6	1.5
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	5.87	2.37	4	9.2	3.6
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	18	1

Data sources:

[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Lead (Pb)

Three of the five water well samples and all of the CBM well samples have Pb concentrations below the analytical detection limit, making the calculation of a mean and standard deviation impossible. The complete chemistry dataset is found in Appendix 8, Table 154.

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. Sample 51 has a Pb concentration that falls within the range of values used to protect aquatic life.

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: Lead (Pb).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	0.002	<0.0001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.001	-	4	<0.001	<0.001
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.0007	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.00043*	0.00060*	21	0.0027	<0.00001
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.00043	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	3.82	1.52	4	5.6	1.9
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Lithium (Li)

The mean Li concentration in the water well samples is 0.126 mg/L with a standard deviation of 0.048 mg/L (N=5). The mean Li concentration in the CBM well water samples is 0.23 mg/L with a standard deviation of 0.04 mg/L. The complete chemistry dataset is found in Appendix 8, Table 154.

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 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: Lithium (Li).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.126	0.048	5	0.173	0.054
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.23	0.04	4	0.28	0.18
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.141	0.086	18	0.383	0.05
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.052	0.036	47	0.208	0.018
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Molybdenum (Mo)

Only one of the water well samples (sample 47) and one of the CBM well samples (sample 65) have a Mo concentration above the analytical detection limits. The complete chemistry dataset is found in Appendix 8, Table 154.

The maximum acceptable concentration of Mo 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. One of the CBM well samples (sample 65) has a Mo concentration that exceeds protection of aquatic life and irrigation guideline values.

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: Molybdenum (Mo).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	0.004	<0.001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	-	-	4	0.01	<0.01
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.007	<0.001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.0013*	0.0013*	21	0.0043	<0.00005
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	30	0.3

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Nickel (Ni)

Two of the water well samples (samples 44 and 45), but none of the CBM well samples have Ni concentrations above the analytical detection limits. The complete chemistry dataset is found in Appendix 8, Table 154.

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. One of the water samples (sample 44) exceeds the protection of freshwater aquatic life 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: Nickel (Ni).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	0.067	<0.0005
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	-	-	4	<0.005	<0.005
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.016	<0.0005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.00037*	0.00055*	21	0.0021	<0.0002
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.0065*	0.0068*	47	0.0354	<0.0005
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	30	1

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Selenium (Se)

None of the sample concentrations are above the analytical detection limits. The complete chemistry dataset is found in Appendix 8, Table 154.

A maximum acceptable concentration of Se 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 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: Selenium (Se).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	<0.002	<0.0002
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	-	-	4	<0.002	<0.002
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.0002	<0.0002
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	4	-	<3
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	2.6	0.4

Data sources:

[a] Lemay (2003)

[b] Goodarzi (2002)

[c] Bachu and Michael (2002)

[d] Rice et al. (2000)

[e] Decker et al. (1987)

[f] O'Neil et al. (1989)

[g] Landheer et al. (1982)

[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Silver (Ag)

None of the sample concentrations are above the analytical detection limits. The complete chemistry dataset is found in Appendix 8, Table 154.

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. Given the variation in the detection limit of the analytical methods, it cannot be determined if any of the water samples exceeds this guideline value.

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: Silver (Ag).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	<0.001	<0.0001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	-	-	4	<0.001	<0.001
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	-	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	1.8	-	2	2.7	0.9
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Strontium (Sr)

The mean Sr concentration in the water wells is 0.19 mg/L, with a standard deviation of 0.13 mg/L (N=5). The mean Sr concentration in the CBM wells is 0.66 mg/L, with a standard deviation of 0.15 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

Canadian environmental quality guidelines have not been developed for Sr.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 71. Horseshoe Canyon Formation: Strontium (Sr).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.19	0.13	5	0.34	0.07
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.66	0.15	4	0.81	0.47
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.255	0.327	18	1.5	0.04
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.692	0.412	47	1.9	0.1
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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[g] – multiple locations by NAA	211*	136*	4	374	<100
Drumheller Coal Zone[g] – multiple locations by PES	299	79	4	374	211
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	492	96

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Thallium (Tl)

None of the water samples has a Tl concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the samples exceeds this guideline value.

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: Thallium (Tl).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	<0.0005	<0.00005
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	-	-	4	<0.0005	<0.0005
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.0013	<0.00005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.00034	<0.0002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Tin (Sn)

None of the water samples has a Sn concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

Canadian environmental water quality guidelines have not been developed for Sn.

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: Tin (Sn).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	<0.01	<0.001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.01	-	4	<0.01	<0.01
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	-	-	-
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.0055	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Titanium (Ti)

The mean Ti concentration in the water well samples is approximately 0.0011 mg/L with a standard deviation of approximately 0.0012 mg/L (N=5). None of the CBM well water samples has a Ti concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

Canadian environmental water quality guidelines have not been developed for Ti.

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: Titanium (Ti).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.0011*	0.0012*	5	0.0025	<0.005
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	<0.005	-	4	<0.005	<0.005
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.0015*	0.0069*	18	0.018	<0.0005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.050
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	273	153	4	500	161
Drumheller Coal Zone[g] – multiple locations by PES	272	88	4	389	194
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Vanadium (V)

The mean V concentration in the water well samples is 0.005 mg/L with a standard deviation of 0.002 mg/L (N=5). The mean V concentration in the CBM well samples is approximately 0.002 mg/L with a standard deviation of approximately 0.001 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

A maximum concentration of 0.100 mg/L has been established for V concentrations in water for irrigation purposes as well as for V concentrations in water for use in livestock operations. None of the water samples have V concentrations that exceed these 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: Vanadium (V).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.005	0.002	5	0.007	0.002
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.002*	0.001*	4	0.002	<0.001
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.0001	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.0002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	2.65	1.58	4	4.72	0.94
Drumheller Coal Zone[g] – multiple locations by PES	4.1	1.61	4	6.3	2.8
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	502	1.6

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Zinc (Zn)

The mean Zn concentration in the water well samples is approximately 0.015 mg/L with a standard deviation of approximately 0.022 mg/L (N=5). The mean Zn concentration in the CBM well samples is approximately 0.007 mg/L with a standard deviation of approximately 0.04 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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 water well Zn concentrations exceed these guidelines, but one of the CBM well samples (sample 55) exceeds the protection of freshwater aquatic life guideline value.

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: Zinc (Zn).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.015*	0.02*	5	0.040	<0.001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.007*	0.04*	4	0.07	<0.01
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.0004*	0.0213*	18	0.05	<0.001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.065	0.113	21	0.470	0.0007
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.0804	<0.001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	32.9	51.9	4	110.6	4.9
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Fluorine (F)

The mean F concentration in the water well samples is 2.0 mg/L with a standard deviation of 0.7 mg/L (N=5). The mean F concentration in the CBM well samples is 4.2 mg/L with a standard deviation of 1 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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. All of the samples, with the exception of sample 43, appear to exceed the maximum concentration guideline values for domestic use, irrigation use and fall within or are greater than the range of values proposed for livestock use.

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: Fluorine (F).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	2.0	0.7	5	3.1	1.2
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	4.2	1	4	5.3	3.2
Horseshoe Canyon water wells[a] (Upper Cretaceous)	2.1	0.71	18	3.2	0.6
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.92	0.32	47	1.7	0.42
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Bromine (Br)

The mean Br concentration in the water well samples is 1.35 mg/L with a standard deviation of 2.62 mg/L (N=5). The mean Br concentration in the CBM well samples is 14.2 mg/L with a standard deviation of 1.77 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

No Canadian environmental water quality guidelines have been established for Br.

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: Bromine (Br).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	1.35	2.62	5	6.03	0.06
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	14.2	1.77	4	16.6	12.5
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.192*	0.538*	18	1.73	<0.035
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.11*	0.18*	47	0.85	<0.02
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	4	1.7	<0.5
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	4.3	0.5

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Iodine (I)

The mean I concentration in the water well samples is approximately 0.33 mg/L with a standard deviation of approximately 0.92 mg/L (N=5). The mean I concentration in the CBM well samples is 4.12 mg/L with a standard deviation of 0.99 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

No Canadian environmental water quality guidelines have been established for I.

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: Iodine (I).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.33*	0.92*	5	1.92	<0.02
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	4.12	0.99	4	5.09	3.20
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.053*	0.151*	18	0.39	<0.013
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	4	-	<20
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Scandium (Sc)

The mean Sc concentration in the water well samples is approximately 0.00007 mg/L with a standard deviation of approximately 0.00004 mg/L (N=5). The mean Sc concentration in the CBM well samples is approximately 0.00008 mg/L with a standard deviation of approximately 0.00006 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

No Canadian environmental water quality guidelines have been established for Sc.

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: Scandium (Sc).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.00007*	0.00004*	5	0.0001	<0.00004
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.00008*	0.00006*	4	0.00012	<0.00006
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.00007	0.00003	18	0.00014	0.00003
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.00120*	0.00079*	47	0.003	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	1.11	0.26	4	1.49	0.92
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Rubidium (Rb)

None of the water samples have a Rb concentration greater than the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

No Canadian environmental water quality guidelines have been established for Rb.

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: Rubidium (Rb).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	<0.03	<0.013
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	-	-	4	<0.039	<0.021
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.024	<0.0048
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.0118	0.0061	47	0.0382	0.0041
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Horseshoe Canyon Formation: Phenols

The mean concentration of phenols in the water well samples is approximately 0.001 mg/L with a standard deviation of approximately 0.002 mg/L (N=5). The mean concentration of phenols in the CBM well water samples is 0.009 mg/L with a standard deviation of 0.006 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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 water well samples (sample 47) and 3 of the CBM well samples (samples 55, 56 and 64) exceed the maximum concentration guideline values for the protection of aquatic life and for water to be used for livestock purposes.

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: Phenols.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.001*	0.002*	5	0.005	<0.001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.009	0.006	4	0.016	0.001
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.005	<0.001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Non-Halogenated Aromatic Hydrocarbons (BTEX)

The table below (Table 83) lists the Canadian environmental water quality guideline maximum concentrations for benzene, toluene, ethylbenzene and xylene. None of the samples has a benzene concentration above the analytical detection limit. One of water well samples (sample 43) has a toluene concentration above the detection limit, but does not exceed any of the water quality guideline values. The mean toluene concentration in the CBM wells is approximately 0.001 mg/L with a standard deviation of approximately 0.002 mg/L (N=4). Only one of the CBM well water samples (sample 64) has a toluene concentration that exceeds any of the water quality guideline values. In this case the concentration exceeds the guideline value established for the protection of freshwater aquatic life. None of the samples has an ethylbenzene concentration above the analytical detection limit. None of the water well samples has xylenes concentration above the analytical detection limit. The mean xylenes concentration in water from the CBM wells is 0.003 mg/L with a standard deviation of 0.003 mg/L (N=4). None of these samples has xylenes concentrations that exceed water quality guideline values. The complete chemistry dataset is found in Appendix 8, Table 154. The summary statistics for water samples collected during this study are presented in Table 84.

Table 83. 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	-	-	-

Table 84. Horseshoe Canyon Formation: Non-halogenated aromatic hydrocarbons (BTEX).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells this study - Benzene	-	-	5	-	<0.001
Horseshoe Canyon water wells this study - Toluene	-	-	5	0.001	<0.001
Horseshoe Canyon water wells this study - Ethylbenzene	-	-	5	-	<0.001
Horseshoe Canyon water wells this study - Xylenes	-	-	5	-	<0.001
Horseshoe Canyon CBM wells this study - Benzene	-	-	4	-	<0.001
Horseshoe Canyon CBM wells this study - Toluene	0.001*	0.002*	4	0.005	<0.001
Horseshoe Canyon CBM wells this study – Ethylbenzene	-	-	4	-	<0.001
Horseshoe Canyon CBM wells this study - Xylenes	0.003	0.003	4	0.007	0.001
Horseshoe Canyon water wells[a] - Benzene	-	-	18	-	<0.001
Horseshoe Canyon water wells[a] - Toluene	-	-	18	0.005	<0.001
Horseshoe Canyon water wells[a] - Ethylbenzene	-	-	18	-	<0.001
Horseshoe Canyon water wells[a] - Xylenes	-	-	18	-	<0.001

Data sources:

[a] Lemay (2003)

*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Purgeable and Extractable Hydrocarbons

Only 1 of the water well samples (sample 43) has a purgeable hydrocarbons concentration above the analytical detection limit and only 1 of the water well samples (sample 51) has an extractable hydrocarbons concentration above the analytical detection limit. The mean concentration of purgeable hydrocarbons in the CBM well samples is approximately 0.10 mg/L with a standard deviation of approximately 0.26 mg/L (N=4). The mean concentration of extractable hydrocarbons in the CBM well water samples is 0.3 mg/L with a standard deviation of 0.2 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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 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: Purgeable and Extractable Hydrocarbons.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study–Purgeable Hydrocarbons	-	-	5	0.01	<0.01
Horseshoe Canyon water wells (Upper Cretaceous) this study–Extractable Hydrocarbons	-	-	5	0.2	<0.1
Horseshoe Canyon CBM wells (Upper Cretaceous) this study–Purgeable Hydrocarbons	0.10*	0.26*	4	0.49	<0.01
Horseshoe Canyon CBM wells (Upper Cretaceous) this study–Extractable Hydrocarbons	0.3	0.2	4	0.6	0.2
Horseshoe Canyon water wells[a] (Upper Cretaceous)–Purgeable Hydrocarbons	-	-	18	0.11	<0.01
Horseshoe Canyon water wells[a] (Upper Cretaceous)–Extractable Hydrocarbons	-	-	18	0.5	<0.1

Data sources:

[a] Lemay (2003)

*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation: Polycyclic Aromatic Hydrocarbons (PAH)

The table below (Table 86) lists the Canadian environmental water quality guideline maximum concentrations for PAH's in water. None of the measured water well concentrations of PAH's exceeds the analytical detection limits and therefore do not exceed guideline values. Naphthalene and Acenaphthene were detected in all four CBM well water samples. Fluorene was detected in 3 of the 4 samples. Acenaphthylene was detected in 2 of the 4 samples. Phenanthrene and Anthracene were each detected in 1 of the 4 samples. Two of the CBM well samples (samples 55 and 56) exceed the naphthalene guideline value for the protection of freshwater aquatic life. One of the CBM well samples (sample 56) exceeds the anthracene guideline value for the protection of freshwater aquatic life.

Table 86. 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	-	-	0.000012	-	-
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	-	-	-	-	-

Means were only calculateable for 4 of the PAH's from the CBM well water samples. The mean concentration of naphthalene in the CBM well water samples is 0.00097 mg/L with a standard deviation of 0.00046 mg/L (N=4). The mean concentration of acenaphthylene is approximately 0.00001 mg/L with a standard deviation of approximately 0.000002 mg/L (N=4). The mean concentration of acenaphthene is 0.00003 mg/L with a standard deviation of 0.00003 mg/L (N=4). Likewise, the mean concentration of fluorene in the CBM well water samples is approximately 0.00003 mg/L with a standard deviation of approximately 0.00003 mg/L (N=4). 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 are presented for comparison purposes (Table 87 and Table 88). The complete chemistry dataset is found in Appendix 8, Table 154.

Table 87. Horseshoe Canyon Formation: Polycyclic Aromatic Hydrocarbons (PAH).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study					
Naphthalene	-	-	5	-	<0.00001
Acenaphthylene	-	-	5	-	<0.00001
Acenaphthene	-	-	5	-	<0.00001
Fluorene	-	-	5	-	<0.00001
Phenanthrene	-	-	5	-	<0.00001
Anthracene	-	-	5	-	<0.00001
Acridine	-	-	5	-	<0.00001
Fluoranthene	-	-	5	-	<0.00002
Pyrene	-	-	5	-	<0.00002
Benzo(a)anthracene	-	-	5	-	<0.00001
Chrysene	-	-	5	-	<0.00001
Benzo(b)fluoranthene	-	-	5	-	<0.00001
Benzo(k)fluoranthene	-	-	5	-	<0.00001
Benzo(a)pyrene	-	-	5	-	<0.00001
Indeno(1,2,3-c,d)pyrene	-	-	5	-	<0.00001
Dibenzo(a,h)anthracene	-	-	5	-	<0.00001
Benzo(g,h,I)perylene	-	-	5	-	<0.00001
Horseshoe Canyon CBM wells (Upper Cretaceous) this study					
Naphthalene	0.00097	0.00046	4	0.00142	0.00033
Acenaphthylene	0.00001*	0.000001*	4	0.00002	<0.00001
Acenaphthene	0.00003	0.00003	4	0.00007	0.00001
Fluorene	0.00003*	0.00003*	4	0.00007	<0.00001
Phenanthrene	-	-	4	0.00003	<0.00001
Anthracene	-	-	4	0.00002	<0.00001
Acridine	-	-	4	-	<0.00001
Fluoranthene	-	-	4	-	<0.00002
Pyrene	-	-	4	-	<0.00002
Benzo(a)anthracene	-	-	4	-	<0.00001
Chrysene	-	-	4	-	<0.00001
Benzo(b)fluoranthene	-	-	4	-	<0.00001
Benzo(k)fluoranthene	-	-	4	-	<0.00001
Benzo(a)pyrene	-	-	4	-	<0.00001
Indeno(1,2,3-c,d)pyrene	-	-	4	-	<0.00001
Dibenzo(a,h)anthracene	-	-	4	-	<0.00001
Benzo(g,h,I)perylene	-	-	4	-	<0.00001

*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Table 88. PAH results from previous studies and other CBM development areas.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon wells[a] (Upper Cretaceous)					
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[b] (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[f] (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] Lemay (2003)

[b] Goodarzi (2002)

[f] O'Neil et al. (1989)

Horseshoe Canyon Formation: Adsorbable Organic Halides (AOX)

Only one of the water well samples (sample 44) has an AOX concentration above the analytical detection limit. The mean concentration of adsorbable organic halides from water samples taken from the CBM wells is 0.011 mg/L with a standard deviation of 0.006 mg/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

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 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: Adsorbable Organic Halides (AOX).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	0.014	<0.004
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.011	0.006	4	0.018	0.006
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.016	0.016	18	0.053	0.0027
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)

Horseshoe Canyon Formation Stable Isotopes of Oxygen and Hydrogen

The mean $\delta^{18}O$ value in water from water wells completed in the Horseshoe Canyon Formation is minus 18‰ VSMOW with a standard deviation of 2.1‰ VSMOW (N=5), while the mean $\delta^{18}O$ value in water from CBM wells completed in the Horseshoe Canyon Formation is -12.4‰ VSMOW with a standard deviation of 0.05‰ VSMOW (N=4). The mean δ^2H value in water from water wells completed in the Horseshoe Canyon Formation is -147‰ VSMOW with a standard deviation of 15‰ VSMOW (N=5), while the mean δ^2H value in water from CBM wells completed in the same Formation is minus 108‰ VSMOW with a standard deviation of 1‰ VSMOW (N=4). The summary statistics for the samples is presented in Table 90. The complete data set can be found in Appendix 8, Table 154.

Table 90. Horseshoe Canyon Formation: $\delta^{18}O$ and δ^2H of H_2O.

Location	Mean (‰ VSMOW)	Std. dev. (‰ VSMOW)	N	Max. (‰ VSMOW)	Min. (‰ VSMOW)
Water samples: $\delta^{18}O$					
Horseshoe Canyon Formation (Upper Cretaceous) water wells – this study	-18.0	2.1	5	-15.6	-20.2
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells – this study	-12.4	0.05	4	-12.3	-12.4
Horseshoe Canyon wells[a] (Upper Cretaceous): coal aquifers	-17.4	2.4	6	-13.7	-19.9
Horseshoe Canyon wells[a] (Upper Cretaceous): mixed coal-sandstone aquifers	-17.7	1.4	13	-15.8	-19.5
Water samples: δ^2H					
Horseshoe Canyon Formation (Upper Cretaceous) water wells – this study	-147	15	5	-129	-163
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells – this study	-108	1	4	-107	-109
Horseshoe Canyon wells[a] (Upper Cretaceous): coal aquifers	-147	14	6	-129	-164
Horseshoe Canyon wells[a] (Upper Cretaceous): mixed coal-sandstone aquifers	-146	9	13	-132	-160

Data sources:
[a] Lemay (2003)

Horseshoe Canyon Formation Stable Isotopes of Carbon and Oxygen in DIC

The mean $\delta^{13}C$ value of DIC in the water well samples is -11.8‰ VPDB with a standard deviation of 13.6‰ VPDB (N=5). The mean $\delta^{13}C$ of DIC in the CBM water samples is 18.3‰ VPDB with a standard deviation of 2.1‰ VPDB (N=4). The mean $\delta^{18}O$ value of DIC in the water well samples is minus 13.6‰ VPDB with a standard deviation of 1.6‰ VPDB (N=5). The mean $\delta^{18}O$ of DIC in the CBM water samples is -9.2‰ VPDB with a standard deviation of 0.5‰ VPDB (N=4). The statistical summary is presented below (Table 91) with additional data from Lemay (2003) for comparison purposes. The complete data set is presented in Appendix 8, Table 154.

Table 91. Horseshoe Canyon Formation: $\delta^{13}C$ and $\delta^{18}O$ of DIC.

Location	Mean (‰ VPDB)	Std. dev. (‰ VPDB)	N	Max. (‰ VPDB)	Min. (‰ VPDB)
Water samples $\delta^{13}C$					
Horseshoe Canyon Formation (Upper Cretaceous) water wells – this study	-11.8	13.6	5	11.6	-22.1
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells – this study	18.3	2.1	4	20.4	16.0
Horseshoe Canyon Formation wells[a] (Upper Cretaceous)–coal aquifers	-11.2	9.3	6	6.8	-18.8
Horseshoe Canyon Formation wells[a] (Upper Cretaceous)–mixed aquifers	-12.7	6.1	13	0.6	-24.9
Water samples $\delta^{18}O$					
Horseshoe Canyon Formation (Upper Cretaceous) water wells – this study	-13.6	1.6	5	-11.5	-15.1
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells – this study	-9.2	0.5	4	-8.6	-9.6
Horseshoe Canyon Formation wells[a] (Upper Cretaceous)–coal aquifers	-13.5	1.9	6	-11.2	-16.0
Horseshoe Canyon Formation wells[a] (Upper Cretaceous)–mixed aquifers	-13.4	1.9	13	-10.3	-17.4

Data sources:
[a] Lemay (2003)

Horseshoe Canyon Formation Stable Isotopes of Sulphur and Oxygen in Sulphate and Sulphide

Only two of the water samples (samples 45 and 47) had sufficient sulphide concentrations for $\delta^{34}S$ determination, but 4 of 5 had sufficient sulphate concentrations. These same 4 samples all have positive $\delta^{34}S$ SO_4 values. None of the CBM well water samples had sufficient sulphide concentrations for $\delta^{34}S$ analysis, but 2 samples (samples 64 and 65) had sufficient sulphate concentrations. The table below (Table 92) provides a statistical summary of the available $\delta^{34}S$ data from this sampling program as well as from the Lemay (2003) sampling program. The complete data set for this study is available in Appendix 8, Table 154.

Table 92. Horseshoe Canyon Formation: $\delta^{34}S$ of sulphide and $\delta^{34}S$ and $\delta^{18}O$ of sulphate.

Location	**Mean (‰ CDT)**	**Std. dev. (‰ CDT)**	**N**	**Max. (‰ CDT)**	**Min. (‰ CDT)**
Water samples $\delta^{43}S$ - Sulphide					
Horseshoe Canyon Formation (Upper Cretaceous) water wells – this study	-5.2	-	2	8.2	-18.7
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells – this study	-	-	0	-	-
Horseshoe Canyon Formation wells[a] (Upper Cretaceous)–coal aquifers	-0.3	4.7	5	5.0	-6.4
Horseshoe Canyon Formation wells[a] (Upper Cretaceous)–mixed aquifers	2.2	14.1	12	34.0	-25.8
Water samples $\delta^{34}S$ - Sulphate					
Horseshoe Canyon Formation (Upper Cretaceous) water wells – this study	15.5	16.9	4	39.6	1.0
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells – this study	5.3	-	2	14.5	-3.8
Horseshoe Canyon Formation wells[a] (Upper Cretaceous)–coal aquifers	0.0	10.5	6	16.5	-10.5
Horseshoe Canyon Formation wells[a] (Upper Cretaceous)–mixed aquifers	0.7	6.8	12	10.0	-13.1
Location	**Mean (‰ VSMOW)**	**Std. dev. (‰ VSMOW)**	**N**	**Max. (‰ VSMOW)**	**Min. (‰ VSMOW)**
Water samples $\delta^{18}O$ - Sulphate					
Horseshoe Canyon Formation (Upper Cretaceous) water wells – this study	-	-	1	10.2	-
Horseshoe Canyon Formation (Upper Cretaceous) CBM wells – this study	-	-	0	-	-

Data sources:

[a] Lemay (2003)

Horseshoe Canyon Formation $^{87}Sr/^{86}Sr$

The mean $^{87}Sr/^{86}Sr$ value in the water well samples is 0.705441 with a standard deviation of 0.000112 (N=5). The mean $^{87}Sr/^{86}Sr$ value in the CBM water samples is 0.705313 with a standard deviation of 0.000076 (N=4). The statistical summary is presented below (Table 93) with additional data from Lemay (2003) for comparison purposes. The complete data set is presented in Appendix 8, Table 154.

Table 93. Horseshoe Canyon Formation: $^{87}Sr/^{86}Sr$ summary statistics.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	0.705441	0.000112	5	0.705621	0.705330
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.705313	0.000076	4	0.705391	0.705232
Horseshoe Canyon water wells[a] (Upper Cretaceous)	0.705609	0.000622	18	0.707849	0.705129

Data sources:
[a] Lemay (2003)

Horseshoe Canyon Formation Radium (Ra)

One of the water well samples (sample 51) has a ^{226}Ra concentration above the analytical detection limits while 3 of the CBM well samples (samples 55, 56 and 64) have ^{226}Ra concentrations above the analytical detection limit. The mean concentration for the CBM well samples is 0.014 Bq/L with a standard deviation of 0.007 Bq/L (N=4). The complete chemistry dataset is found in Appendix 8, Table 154.

None of the water samples have ^{226}Ra concentrations that exceed the maximum acceptable concentration of 0.6 Bq/L established for community water use.

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 are presented for comparison purposes.

Table 94. Horseshoe Canyon Formation: Radium-226 (^{226}Ra).

Water samples					
Location	**Mean (Bq/L)**	**Std. dev. (Bq/L)**	**N**	**Max. (Bq/L)**	**Min. (Bq/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	0.02	<0.01
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	0.014	0.007	4	0.02	<0.01
Horseshoe Canyon water wells[a] (Upper Cretaceous) – mixed coal/sandstone aquifer	0.22	0.08	3	0.29	0.13
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation Uranium (U)

None of the water samples has a U concentration above the analytical detection limits. The complete chemistry dataset is found in Appendix 8, Table 154.

An interim maximum acceptable concentration of 0.020 mg/L has been established for U concentrations in water for domestic use. A maximum concentration of 0.010 mg/L has been established for U concentrations in water for irrigation purposes and a maximum concentration of 0.200 mg/L has been established for U concentrations in water for use in livestock operations. None of the water samples have U concentrations that 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 (U).

Water samples

Location	Mean (mg/L)	Std. dev. (mg/L)	N	Max. (mg/L)	Min. (mg/L)
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	<0.005	<0.0005
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	-	-	4	<0.005	<0.005
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	-	<0.001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.0014*	0.0023*	21	0.0078	<0.000005
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.020
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Coal samples Horseshoe Canyon Formation

Location	Mean (ppm)	Std. dev. (ppm)	N	Max. (ppm)	Min. (ppm)
Drumheller Coal Zone[g] – multiple locations by NAA	0.89	0.29	4	1.11	0.49
Drumheller Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	8	0.2

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Horseshoe Canyon Formation Thorium (Th)

Only one of the water well samples, but none of the CBM water samples has a Th concentration above the analytical detection limit (sample 45). The complete chemistry dataset is found in Appendix 8, Table 154.

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.

The summary statistics for water samples collected during this study are presented in Table 96. 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 96. Horseshoe Canyon Formation: Thorium (Th).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Horseshoe Canyon water wells (Upper Cretaceous) this study	-	-	5	0.0003	<0.0002
Horseshoe Canyon CBM wells (Upper Cretaceous) this study	-	-	4	-	<0.0004
Horseshoe Canyon water wells[a] (Upper Cretaceous)	-	-	18	0.0003	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Edmonton Group wells[c] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.020
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Drumheller Coal Zone[g] – multiple locations by NAA	2.07	0.60	4	2.88	1.48
Drumheller Coal Zone[g] – multiple locations by PES	4.53	2.43	4	6.7	1.9
Horseshoe Canyon Formation[h] – multiple locations	-	-	-	25	0.4

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)

Appendix 7 – Parameter Specific Concentration Summaries for the Scollard and Paskapoo Formations Water Samples

Scollard and Paskapoo Formations: Calcium (Ca)

The mean concentration of Ca in Scollard and Paskapoo formation water well samples is 43.6 mg/L, with a standard deviation of 39.4 mg/L (N=9). The complete chemistry dataset is found in Appendix 8 Table 154.

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 97. 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 97. Scollard and Paskapoo formations: Calcium (Ca).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	43.6	39.4	9	89.5	4.0
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	45.2	45.9	6	96.3	3.6
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	37.0	32.7	640	198	0.8
U.S.A. – Powder River Basin[d] (Tertiary)	32.1	14.9	47	69	5.9
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	16.1	2.9	3	18.9	13.2
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	63.4	37.6	6	118.7	6.5
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	33.4	29.4	13	100	2.5
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	12872	845.6	4	14100	12270
Ardley Coal Zone[g] – multiple locations by PES					
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:

[a] Lemay (2003)

[b] Goodarzi (2002)

[c] Bachu and Michael (2002)

[d] Rice et al. (2000)

[e] Decker et al. (1987)

[f] O’Neil et al. (1989)

[g] Landheer et al. (1982)

[h] Gentzis and Goodarzi (1998)

[i] Pollock et al. (2000)

[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Magnesium (Mg)

The mean Mg concentration from water well samples from within the Scollard and Paskapoo formations is approximately 8.9 mg/L, with a standard deviation of approximately 8.0 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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 98. 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 98. Scollard and Paskapoo formations: Magnesium (Mg).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	8.9*	8.0*	9	18.9	0.3
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	10.4	11.0	6	22.1	0.3
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	16.0	18.0	639	192	0.1
U.S.A. – Powder River Basin[d] (Tertiary)	16.1	8.1	47	46	1.6
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	6.0	-	2	7.8	4.3
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	16.3	16.3	6	39	2.9
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	12.1	10.2	13	34	1.1
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	1668	950	4	3050	903
Ardley Coal Zone[g] – multiple locations by PES	1043	361	4	1542	730
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Sodium (Na)

The mean Na concentration from coal aquifer water well samples from within the Scollard and Paskapoo formations is 224.4 mg/L, with a standard deviation of 180.2 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

An aesthetic objective concentration value for sodium of 200 mg/L has been established. Both Paskapoo Formation samples (samples 48 and 53) and 3 Scollard Formation samples (samples 46, 49 and 54) have sodium concentrations that exceed the aesthetic objective.

The summary statistics for water samples collected during this study are presented in Table 99. 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 99. Scollard and Paskapoo formations: Sodium (Na).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	224.4	180.2	9	596	48.8
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	216.7	196.7	6	503	42.7
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	181	454	640	10932	0.2
U.S.A. – Powder River Basin[d] (Tertiary)	305.3	175.5	47	800	110
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	2240	378.2	3	2673	1976
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	5339	841.8	6	5939	3674
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	1503	795.8	13	3100	570
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	1947	1258	4	3180	228
Ardley Coal Zone[g] – multiple locations by PES	2630	1460	3	3709	969
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Potassium (K)

The mean K concentration from water samples from the Scollard and Paskapoo formations is approximately 1.8 mg/L, with a standard deviation of approximately 1.2 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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 100. 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 100. Scollard and Paskapoo formations: Potassium (K).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	1.8*	1.2*	9	4.5	1.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	2.1	1.2	6	3.8	0.8
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	8.4	3.1	47	18	3.8
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	3.5	1.4	13	6	2
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	723	520	4	1460	352
Ardley Coal Zone[g] – multiple locations by PES	511	234	4	756	266
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Chloride (Cl)

The mean Cl concentration from water well samples from within the Scollard and Paskapoo formations is approximately 1.5 mg/L, with a standard deviation of approximately 2.8 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the water well samples exceeds either of the aesthetic objective or the irrigation water quality guideline values.

The summary statistics for water samples collected during this study are presented in Table 101. 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 101. Scollard and Paskapoo formations: Chloride (Cl).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	1.5*	2.8*	9	6.9	<0.4
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	52.8*	195*	6	425	<0.5
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous) - NAA	67.6	153	6	379	0.4
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	37.0	702	583	16953	0.5
U.S.A. – Powder River Basin[d] (Tertiary)	13.2	12.1	47	64	5.2
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	204.7	343	3	600	4
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	1187	734	6	2499	668
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	1828	1149	13	4200	450
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	4	-	<200
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	21.5	3.25	8	27	18
Ardley Coal Zone[j] – one location	77.7	41.0	82	231	35
Ardley Coal Zone[h] – multiple locations	-	-	-	212	12

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Sulphate (SO_4)

The mean SO_4 concentration from water well samples from within the Scollard and Paskapoo formations is approximately 81.0 mg/L, with a standard deviation of approximately 174.4 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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. One of the samples collected (sample 54) exceeds the aesthetic objective guideline value.

The summary statistics for water samples collected during this study are presented in Table 102. 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 102. Scollard and Paskapoo formations: Sulphate (SO_4).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	81.0	174.4	9	541	2.0
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	6.33	6.62	6	12.3	0.3
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	95.9	169	640	2075	0.7
U.S.A. – Powder River Basin[d] (Tertiary)	2.41	3.63	47	17	0.01
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	56.2	69.2	3	135.5	8.32
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	51.3	66.5	6	166.8	0
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	<0.5

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Bicarbonate (HCO_3)

The mean HCO_3 concentration from water well samples from within the Scollard and Paskapoo formations is 669.3 mg/L, with a standard deviation of 196.1 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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 103. 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 103. Scollard and Paskapoo formations: Bicarbonate (HCO_3).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	669.3	196.1	9	1030	483
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	591.2	160.9	6	854	408
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	471	234	640	4000	54
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	5737	759	3	6612	5250
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	11833	2961	6	14701	6083
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	883	125	13	1120	670

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)

Scollard and Paskapoo Formations: Total Dissolved Solids (TDS)

The mean TDS concentration from water well samples from within the Scollard and Paskapoo formations is 697 mg/L, with a standard deviation of 376 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

An aesthetic objective of TDS ≤ 500 mg/L has been established for water for domestic use. Six of the water samples (46, 48, 49, 53, 54 and 60) 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. The same 6 samples listed earlier fall within this range of values. A recommended maximum TDS value of 3000 mg/L has been established for water to be used for livestock purposes. None of the reported TDS values 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 104. 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 104. Scollard and Paskapoo formations: Total Dissolved Solids (TDS).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	697	376	9	1590	403
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	591.2	160.9	6	854	408
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	605	1154	640	28409	51
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	6470	1639	3	8328	5230
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	15561	3443	6	19392	10667
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	3971	2073	13	7900	1700

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)

Scollard and Paskapoo Formations: Turbidity

The mean turbidity value from water well samples from within the Scollard and Paskapoo formations is approximately 0.9 NTU, with a standard deviation of approximately 1.6 NTU (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the water well samples exceeds the aesthetic objective value. Three of the water well water samples (samples 60, 61 and 62) exceed the maximum acceptable value.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 105. Scollard and Paskapoo formations: Turbidity.

Water samples					
Location	**Mean (NTU)**	**Std. dev. (NTU)**	**N**	**Max. (NTU)**	**Min. (NTU)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.9*	1.6*	9	3.7	<0.1
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	1.38	1.94	6	5.3	0.2
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Data sources:

[a] Lemay (2003)

[b] Goodarzi (2002)

[c] Bachu and Michael (2002)

[d] Rice et al. (2000)

[e] Decker et al. (1987)

[f] O'Neil et al. (1989)

*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: 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 no 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) $ESR = 0.5 \text{ x } 1000/\sqrt{}1000 \text{ x } m_{Na+}/(\sqrt{}m_{Ca2+} + m_{Mg2+})$ 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 x 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 Scollard and Paskapoo formations water well samples is 19.9 $(mmol/L)^{0.5}$, with a standard deviation of 25.7 $(mmol/L)^{0.5}$ (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

All of the water samples 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 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. Scollard and Paskapoo formations: 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)$^{0.5}$**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	19.9	25.7	9	74.7	1.2
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	25.3	27.2	6	60	1.16
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	14.4	19	639	207	0.01
U.S.A. – Powder River Basin[d] (Tertiary)	11.7	7.3	47	32	5.7
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	131	21	3	144	107
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	149	45	6	199	111
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	64	18	13	108	43

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
)

Scollard and Paskapoo Formations: Iron (Fe)

Only 3 of the 9 samples (samples 46, 48 and 60) have Fe concentrations above the analytical detection limits. The complete chemistry dataset is found in Appendix 8, Table 154.

An aesthetic objective of less than or equal to 0.3 mg/L Fe in water 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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 107. Scollard and Paskapoo formations: Iron (Fe).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	0.02	<0.01
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.04	<0.01
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.78	0.94	47	4.9	0.2
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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)**
Ardley Coal Zone[g] – multiple locations by NAA	4187	998	4	5070	2760
Ardley Coal Zone[g] – multiple locations by PES	4553	810	4	5250	3418
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Manganese (Mn)

The mean Mn concentration in the sampled water wells is approximately 0.188 mg/L, with a standard deviation of approximately 0.399 mf/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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. Four of the 9 samples (samples 60, 61, 62 and 63) have Mn concentrations that exceed the aesthetic objective and one of the samples (sample 63) also exceeds the irrigation water quality guideline value.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 108. Scollard and Paskapoo formations: Manganese (Mn).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.188*	0.399*	9	1.24	0.006
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.101*	0.171*	6	0.376	<0.005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.091*	0.26*	21	1.21	<0.001
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.032	0.026	47	0.101	0.002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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)**
Ardley Coal Zone[g] – multiple locations by NAA	106.1	43.4	4	144	56.8
Ardley Coal Zone[g] – multiple locations by PES	111.9	34.8	3	151.6	86.8
Ardley Coal Zone[i] – one location	44.5	11.6	8	68	35
Ardley Coal Zone[j] – one location	92.5	133.3	82	1215	16.6
Ardley Coal Zone[h] – multiple locations	-	-	-	249	16

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Silicon (Si)

The mean Si concentration in the sampled water wells is 8.08 mg/L, with a standard deviation of 3.15 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

No Canadian environmental water quality guidelines have been established for Si.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 109. Scollard and Paskapoo formations: Silicon (Si).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	8.08	3.15	9	12.1	3.63
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	7.49	3.93	6	14.4	4.45
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)					
U.S.A. – Powder River Basin[d] (Tertiary)	4.76	0.62	47	7.1	3.7
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)

Scollard and Paskapoo Formations: Mercury (Hg)

Two of the 9 water samples (samples 48 and 53) have Hg concentrations that exceed the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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 between 0.000005 and 0.000026 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. None of the water well samples have concentrations that exceed established guidelines.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 110. Scollard and Paskapoo formations: Mercury (Hg).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	0.0001	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	-	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	21	0.000913	<0.000002
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.00025	<0.000005
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	0.082	0.16	8	0.46	0.01
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:

[a] Lemay (2003)

[b] Goodarzi (2002)

[c] Bachu and Michael (2002)

[d] Rice et al. (2000)

[e] Decker et al. (1987)

[f] O'Neil et al. (1989)

[g] Landheer et al. (1982)

[h] Gentzis and Goodarzi (1998)

[i] Pollock et al. (2000)

[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Aluminum (Al)

None of the water samples have Al concentrations that exceed the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the water well samples exceed these water quality guidelines.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 111. Scollard and Paskapoo formations: Aluminum (Al).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	<0.05	<0.005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.013	<0.005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.05
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	17800	3243	4	20700	14700
Ardley Coal Zone[g] – multiple locations by PES	20247	6402	4	29050	15420
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:

[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Antimony (Sb)

None of the water samples have Sb concentrations that exceed the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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 112. 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 112. Scollard and Paskapoo formations: Antimony (Sb).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	<0.002	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	-	<0.0002
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	2	0.61	0.29
Ardley Coal Zone[g] – multiple locations by PES					
Ardley Coal Zone[i] – one location	0.764	1.03	8	3.05	0.0
Ardley Coal Zone[j] – one location	0.743	0.858	82	3.39	<0.10
Ardley Coal Zone[h] – multiple locations	-	-	-	2.5	0.1

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Arsenic (As)

Five of the water samples (samples 46, 48, 49, 53 and 63) have As concentrations that exceed the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154. The As mean concentration for the water wells is approximately 0.00008 mg/L with a standard deviation of approximately 0.0015 mg/L (N=9).

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. None of the water well samples exceed water quality guidelines.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 113. Scollard and Paskapoo formations: Arsenic (As).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.00008*	0.0015*	9	0.0031	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.0004*	0.0010*	6	0.0022	<0.0002
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	21	0.0249	<0.0004
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.0004*	0.0004*	47	0.0026	<0.0002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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)**
Ardley Coal Zone[g] – multiple locations by NAA	3.93	5.20	4	11.65	0.62
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	1.44	1.62	8	5.4	0.6
Ardley Coal Zone[j] – one location	5.12	12.9	82	116	1.53
Ardley Coal Zone[h] – multiple locations	-	-	-	21	1.5

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Barium (Ba)

The mean Ba concentration in these water samples is 0.143 mg/L, with a standard deviation of 0.099 mg/L (=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 114. Scollard and Paskapoo formations: Barium (Ba).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.143	0.099	9	0.340	0.020
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.176	0.097	6	0.299	0.065
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.149	0.169	21	0.761	0.007
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.617	0.300	47	1.60	0.14
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	518	171	4	623	264
Ardley Coal Zone[g] – multiple locations by PES	533	84	4	597	415
Ardley Coal Zone[i] – one location	761	447	8	1600	470
Ardley Coal Zone[j] – one location	714	218	82	1269	288
Ardley Coal Zone[h] – multiple locations	-	-	-	261	987

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Beryllium (Be)

None of the water sample Be concentrations exceed the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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 115. 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 115. Scollard and Paskapoo formations: Beryllium (Be).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	<0.001	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	-	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	0.767	0.473	3	1.3	0.4
Ardley Coal Zone[i] – one location	1.65	2.36	8	7.3	0.5
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
)

Scollard and Paskapoo Formations: Bismuth (Bi)

None of the water sample Bi concentrations exceed the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

No 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 116. 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 116. Scollard and Paskapoo formations: Bismuth (Bi).

Water samples

Location	Mean (mg/L)	Std. dev. (mg/L)	N	Max. (mg/L)	Min. (mg/L)
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	<0.005	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	-	<0.0005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.032	<0.020
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Coal samples Horseshoe Canyon Formation

Location	Mean (ppm)	Std. dev. (ppm)	N	Max. (ppm)	Min. (ppm)
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:

[a] Lemay (2003)

[b] Goodarzi (2002)

[c] Bachu and Michael (2002)

[d] Rice et al. (2000)

[e] Decker et al. (1987)

[f] O'Neil et al. (1989)

[g] Landheer et al. (1982)

[h] Gentzis and Goodarzi (1998)

[i] Pollock et al. (2000)

[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Boron (B)

The mean concentration of B in these water samples is 0.167 mg/L, with a standard deviation of 0.074 mg/L. The complete chemistry dataset is found in Appendix 8, Table 154.

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 exceed the water quality guidelines.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 117. Scollard and Paskapoo formations: Boron (B).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.167	0.074	9	0.28	0.044
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.195	0.175	6	0.457	0.041
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.217	<0.100
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	1129	256	3	1413	917
Ardley Coal Zone[i] – one location	73.1	12.4	8	90	51
Ardley Coal Zone[j] – one location	27.1	11.8	82	63	7
Ardley Coal Zone[h] – multiple locations	-	-	-	50	14

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Cadmium (Cd)

None of the water sample Cd concentrations is above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the water sample Cd concentrations exceed the guideline values.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 118. Scollard and Paskapoo formations: Cadmium (Cd).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	<0.0001	<0.00001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.00008	<0.00001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	21	0.00011	<0.00005
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	2	7.9	7
Ardley Coal Zone[i] – one location	0.375	0.495	8	1.60	0.200
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Chromium (Cr)

The mean Cr concentration in these samples is approximately 0.0011 mg/L, with a standard deviation of approximately 0.0008 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the water samples exceed these 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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 119. Scollard and Paskapoo formations: Chromium (Cr).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.0011*	0.0008*	9	0.0022	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.0047	0.0043	6	0.0133	0.0019
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	21	-	<0.001
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	2	3.01	2.29
Ardley Coal Zone[g] – multiple locations by PES	8.12	5.40	4	16	4.4
Ardley Coal Zone[i] – one location	28.5	21.1	8	67	9
Ardley Coal Zone[j] – one location	13.8*	20.5*	82	107	<2.50
Ardley Coal Zone[h] – multiple locations	-	-	-	802	0.7

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Cobalt (Co)

Two of the 9 water samples (samples 46 and 63) have a Co concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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 120. 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 120. Scollard and Paskapoo formations: Cobalt (Co).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	0.0004	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.0003	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.0002	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	1.85	0.52	4	2.41	1.39
Ardley Coal Zone[g] – multiple locations by PES	-	-	1	16.2	-
Ardley Coal Zone[i] – one location	1.99	0.70	8	3.50	1.20
Ardley Coal Zone[j] – one location	2.80	2.99	82	23.4	0.54
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Copper (Cu)

The mean Cu concentration in these samples is approximately 0.007 mg/L, with a standard deviation of approximately 0.011 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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 3 of the water well samples (samples 60, 61 and 62) falls within the maximum Cu concentration range for the protection of freshwater aquatic life and 4 of the samples (48, 49, 53 and 63) have Cu concentrations that exceed this range of 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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 121. Scollard and Paskapoo formations: Copper (Cu).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.007*	0.011*	9	0.025	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.001	<0.001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.009*	0.0042*	21	0.148	<0.002
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	5.36	4.26	47	28.6	1.5
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	7.1	2.89	4	9.7	4.4
Ardley Coal Zone[i] – one location	16.5	31.1	8	93	2
Ardley Coal Zone[j] – one location	24.7	14.2	82	68.9	6.2
Ardley Coal Zone[h] – multiple locations	-	-	-	23.2	0.7

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Lead (Pb)

None of the Pb concentrations exceed the analytical detection limits. The complete chemistry dataset is found in Appendix 8, Table 154.

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 have a Pb concentration that exceeds water quality guidelines.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 122. Scollard and Paskapoo formations: Lead (Pb).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	<0.001	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.0003	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.00043*	0.00060*	21	0.0027	<0.00001
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.00043	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	10.7	6.21	4	19.4	5.5
Ardley Coal Zone[i] – one location	22	42	8	125	2
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:

[a] Lemay (2003)

[b] Goodarzi (2002)

[c] Bachu and Michael (2002)

[d] Rice et al. (2000)

[e] Decker et al. (1987)

[f] O'Neil et al. (1989)

[g] Landheer et al. (1982)

[h] Gentzis and Goodarzi (1998)

[i] Pollock et al. (2000)

[j] Gentzis and Goodarzi (1995)

*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Lithium (Li)

The mean Li concentration in these samples is 0.047 mg/L, with a standard deviation of 0.025 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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 123. 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 123. Scollard and Paskapoo formations: Lithium (Li).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.047	0.025	9	0.10	0.019
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.049	0.030	6	0.11	0.014
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.052	0.036	47	0.208	0.018
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	7	4.3	8	17	4
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
)

Scollard and Paskapoo Formations: Molybdenum (Mo)

Three of the 9 water samples (samples 46, 48 and 53) have a Mo concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

The maximum acceptable concentration of Mo 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. One of the water samples (sample 46) has a Mo concentration that falls within the range of values listed for the protection of freshwater aquatic life.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 124. Scollard and Paskapoo formations: Molybdenum (Mo).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	0.012	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.008	<0.001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.0013*	0.0013*	21	0.0043	<0.00005
Paskapoo wells[c] (Tertiary)					
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	4.87	3.80	8	13	2
Ardley Coal Zone[j] – one location	1.25*	2.33*	82	9.22	<0.25
Ardley Coal Zone[h] – multiple locations	-	-	-	90	0.5

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Nickel (Ni)

Only 1 of the 9 water samples (sample 63) has a Ni concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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 the Ni concentrations listed in the guidelines.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 125. Scollard and Paskapoo formations: Nickel (Ni).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	0.0006	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.0007	<0.0005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.00037*	0.00055*	21	0.0021	<0.0002
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.0065*	0.0068*	47	0.0354	<0.0005
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	8.3	1.85	3	9.7	6.2
Ardley Coal Zone[i] – one location	13.5	9.44	8	29	5
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	491	2.5

Data sources:

[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Selenium (Se)

None of the water samples has a Se concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

A maximum acceptable concentration of Se 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 126. 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 126. Scollard and Paskapoo formations: Selenium (Se).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	<0.002	<0.0002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.0002	<0.0002
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	4	-	<2
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	2.25	4.37	8	13	0
Ardley Coal Zone[j] – one location	0.753*	2.59*	82	5.86	<0.59
Ardley Coal Zone[h] – multiple locations	-	-	-	5.4	0.7

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Silver (Ag)

None of the water samples has an Ag concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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. Given the variation in the detection limit of the analytical methods, it cannot be determined if any of the water samples exceeds this guideline value.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 127. Scollard and Paskapoo formations: Silver (Ag).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	<0.001	<0.0001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	-	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	1	0.8	-
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Strontium (Sr)

The mean concentration of Sr in these samples is 0.382 mg/L, with a standard deviation of 0.282 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

Canadian environmental water quality guidelines have not been developed for Sr.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 128. Scollard and Paskapoo formations: Strontium (Sr).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.382	0.282	9	0.832	0.101
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.503	0.649	6	1.69	0.05
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.692	0.412	47	1.9	0.1
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	4	-	<400
Ardley Coal Zone[g] – multiple locations by PES	121.4	40.0	4	145.7	62
Ardley Coal Zone[i] – one location	201.5	38.4	8	284	162
Ardley Coal Zone[j] – one location	146.9	58.2	82	380	64.7
Ardley Coal Zone[h] – multiple locations	-	-	-	380	66

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Thallium (Tl)

None of the samples have a Tl concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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. None of the samples exceeds this guideline 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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 129. Scollard and Paskapoo formations: Thallium (Tl).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	<0.0005	<0.00005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	-	<0.00005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.00034	<0.0002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Tin (Sn)

None of the samples have a Sn concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

Canadian environmental water quality guidelines have not been developed for Sn.

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 United States, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 130. Scollard and Paskapoo formations: Tin (Sn).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	<0.01	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)		-	47	0.0055	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Titanium (Ti)

Four of the 9 samples (samples 48, 53, 54 and 60) have a Ti concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

Canadian environmental water quality guidelines have not been developed for Ti.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 131. Scollard and Paskapoo formations: Titanium (Ti).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	0.01	<0.0005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.104*	0.176*	6	0.307	<0.0005
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.050
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	588	244	4	942	403
Ardley Coal Zone[g] – multiple locations by PES	637	243	4	1001	500
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Vanadium (V)

The mean V concentration in these samples is 0.0031 mg/L, with a standard deviation of 0.0016 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

A maximum concentration of 0.100 mg/L has been established for V concentrations in water for irrigation purposes as well as for V concentrations in water for use in livestock operations. None of the water samples have V concentrations that 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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 132. Scollard and Paskapoo formations: Vanadium (V).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.0031	0.0016	9	0.0054	0.0012
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.0014	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.0002
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	8.37	2.91	4	10.6	4.09
Ardley Coal Zone[g] – multiple locations by PES	10.3	3.65	4	15.2	6.5
Ardley Coal Zone[i] – one location	13.4	23.4	8	71	2
Ardley Coal Zone[j] – one location	21.4*	27.0*	82	140	<1.36
Ardley Coal Zone[h] – multiple locations	-	-	-	57	0.4

Data sources:

[a] Lemay (2003)

[b] Goodarzi (2002)

[c] Bachu and Michael (2002)

[d] Rice et al. (2000)

[e] Decker et al. (1987)

[f] O'Neil et al. (1989)

[g] Landheer et al. (1982)

[h] Gentzis and Goodarzi (1998)

[i] Pollock et al. (2000)

[j] Gentzis and Goodarzi (1995)

*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Zinc (Zn)

The mean Zn concentration in these samples is approximately 0.015 mg/L, with a standard deviation of approximately 0.017 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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. Two of the samples (samples46 and 63) exceed the protection of freshwater aquatic life 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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 133. Scollard and Paskapoo formations: Zinc (Zn).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.015*	0.017*	9	0.044	0.002
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.004*	0.002*	6	0.007	<0.001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.065	0.113	21	0.470	0.0007
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	0.0804	<0.001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (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)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	15.6	5.65	4	22.9	9.2
Ardley Coal Zone[i] – one location	29.9	61.5	8	182	6
Ardley Coal Zone[j] – one location	-	-	82	182	<5.1
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Fluorine (F)

The mean F concentration in these samples is 1.37 mg/L, with a standard deviation of 0.95 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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. Five of the 9 samples (samples 46, 48, 49, 53 and 54) exceed the maximum concentration guideline values for irrigation use and fall within or are greater than the range of values proposed for livestock use. Four of these samples (samples 46, 48, 49 and 54) also exceed the domestic use guideline value.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 134. Scollard and Paskapoo formations: Fluorine (F).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	1.37	0.95	9	3.1	0.4
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	1.5*	1.4*	6	3.2	<0.5
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.92	0.32	47	1.7	0.42
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Bromine (Br)

Only 2 samples (samples 46 and 54) have Br concentrations greater than the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

No Canadian environmental water quality guidelines have been established for Br.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 135. Scollard and Paskapoo formations: Bromine (Br).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	0.12	<0.05
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	2.82	<0.013
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.11*	0.18*	47	0.85	<0.02
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	6.98*	7.81*	4	16.2	<1
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	1.45	0.62	8	2.6	0.9
Ardley Coal Zone[j] – one location	420	402	82	1850	23
Ardley Coal Zone[h] – multiple locations	-	-	-	639	78

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Iodine (I)

Only 1 sample (sample 46) has an I concentration greater than the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

No Canadian environmental water quality guidelines have been established for I.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 136. Scollard and Paskapoo formations: Iodine (I).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	0.03	<0.02
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.82	<0.0048
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	4	-	<20
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	-	-	-	-	-
Ardley Coal Zone[j] – one location	-	-	-	-	-
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Scandium (Sc)

The mean Sc concentration in these samples is 0.00008 mg/L, with a standard deviation of 0.00002 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

No Canadian environmental water quality guidelines have been established for Sc.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 137. Scollard and Paskapoo formations: Scandium (Sc).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.00008	0.00002	9	0.0001	0.00005
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	0.00006	0.00003	6	0.00011	0.00003
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.00120*	0.00079*	47	0.003	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	2.08	0.77	4	3.20	1.51
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	3.14	3.49	8	11.1	0.598
Ardley Coal Zone[j] – one location	3.70	3.19	82	16.0	0.610
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Rubidium (Rb)

Only 1 of the 9 samples (sample 61) has a Rb concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

No Canadian environmental water quality guidelines have been established for Rb.

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, as well as coal analyses from Alberta, are presented for comparison purposes.

Table 138. Scollard and Paskapoo formations: Rubidium (Rb).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	-	-	9	0.008	<0.006
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	-	<0.0052
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	0.0118	0.0061	47	0.0382	0.0041
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Horseshoe Canyon Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	-	-	-	-	-
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	-	-	8	5.7	0
Ardley Coal Zone[j] – one location	-	-	82	92.5	<3.78
Ardley Coal Zone[h] – multiple locations	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[g] Landheer et al. (1982)
[h] Gentzis and Goodarzi (1998)
[i] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Scollard and Paskapoo Formations: Phenols

The mean phenols concentration in these samples is approximately 0.001 mg/L, with a standard deviation of approximately 0.001 mg/L (N=9). The complete chemistry dataset is found in Appendix 8, Table 154.

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. Two of the water well samples (samples 48 and 61) exceed or meet the maximum concentration guideline values for water to be used for livestock purposes.

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, as well as coal analyses from Alberta are presented for comparison purposes.

Table 139. Scollard and Paskapoo formations: Phenols.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study	0.001*	0.001*	9	0.003	<0.001
Paskapoo-Scollard wells[a] (Tertiary-Cretaceous)	-	-	6	0.001	<0.001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations: Non-Halogenated Aromatic Hydrocarbons (BTEX)

The table below (Table 140) lists the Canadian environmental water quality guideline maximum concentrations for benzene, toluene, ethylbenzene and xylene. None of the samples has a benzene concentration above the analytical detection limit. One of water well samples (sample 54) has a toluene concentration above the detection limit, but does not exceed any of the water quality guideline values. None of the samples has an ethylbenzene concentration above the analytical detection limit. In addition, none of the water well samples has xylenes concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

Table 140. 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 Table 141. 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 141. Scollard and Paskapoo formations: Non-halogenated aromatic hydrocarbons (BTEX).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study - Benzene	-	-	9	-	<0.001
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study - Toluene	-	-	9	0.001	<0.001
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study - Ethylbenzene	-	-	9	-	<0.001
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study - Xylenes	-	-	9	-	<0.001
Scollard and Paskapoo water wells[a] (Tertiary-Cretaceous) - Benzene	-	-	6		<0.001
Scollard and Paskapoo water wells[a] (Tertiary-Cretaceous) - Toluene	-	-	6		<0.001
Scollard and Paskapoo water wells[a] (Tertiary-Cretaceous) - Ethylbenzene	-	-	6		<0.001
Scollard and Paskapoo water wells[a] (Tertiary-Cretaceous) - Xylenes	-	-	6		<0.001

Data sources:

[a] Lemay (2003)

Scollard and Paskapoo Formations: Purgeable and Extractable Hydrocarbons

Three of the water well samples (sample 54, 61 and 62) have a purgeable hydrocarbons concentration above the analytical detection limit, but none have an extractable hydrocarbons concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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 Table 142. 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 142. Scollard and Paskapoo formations: Purgeable and Extractable Hydrocarbons.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study–Purgeable Hydrocarbons	-	-	9	0.59	<0.01
Scollard and Paskapoo water wells (Tertiary-Cretaceous) this study–Extractable Hydrocarbons	-	-	9	-	<0.1
Scollard and Paskapoo water wells[a] (Tertiary-Cretaceous)–Purgeable Hydrocarbons	-	-	6	0.02	<0.01
Scollard and Paskapoo water wells[a] (Tertiary-Cretaceous)–Extractable Hydrocarbons	-	-	6	0.2	<0.1

Data sources:

[a] Lemay (2003)

Scollard and Paskapoo Formations: Polycyclic Aromatic Hydrocarbons (PAH)

The table below (Table 143) lists the Canadian environmental water quality guideline maximum concentrations for PAH's in water. None of the measured water well concentrations of PAH's exceeds the analytical detection limits and therefore do not exceed guideline values. The summary statistics for water samples collected during this study are presented in Table 144.

Table 143. 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	-	-	0.000012	-	-
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	-	-	-	-	-

In addition, water samples collected from other coal and sandstone aquifers in Alberta and the United States are presented for comparison purposes (Table 145). The complete chemistry dataset is found in Appendix 8, Table 154.

Table 144. Scollard and Paskapoo formations: Polycyclic Aromatic Hydrocarbons (PAH).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo formations water wells (Tertiary - Cretaceous) this study					
Naphthalene	-	-	9	-	<0.00001
Acenaphthylene	-	-	9	-	<0.00001
Acenaphthene	-	-	9	-	<0.00001
Fluorene	-	-	9	-	<0.00001
Phenanthrene	-	-	9	-	<0.00001
Anthracene	-	-	9	-	<0.00001
Acridine	-	-	9	-	<0.00001
Fluoranthene	-	-	9	-	<0.00002
Pyrene	-	-	9	-	<0.00002
Benzo(a)anthracene	-	-	9	-	<0.00001
Chrysene	-	-	9	-	<0.00001
Benzo(b)fluoranthene	-	-	9	-	<0.00001
Benzo(k)fluoranthene	-	-	9	-	<0.00001
Benzo(a)pyrene	-	-	9	-	<0.00001
Indeno(1,2,3-c,d)pyrene	-	-	9	-	<0.00001
Dibenzo(a,h)anthracene	-	-	9	-	<0.00001
Benzo(g,h,I)perylene	-	-	9	-	<0.00001

Table 145. PAH results from previous studies and other CBM development areas.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo formations wells[a] (Tertiary - Cretaceous)					
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[b] (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[f] (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] Lemay (2003)

[b] Goodarzi (2002)

[f] O'Neil et al. (1989)

Scollard and Paskapoo Formations: Adsorbable Organic Halides (AOX)

None of the water well samples has an AOX concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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 Table 146. 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 146. Scollard and Paskapoo formations: Adsorbable Organic Halides (AOX).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo formations water wells (Tertiary - Cretaceous) this study	-	-	9	-	<0.004
Scollard and Paskapoo formations water wells[a] (Tertiary - Cretaceous)	0.0042*	0.0070*	6	0.016	<0.0025
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary – Cretaceous)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations stable isotopes of oxygen and hydrogen in water

The mean $\delta^{18}O$ concentration in water well samples is -17.1‰ VSMOW with a standard deviation of 1.3‰VSMOW (N=9). The mean δ^2H value in water well samples is -139‰ VSMOW with a standard deviation of 7‰ VSMOW (N=9). The statistical summary can be found in Table 147. The complete data set can be found in Appendix 8, Table 154.

Table 147. Scollard and Paskapoo formations: $\delta^{18}O$ and δ^2H of H_2O.

Location	Mean (‰ VSMOW)	Std. dev. (‰ VSMOW)	N	Max. (‰ VSMOW)	Min. (‰ VSMOW)
Water samples: $\delta^{18}O$					
Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells – this study	-17.1	1.3	9	-15.2	-18.5
Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells[a]	-16.9	2.0	6	-13.0	-17.9
Water samples: δ^2H					
Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells – this study	-139	7	9	-129	-148
Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells[a]	-138	12	6	-117	-151

Data sources:

[a] Lemay (2003)

Scollard and Paskapoo Formations stable isotopes of carbon and oxygen in DIC

The mean value of $\delta^{13}C$ of DIC in the water well samples is -13.7‰ VPDB with a standard deviation of 3.2‰ VPDB (N=9). The mean value of $\delta^{18}O$ of DIC is -13.2‰ VPDB with a standard deviation of 0.9‰ VPDB (N=9). The summary statistics are presented in the table below (Table 148). The complete data set is presented in Appendix 8, Table 154.

Table 148. Scollard and Paskapoo formations: $\delta^{13}C$ and $\delta^{18}O$ of DIC.

Location	Mean (‰ VPDB)	Std. dev. (‰ VPDB)	N	Max. (‰ VPDB)	Min. (‰ VPDB)
Water samples: $\delta^{13}C$					
Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells – this study	-13.7	3.2	9	-8.4	-18.5
Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells[a]	-5.7	11.7	6	17.0	-14.0
Water samples: $\delta^{18}O$					
Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells – this study	-13.2	0.9	9	-11.3	-14.2
Scollard and Paskapoo formations (Tertiary - Cretaceous) water wells[a]	-12.1	1.5	6	-9.3	-13.8

Data sources:
[a] Lemay (2003)

Scollard and Paskapoo Formations stable isotopes of sulphur and oxygen in sulphate and sulphide

Three of the 9 water well samples (samples 48, 49, 54) had sufficient sulphide concentrations for the determination of δ^{34}S of sulphide. Eight of the 9 water samples had sufficient sulphate concentrations to determine the δ^{34}S of sulphate. The mean value of δ^{34}S in these samples is 2.6‰ CDT with a standard deviation of 7‰ CDT (N=8). The table below presents a statistical summary of the δ^{34}S results (Table 149). The complete data set is presented in Appendix 8, Table 154.

Table 149. Scollard and Paskapoo formations: δ^{34}S of sulphide and δ^{34}S and δ^{18}O of sulphate.

Location	**Mean (‰ CDT)**	**Std. dev. (‰ CDT)**	**N**	**Max. (‰ CDT)**	**Min. (‰ CDT)**
Water samples δ^{43}S - Sulphide					
Scollard and Paskapoo formations (Tertiary – Cretaceous) water wells – this study	-10.1	26.8	3	17.3	-36.2
Scollard and Paskapoo formations (Tertiary – Cretaceous) water wells[a]	-0.5	6.2	6	6.8	-11.8
Water samples δ^{34}S - Sulphate					
Scollard and Paskapoo formations (Tertiary – Cretaceous) water wells – this study	2.6	7.0	8	12.0	-7.7
Scollard and Paskapoo formations (Tertiary – Cretaceous) water wells[a]	12.0	13.4	5	34.8	3.1
Location	**Mean (‰ VSMOW)**	**Std. dev. (‰ VSMOW)**	**N**	**Max. (‰ VSMOW)**	**Min. (‰ VSMOW)**
Water samples δ^{18}O - Sulphate					
Scollard and Paskapoo formations (Tertiary – Cretaceous) water wells – this study	1.1	-	2	2.0	0.2
Scollard and Paskapoo formations (Tertiary – Cretaceous) water wells[a]	-	-	0	-	-

Data sources:
[a] Lemay (2003)

Scollard and Paskapoo Formations $^{87}Sr/^{86}Sr$

The mean $^{87}Sr/^{86}Sr$ value in the water well samples is 0.706157 with a standard deviation of 0.000752 (N=9). The statistical summary is presented below (Table 150) with additional data from Lemay (2003) for comparison purposes. The complete data set is presented in Appendix 8, Table 154.

Table 150. Scollard and Paskapoo formations: $^{87}Sr/^{86}Sr$ summary statistics.

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo formations (Tertiary – Cretaceous) water wells – this study	0.706157	0.000752	9	0.707685	0.705278
Scollard and Paskapoo formations (Tertiary – Cretaceous) water wells[a]	0.706094	0.000843	6	0.707659	0.705353

Data sources:
[a] Lemay (2003)

Scollard and Paskapoo Formations Radium (Ra)

Two of the water well samples (samples 60 and 63) have a ^{226}Ra concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

None of the water samples have ^{226}Ra concentrations that exceed the maximum acceptable concentration of 0.6 Bq/L established for community water use.

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

Table 151. Scollard and Paskapoo formations: Radium-226 (^{226}Ra).

Water samples					
Location	**Mean (Bq/L)**	**Std. dev. (Bq/L)**	**N**	**Max. (Bq/L)**	**Min. (Bq/L)**
Scollard and Paskapoo formations water wells (Tertiary - Cretaceous) this study	-	-	6	0.01	<0.01
Scollard and Paskapoo formations water wells[a] (Tertiary - Cretaceous)	-	-	1	0.13	-
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)

Scollard and Paskapoo Formations Uranium (U)

Two of the water well samples (samples 53 and 63) have a U concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

An interim maximum acceptable concentration of 0.020 mg/L has been established for U concentrations in water for domestic use. A maximum concentration of 0.010 mg/L has been established for U concentrations in water for irrigation purposes and a maximum concentration of 0.200 mg/L has been established for U concentrations in water for use in livestock operations. None of the water samples have U concentrations that exceed these guideline values.

The summary statistics for water samples collected during this study are presented in Table 152. In addition, water samples collected from other coal and sandstone aquifers in Alberta are presented for comparison purposes.

Table 152. Scollard and Paskapoo formations: Uranium (U).

Water samples					
Location	**Mean (mg/L)**	**Std. dev. (mg/L)**	**N**	**Max. (mg/L)**	**Min. (mg/L)**
Scollard and Paskapoo formations water wells (Tertiary - Cretaceous) this study	-	-	9	0.0015	<0.0005
Scollard and Paskapoo formations water wells[a] (Tertiary - Cretaceous)	-	-	6	0.001	<0.001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	0.0014*	0.0023*	21	0.0078	<0.000005
Paskapoo wells[c] (Tertiary)	-	-	-	-	-
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	47	-	<0.0001
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-
Coal samples Scollard Formation					
Location	**Mean (ppm)**	**Std. dev. (ppm)**	**N**	**Max. (ppm)**	**Min. (ppm)**
Ardley Coal Zone[g] – multiple locations by NAA	0.89	0.29	4	1.11	0.49
Ardley Coal Zone[g] – multiple locations by PES	-	-	-	-	-
Ardley Coal Zone[i] – one location	7.3	15.7	8	46.1	0.4
Ardley Coal Zone[j] – one location	3.5	2.8	82	33	0.54
Ardley Coal Zone[h] – multiple locations	-	-	-	6	0.5

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O’Neil et al. (1989)
[h] Gentzis and Goodarzi (1998)
[l] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)
*Mean and standard deviation for populations with non-detects were determined according to Environmental Protection Agency (1992)

Scollard and Paskapoo Formations Thorium (Th)

None of the water well samples have a Th concentration above the analytical detection limit. The complete chemistry dataset is found in Appendix 8, Table 154.

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 153. In addition, water samples collected from other coal and sandstone aquifers in Alberta are presented for comparison purposes.

Table 153. Scollard and Paskapoo formations: Thorium (Th).

Water samples

Location	Mean (mg/L)	Std. dev. (mg/L)	N	Max. (mg/L)	Min. (mg/L)
Scollard and Paskapoo formations water wells (Tertiary - Cretaceous) this study	<0.0002	-	9	-	-
Scollard and Paskapoo formations water wells[a] (Tertiary - Cretaceous)	-	-	6	0.0002	<0.0001
Paskapoo-Scollard wells[b] (Tertiary-Cretaceous)	-	-	-	-	-
Paskapoo wells[c] (Tertiary)	-	-	47	-	<0.020
U.S.A. – Powder River Basin[d] (Tertiary)	-	-	-	-	-
U.S.A. – Piceance Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – San Juan Basin[e] (Upper Cretaceous)	-	-	-	-	-
U.S.A. – Black Warrior Basin[f] (Pennsylvanian)	-	-	-	-	-

Coal samples Scollard Formation

Location	Mean (ppm)	Std. dev. (ppm)	N	Max. (ppm)	Min. (ppm)
Ardley Coal Zone[g] – multiple locations by NAA	3.60	1.72	4	6.17	2.55
Ardley Coal Zone[g] – multiple locations by PES	4.45	3.14	4	9	1.8
Ardley Coal Zone[i] – one location	7.94	10.2	8	29.2	0.6
Ardley Coal Zone[j] – one location	8.89	7.26	82	30.5	0.86
Ardley Coal Zone[h] – multiple locations	-	-	-	25	1

Data sources:
[a] Lemay (2003)
[b] Goodarzi (2002)
[c] Bachu and Michael (2002)
[d] Rice et al. (2000)
[e] Decker et al. (1987)
[f] O'Neil et al. (1989)
[h] Gentzis and Goodarzi (1998)
[l] Pollock et al. (2000)
[j] Gentzis and Goodarzi (1995)

Appendix 8 – Chemical and geomicrobiological datasets

Table 154a. Inorganic geochemistry summary table.

ID	Sample	Approximate Location TTT-RRWM	Formation	Approximate Coal Zone	Depth (mbGL)	Depth (mbKB)	Elevation (masl)	Sample Date (mm/dd/yy)	Field measurements: pH	Conductivity mS/cm	ORP mV	Electrode constant mV	Eh mV	Temperature °C	DO mg/L	T-Alkalinity mg/L	P-Alkalinity mg/L
43	AERI0501	053-22W4	HC	Drumheller or equivalent	27.4		686.6	07/06/05	7.03	1565	-4	209.6	205.6	14.4	0.19	796	
44	AERI0502	048-19W4	HC	Drumheller or equivalent	42.5		713.5	07/07/05	8.06	3970	-131	216.8	85.8	7.2	0.06	518	
45	AERI0503	049-20W4	HC	Drumheller or equivalent	78.7		717.3	07/07/05	8.30	1687	-351	216.5	-134.5	7.5	0.12	766	
46	AERI0505	047-26W4	Scollard	Ardley	19.5		770.5	07/08/05	8.46	1551	-173	215.3	42.3	8.7	0.15	820	
47	AERI0506	050-23W4	HC	Drumheller or equivalent	27.1		730.9	07/11/05	8.47	1371	-307	216.2	-90.8	8.1	0.25	810	
48	AERI0507	048-01W5	Paskapoo	Unknown	27.0		751.0	07/11/05	7.70	922	-102	213.8	111.8	10.4		484	
49	AERI0508	053-05W5	Scollard	Ardley	34.1		696.9	07/12/05	7.59	1198	-329	216.0	-113.0	8.0	0.10	600	
50	AERI0509	053-05W5	Scollard	Ardley	34.1		696.9	07/12/05	7.59	1198	-329	216.0	-113.0	8.0	0.10	600	
51	AERI0510	041-18W4	HC	Drumheller or equivalent	41.2		732.8	07/13/05	7.55	1398	21	214.9	235.9	9.2		840	
52	AERI0511	041-18W4	HC	Drumheller or equivalent	41.2		732.8	07/13/05	7.55	1398	21	214.9	235.9	9.2		840	
53	AERI0512	050-07W5	Paskapoo	Unknown	51.7		760.3	07/14/05	7.94	872	-95	216.9	121.9	7.1	0.06	446	
54	AERI0513	053-04W5	Scollard	Ardley	34.8		700.2	07/15/05	8.27	2400	-245	216.8	-28.2	7.1	0.15	724	
55	AERI0516	039-20W4	HC	Drumheller or equivalent		256.7	567.4	07/26/05	8.15	5930	20	209.8	229.8	14.2		800	
56	AERI0517	047-23W4	HC	Drumheller or equivalent		250.9	506.5	07/26/05	8.28	5520	-80	214.6	134.6	9.4		358	
57	AERI0518	047-23W4	HC	Drumheller or equivalent		250.9	506.5	07/26/05	8.28	5520	-80	214.6	134.6	9.4		358	
58	AERI0519	038-23W4	HC	Drumheller or equivalent		382.3	482.2	08/02/05	10.55	8830	-160	211.5	51.5	12.5	0.05	960	120
59	AERI0520	043-26W4	Belly River	Unknown		729.7	119.1	08/02/05	10.40	9420	-275	208.5	-66.5	15.5	0.85	162	110
60	AERI0521	053-04W5	Scollard	Ardley	26.2		751.9	09/02/05	7.23	849	15	216.5	231.5	7.5		414	
61	AERI0522	053-04W5	Scollard	Ardley	37.0		751.4	09/02/05	7.20	757	-24	214.8	190.8	9.2		392	
62	AERI0523	053-04W5	Scollard	Ardley	39.3		745.7	09/02/05	7.15	784	14	216.1	230.1	7.9		380	
63	AERI0524	053-04W5	Scollard	Ardley	31.2		757.6	09/02/05	7.16	701	111	217.3	328.3	6.7		378	
64	AERI0525	045-22W4	HC	Drumheller or equivalent		257.5	514.2	09/08/05	8.06	5790	-144	212.8	68.8	11.2		540	
65	AERI0526	044-22W4	HC	Drumheller or equivalent		255.2	496.1	09/08/05	8.47	4520	70	212.1	282.1	11.9		448	
MAC, IMAC[a]																	
AO[a]									6.5-8.5								
Irrigation[b]																	
Livestock[b]																	
Freshwater[b]									6.5-8.5								
Freshwater[c]									6.5-9.0								

ID	Sample	Lab measurements: pH	Conductivity mS/cm	Turbidity NTU	P-Alkalinity mg/L as $CaCO_3$	T-Alkalinity mg/L as $CaCO_3$	Hardness mg/L as $CaCO_3$	Ionic Balance %	TDS mg/L
43	AERI0501	7.60	1620	0.7	<5	738	19	96	993
44	AERI0502	8.35	3950	0.1	<5	651	45	99	2220
45	AERI0503	8.51	1690	0.2	16	789	11	105	1010
46	AERI0505	8.59	1590	<0.1	30	908	12	95	956
47	AERI0506	8.52	1370	0.2	36	736	20	96	831
48	AERI0507	8.04	919	0.2	<5	499	22	99	551
49	AERI0508	7.92	1190	<0.1	<5	692	83	97	727
50	AERI0509	7.92	1190	<0.1	<5	689	86	98	727
51	AERI0510	8.03	1390	0.4	<5	787	69	101	861
52	AERI0511	8.04	1390	0.2	<5	787	74	99	854
53	AERI0512	8.21	988	0.3	<5	472	57	100	612
54	AERI0513	8.39	2200	0.5	10	743	10	100	1590
55	AERI0516	8.48	5820	19.7	28	908	70	96	3460
56	AERI0517	8.44	5200	99.1	9	422	55	96	2930
57	AERI0518	8.45	5240	47.7	11	417	44	98	2980
58	AERI0519	10.50	8160	11.3	148	2210	20	122	5620
59	AERI0520	10.00	9110	10.5	115	305	7	95	5290
60	AERI0521	7.78	859	2.0	<5	452	301	100	525
61	AERI0522	7.80	752	3.7	<5	427	258	99	447
62	AERI0523	7.75	783	2.70	<5	435	271	99	458
63	AERI0524	7.98	692	0.4	<5	396	294	101	403
64	AERI0525	8.36	5740	0.1	7	502	70	97	3140
65	AERI0526	8.41	4950	0.2	10	497	43	96	2730
MAC, IMAC[a]				1					
AO[a]		6.5-8.5		5*					500
Irrigation[b]									500-3500
Livestock[b]									3000
Freshwater[b]		6.5-8.5							
Freshwater[c]		6.5-9.0							

ID	Sample	Major constituents: Sodium mg/L	Magnesium mg/L	Silicon mg/L	Extractable Silicon mg/L	Chloride mg/L	Chloride (NAA) ppm	Calcium mg/L	Bicarbonate mg/L	Extractable Silica mg/L	Sulphate mg/L	CBE %
43	AERI0501	386	0.6	12.6	13.0	3.3	1.0	6.5	900	27.9	152	-2.29
44	AERI0502	869	1.0	5.0	5.00	933	883	16.0	794	11.0	<9	-0.63
45	AERI0503	427	0.2	7.7	7.47	13.7	13.4	4.1	922	16.0	86.7	2.32
46	AERI0505	396	0.3	5.1	5.13	6.9	7.6	4.3	1030	11.0	3.0	-2.26
47	AERI0506	336	0.6	3.8	4.00	7.9	7.6	7.0	809	8.6	36.6	-2.05
48	AERI0507	224	1.1	4.9	5.29	0.5	0.6	7.2	609	11.3	17.0	-0.61
49	AERI0508	274	5.0	9.7	10.4	4.7	3.4	25.2	843	22.3	2.0	-1.31
50	AERI0509	274	5.1	9.6	10.7	5.5	3.9	25.9	840	22.8	2.0	-1.05
51	AERI0510	343	3.7	7.9	7.68	13.5	12.7	21.4	960	16.4	5.3	0.39
52	AERI0511	334	3.8	7.4	7.68	13.5	13.8	23.5	959	16.4	4.2	-0.36
53	AERI0512	228	5.4	3.6	3.82	0.5	0.4	13.8	576	8.2	79.5	-0.14
54	AERI0513	596	<1	6.7	6.16	1.9	1.6	4.0	881	13.2	541	0.05
55	AERI0516	1340	4.0	6.2	6.70	1540	1590	21.0	1040	14.0	9.0	-1.61
56	AERI0517	1120	2.0	3.8	4.30	1530	1650	18.0	492	9.3	<9	-1.68
57	AERI0518	1150	2.0	3.9	4.30	1550	1640	15.0	483	9.2	<9	-0.97
58	AERI0519	2520	<1	2.4	3.04	1600		7.0	2340	6.5	110	9.76
59	AERI0520	2000	<1	5.9	6.04	3050		3.0	92	12.9	20.0	-2.68
60	AERI0521	92.1	18.9	12.1	12.1	1.3	1.6	89.5	552	26.0	50.1	-0.21
61	AERI0522	81.4	14.8	11.3	11.2	0.5	0.7	78.9	520	23.9	13.0	-0.31
62	AERI0523	79.7	15.4	11.2	11.3	<0.4	0.5	83.2	530	24.1	16.0	-0.45
63	AERI0524	48.8	18.9	8.1	8.00	<0.4	0.5	86.7	483	17.1	7.0	0.32
64	AERI0525	1200	3.0	3.6	3.70	1600	1730	22.0	595	7.8	10.0	-1.60
65	AERI0526	1050	2.0	4.0	4.10	1360	1410	14.0	583	8.8	<9	-1.66
MAC, IMAC[a]												
AO[a]		200				250	250				500	
Irrigation[b]						100-700	100-700					
Livestock[b]								1000			1000	
Freshwater[b]						230-860**	230-860**					
Freshwater[c]												

ID	Sample	Minor constituents: Boron mg/L	Fluoride (NAA) ppm	Potassium mg/L	Iron mg/L	Strontium mg/L	Hydroxide mg/L	Carbonate mg/L	Nitrate mg/L as N	Nitrite mg/L as N	Nitrate+Nitrate mg/L as N
43	AERI0501	0.477	1.2	1.5	0.09	0.107	<5	<6	<0.01	<0.005	<0.02
44	AERI0502	0.220	3.1	6.0	<0.1	0.340	<5	<6	0.05	<0.02	0.05
45	AERI0503	0.195	2.4	1.1	0.04	0.070	<5	20	0.01	<0.005	<0.02
46	AERI0505	0.244	3.1	1.2	0.02	0.101	<5	35	<0.01	<0.005	<0.02
47	AERI0506	0.255	1.6	1.3	<0.01	0.132	<5	43	<0.01	<0.005	<0.02
48	AERI0507	0.145	1.8	1.2	0.02	0.173	<5	<6	<0.01	<0.005	<0.02
49	AERI0508	0.152	1.6	1.6	<0.01	0.334	<5	<6	0.01	<0.005	<0.02
50	AERI0509	0.157	1.3	1.7	<0.01	0.335	<5	<6	<0.01	<0.005	<0.02
51	AERI0510	0.190	1.8	2.3	0.03	0.320	<5	<6	0.08	0.016	0.10
52	AERI0511	0.167	1.4	2.2	<0.01	0.333	<5	<6	0.08	0.017	0.09
53	AERI0512	0.232	1.0	1.1	<0.01	0.161	<5	<6	<0.01	<0.005	<0.02
54	AERI0513	0.280	2.5	<4	<0.1	0.160	<5	13	<0.05	<0.02	<0.07
55	AERI0516	0.440	3.2	6.0	<0.1	0.810	<5	33	<0.1	<0.05	<0.1
56	AERI0517	0.280	5.3	4.0	<0.1	0.610	<5	11	<0.1	<0.05	<0.1
57	AERI0518	0.280	4.4	5.0	<0.1	0.620	<5	13	<0.1	<0.05	<0.1
58	AERI0519	0.850		58	0.16	0.360	<5	177	<0.1	<0.05	<0.1
59	AERI0520	1.38		21	<0.1	1.17	<5	138	<0.1	<0.05	<0.1
60	AERI0521	0.102	0.6	2.2	0.01	0.632	<5	<6	<0.01	<0.005	<0.02
61	AERI0522	0.143	0.8	2.2	<0.01	0.755	<5	<6	<0.01	<0.005	<0.02
62	AERI0523	0.157	0.4	2.3	<0.01	0.832	<5	<6	<0.01	<0.005	<0.02
63	AERI0524	0.044	0.5	4.5	<0.01	0.286	<5	<6	0.04	<0.005	0.04
64	AERI0525	0.430	4.6	4.0	<0.1	0.730	<5	9	<0.2	<0.1	<0.3
65	AERI0526	0.320	3.6	8.0	<0.1	0.470	<5	12	<0.2	<0.1	<0.3
MAC, IMAC[a]		5	~1.5						10	~1	
AO[a]					0.3						
Irrigation[b]		0.5 - 6	~1		5						
Livestock[b]		5	~1 to 2							~3	~13
Freshwater[b]					0.3					~0.019	
Freshwater[c]					0.3				~2.9	~0.019	

ID	Sample	Trace constituents: Aluminum mg/L	Antimony mg/L	Arsenic mg/L	Barium mg/L	Beryllium mg/L	Bismuth mg/L	Bromine (NAA) ppm	Cadmium mg/L	Chromium mg/L	Cobalt mg/L	Copper mg/L
43	AERI0501	<0.005	<0.0002	<0.0002	0.017	<0.0001	<0.0005	0.06	<0.00001	0.0027	<0.0001	<0.001
44	AERI0502	<0.05	<0.002	0.01	0.660	<0.001	<0.005	6.03	0.00678	<0.005	<0.001	<0.01
45	AERI0503	0.010	<0.0002	0.0006	0.105	<0.0001	<0.0005	0.23	<0.00001	0.0025	0.0002	<0.001
46	AERI0505	<0.005	<0.0002	0.0003	0.151	<0.0001	<0.0005	0.12	<0.00001	0.0022	0.0001	<0.001
47	AERI0506	<0.005	<0.0002	0.0006	0.164	<0.0001	<0.0005	0.22	<0.00001	0.0020	0.0001	0.014
48	AERI0507	<0.005	<0.0002	0.0002	0.072	<0.0001	<0.0005	<0.05	<0.00001	0.0016	<0.0001	0.014
49	AERI0508	<0.005	<0.0002	0.0002	0.340	<0.0001	<0.0005	<0.05	<0.00001	0.0020	<0.0001	0.018
50	AERI0509	<0.005	<0.0002	<0.0002	0.340	<0.0001	<0.0005	<0.05	<0.00001	0.0220	<0.0001	0.004
51	AERI0510	<0.05	<0.002	<0.002	0.160	<0.001	<0.005	0.21	<0.0001	<0.005	<0.001	0.13
52	AERI0511	<0.005	<0.0002	0.0006	0.161	<0.0001	<0.0005	0.27	<0.00001	0.0028	<0.0001	0.017
53	AERI0512	<0.005	<0.0002	0.0031	0.024	<0.0001	<0.0005	<0.05	<0.00001	0.0017	<0.0001	0.025
54	AERI0513	<0.05	<0.002	<0.002	0.020	<0.001	<0.005	0.08	<0.0001	<0.005	<0.001	<0.01
55	AERI0516	<0.05	<0.002	0.032	1.14	<0.001	<0.005	14.5	0.0001	<0.005	<0.001	<0.01
56	AERI0517	0.61	<0.002	0.028	0.830	<0.001	<0.005	13.4	<0.0001	<0.005	<0.001	<0.01
57	AERI0518	0.82	<0.002	0.026	0.840	<0.001	<0.005	13.4	<0.0001	<0.005	<0.001	<0.01
58	AERI0519	0.38	0.009	0.036	0.140	<0.001	<0.005		<0.0001	<0.005	0.019	0.28
59	AERI0520	<0.05	<0.002	0.063	1.28	<0.001	<0.005		<0.0001	<0.005	<0.001	0.02
60	AERI0521	<0.005	<0.0002	<0.0002	0.148	<0.0001	<0.0005	<0.05	<0.00001	0.0008	<0.0001	0.002
61	AERI0522	<0.005	<0.0002	<0.0002	0.205	<0.0001	<0.0005	<0.05	<0.00001	0.0008	<0.0001	0.004
62	AERI0523	<0.005	<0.0002	<0.0002	0.158	<0.0001	<0.0005	<0.05	<0.00001	0.0006	<0.0001	0.004
63	AERI0524	<0.005	<0.0002	0.0013	0.167	<0.0001	<0.0005	<0.05	<0.00001	<0.0005	0.0004	0.01
64	AERI0525	<0.05	<0.002	0.024	1.08	<0.001	<0.005	16.6	<0.0001	<0.005	<0.001	<0.01
65	AERI0526	<0.05	<0.002	0.02	0.620	<0.001	<0.005	12.5	<0.0001	<0.005	<0.001	<0.01
MAC, IMAC[a]		0.1	(0.006)	0.025	1				0.00001	0.005	0.0001	0.001
AO[a]									0.005	0.05		
Irrigation[b]		5		0.1		0.1						1
Livestock[b]		5		0.025		0.1			0.0051	0.0049***	0.05	0.2 - 1
Freshwater[b]		0.005 - 0.1		0.005					0.08	0.05***	1	0.5 - 5
Freshwater[c]		0.005 - 0.1		0.005					$10^{0.86[\log(hardness)]-3.2}$ 0.000017	0.0089*** 0.0089***		$e^{[0.979123*\ln(hardness)-8.64497]}$ 0.002 - 0.004

ID	Sample	Iodine mg/L	Iodine (NAA) ppm	Lead mg/L	Lithium mg/L	Manganese mg/L	Molybdenum mg/L	Nickel mg/L	Rubidium (NAA) ppb	Scandium (NAA) ppb
43	AERI0501	0.105	<0.02	<0.0001	0.173	0.014	<0.001	<0.0005	<16	0.09
44	AERI0502	0.270	1.92	<0.001	0.160	<0.05	<0.01	0.0670	<30	0.09
45	AERI0503	0.090	0.11	<0.0001	0.101	<0.005	<0.001	0.0006	<17	<0.04
46	AERI0505	0.024	0.03	<0.0001	0.065	0.006	0.012	<0.0005	<16	0.08
47	AERI0506	0.009	0.12	0.0002	0.054	0.007	0.004	<0.0005	<14	0.10
48	AERI0507	0.004	<0.02	<0.0001	0.019	0.009	0.008	<0.0005	<11	0.06
49	AERI0508	0.004	<0.02	<0.0001	0.058	0.012	<0.001	<0.0005	<13	0.06
50	AERI0509	0.004	<0.02	<0.0001	0.064	0.010	<0.001	<0.0005	<13	0.05
51	AERI0510	0.142	0.17	0.002	0.140	0.017	<0.01	<0.005	<13	0.08
52	AERI0511	0.142	0.15	<0.0001	0.136	0.046	<0.001	<0.0005	<14	0.05
53	AERI0512	0.003	<0.02	<0.0001	0.041	0.039	0.005	<0.0005	<11	0.05
54	AERI0513	0.011	<0.02	<0.001	0.100	<0.05	<0.01	<0.005	<16	0.09
55	AERI0516	5.076	5.09	<0.001	0.280	<0.05	<0.01	<0.005	<27	<0.06
56	AERI0517	2.875	3.2	<0.001	0.180	<0.05	<0.01	<0.005	<39	0.12
57	AERI0518	2.941	3.14	<0.001	0.170	<0.05	<0.01	<0.005	<24	<0.05
58	AERI0519			0.005	0.350	<0.05	0.080	0.0160		
59	AERI0520			0.004	0.210	<0.05	<0.01	<0.005		
60	AERI0521	0.005	<0.02	<0.0001	0.036	0.175	<0.001	<0.0005	<8	0.10
61	AERI0522	0.005	<0.02	<0.0001	0.036	0.091	<0.001	<0.0005	8	0.09
62	AERI0523	0.005	<0.02	<0.0001	0.044	0.116	<0.001	<0.0005	<7	0.09
63	AERI0524	0.003	<0.02	<0.0001	0.021	1.24	<0.001	0.0006	<6	0.08
64	AERI0525	4.046	4.84	<0.001	0.230	<0.05	<0.01	<0.005	<21	0.06
65	AERI0526	3.049	3.34	<0.001	0.240	<0.05	0.010	<0.005	<21	0.12
MAC, IMAC[a]				0.0001	0.001					
AO[a]				0.01		0.05				
Irrigation[b]						0.2	0.01 - 0.05	0.2		
Livestock[b]				0.2	2.5		0.5	1		
Freshwater[b]				0.1			0.073	0.025 - 0.15		
Freshwater[c]				0.001 - 0.007 0.001 - 0.007			0.073	0.025 - 0.15		

ID	Sample	Selenium mg/L	Silver mg/L	Thallium mg/L	Thorium (NAA) ppb	Tin mg/L	Titanium mg/L	Uranium mg/L	Uranium (NAA) ppb	Vanadium mg/L	Zinc mg/L
43	AERI0501	<0.0002	<0.0001	<0.00005	<0.3	<0.001	0.0025	<0.0005	<1	0.0069	0.008
44	AERI0502	<0.002	<0.001	<0.0005	<0.5	<0.01	<0.005	<0.005	<2	0.0020	0.040
45	AERI0503	<0.0002	<0.0001	<0.00005	0.3	<0.001	0.0021	<0.0005	<1	0.0070	<0.001
46	AERI0505	<0.0002	<0.0001	<0.00005	<0.2	<0.001	<0.0005	<0.0005	1	0.0054	0.038
47	AERI0506	<0.0002	<0.0001	<0.00005	<0.2	<0.001	0.0008	<0.0005	<1	0.0051	0.002
48	AERI0507	<0.0002	<0.0001	<0.00005	<0.2	<0.001	0.0007	<0.0005	<1	0.0040	0.002
49	AERI0508	<0.0002	<0.0001	<0.00005	<0.2	<0.001	<0.0005	<0.0005	<1	0.0051	0.002
50	AERI0509	<0.0002	<0.0001	<0.00005	<0.2	<0.001	<0.0005	<0.0005	<1	0.0060	0.001
51	AERI0510	<0.002	<0.001	<0.0005	<0.2	<0.01	<0.005	<0.005	<1	0.0030	0.040
52	AERI0511	<0.0002	<0.0001	<0.00005	<0.2	<0.001	<0.0005	<0.0005	<1	0.0073	0.024
53	AERI0512	<0.0002	<0.0001	<0.00005	<0.2	<0.001	0.0016	0.0014	2	0.0043	0.003
54	AERI0513	<0.002	<0.001	<0.0005	<0.2	<0.01	0.0100	<0.005	<1	0.0020	<0.01
55	AERI0516	<0.002	<0.001	<0.0005	<0.7	<0.01	<0.005	<0.005	<3	0.0020	0.070
56	AERI0517	<0.002	<0.001	<0.0005	<0.8	<0.01	<0.005	<0.005	<5	<0.001	<0.01
57	AERI0518	<0.002	<0.001	<0.0005	<0.4	<0.01	<0.005	<0.005	<2	<0.001	<0.01
58	AERI0519	<0.002	<0.001	<0.0005		<0.01	<0.005	<0.005		0.0040	<0.01
59	AERI0520	<0.002	<0.001	<0.0005		<0.01	<0.005	<0.005		<0.001	<0.01
60	AERI0521	<0.0002	<0.0001	<0.00005	<0.2	<0.001	0.0009	<0.0005	<1	0.0023	0.028
61	AERI0522	<0.0002	<0.0001	<0.00005	<0.2	<0.001	<0.0005	<0.0005	<1	0.0021	0.008
62	AERI0523	<0.0002	<0.0001	<0.00005	<0.2	<0.001	<0.0005	<0.0005	<1	0.0016	0.012
63	AERI0524	<0.0002	<0.0001	<0.00005	<0.2	<0.001	<0.0005	0.0015	1	0.0012	0.044
64	AERI0525	<0.002	<0.001	<0.0005	<0.4	<0.01	<0.005	<0.005	<2	0.0020	0.020
65	AERI0526	<0.002	<0.001	<0.0005	<0.4	<0.01	<0.005	<0.005	<2	0.0020	<0.01
MAC, IMAC[a]		0.01						(0.02)			
AO[a]											5
Irrigation[b]		0.02 - 0.05						0.01		0.1	1-5
Livestock[b]		0.05						0.2		0.1	50
Freshwater[b]		0.001	0.0001	0.0008							0.03
Freshwater[c]		0.001	0.0001	0.0008							0.03

Notes:

Major, minor and trace constituent designations based on the classification of Davis and De Wiest (1966)

MAC = Maximum acceptable concentration of an element or compound in water for community or personal use

IMAC = Interim maximum acceptable concentration of an element or compound in water for community or personal use. Denoted by a value in parentheses

AO = Aesthetic objective concentration for an element or compound in water for community or personal use

Irrigation = Maximum concentration value or range of concentration values for an element or compound in water to be used for irrigation purposes

Livestock = Maximum concentration value or range of concentration values for an element or compound in water to be used for livestock watering purposes.

Freshwater = Maximum concentration value or range of concentration values for an element or compound at or above which impacts to freshwater organisms may be observed.

< denotes a value less than the detection limit

*At point of consumption

**Based on USEPA continuous and maximum concentration values

Sources of Guideline information:

[a] Federal-Provincial-Territorial Committee on Drinking Water of the Federal-Provincial-Territorial Committee on Health and the Environment (April, 2004)

[b] Alberta Environment Surface Water Quality Guidelines for Use in Alberta (November, 1999)

[c] CCME Canadian Environmental Quality Guidelines (December, 2003)

Table 154b. Organic geochemistry summary table.

									Polycyclic aromatic hydrocarbon (PAH) constituents																				Non-halogenated aromatic hydrocarbons				
ID	Sample	Approximate Location TTT-RRWM	Formation	Approximate Coal Zone	Depth (mbGL)	Depth (mbKB)	Elevation (masl)	Sample Date (mm/dd/yy)	Naphthalene mg/L	Acenaphthylene mg/L	Acenaphthene mg/L	Fluorene mg/L	Phenanthrene mg/L	Anthracene mg/L	Acridine mg/L	Fluoranthene mg/L	Pyrene mg/L	Benzo(a)anthracene mg/L	Chrysene mg/L	Benzo(b)fluoranthene mg/L	Benzo(k)fluoranthene mg/L	Benzo(a)pyrene mg/L	Indeno(1,2,3-c,d)pyrene mg/L	Dibenzo(a,h)anthracene mg/L	Benzo(g,h,i)perylene mg/L	Adsorbable Organic Halides mg/L	Total Hydrocarbon C6-C10 mg/L	Total Hydrocarbon C11-C40+ mg/L	Benzene mg/L	Toluene mg/L	Ethylbenzene mg/L	Xylenes mg/L	Phenols mg/L
43	AERI0501	053-22W4	HC	Drumheller or equivalent	27.4		686.6	07/06/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	0.01	<0.1	<0.001	0.001	<0.001	<0.001	0.001
44	AERI0502	048-19W4	HC	Drumheller or equivalent	42.5		713.5	07/07/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.014	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.001
45	AERI0503	049-20W4	HC	Drumheller or equivalent	78.7		717.3	07/07/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.001
46	AERI0505	047-26W4	Scollard	Ardley	19.5		770.5	07/08/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.001
47	AERI0506	050-23W4	HC	Drumheller or equivalent	27.1		730.9	07/11/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.005
48	AERI0507	048-01W5	Paskapoo	Unknown	27.0		751.0	07/11/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.003
49	AERI0508	053-05W5	Scollard	Ardley	34.1		696.9	07/12/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.001
50	AERI0509	053-05W5	Scollard	Ardley	34.1		696.9	07/12/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	<0.001
51	AERI0510	041-18W4	HC	Drumheller or equivalent	41.2		732.8	07/13/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	<0.01	0.2	<0.001	<0.001	<0.001	<0.001	<0.001
52	AERI0511	041-18W4	HC	Drumheller or equivalent	41.2		732.8	07/13/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.016	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.001
53	AERI0512	050-07W5	Paskapoo	Unknown	51.7		760.3	07/14/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.001
54	AERI0513	053-04W5	Scollard	Ardley	34.8		700.2	07/15/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	0.59	<0.1	<0.001	0.001	<0.001	<0.001	<0.001
55	AERI0516	039-20W4	HC	Drumheller or equivalent		256.7	567.4	07/26/05	0.00142	0.00002	0.00002	0.00005	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.014	0.07	0.6	<0.001	<0.001	<0.001	0.001	0.008
56	AERI0517	047-23W4	HC	Drumheller or equivalent		250.9	506.5	07/26/05	0.00114	0.00002	0.00001	<0.00001	<0.00001	0.00002	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.007	0.49	0.2	<0.001	0.001	<0.001	0.007	0.016
57	AERI0518	047-23W4	HC	Drumheller or equivalent		250.9	506.5	07/26/05	0.00178	0.00005	<0.00001	0.00045	0.00016	0.00002	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.005	0.29	0.2	<0.001	<0.001	<0.001	0.004	0.006
58	AERI0519	038-23W4	HC	Drumheller or equivalent		382.3	482.2	08/02/05	0.00137	0.00012	0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.019	<0.01	<0.1	0.007	0.002	<0.001	0.005	0.14
59	AERI0520	043-26W4	Belly River	Unknown		729.7	119.1	08/02/05	0.00079	0.00005	0.00003	0.00005	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.222	0.02	<0.1	0.004	0.003	<0.001	0.001	0.008
60	AERI0521	053-04W5	Scollard	Ardley	26.2		751.9	09/02/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.001
61	AERI0522	053-04W5	Scollard	Ardley	37.0		751.4	09/02/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.002
62	AERI0523	053-04W5	Scollard	Ardley	39.3		745.7	09/02/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	0.01	<0.1	<0.001	<0.001	<0.001	<0.001	0.001
63	AERI0524	053-04W5	Scollard	Ardley	31.2		757.6	09/02/05	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.004	<0.01	<0.1	<0.001	<0.001	<0.001	<0.001	<0.001
64	AERI0525	045-22W4	HC	Drumheller or equivalent		257.5	514.2	09/08/05	0.00098	<0.00001	0.00007	0.00007	<0.00001	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.0059	0.03	0.2	<0.001	0.005	<0.001	0.004	0.01
65	AERI0526	044-22W4	HC	Drumheller or equivalent		255.2	496.1	09/08/05	0.00033	<0.00001	0.00001	0.00001	0.00003	<0.00001	<0.00001	<0.00002	<0.00002	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.018	<0.01	0.2	<0.001	0.001	<0.001	0.001	0.001
MAC, IMAC[a]																						0.00001							0.005				
AO[a]																														0.024	0.0024	0.3	
Irrigation[b]																																	
Livestock[b]																														0.024	0.0024		0.002
Freshwater[b]									0.0011		0.0058	0.003	0.0004	0.000012	0.0044	0.00004	0.000025	0.000018				0.000015							0.37	0.002	0.09		0.004
Freshwater[c]									0.0011		0.0058	0.003	0.0004	0.000012	0.0044	0.00004	0.000025	0.000018				0.000015							0.37	0.002	0.09		0.004

Notes:

MAC = Maximum acceptable concentration of an element or compound in water for community or personal use

IMAC = Interim maximum acceptable concentration of an element or compound in water for community or personal use. Denoted by a value in parentheses

AO = Aesthetic objective concentration for an element or compound in water for community or personal use

Irrigation = Maximum concentration value or range of concentration values for an element or compound in water to be used for irrigation purposes

Livestock = Maximum concentration value or range of concentration values for an element or compound in water to be used for livestock watering purposes.

Freshwater = Maximum concentration value or range of concentration values for an element or compound at or above which impacts to freshwater organisms may be observed.

< denotes a value less than the detection limit

Sources of Guideline information:

[a] Federal-Provincial-Territorial Committee on Drinking Water of the Federal-Provincial-Territorial Committee on Health and the Environment (April, 2004)

[b] Alberta Environment Surface Water Quality Guidelines for Use in Alberta (November, 1999)

[c] CCME Canadian Environmental Quality Guidelines (December, 2003)

Table 154c. Stable and radiogenic isotope geochemistry summary table.

									Isotopes of water or dissolved inorganic constituents in water														Isotopes of dissolved or produced gases						
ID	Sample	Approximate Location TTT-RRWM	Formation	Approximate Coal Zone	Depth (mbGL)	Depth (mbKB)	Elevation (masl)	Sample Date (mm/dd/yy)	δ^{18}O-H$_2$O ‰ VSMOW	δ^{2}H-H$_2$O ‰ VSMOW	δ^{13}C-CO$_3$ ‰ VPDB	δ^{18}O-CO$_3$ ‰ VPDB	δ^{34}S-S^{2-} ‰ CDT	δ^{34}S-SO$_4$ ‰ CDT	δ^{18}O-SO$_4$ ‰ VSMOW	^{87}Sr/^{86}Sr	^{87}Sr/^{86}Sr error	^{129}I	^{129}I error	^{36}Cl/Cl	^{36}Cl/Cl error	^{226}Ra Bq/L	δ^{13}C-CH$_4$ ‰ VPDB	δ^{2}H-CH$_4$ ‰ VSMOW	δ^{13}C-C$_2$H$_6$ ‰ VPDB	δ^{13}C-C$_3$H$_8$ ‰ VPDB	δ^{13}C-iC$_4$H$_{10}$ ‰ VPDB	δ^{13}C-nC$_4$H$_{10}$ ‰ VPDB	δ^{13}C-CO$_2$ ‰ VPDB
43	AERI0501	053-22W4	HC	Drumheller or equivalent	27.4		686.6	07/06/05	-15.6	-135	-14.1	-12.6	i.s.	1	10.2	0.705414	0.000012	0.8	0.5			<0.01	-48.82	-374				-24.34	-17.59
44	AERI0502	048-19W4	HC	Drumheller or equivalent	42.5		713.5	07/07/05	-16.2	-129	11.6	-11.5	i.s.	7.5	i.s.	0.705462	0.000011	4.6	3.4			<0.01							
45	AERI0503	049-20W4	HC	Drumheller or equivalent	78.7		717.3	07/07/05	-20.2	-163	-22.1	-15.0	8.2	39.6	i.s.	0.705377	0.000012	2.0	0.4			<0.01							
46	AERI0505	047-26W4	Scollard	Ardley	19.5		770.5	07/08/05	-17.7	-148	-8.4	-13.0	i.s.	8.2	i.s.	0.705375	0.000012	3.4	0.6			<0.01	-74.51	-374	-49.38				
47	AERI0506	050-23W4	HC	Drumheller or equivalent	27.1		730.9	07/11/05	-18.2	-148	-20.8	-13.6	-18.7	i.s.	i.s.	0.705330	0.000012	3.1	0.6			<0.01							
48	AERI0507	048-01W5	Paskapoo	Unknown	27.0		751.0	07/11/05	-18.5	-148	-14.4	-14.1	-11.3	i.s.	i.s.	0.705802	0.000011	2.1	0.4			<0.01							
49	AERI0508	053-05W5	Scollard	Ardley	34.1		696.9	07/12/05	-18.4	-143	-9.0	-13.9	17.3	6.7	i.s.	0.705883	0.000012	2.0	0.4			<0.01							
50	AERI0509	053-05W5	Scollard	Ardley	34.1		696.9	07/12/05	-18.3	-144	-9.3	-13.8	17.1	i.s.	i.s.	0.705873	0.000011	3.4	0.6			0.01							
51	AERI0510	041-18W4	HC	Drumheller or equivalent	41.2		732.8	07/13/05	-19.9	-158	-13.6	-15.1	i.s.	13.9	i.s.	0.705621	0.000012	2.3	0.4			0.02							
52	AERI0511	041-18W4	HC	Drumheller or equivalent	41.2		732.8	07/13/05	-19.9	-160	-13.9	-15.8	i.s.	12.3	i.s.	0.705616	0.000013	2.0	0.4			0.01							
53	AERI0512	050-07W5	Paskapoo	Unknown	51.7		760.3	07/14/05	-18.2	-142	-15.8	-13.4	i.s.	-6.1	2	0.706880	0.000018	3.8	0.6			<0.01							
54	AERI0513	053-04W5	Scollard	Ardley	34.8		700.2	07/15/05	-18.1	-145	-18.5	-12.8	-36.2	-7.7	0.2	0.705278	0.000021	2.8	0.5			<0.01							
55	AERI0516	039-20W4	HC	Drumheller or equivalent		256.7	567.4	07/26/05	-12.4	-107	20.4	-9.5	i.s.	i.s.	i.s.	0.705391	0.000012	43.7	1.7			0.02	-58.27	-346	-45.89	-30.67	-33.19	-35.57	13.06
56	AERI0517	047-23W4	HC	Drumheller or equivalent		250.9	506.5	07/26/05	-12.4	-109	17.3	-9.3	i.s.	i.s.	i.s.	0.705267	0.000014	33.4	1.4			0.01	-59.24		-43.57	-28.45	-26.68	-26.83	-21.83
57	AERI0518	047-23W4	HC	Drumheller or equivalent		250.9	506.5	07/26/05	-12.6	-110	17.6	-9.2	i.s.	i.s.	i.s.	0.705238	0.000012	33.3	2.3			<0.01							
58	AERI0519	038-23W4	HC	Drumheller or equivalent		382.3	482.2	08/02/05															-57.27	-339	-42.04	-30.94	-29.82	-29.96	-15.13
59	AERI0520	043-26W4	Belly River	Unknown		729.7	119.1	08/02/05															-57.20	-311	-38.95	-31.03	-28.80	-31.96	-13.19
60	AERI0521	053-04W5	Scollard	Ardley	26.2		751.9	09/02/05	-16.2	-135	-14.4	-11.3	i.s.	-0.8	i.s.	0.706395	0.000020	31.7	1.2			0.01							
61	AERI0522	053-04W5	Scollard	Ardley	37.0		751.4	09/02/05	-15.9	-134	-14.4	-13.2	i.s.	2.7	i.s.	0.706102	0.000010	6.8	0.7			<0.01							
62	AERI0523	053-04W5	Scollard	Ardley	39.3		745.7	09/02/05	-15.2	-129	-13.5	-12.6	i.s.	5.9	i.s.	0.706016	0.000021	1.9	0.4			<0.01							
63	AERI0524	053-04W5	Scollard	Ardley	31.2		757.6	09/02/05	-15.8	-130	-14.6	-14.2	i.s.	12.0	i.s.	0.707685	0.000010	5.6	0.6			0.01							
64	AERI0525	045-22W4	HC	Drumheller or equivalent		257.5	514.2	09/08/05	-12.3	-108	19.7	-8.6	i.s.	-3.8	i.s.	0.705232	0.000015	40.9	1.3			0.02	-57.78	-332	-42.11	-30.61	-29.37	-26.48	21.08
65	AERI0526	044-22W4	HC	Drumheller or equivalent		255.2	496.1	09/08/05	-12.4	-107	16.0	-9.6	i.s.	14.5	i.s.	0.705362	0.000014	37.2	1.5			<0.01	-58.14	-313	-40.88	-30.78	-26.31	-30.85	1.44
MAC, IMAC[a]																						0.6							
AO[a]																													
Irrigation[b]																													
Livestock[b]																													
Freshwater[b]																													
Freshwater[c]																													

Notes:

MAC = Maximum acceptable concentration of an element or compound in water for community or personal use

IMAC = Interim maximum acceptable concentration of an element or compound in water for community or personal use. Denoted by a value in parentheses

AO = Aesthetic objective concentration for an element or compound in water for community or personal use

Irrigation = Maximum concentration value or range of concentration values for an element or compound in water to be used for irrigation purposes

Livestock = Maximum concentration value or range of concentration values for an element or compound in water to be used for livestock watering purposes.

Freshwater = Maximum concentration value or range of concentration values for an element or compound at or above which impacts to freshwater organisms may be observed.

< denotes a value less than the detection limit

Sources of Guideline information:

[a] Federal-Provincial-Territorial Committee on Drinking Water of the Federal-Provincial-Territorial Committee on Health and the Environment (April, 2004)

[b] Alberta Environment Surface Water Quality Guidelines for Use in Alberta (November, 1999)

[c] CCME Canadian Environmental Quality Guidelines (December, 2003)

Table 154d. Geomicrobiology summary table.

ID	Sample	Approximate Location TTT-RRWM	Formation	Approximate Coal Zone	Depth (mbGL)	Depth (mbKB)	Elevation (masl)	Sample Date (mm/dd/yy)	Methanogens by qPCR cells/mL	SRB and IRB by qPCR cells/mL	Methanotrophs Type I MOB cells/mL	Methanotrophs Type II MOB cells/mL	Total Biomass by PLFA cells/mL	Firmicutes (TerBrSats) %	Proteobacteria (Monos) %	Anaerobic metal reducers (BrMonos) %	SRB/Actinomycetes (MidBrSats) %	General (Nsats) %	Eukaryotes (Polyenoics) %
43	AERI0501	053-22W4	HC	Drumheller or equivalent	27.4		686.6	07/06/05	101000	<0.765	165000	49600	195	0	0	0	0	100	0
44	AERI0502	048-19W4	HC	Drumheller or equivalent	42.5		713.5	07/07/05	37400	15.5	269000	101000	5670	0	64.49	3.62	0	29	2.9
45	AERI0503	049-20W4	HC	Drumheller or equivalent	78.7		717.3	07/07/05	729000	3.29	2280	556000	2320	0	44.31	18.97	0	36.73	0
46	AERI0505	047-26W4	Scollard	Ardley	19.5		770.5	07/08/05	24300	16.1	73.6	66.4	211000	23.66	56.59	2.74	0.54	9.86	6.6
47	AERI0506	050-23W4	HC	Drumheller or equivalent	27.1		730.9	07/11/05	386000	249	504000	293000	1550	0	51.88	0	0	48.13	0
48	AERI0507	048-01W5	Paskapoo	Unknown	27.0		751.0	07/11/05	18600	40.7	4480	11900	1470	0	11.84	32.8	0	48.43	6.92
49	AERI0508	053-05W5	Scollard	Ardley	34.1		696.9	07/12/05	54400	17.7	8120	52300	2670	0	56.99	0	0	35.91	7.11
50	AERI0509	053-05W5	Scollard	Ardley	34.1		696.9	07/12/05	16500	<0.725	3500	290000	2130	0	49.39	0	0	42.99	7.63
51	AERI0510	041-18W4	HC	Drumheller or equivalent	41.2		732.8	07/13/05	23600	7.91	2	9360	1900	0	46.35	0	0	53.65	0
52	AERI0511	041-18W4	HC	Drumheller or equivalent	41.2		732.8	07/13/05	9520	18.1	146000	106000	10300	0	79.24	3.27	0	17.49	0
53	AERI0512	050-07W5	Paskapoo	Unknown	51.7		760.3	07/14/05	48100	9.79	4430000	<0.955	1350	0	37.44	0	0	52.57	10
54	AERI0513	053-04W5	Scollard	Ardley	34.8		700.2	07/15/05	381000	60.3	53200	<0.939	6570	0	52.68	0	0	34.84	12.5
55	AERI0516	039-20W4	HC	Drumheller or equivalent		256.7	567.4	07/26/05	54400	1550	657000	3090	116000	20.23	35.88	4.04	7.18	29.55	3.11
56	AERI0517	047-23W4	HC	Drumheller or equivalent		250.9	506.5	07/26/05	927	3670	76600	44600	8370	0	23.36	0	0	71.34	5.31
57	AERI0518	047-23W4	HC	Drumheller or equivalent		250.9	506.5	07/26/05	1140	5630	<0.958	1810000	10100	0	38.6	0	0	54.18	7.22
58	AERI0519	038-23W4	HC	Drumheller or equivalent		382.3	482.2	08/02/05	681000	0.791	<1	105000	4100	0	21.73	0	0	55.79	22.47
59	AERI0520	043-26W4	Belly River	Unknown		729.7	119.1	08/02/05	5.66	0.214	859000	740000	1990	0	9.7	0	0	90.29	0
60	AERI0521	053-04W5	Scollard	Ardley	26.2		751.9	09/02/05	3640	631	5560	2550	64200	0.21	47.86	0	0	51.43	0.52
61	AERI0522	053-04W5	Scollard	Ardley	37.0		751.4	09/02/05	<1	2.67	748	2110	16000	0	71.26	0	0	28.73	0
62	AERI0523	053-04W5	Scollard	Ardley	39.3		745.7	09/02/05	6.06	23.2	89700	1230	10400	0	67.01	0	0	32.98	0
63	AERI0524	053-04W5	Scollard	Ardley	31.2		757.6	09/02/05	<1	<0.727	16800	108	64600	1.81	80.85	0	0.53	14.53	2.3
64	AERI0525	045-22W4	HC	Drumheller or equivalent		257.5	514.2	09/08/05	1440000	4490	6480	6260	69300	1.48	71.93	0.25	0.53	24.81	1.02
65	AERI0526	044-22W4	HC	Drumheller or equivalent		255.2	496.1	09/08/05	3820	35600	6360	1660	14600	4.86	52.11	1.55	2.13	36.99	2.35

Appendix 9 – 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°C are generally required, for instance, at temperatures above 600°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 $Br_2 \cdot 7^2/_3 H_2O$ (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 $1.57 x 10^7$ 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 $110^{o}K$) 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 occur 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 by product 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).

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.

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 4.75×10^{10} years (Firestone, 2000). Only one of these radiogenic isotopes, ^{87}Rb (half-life 4.75×10^{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 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 1.405×10^{10} years. Six of these radiogenic isotopes, ^{227}Th (half-life 18.72 d), ^{228}Th (1.9116 years), ^{230}Th (7.538×10^4 years), ^{231}Th (25.52 h), ^{232}Th (1.405×10^{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 $1.4x10^{17}$ 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

5×10^{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 10 – Characteristics of Analytical Parameters DGGE Results

The author wishes to thank the staff of Microbial Insights for providing the photographs of the DGGE profiles for the submitted samples.

The following tables and figures provide a summary of the results of the denaturing gradient gel electrophoresis (DGGE) analysis of DNA extracted from water samples. These samples were collected as part of a water sampling program conducted by the Alberta Geological Survey (AGS) between July and September of 2005 from water wells completed in coal-bearing aquifers and CBM wells. DGGE profiles are based on amplified DNA from a portion of the 16S rRNA gene. The labelled bands were sequenced and compared to DNA sequences compiled by the Ribosomal Database Project (http://rdp.cme.msu.edu/). Similarity indices of 0.900 or above are considered excellent. Indices between 0.700 and 0.800 are considered good, and below 0.600 are considered to be unique sequences. Table 1 and Figure 1 provide the DGGE results from samples AERI 0501 to AERI 0513. Table 2 and Figure 2 provide the DGGE results from samples AERI 0521 to AERI 0526.

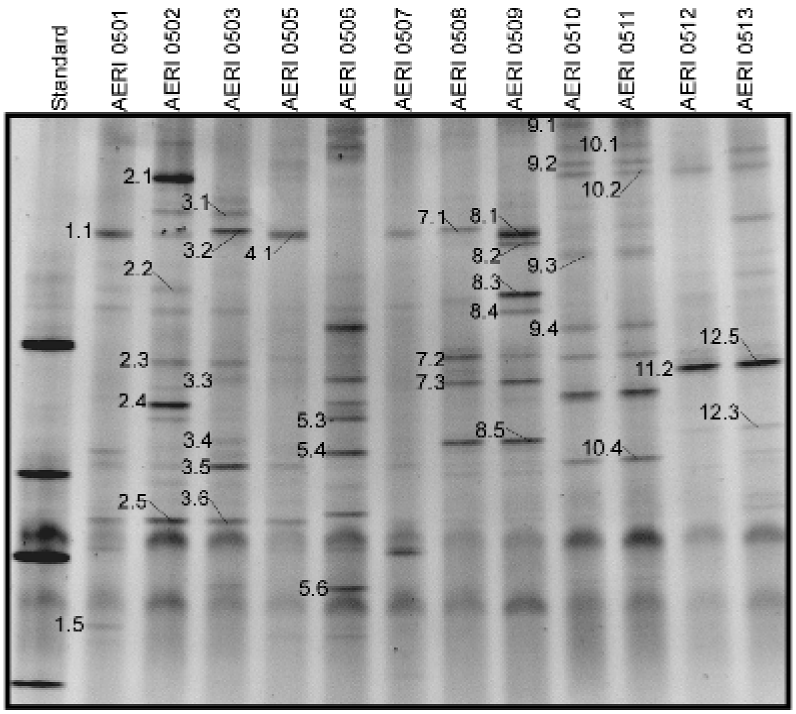


Figure 1. DGGE profile of amplified DNA for samples AERI 0501 to AERI 0513. Note: Bacteria must make up at least 1-2% of the total bacterial community to form a band. Bands denoted by a label were sequenced. Results from sequencing can be found in the following table (Table 1). Photograph courtesy of Microbial Insights.

Table 1. Sequence results samples AERI 6501 to 0513.

Band	Similar Genus	Similarity Index	GenBank Accession Number
1.1	*Sufurihydrogenibium*	0.545	AY862070
1.5	*Syntrophus spp.*	0.947	AJ853548
2.1	*Methylobacter/Methylobacterium*	0.808	PRD18F06
2.2	*Methylobacillus spp.*	0.940	DQ287786
2.3	*Methylobacillus spp.*	0.781	PRD18F06
2.4	*Methylobacillus spp.*	0.942	AB179689
2.5	*Uncultured bacteria*	0.625	DQ223088
2.5	*Thermodesulfatator*	0.594	AF393376
3.1	*Novel bacterium*	0.580	AY667267
3.2	*Syntrophothermus*	0.831	AB021305
3.3	*Methylobacillus spp.*	0.898	AJ583175
3.4	*Xanthomonadaceae*	0.894	DQ125750
3.5	*Desulfobulbaceae*	0.643	AF177428
3.6	*Uncultured bacteria*	0.709	DQ223076
4.1	*Paenibacillus spp.*	0.634	DQ288948
5.3	*Nitrospiraceae*	0.740	AF524008
5.4	*Magnetobacterium*	0.788	X71838
5.6	*Geobacter*	0.637	AJ009485
7.1	*Bacillus spp.*	0.615	D16282
7.2	*Pseudomonas spp.*	0.622	AJ846279
7.3	*Pandoraea*	0.846	AJ011509
8.1	*Arcobacter spp.*	0.959	AY962285
8.2	*Arcobacter spp.*	0.981	AY962285
8.3	*Arcobacter spp.*	0.938	AY069963
8.4	*Arcobacter spp.*	0.941	AJ132724
8.4	*Wolinella*	0.941	AY225611
8.5	*Delftia*	0.620	AF210313
9.1	*Methylobacter/Methylobacterium*	0.720	AF304195
9.2	*Methylobacter/Methylobacterium*	0.826	AY661999
9.3	*Sterolibacterium*	0.675	AF072922
9.4	*Methylobacter/Methylobacterium*	0.735	AY661999
10.1	*Methylobacter/Methylobacterium*	0.858	AF304197
10.2	*Rhodocyclaceae (family)*	0.950	AJ009484
10.4	*Desulfatibacillum*	0.828	AY184360
11.2	*Acinetobacter spp.*	0.934	X81664
12.3	*Burkholderia spp.*	0.862	U96941
12.5	*Acinetobacter spp.*	1.000	AB101444

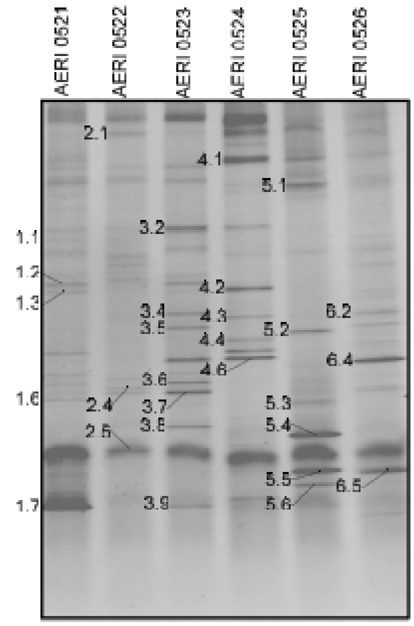


Figure 2. DGGE profile of amplified DNA for sample AERI 0521 to AERI 0526. Note: Bacteria must make up at least 1-2% of the total bacterial community to form a band. Bands denoted by a label were sequenced. Results from sequencing can be found in the following table (Table 2). Photograph courtesy of Microbial Insights.

Table 2. Sequence results for samples AERI 0521 to AERI 0526.

Band	Similar genus	Similarity Index	GenBank Accession Number
1.1	*Nitrosomonas spp.*	0.679	AJ224410
1.2	*Polaromonas*	0.823	AF407405
1.3	*Polaromonas*	0.881	AJ523015
1.5	*Pseudomonas spp.*	0.780	AJ704788
1.6	*Roseateles spp.*	0.738	AY515389
1.7	*Polaromonas*	1.000	AF407405
2.1	*Rhodocyclus*	0.805	M34132
2.4	*Polaromonas*	0.906	AF523012
2.5	*Lysobacter spp.*	0.700	AB166878
3.2	*Methylobacillus spp.*	0.891	AJ583175
3.4	*Methylobacillus spp.*	0.706	Z99999
3.5	*Betaproteobacterium*	0.738	AY955085
3.6	*Nitrosospira*	0.745	M96397
3.7	*Hydrogenophaga spp.*	0.978	
3.8	*Azoarcus spp.*	0.696	AF011345
3.9	*Comamonadaceae*	0.932	AJ606334
4.1	*Methylobacter/Methylobacterium*	0.862	AF304197
4.2	*Methylobacter/Methylobacterium*	0.739	AJ868427
4.3	*Flavobacterium spp.*	0.877	AM177630
4.4	*Gammaproteobacteria*	0.638	AY590681
4.6	*Methylobacillus spp.*	0.859	DQ337096
5.1	*Burkholderia spp.*	0.828	AJ318182
5.2	*Pseudomonas spp.*	0.671	AF511510
5.3	*Hydrogenophaga spp.*	0.832	AF523009
5.4	*Hydrogenophaga spp.*	1.000	AF523009
5.5	*Rhodocyclaceae (family)*	0.727	DQ241393
5.6	*Rhodocyclaceae (family)*	0.858	AY532567
5.6	*Thiobacillus spp.*	0.808	AJ243144
6.2	*Pseudomonas spp.*	0.837	AM111052
6.4	*Pseudomonas spp.*	0.979	AY212594
6.5	*Desulfovibrio spp.*	0.902	AJ012593