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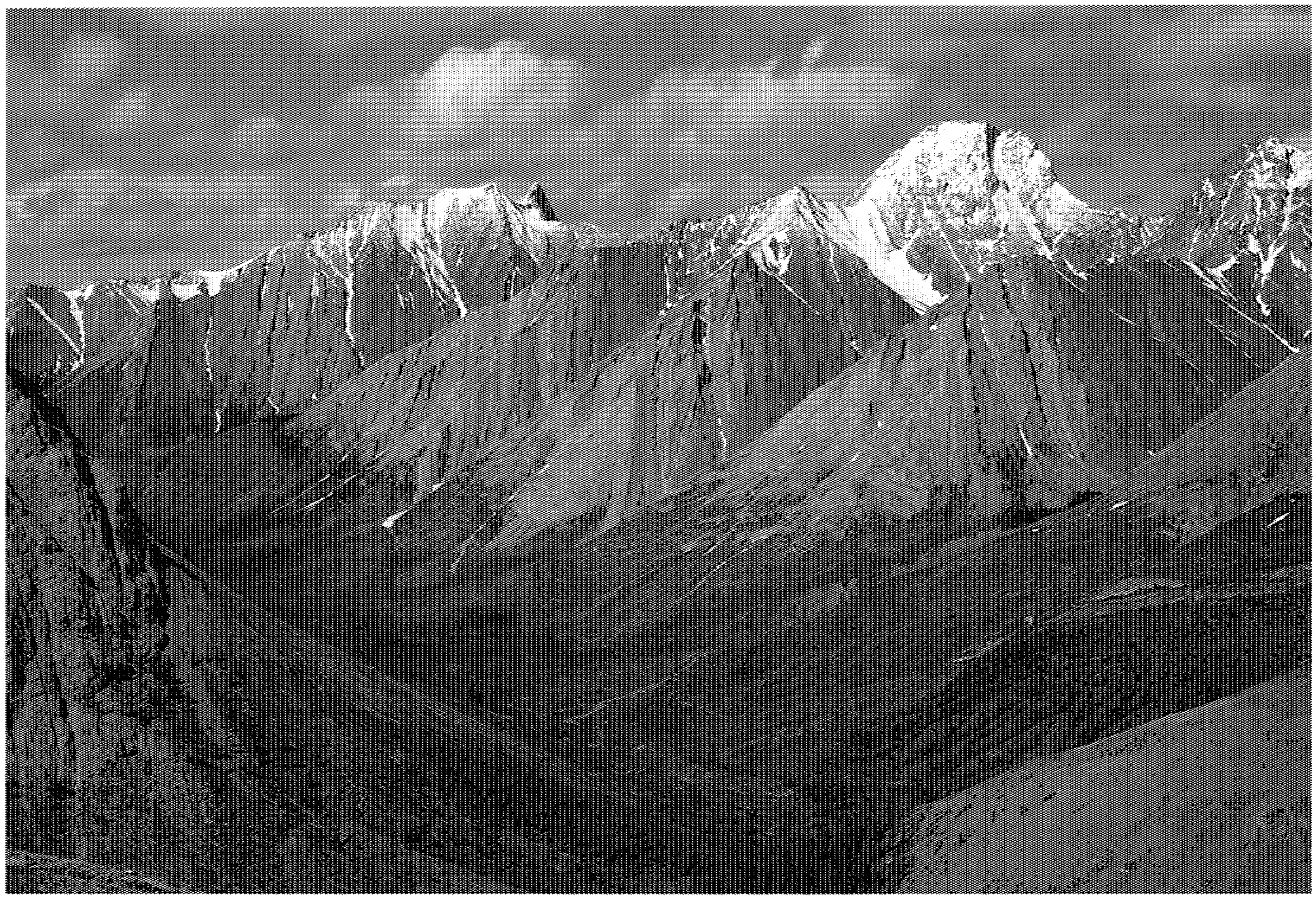
Geology and resource potential of phosphates in Alberta

D.E. Macdonald



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Abstract

In this study is an outline of the resource potentials of phosphate rock in Alberta and portions of southeastern British Columbia, primarily of the phosphorus content and secondarily of the associated uranium, vanadium, fluorine and rare earth elements.

Phosphate is found in four major geological units in the Cordillera of Alberta and southeastern British Columbia: the Devonian-Mississippian Exshaw Formation, the Permo-Pennsylvanian Rocky Mountain Supergroup, the Jurassic Fernie Formation and the Triassic Spray River Group. Within these four major units, 33 stratigraphic zones contain varying amounts of phosphatic material. Only two zones seem to have any real future potential—the base of the Ranger Canyon Formation and the base of the Fernie Formation.

The Exshaw Formation has its best phosphate potential in the Crowsnest Pass region of Alberta. Grades of phosphate are up to 25 percent P_2O_5*. However, none of the seams are thicker than 50 cm, and mining would be very difficult because the deposits are not easily accessible and are under thick overburden. The maximum in situ resources of the Exshaw Formation are estimated to be less than 10 million t of low-grade phosphate rock.*

The Rocky Mountain Supergroup has its best phosphate potential in the Johnston Canyon Formation (16-99 million t) and at the base of the Ranger Canyon Formation (39-235 million t). These resources are mostly low grade.

Within the Fernie Formation, there are 29 to 175 million t of medium-grade phosphate in the Fernie Basin area of British Columbia. There are an additional 260 million t of low-grade phosphate in Alberta.

Uranium contents have a mean value of 34 ppm in the Alberta phosphorites and show a weakly positive linear relationship with phosphorus. The correlation is stronger within certain P_2O_5 *ranges (particularly 18-32 percent* P_2O_5*).*

Vanadium content in phosphatic rocks was found to have very little relationship to phosphorus content, with only a slight tendency to be negatively correlated. Vanadium contents in phosphorites vary from 46 to 255 ppm, and reach up to 0.4 percent in non-phosphatic shales.

Fluorine content averages 4.09 percent in phosphorites. Rare earth and trace elements show anomalous concentrations above normally enriched phosphorites, especially in the elements La, Ce, Nd, Sm, Eu, Tb, Dy, Ho, Tm, Yb, Lu, As, Cd, Mo, Ni, Se, V, Zn and Zr.

The mineralogy of the phosphorites is transitional between pure francolite and pure fluorapatite. A variety of petrographic lithotypes are present and include pellets—nucleated, elliptical and structureless; cements—including microsphorite, fluorapatite, and francolite; intraclasts and pebbles; nodules; and fossil material.

All phosphate occurrences were, at the time of deposition, in a low paleolatitude (< 40°N) within the Trade Wind belt and had shorelines paralleling or nearly paralleling the dominant winds. Such conditions, together with the presence of a landmass or submarine rise area in the northern Montana/Idaho area (Montania?), may have contributed significantly to promoting oceanic upwelling and phosphate precipitation. It is believed that the Fernie Formation pelletal phosphates formed somewhere between the shelf margin to basin position, within a sequence of black shales, cherts and mudstones. The Exshaw Formation, Rocky Mountain Supergroup and Spray River Group phosphorites apparently formed in shallower water shelf positions.

Most of the phosphorites studied are related to worldwide sea level rises throughout the Paleozoic and early Mesozoic, marked by major transgressive events. The remaining occurrences are found at unconformities.

Background

Introduction

Phosphate rock is an important industrial mineral commodity in Alberta that is used principally in the production of agricultural fertilizers. Nonetheless, no phosphate resources are currently developed in either Alberta or the rest of Canada.

For the last 70 years, Canada has been wholly dependent on imported phosphate rock, particularly from the United States. It is important for Canada, and Alberta specifically, to have a clear understanding of the phosphate rock resources that are available for development in the near future.

This report is divided into three parts. The first is a brief overview of the uses and treatment of phosphate rocks and some general background material. The second part forms the bulk of the study and includes an outline of the phosphate resource potential in Alberta and portions of southeastern British Columbia. The third part comprises speculations on depositional environments that may have contributed to the formation of phosphates in Alberta.

Uses of phosphates

Phosphate rock is used in Canada to produce four main commodities: elemental phosphorous, phosphoric acid, phosphate chemicals and phosphatic fertilizers.

Elemental phosphorous is produced at two plants in eastern Canada (Varennes, Quebec and Long Harbour, Newfoundland) and, in turn, is used to produce technical and food grade phosphoric acid. Elemental phosphorous is also used to produce red phosphorous sesquisulfide, an important commodity used in steel making and in the match industry. Canadian consumption of Florida-derived phosphate rock for the elemental phosphorous industry amounts to about 600,000 t per year (Energy, Mines and Resources, 1982).

Phosphoric acid is produced at nine plants across Canada (table 1), most of the product being used in the manufacture of various types of fertilizers, with a minor amount used to produce calcium phosphate.

Phosphate chemicals, mainly calcium and secondarily sodium phosphates, are produced at two

Table 1. Phosphate fertilizer plants in Canada.*

Company	Plant Location	Annual Capacity (tonnes P_2O_5)	Basis for Principal End Products	Source of Phosphate Rock	H_2SO_4 Supply for Fertilizer Plants
Eastern Canada					
Canada Wire and Cable Ltd.	Belledune, N.B.	150 000	am ph	Florida	SO_2 smelter gas
C-I-L Inc.	Courtright, Ont.	90 000	am ph	Florida	SO_2 smelter gas, pyrrhotite roast and waste acid
International Minerals & Chemical Corporation (Canada) Limited	Port Maitland, Ont.	118 000	H_3PO_4, as ts, ca ph	Florida	Sulfur, and SO_2 smelter gas
		358 000			
Western Canada					
Cominco Ltd.	Kimberley, B.C.	86 000	am ph	Montana, Utah	SO_2 pyrite roast
	Trail, B.C.	77 300	am ph	Utah	SO_2 smelter gas
Esso Chemical Canada	Redwater, Alberta	370 000	am ph	Florida	Sulfur
Sherritt Gordon Mines Ltd.	Fort Sask., Alberta	50 000	am ph	Florida	Sulfur
Western Co-operative Fertilizers Limited	Calgary, Alberta	140 000	am ph	Idaho	Sulfur
	Medicine Hat, Alberta	65 000		Idaho	
		788 300			
Total phosphate fertilizer		1 146 300			

am ph - ammonium phosphates; ss - single superphosphate; ts - triple superphosphate.
ca ph - food supplement calcium phosphate; H_3PO_4 - phosphoric acid for commercial sales.
* Data from Energy, Mines and Resources (1985).

eastern Canadian plants and are used mainly in animal feedstocks, in the paper industry and in the detergent/soap industry. Some ammonium phosphate is produced for use in the manufacturing of fire retardants.

Phosphate fertilizers—mainly of the ammonium phosphate variety—comprise diammonium phosphate (18-46-0), monoammonium phosphate (11-48-0 to 11-55-0) and ammonium phosphate-sulfate (16-20-0-14). Total Canadian production of these fertilizers amounts to 1 146 300 t P_2O_5 per year (table 1).

Fertilizer production methods

Canadian fertilizer plants are designed to accept raw, high-grade phosphate rock in the 31.1 to 33.0 percent P_2O_5 range. The first step in the production of fertilizers is producing phosphoric acid. This is done by either the "dry" or "wet" process. In the dry process, phosphate rock is thermally reduced to elemental phosphorous in a furnace. The phosphorus is then oxidized to form P_2O_5 and finally absorbed in water to yield H_3PO_4. This process produces a very high quality acid; however, the high cost involved usually precludes it from being the most favorable method for making fertilizers.

In the wet process, raw phosphate rock is treated with a strong acid such as sulfuric, nitric, phosphoric or hydrochloric acid. Sulfuric acid is favored because of its low cost, high availability in Western Canada and low corrosiveness. Usable energy is also generated by the exothermic reaction of making sulfuric acid. That heat is used in other stages of processing and for generating electricity (Nielson and Janke, 1980). The wet process is shown by the reaction:

$$\begin{array}{ccc} \text{rock phosphate} & & \text{phosphoric (filter) acid} \\ \lbrack (Ca,Na)_5(PO_4,CO_3)_3(F) \rbrack & \rightleftharpoons & \lbrack H_3PO_4 \rbrack \\ + & & + \\ \text{sulfuric acid } \lbrack H_2SO_4 \rbrack & & \text{gypsum } \lbrack CaSO_4 \cdot 2H_2O \rbrack \\ & & + \\ & & \text{hydrofluoric acid } \lbrack HF \rbrack \end{array}$$

The resulting crystallized gypsum is removed, and the filter acid (26 to 30 percent P_2O_5) is evaporated under vacuum to produce a more-concentrated *plant phosphoric acid* (40 to 44 percent P_2O_5) or higher-grade *commercial* or *merchant* grade (45 to 54 percent P_2O_5) acid. *Superphosphoric acid,* though not widely produced in Canada, is formed by further concentration to the 69 to 72 percent P_2O_5 range. Plant phosphoric acid is usually transferred to the fertilizer production units, where varying amounts of ammonia are added. The final step is the formation and subsequent drying of uniform-size granules.

The overall production of ammonium phosphate fertilizers by the wet process is about 88 to 92 percent efficient in recovering the available P_2O_5 of the raw phosphate rock.

Canadian sources of phosphate rock

Four fertilizer companies operate six plants across western Canada, for a total fertilizer capacity of approximately 788 000 t (table 1). Of these companies, Cominco and Western Co-operative Fertilizers both own and operate their own phosphate mines in Utah, Idaho and Montana. The other producers obtain phosphate from Florida via shipping up the west coast to Vancouver and then rail transport to Alberta. A small quantity is imported from outside North America.

Canada has been dependent on imports of phosphate rock from the United States since about 1912 when the fledgling Canadian phosphate mining industry died. For example, the Canadian phosphate fertilizer industry imported a total of 2.66 million t of phosphate rock in 1983 (Energy, Mines and Resources, Canada, 1985) at an estimated cost of U.S. $239 million (1986). No disruption of this supply is anticipated through the 1980s. By the year 1991, however, reserves of the better Florida rock will be exhausted, and leaner grade ores will be mined, so that U.S. exports of raw phosphate rock may be replaced by a more upgraded product (Weaver and Thomas, 1978). It is anticipated that, by the next century, U.S. domestic demands will equal production capacity; thus, U.S. exports of phosphate rock will gradually decline (U.S. Bureau of Mines, 1981).

By the year 2000, the Canadian fertilizer industry may have to look for alternative supplies of phosphate rock. Such alternatives include Mexico (which is now trying to establish a phosphate mining industry based on its Baja California deposits), Morocco or other sources in Africa (which are estimated to hold 68 percent of the world reserves of phosphate). The most likely scenario, however, is that less phosphate will be imported from Florida while more will be derived from the western U.S. phosphate deposits (Cathcart et al., 1984). If the western U.S. deposits are to fit this scenario, they will have to compete with the very high grade Canadian Precambrian deposits (e.g., Cargill or Nemegos in Ontario), the ever-increasing exports from the African producers and the possible development of sedimentary phosphorites of Western Canada (that are discussed in this report).

The dramatic price increases of phosphate rock in the 1972-74 period, coupled with the fact that Canada was, and still is, solely dependent on imported phosphate, prompted the federal government to produce the Canadian Mineral Policy with respect to phosphates in 1976. In part, that policy stated that, with respect to adequate future supplies of phosphate rock in Canada ...

> *"The discovery and development of domestic resources should be the prime consideration. In this respect, federal and provincial agencies should provide support by providing increased geological and geophysical data to assist exploration and by providing research to develop means to beneficiate known low-grade ores."*
>
> (Energy, Mines and Resources, 1976).

In response to that policy statement, the Geological Survey of Canada instigated a country-wide phosphate resource evaluation program. Similarly, the Alberta Research Council initiated the current study.

Phosphate byproducts

Introduction

Phosphates contain substantial amounts of a number of potentially exploitable elements, which could be extracted as byproducts. Uranium, vanadium, fluorine and a number of rare earth elements are the most commonly reported. Gulbrandsen (1977) argues that byproduct extraction and production from U.S. phosphates would be very uniform and dependable for a long time due to the enormous resource of phosphate rock in the United States. He further argues that, for environmental, conservational and national self-sufficiency, these elements should be extracted.

Uranium

Uranium has probably the best potential for recovery as a byproduct in a phosphate processing plant.[1] For example, Gulbrandsen (1977) estimated the average concentration of uranium in phosphates of southeastern Idaho to be 90 ppm: a concentration of 33 times average crustal abundance. Gulbrandsen further calculated that, in southeastern Idaho, 600 t/yr of uranium is being mined with phosphate ore and that most of it is not being recovered. That amount represents 8.1 percent of the U.S. consumption, being equivalent to 42 percent of the U.S. imports of uranium. DeVoto and Stevens (1980) estimated that, if U.S. phosphates were mined solely for their uranium content, the cost would be about U.S. $175-250/lb U_3O_8 (1979 dollars), and these uranium phosphate reserves could supply all the western world demands until about 2025.

Uranium pricing reached a peak in about 1976 (U.S. $40/lb U_3O_8), stabilized until 1979, and then declined to the 1986 price of (U.S.$17.50/lb U_3O_8). Market demands are expected to increase by the late 1980s to early 1990s and continue to be high through to 2025. World production is forecasted to keep pace with demand until about 1995, at which time, production capability from known sources (including phosphates) will begin to fall and be overtaken by world demand (Whillans, 1980).[2]

Vanadium

Vanadium's principal use is in the iron and steel industry as ferrovanadium or vanadium-carbon ferroalloys. Very little vanadium is produced in Canada; however, the Canadian steel industry imported nearly 0.5 million pounds of vanadium compounds from the U.S. in 1980 (Kuck, 1980).

Gulbrandsen (1977) states that vanadium is concentrated in phosphates of southeast Idaho by 5.9 times crustal averages, that approximately 5400 tonnes of vanadium are mined with the phosphate ore, and that this amount represents 83 percent of U.S. consumption and 250 percent of U.S. imports of vanadium. Vanadium is the only element that is currently being recovered as a byproduct of phosphate extraction in the U.S.; however, only a portion of the 5400 tonnes is in fact recovered. In 1982, only one phosphate mine in Idaho was producing vanadium as a byproduct (Kuck, 1983).

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[1] One fertilizer plant in southern Alberta is, in fact, extracting uranium from imported phosphate rock (Energy Mines and Resources, 1982).

[2] This is about the time that the U.S. export market in phosphate rock, particularly to Canada, may start to decrease as domestic U.S. consumption increases.

The price of vanadium has shown a slow but steady increase from about U.S. \$2.70/lb V_2O_5 in 1973 to about U.S. \$6.25/lb in 1982 (Kuck, 1983). World production of vanadium exceeds demand, and presently the vanadium market is slumped. The future market potential is expected to increase worldwide by about 2.9 percent/year until the year 2000 (Kuck, 1983).

Fluorine

Fluorine, as an element of fluorspar (CaF_2), is used in the chemical, ceramics and steel industries and in the refining of uranium ores. The chemical (producing HF acid) and steel industries account for 97 percent of U.S. consumption. Canadian production of fluorspar ceased in 1977, and most fluorspar is now imported from Mexico.

Fluorine can also be recovered as flurosilic acid. Two phosphate rock processing plants in Canada (Erco Industries, Ontario; Cominco Ltd., British Columbia) (Boyd, 1980) and eleven plants in the United States use this process.

Phosphate rock in the U.S. commonly contains 3.5 percent fluorine; thus, given the 1973 estimates of phosphate rock reserves in the U.S. (10.5 billion tons), there are approximately 740 million tons of fluorspar present (Grogan and Montgomery, 1975). That is an enormous quantity given that the total world production of fluorspar (1980) was a little over 5 million tons (Morse, 1980). However, most fluorine in phosphate processing plants is not recovered and is usually dumped in settling ponds.

Fluorspar production is governed to a large extent by the steel, chemical and aluminum industries. Very little growth in these industries was experienced through the 1970s, and only modest growth is predicted in the steel-aluminum usage areas. The chemical industry is seen as the best user of fluorine in the long term (Boyd, 1980). The price of fluorspar in 1980 was between U.S. \$93 to \$122/short ton.

Rare earth elements

A number of rare earth elements (REE) are found in anomalously high quantities in phosphates. In Canada, some REE were produced as byproducts from uranium and base metal mines until 1973, but production has since ceased. Yttriuum was the main element produced, with many of the other REE being present. Australia and the United States are presently the major REE producers, with a total world production (1978) of nearly 40 thousand short tons (Cranstone, 1980). The REE vary in price, depending on the particular element, from U.S. \$7/lb for lanthanum to U.S. \$900/lb for europium (Cranstone, 1980). Little is known about the future supply/demand situation of rare earth elements.

Phosphate mineralogy and petrography

The primary mineral of the phosphate deposits in this study is carbonate fluorapatite (francolite): the phosphate mineral of all marine sedimentary phosphate deposits. Its chemical composition can best be described with reference to the composition of fluorapatite, which is:

$$Ca_{10}(PO_4)_6F_2$$

The substitution of CO_3 for PO_4 is the characterizing substitution for carbonate fluorapatite, and it typically occurs in amounts varying from a few percent (expressed as CO_2), to over six percent (McArthur, 1985, pg. 25). SO_4 can also substitute for PO_4. Sometimes, Ca is substituted by Na and Mg, both in small amounts. Chemical analyses generally show that more F is present in the mineral than is required to occupy the two F positions in the unit cell. This is generally considered to indicate that the excess F goes to form CO_3F groups that replace the PO_4.

Carbonate fluorapatite occurs in marine sedimentary phosphate deposits basically as aggregates of submicrocrystals—crystals that are generally less than 1000 angstroms in maximum dimension (McClellan

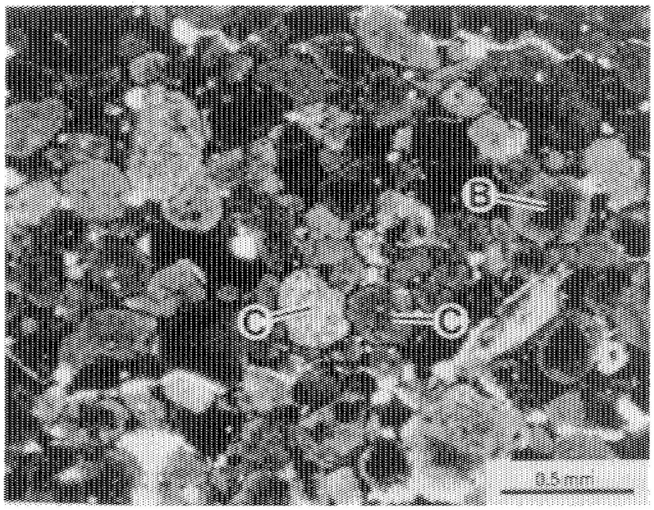

Plate 1. Tightly packed structureless pellets from the Basal Fernie Phosphate Zone showing some bleaching (B) due to weathering, and several pellets showing compromising boundaries (C). Plain light.

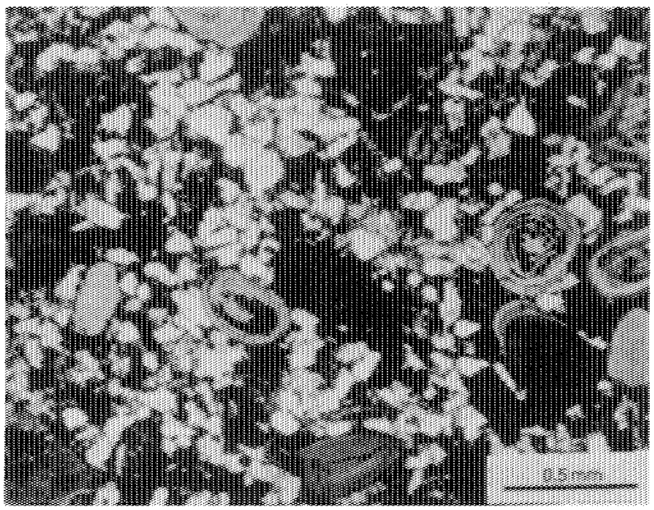

Plate 2. Oolites set in a fine-grained calcareous sandstone of the Rock Creek Upper Phosphate Zone, Fernie Formation. Dark layers within pellets are pyrite. Plain light.

and Lehr, 1969). Most of the aggregates appear to be isotropic, probably because of the random orientation of the crystals. Aggregates that show anisotropism are believed to result from the preferred orientation of the crystals (e.g., oolites with anisotropic rings that define a spherulitic cross, and all biogenic apatite that commonly appears fibrous in structure).

The modes of occurrence of the aggregates of carbonate fluorapatite in this study are defined as follows:

Pellets – ovulitic to spherulitic, sand-size aggregates without internal variation (plate 1).

Oolites – ovulitic to spherulitic, sand-size aggregates with one or more concentric layers (plate 2).

Cement – phosphate that is interstitial to the major components of the rock (plate 3).

Laminae and beds – strata-form phosphate (plate 4).

Fossils – biogenic phosphates that comprise bone, teeth, phosphatic shells and conodonts(?) (plate 5).

Nodules – phosphates that are larger than 4 mm in size and that are usually irregular in shape and contain more than one of the above modes of occurence (plate 6).

Intraclasts – transported and reworked phosphate material.

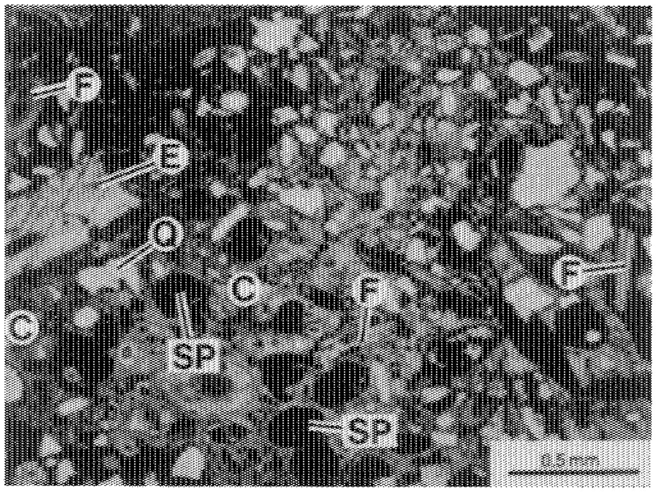

Plate 3. Johnston Canyon Upper Phosphate Zone showing a variety of phosphate petrographic textural forms. Francolite sponge spicule remains (F), francolite cement (C), and structureless pellets (SP). Echinoderm fragments (E) and etched quartz grains (Q) are also present. Plain light.

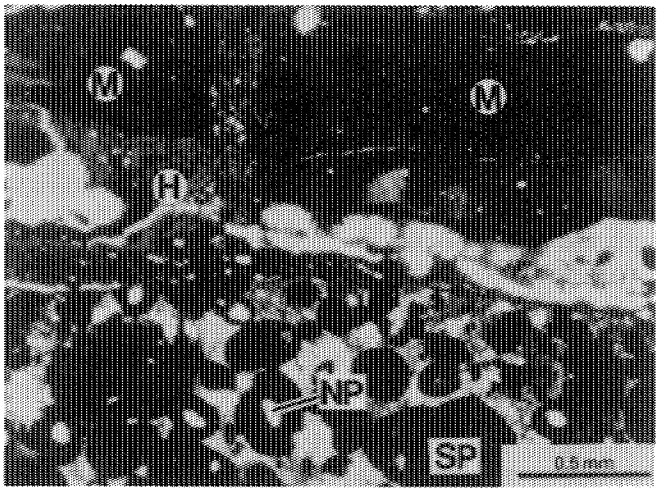

Plate 4. Middle Phosphate Zone of the Exshaw Formation south of Crowsnest Pass showing laminated phosphate (M) set in a hematite cement (H), structureless pellets (SP) and quartz-cored pellets (NP), loosely packed in a chert cement. Plain light.

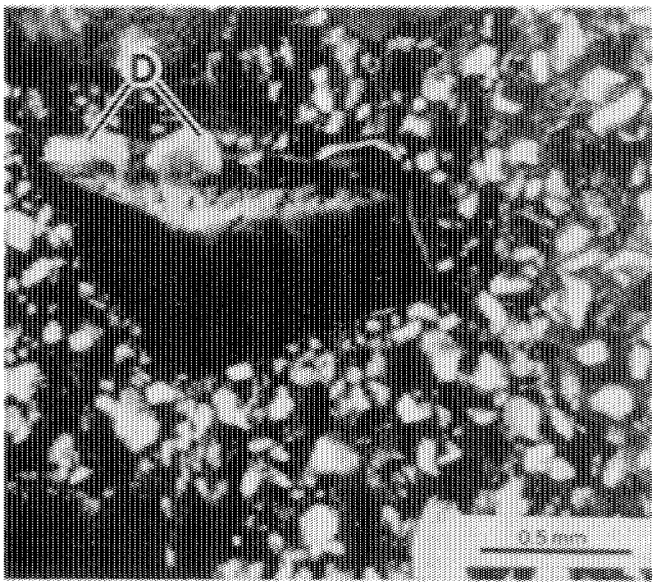

Plate 5. Conodont or bone fragment showing fluorapatite bone material (center) and white dahllite (D). Plain light.

Plate 6. Jurassic Fernie Formation, Rock Creek Member, Rock Creek Upper Phosphate Zone at Whitehorse Creek - Section 13 near Cadomin. Mixture of belemnites, bivalves and phosphate nodules, set in an iron-rich sandstone.

Phosphate resources in Alberta and southeastern British Columbia

Previous investigations

Phosphate, as apatite veins and pockets within igneous intrusive rocks, was explored for and produced in Quebec and Ontario from 1829 to 1919 (Spence, 1920). However, the discovery in the early 1890s of the vast, easily exploitable sedimentary phosphate deposits in Florida undermined the Canadian industry, and it slowly collapsed.

The search for phosphorous sources in Canada shifted to sedimentary phosphate deposits in the west with the discovery by Adams and Dick (1915) of phosphate near Banff in Rocky Mountain Park (Banff National Park). Subsequent investigation of the Banff deposits by de Schmid (1916) concluded that the phosphate beds were of insufficient grade and thickness to be economically exploited. Leo Telfer, in 1925, conducted an extensive phosphate exploration program in the Rocky Mountains in Alberta for Consolidated Mining and Smelting Company (Cominco), (Telfer, 1933). Telfer's general conclusions were that phosphate was present in four distinct stratigraphic zones, but was of low grade with an undetermined commercial value.

From 1925 to 1975, Cominco held several phosphate leases in southeastern British Columbia and in the Crowsnest Pass area of Alberta. Adits were constructed by Cominco, prior to 1960, at the Crow, Lizard and Corban mine sites in British Columbia to test the metallurgical properties of phosphate found in the lower Fernie Formation. None of these sites went into commercial production.

In the 1960s, renewed interest in phosphates saw another surge of exploration in Alberta and British Columbia by Cominco, Western Warner Oil, Hudson Bay Oil and Gas, and Mobil Oil. From 1972-74, the world price of phosphate nearly tripled, causing another wave of exploration activity by Cominco, Esso and First Nuclear Corporation. This recent activity was centered on the southeastern Fernie Basin and northeastern areas of British Columbia.

In the 1980s, little activity has been undertaken by industry to develop western Canadian phosphate deposits. However, the Geological Survey of Canada has recently produced a series of review papers on phosphorites (Christie, 1980, 1981b).

Field methods

After compiling all known occurrences of phosphate from published literature and from publicly available exploration permit reports, a field program was set up to fill in gaps and verify existing data. All known phosphate-bearing formations in the Rocky Mountains of Alberta and southeastern British Columbia were examined, regardless of their land zone location and political status, in an attempt to obtain a geometrically equidistant spacing of data points. Particular attention was paid to obtaining good quantitative data regarding grade and thickness, and establishing the stratigraphic and sedimentological setting of each phosphate occurrence.

Field procedures consisted of measuring, describing and sampling all accessible stratigraphic sections of formations known to be phosphate-bearing. A gamma ray spectrometer was used to assist in detecting phosphate beds based on a known affinity between uranium and phosphates.

Laboratory methods

All samples collected in the field were split in two, with one half kept for visual examination and one half pulverized for chemical analysis. The pulverized portion was further split into two representative halves, one being analyzed for phosphorous and vanadium content, and the other for uranium. Uranium was analyzed by Neutron Activation by Atomic Energy of Canada Limited. Detection limits of 0.1 ppm for a 1-g sample and a precision limit of about ± 1 percent are claimed by AECL. Eight replicate samples submitted to AECL yielded a precision of ±5 percent within the 4-10 ppm range. Phosphorous and vanadium contents were determined at the Alberta Research Council laboratories using standard wet chemical methods. The same eight replicate samples revealed a precision here of about ± 13 percent for phosphorous and ± 11 percent for vanadium of the amount detected.

Standard petrographic thin sections were prepared and examined for all samples containing substantial proportions of phosphate. A small portion of these samples was examined using a scanning electron microscope.

Twenty-one samples from all stratigraphic units where phosphogenesis occurred, all major phosphate petrographic and mineralogical forms, and a variety of geographic positions were selected for study with the electron microprobe.[3] This same group of twenty-one samples was also used for standard mineral identification and apatite CO_2 content by x-ray diffraction.

Four composite samples representing the four major phosphogenic stratigraphic units were analyzed for trace and REE determinations. Each sample was prepared by combining equal portions of 6 to 12 (depending on availability) individual samples. Trace and REE determinations were performed by Neutron Activation -Gamma Ray counting techniques.

All stratigraphic and chemical analysis data from all sections were entered into a computer data base management system termed "Datatrieve" (Digital Corporation). Contoured maps were made using the University of Kansas program "Surface II," and statistics were derived from the University of Michigan program "Midas." These programs were run on the University of

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[3] The operating conditions for all probe runs were as follows: Fluorine analyzed by Wave Length Dispersive technique utilizing a TAP3 crystal-detecting Fluorine K alpha wavelength. Peak position for Fluorine set at 18.31999A. All other elements by Energy Dispersive analysis. Operating voltage = 15 Kev, Aperture Current = 260 nanoamps, Probe Current = 26 nanoamps. Beam was kept in constant motion over chosen apatite sample to avoid burning of Fluorine and CO_2. Data were processed using computer program "EDATA II' (Smith et al., 1979).

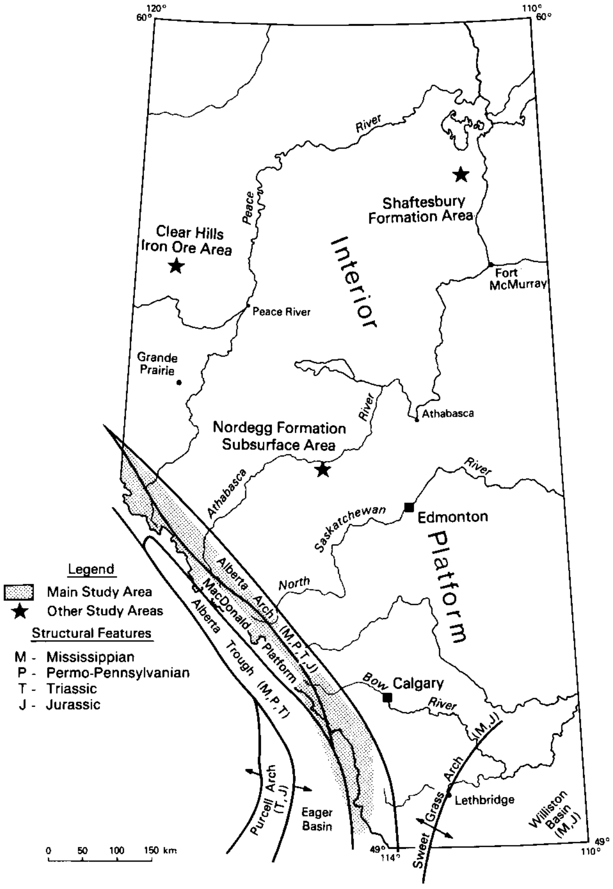

Figure 1. Study areas and major tectonic features.

Alberta's Amdahl 470 and the Alberta Research Council's VAX 11/780 mainframe computers.

Terminology

There are many conflicting usages of terms in describing phosphatic rocks. Within this report, the following well-recognized terms and symbols were adopted:

- P - the chemical element phosphorus.
- P_2O_5 - phosphorus pentoxide.
- Percent P_2O_5 - the standard way of expressing the content of phosphorus, as weight percent.
  - BPL (Bone Phosphate of Lime) = 2.1852 x percent P_2O_5
  - Percent P (Elemental Phosphorus) = 0.4364 x percent P_2O_5
- Phosphate - a long-used term that refers to the group of chemical compounds that contain the phosphate radical, PO_4. It refers here to the mineral carbonate fluorapatite, also called francolite, which is the phosphate mineral of marine sedimentary rocks.

Terms and definitions specific to this report include:

- Phosphate rock (phosphorite): contains greater than 18 percent P_2O_5, being greater than 45 percent carbonate fluorapatite for most apatite compositions. Thickness greater than or equal to 1.0 m.
- Phosphatic rock: contains 6 to 18 percent P_2O_5, being equivalent to 15 to 45 percent carbonate fluorapatite. Thickness is greater than or equal to 1.0 m.
- Phosphate-bearing rock: contains 1 to 6 percent P_2O_5, being equivalent to 2.5 to 15 percent carbonate fluorapatite. No thickness specified.

Geology, distribution and potential of deposits

Phosphate is found in ten geological formations that outcrop in the Cordilleran region of Alberta and southeastern British Columbia. All strata now exposed in the Cordilleran were deposited in the Alberta Trough or on the adjacent Platforms (figure 1).[4] From the Cambrian to about Middle Jurassic, sediment was derived from a landmass to the east, now on the Canadian Shield. From Upper Jurassic to Tertiary, a molasse sequence of sediments was shed from a rising orogenic belt to the west, where once the Alberta Trough had been situated (McCrossan and Glaister, 1964).

Phosphate was deposited in the Late Devonian-Mississippian Exshaw Formation, the Pennsylvanian Spray Lakes Group, the Permian Ishbel Group, the Triassic Spray River Group, and the Jurassic Fernie Formation (figure 2). The Exshaw, Ishbel and Fernie phosphates are the most widespread and are the ones of main economic interest.

The ten main phosphate-bearing formations are exposed only within the Front Ranges and Foothills of the Cordilleran region. Outcrop configurations are typically narrow and lenticular, broken up and contorted along strike by folding and faulting. The distribution pattern is the result of the Cretaceous/Paleocene Laramide orogenic event that produced a series of low-angle, imbricate, southwest to westward-dipping thrust faults. The main deformation took place between early Campanian and late Eocene and proceeded from west to east (Price, 1981). Figure 3 shows the typical structural/stratigraphic setting of the main phosphate-bearing formations.

All stratigraphic sections presented in this study were palinspastically restored, based on estimates from Norris (1965), Price (1981) and Price and Mountjoy (1970). Palinspastic restoration was done so that a reconstruction of the facies depositional environment could be attempted. Appendix 1 lists all stratigraphic sections studied and their present and inferred palinspastic position. More detailed stratigraphic, lithologic and chemical analysis data for all sections examined can be found in Macdonald (1984).

Exshaw Formation

The Exshaw Formation is of late Devonian-early Mississippian age, and consists of a thin basal sandstone member, a lower shale member and an upper limestone member (Harker and McLaren, 1958). Macqueen and Sandberg (1970) recognized only an upper calcareous siltstone unit and a lower black shale unit. In this study, the three members of Harker and McLaren (1958) are recognized along with five mappable zones and beds and the Lower Sappinton Member (figure 4, plate 7).

Phosphatic rocks are found within four stratigraphic units in the Exshaw Formation: the Upper, Middle and Lower Phosphate Zones, and the Basal Sandstone Member (figure 4).

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[4] Six phosphate deposits are found in formations outside of the Cordilleran region in the Western Canada Sedimentary Basin.

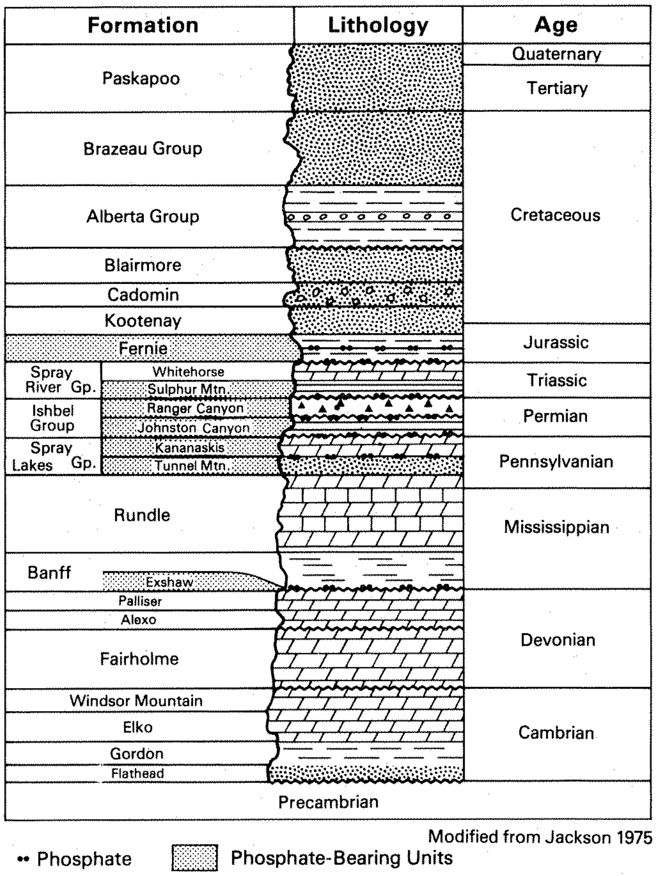

Figure 2. Generalized stratigraphic section—Cordilleran region and major phosphate bearing units (modified from Jackson, 1975).

Basal Sandstone Member

The Basal Sandstone disconformably overlies the Devonian Palliser Formation over much of the area from north of Crowsnest Pass to Willmore Wilderness Park. In most sections, the sandstone is 10 to 20 cm thick and is nearly always overlain by a 2 to 30 cm (section 76) bentonite bed (figure 4). Lithologically, the unit varies from a siltstone to a pebbly sandstone, with phosphate pebbles (0.5-3 cm in diameter), bone remains and occasional pellets. The unit weathers rusty brown, and is only slightly less resistant than the underlying Palliser Formation. Contact with the Palliser Formation is always sharp and slightly undulating, although no distinct erosional surface is evident.

The Basal Sandstone consists primarily of quartz, orthoclase, calcite, dolomite, fluorapatite, illite, jarosite and pyrite, as determined by XRD. Hematite is very common throughout the zone, often as detrital grains, and less commonly as a fine-grained cement. The member is a characteristically angular to subangular, very fine to very coarse grained, poorly sorted, illite/carbonate/ hematite-cemented sandstone. The phosphate material consists of nodules (up to 2 cm long), bone fragments, structureless, nucleated and rimmed pellets, intraclasts—often composed of aggregated pellets—and some indication of laminated phosphate. Replacement features include feldspars that have been altered and replaced by sericite and calcite, and calcite that has been replaced by phosphate. Perhaps the most important texture observed was detrital grains of hematite-rich pisolitic structures at section 154. Structures very similar to these have been described as lateritic hardpan deposits, characteristic of subaerial weathering horizons (Scholle, 1979).

The member is phosphatic in parts of the northern, south-central and southern regions.[5] Grades are in the 1.4 to 8.7 percent P_2O_5 range, with corresponding thicknesses in the 10 to 45 cm range (appendix 2). The best grade/thickness combination is at Section 76 (Medicine Lake - 7.77 percent P_2O_5/45 cm). This zone has no forseeable economic potential due to low grade/ thickness combinations.

Lower Cherty Black Shale Member

The Lower Cherty Black Shale Member contains the two principal phosphate zones—the Lower and Middle phosphate zones—plus an upper and basal bentonite bed. It is areally distributed from Crowsnest Pass northward to Medicine Lake (figure 5 in pocket). The member consists of a cherty black shale that is fissile

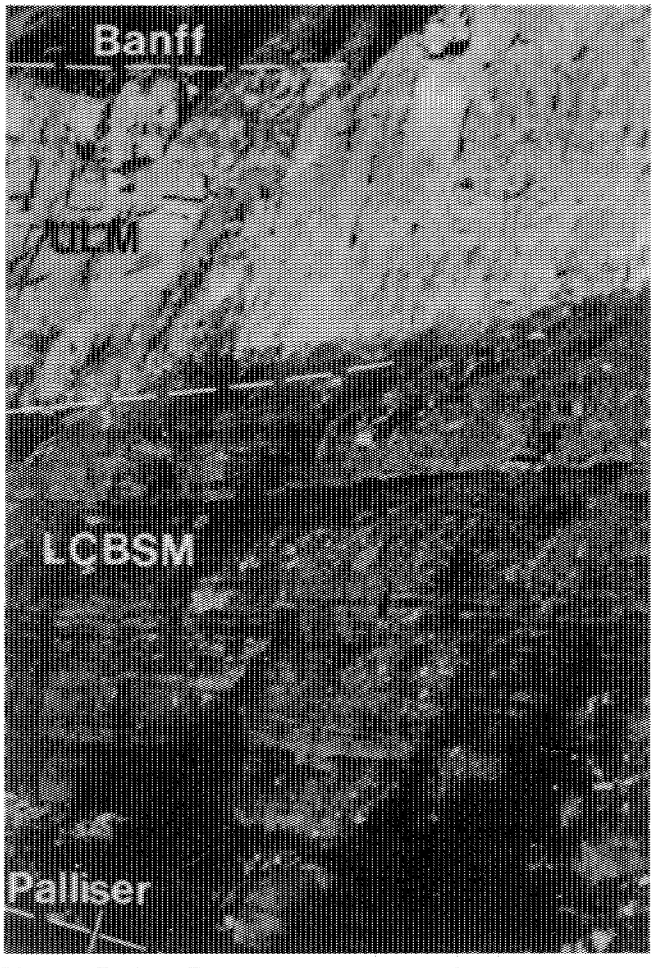

Plate 7. Exshaw Formation outcrop near Canmore-Mt. Rundle Gap - Section 249. Palliser Formation - extreme lower left, LCBSM - lower cherty black shale member, ULM - upper limestone member. Person at bottom for scale.

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[5] The Rocky Mountains of Alberta are traditionally divided into the southern (USA border to Bow River), central (Bow River to Athabasca River) and northern Rocky Mountains (Athabasca River to British Columbia - Alberta border).

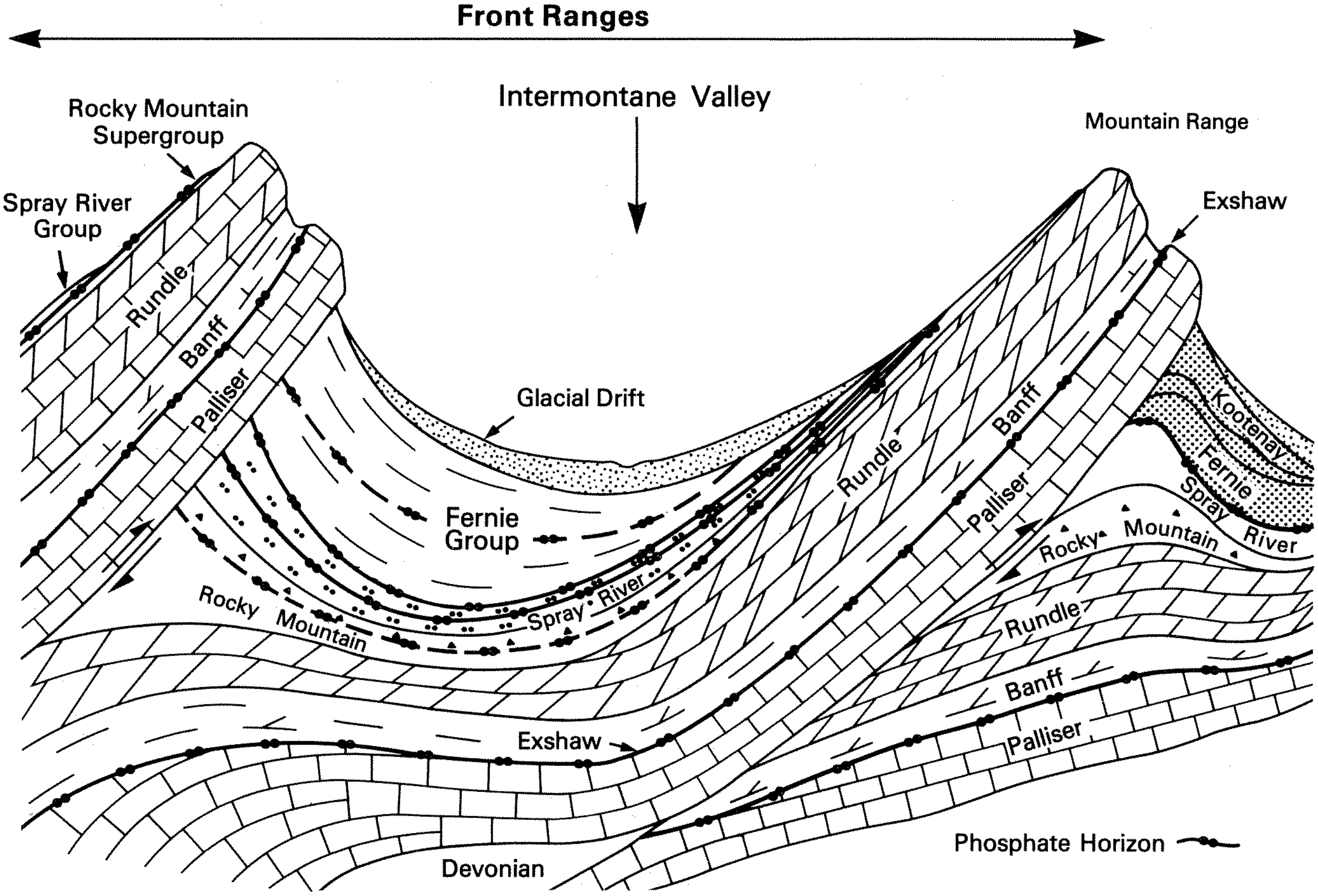

Figure 3. Idealized sketch of the Canadian Front Ranges and the typical structural/stratigraphic setting of the main phosphate bearing units.

to thin bedded, generally non-calcareous, and has recessive and yellowish-red weathering. It is very sparsely fossiliferous, non-bioturbated, contains large (up to 1 m) diagenetic concretions and often shows synsedimentary depositional folding. Contact with the Basal Sandstone is sharp though somewhat undulating. The upper contact, with the Upper Limestone, is gradational, becoming increasingly calcareous and increasingly silty up section. The thickness of the Lower Chert in most places varies from 3 to 10 m, but it thins to near zero northward and thickens to more than 47 m in the southwest (figure 6).

The Lower and Middle phosphate zones are largely confined to the southern portions of the study area. Both are pelletal phosphorites, pellet-bearing sandstones or pelletal shales. Both are organic rich and show sharp upper and lower contacts within the Lower Chert. Figure 5 illustrates the stratigraphic position and correlation of these two phosphate zones.

The Lower and Middle zones are best developed near Crowsnest Pass and contain mostly pelletal phosphates. They can be divided into two regions north and south of the pass. In the region north of Crowsnest Pass, pellets are characteristically bleached, very tightly compressed, flattened, show moderate sorting, are 0.3 to 0.8 m in size, and are surrounded by an organic-rich argillaceous matrix. In the region south of Crowsnest Pass, pelletal phosphorites predominate and are characterized by: (a) pellets cored with other smaller pellets or with detrital quartz/hematite/bones; (b) a well-rounded shape; (c) a moderate to well-sorted texture; (d) lack of a matrix; (e) 0.2 to 2.0 mm size; and (f) a very loosely packed to floating matrix, cemented with chert, and less commonly, phosphate (plate 4). All the lithotypes are medium to dark brown in plain polarized light (believed to be a reflection of high organic contents) and are virtually isotropic under crossed nicols. Both the northern and southern regions contain structureless nodules and intraclasts.

The Lower and Middle zones are treated together, as they are usually separated by less than 2.0 m of shale, and if considered separately, would have little economic potential. Three occurrences are known from the central and northern parts of the study area (sections 59, 24 and 382); however, only sections 59 and 293 have P_2O_5 values in the 1 to 3 percent range for a minimum 1 m thickness (Appendix 3). These zones have their best development in the region north of Crowsnest Pass from Phillipps Pass to Racehorse Pass (Sections 226, 199, 214, figure 5). In this region, the grades are in the 6 to 10 percent P_2O_5 range for a minimum 1 m thickness. These horizons appear to drop in grade/thickness farther to the south (Sections 191 and 228), with P_2O_5 values being in the 1 to 3 percent range for a 1 m thickness. They also decrease in grade/thickness to the north.

The structural/stratigraphic configuration of the Exshaw Formation is not a favorable one with respect to mining potential. Generally, the formation dips into the High Rock Range and is overlain by several hundred metres of Banff/Rundle Formation (figure 3); open pit mining is therefore not feasible. Strip or slot-trench type mining may be possible within Phillipps, Deadman and Racehorse Passes. At these locations, the Exshaw subcrops at low elevations, is in a structurally/stratigraphically more favorable position, and dips moderately (20-45°) to the west.

Upper Limestone Member

The Upper Limestone Member has a wide distribution (figure 5), thickening from east to west. It is a silty to argillaceous limestone or calcareous siltstone, weathers to yellowish-orange, and contains the Upper Phosphate Zone.

The Upper Phosphate is found on the uppermost surface of the Upper Limestone Member at the contact with the overlying Banff Formation. This zone is usually expressed as a conglomeratic mixture of nodules and bone fragments.

At the northern location (Section 37), the Upper Phosphate consists of a conglomeratic mixture of quartz, dolomite, pyrite, phosphatic bones, nodules, intraclasts, structureless, elongated and nucleated pellets, laminated phosphate intraclasts and phosphate cements. In the south (Section 191), the phosphate occurs as bone, elongated pellets, intraclasts and some cement within an organic-rich, well-sorted siltstone. Glauconite appears to have replaced some bone material at this location. The Upper Phosphate is therefore seen primarily as a reworking of previously precipitated phosphatic materials into a pebble conglomerate. Apparently, some replacement by phosphate of an original, unknown cement within the siltstones also took place.

The Upper Phosphate has a very limited regional distribution, having been recognized only at sections 37 and 191 (figure 5, Appendix 1). The P_2O_5 content of this horizon always exceeds 15 percent; however, the thickness is always less than 10 cm. Therefore, this horizon appears to have no economic potential.

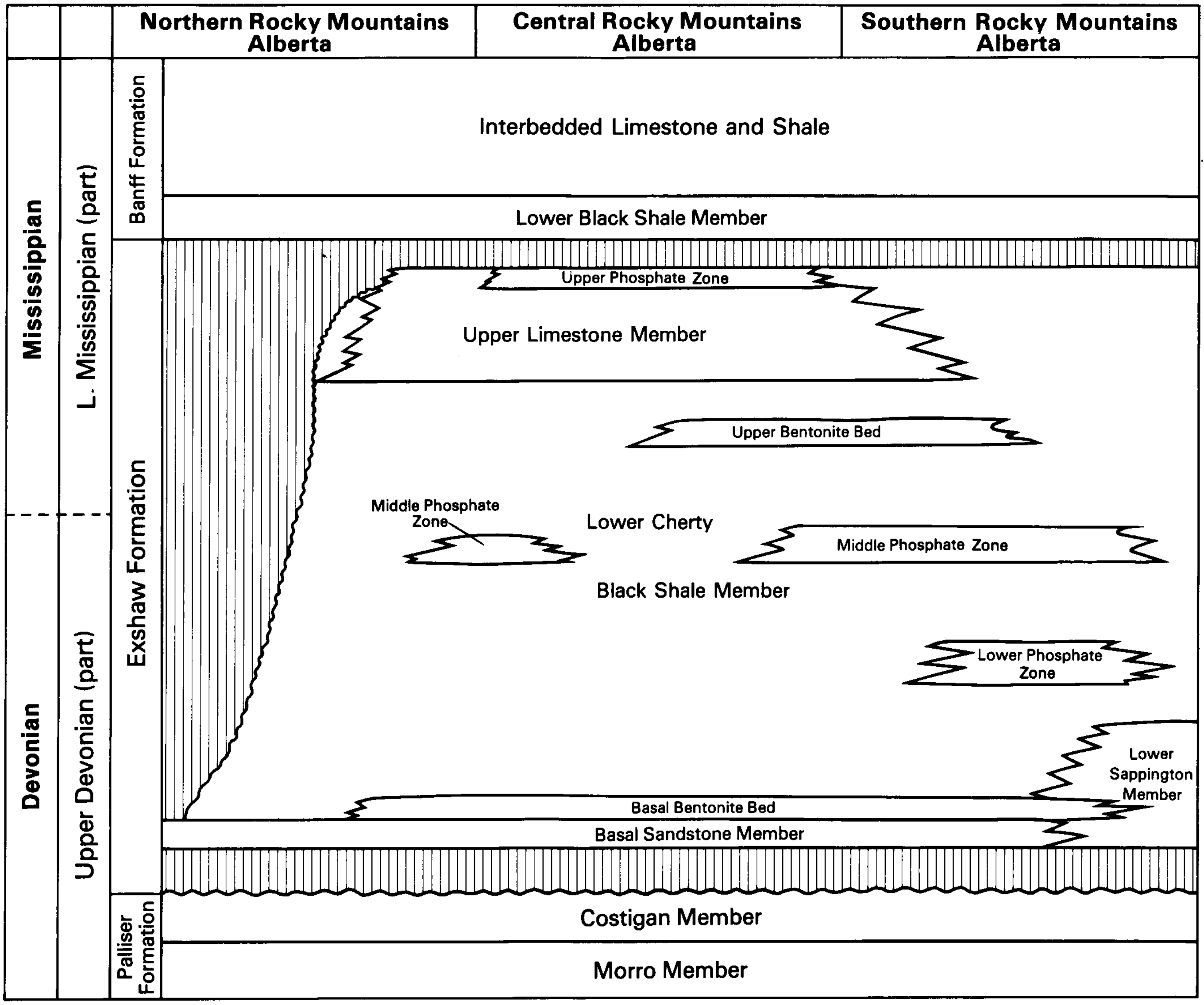

Figure 4. Age, nomenclature and stratigraphic relations—Exshaw Formation.

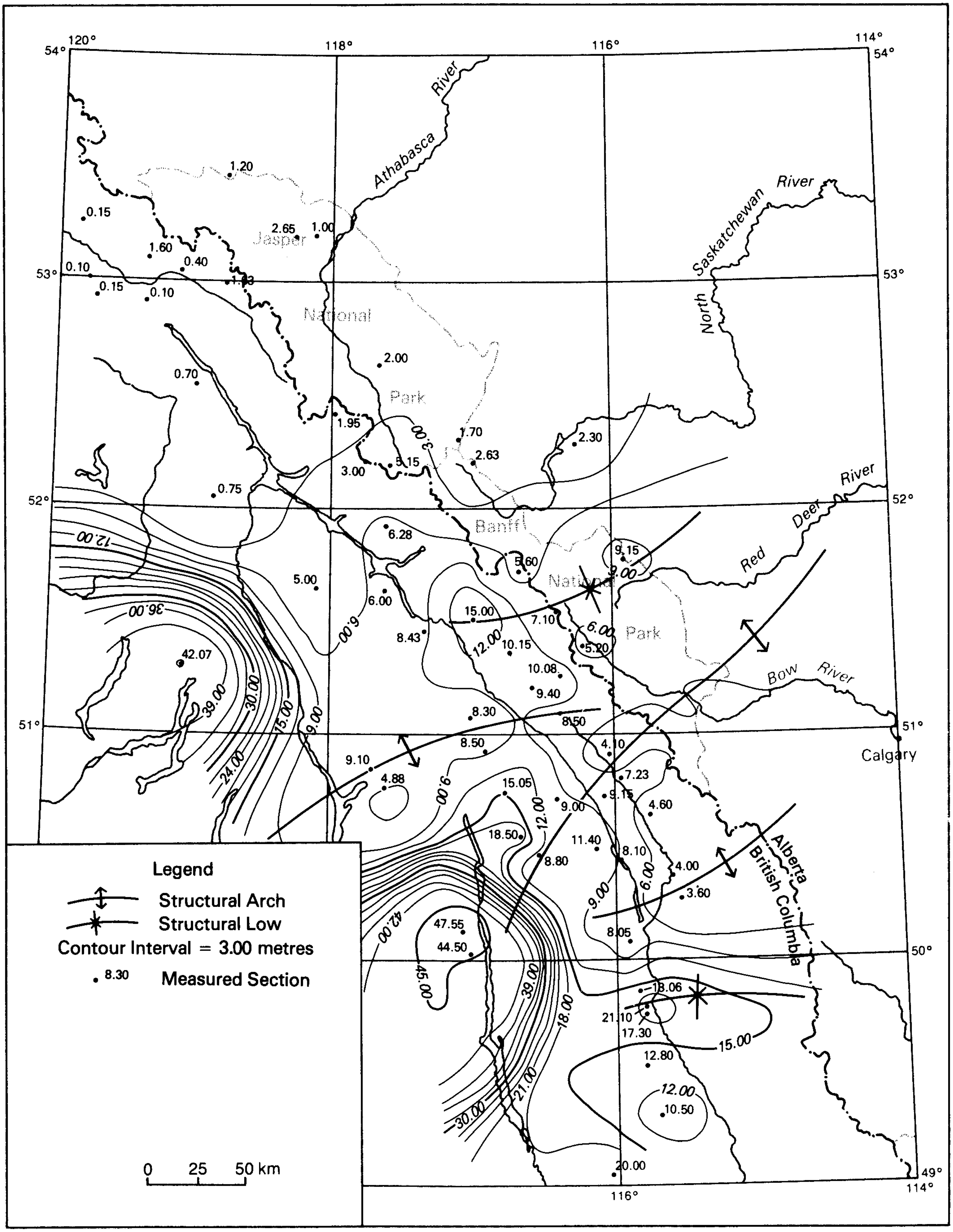

Figure 6. Isopach map of Lower Cherty Black Shale Member, Exshaw Formation (sections palinspastically restored).

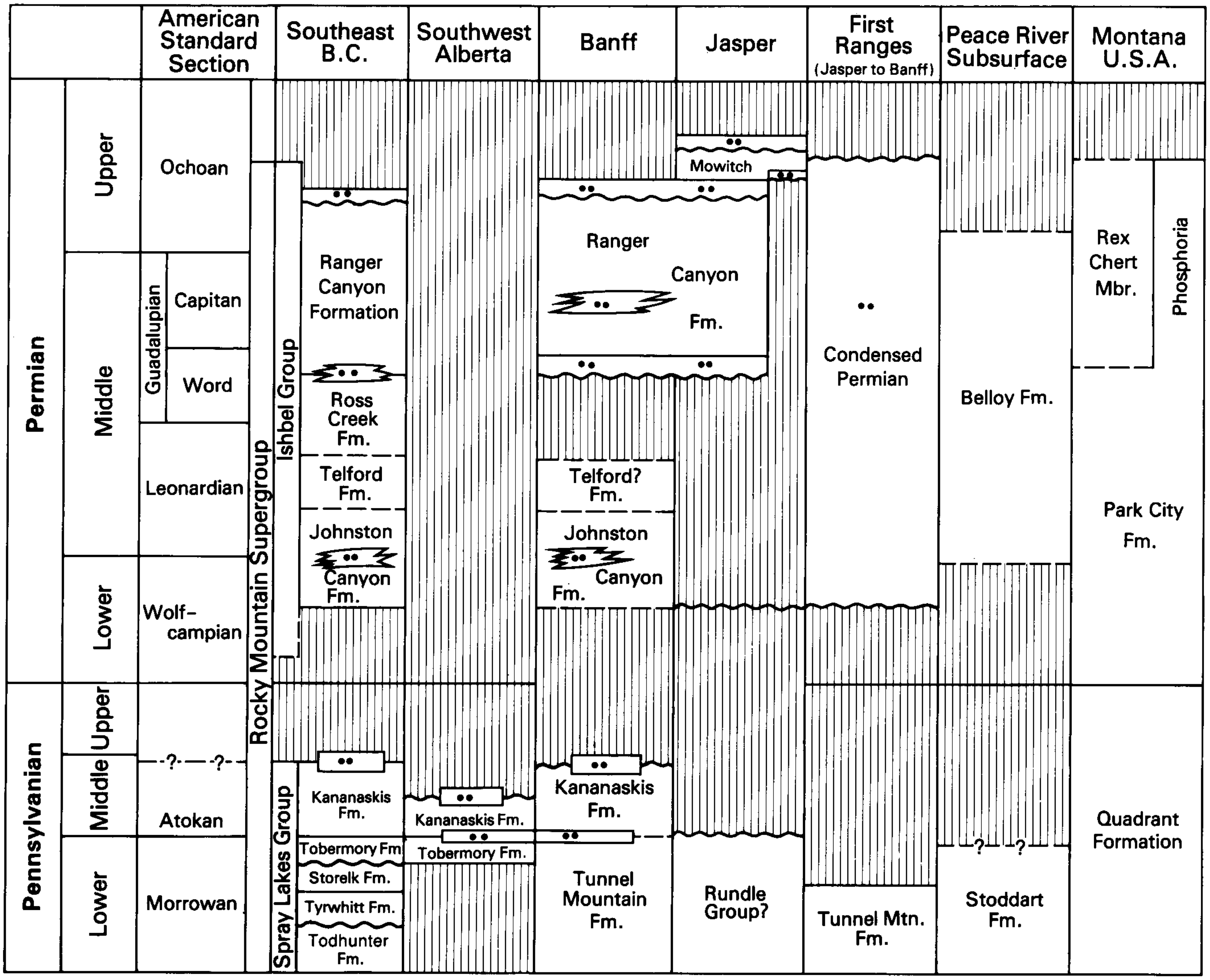

Figure 7. Nomenclature and stratigraphic correlation chart of the Rocky Mountain Supergroup, Alberta, British Columbia and Montana (•• phosphate zones).

Tunnel Mountain Formation

The Lower Pennsylvanian Tunnel Mountain Formation consists of a very uniform, monotonous sequence of resistant, reddish-brown weathering, dolomitic sandstones and siltstones. Some of the sandstones approach orthoquartzites. The formation characteristically shows medium- and large-scale trough cross-bedding, is very clean and well sorted, and is sparsely fossiliferous,[6] with some unidentified vertical burrows. The Tunnel Mountain in Alberta has been correlated with the Tobermory, Storelk, Tyrwhitt and Todhunter Formations (figure 7) in southeastern British Columbia (Stewart and Walker, 1980). Regional unconformities between the Todhunter/Tyrwhitt and Storelk/Tobermory are suggested by Stewart and Walker, citing evidence of phosphate pebble, *Orbiculoidea*-bearing conglomerates at these contacts. The Tobermory is thought to rest unconformably on the Mississippian Rundle Group in the Livingstone Range (Stewart and Walker, 1980).

Phosphate within the Tunnel Mountain in Alberta is found associated with intraformational conglomerates that may mark Todhunter/Tyrwhitt or Storelk/Tobermory regional unconformities (suggested by Stewart and Walker, 1980). The other association is at the top of the Tunnel Mountain, as phosphatic conglomerates. The intraformational phosphate occurs sporadically within the Tunnel Mountain Formation, although no continuous mappable zone was identified. The phosphate occurs as reworked pebbles in a thin (< 10 cm), predominantly chert pebble conglomerate or pebbly sandstone. The intraformational phosphates consist of a conglomeratic, pebbly or phosphatic sandstone bed composed of phosphate and chert pebbles (up to 2 cm), nodules, pellets and cement. It is commonly found directly overlying the Tunnel Mountain Formation (figure 7). The Tunnel Mountain Formation is disconformably overlain by the Kananaski Formation, except at Section 194, where it is directly overlain by the Triassic-Sulphur Mountain Formation, and in the west side of the Elk Valley, British Columbia, where the Tunnel Mountain is overlain by the Johnston Canyon Formation.

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[6] Most commonly phosphatic brachiopods, *Orbiculoidea* sp., *Spirifers* sp., and occasional bryozoans (McGugan and Rapson, 1962).

The most common phosphate petrographic lithotype in the Tunnel Mountain phosphates appears as scattered bone remains, cement, pellets and pebbles. The phosphates are usually found in thin chert pebble conglomerates or within well-sorted, subangular to subrounded, fine to very fine grained, dolomitic, quartzose sandstone. The phosphate pebbles are generally well rounded, up to 2 cm in size, and composed of the recrystallized phosphate cement. Pebbles are often multiple aggregates of former pellets, clastic debris and sponge spicules. Chertification has been a very widespread phenomenon throughout the Spray Lakes Group (Rapson, 1962) and, as such, some phosphatic materials, particularly bones, have been replaced by chert or chalcedony. Well-sorted, calcite-cemented sandstone—containing scattered, structureless pellets—is encountered in the easternmost Livingstone Range. These pellets are rich in organic matter, 0.2 to 0.3 mm in size, rounded to well rounded and show some evidence of calcite replacement. Nodules up to 3 cm in size are also present.

Of the three known occurrences of intraformational phosphates (Sections 21, 48 and 281), only one grade/thickness determination is available (Section 21: 1.22 percent P_2O_5/0.10 m). Four of the nine known occurrences of phosphates found at the top of the formation are in the northern part of the Livingstone Range.[7] The other three are in scattered locations as far north as the North Saskatchewan River area. This zone varies from 0.01 to 1.50 m thick, and has a phosphate content ranging from 0.08 to 8.90 percent P_2O_5. Appendix 4 summarizes the analytical data available on this zone. No economic potential is foreseen for the Tunnel Mountain Formation phosphates, as thickness/grade combinations never reach an acceptable level.

Kananaskis Formation

The Middle Pennsylvanian Kananaskis Formation consists of up to 70 m of light gray, resistant-weathering silty dolomites, dolomitic siltstones, orthoquartzites, cherty and calcareous sandstones, a diverse marine invertebrate fauna and fusilinid-bearing novaculitic cherts (McGugan and Rapson, 1979). Intraformational chert breccias are found throughout the upper parts of the Formation in many eastern sections (Rapson, 1962), though few are reported to be phosphatic. Two phosphatic zones are recognized in the Kananaskis Formation: Intraformational and Interformational Phosphates.

The upper contact of the Kananaskis Formation with Permian strata is unconformable and is marked locally by Interformational Phosphates.

Intraformational Phosphates

Phosphate occurs sporadically within the Kananaskis Formation, with a slight tendency to be found near the top. The phosphate is expressed as patchy cement in sandstones and quartzites, and, less commonly, as reworked pebbles within conglomerates. Four occurrences from the southern and central regions are known.[8] Appendix 5 provides details of grade/thickness and lithology. Section 210, near Tent Mountain in the Crowsnest Pass, has a grade/thickness of 8.40 percent P_2O_5/1.0 m.

Interformational Phosphates

A chert breccio-conglomerate is found at the top of the Kananaskis Formation (figure 7) over a wide geographic area (figure 8 in pocket). This conglomerate is generally cemented with phosphate and/or contains reworked phosphate pebbles. The Johnston Canyon Formation disconformably overlies this zone in all areas. Figure 8 shows the location of phosphate-bearing outcrops of the zone, and Appendix 5 summarizes all available lithological and chemical analysis data.

Section 281 - Mist Mountain contains greater than 9 percent P_2O_5 for a 1 m thickness and may be of economic interest. More-detailed sampling is necessary to evaluate the potential of this zone.

The Interformational Phosphates are characterized petrographically by a predominance of phosphate cements within pebble conglomerates or fine- to medium-grained sandstones. Francolite cement, laminated phosphatic intraclasts and pebbles are present, though not common. The phosphate cement has extensively replaced abundant sponge spicules throughout most of the samples studied. Carbonate has also replaced sponge spicules to a lesser degree. The sandstone or conglomerate hosting the phosphate is poorly to well sorted, with clasts that are angular to rounded. Chert and dolomite are the main clastic materials within these sandstones and conglomerates. The phosphate pebble material generally comprises reworked detritus-free phosphate cements that are well rounded and up to 2 cm in size. The phosphates associated with the Kananaskis Formation tend to contain a lot of reworked and phosphatized preexisting material. Chert has replaced earlier primary phosphate cements in many cases.

Johnston Canyon Formation

The Lower to Middle Permian Johnston Canyon Formation is a series of recessive-weathering, dark colored, thinly and rhythmically bedded fine- to medium-grained clastic rocks (MacRae and McGugan, 1977). Phosphatic and argillaceous siltstones, silty carbonates and dark spicular cherts are the most common lithologies. The formation becomes more carbonate and coarse clastic-rich northward. Thin, intraformational, phosphate pebble conglomerate beds are fairly common throughout the formation (see Section 295). Pelletal phosphate zones are also found, particularly in southeastern British Columbia. MacRae and McGugan (1977) noted a general increase in phosphatic material toward the top of the formation. In the Telford thrust sheet in British Columbia, they recognized a threefold division of the formation: an upper cherty calcareous member, a middle silty phosphatic member and a lower sandy phosphatic member. However, this threefold division has not been recognized in Alberta.

The Johnston Canyon Formation lower contact is marked over most areas at the Kananaskis phosphatic

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[7] Sections 194, 264, 266 and 267 in the Livingstone Range, and Sections 206, 230, 232, 38 and 395 in scattered locations.

[8] Sections 210, 267, 332 and 381.

zone. The upper contact is generally well marked at the unconformable Ranger Canyon Phosphatic Zone when overlain by the Ranger Canyon Formation.

The Johnston Canyon Formation contains sponge spicules, sparse fusulinid remains, brachiopods, solitary corals and the trace fossil *Zoophycus,* a Permian index fossil (MacRae and McGugan, 1977).

Sedimentary and biogenic structures within the Johnston Canyon include intraformational phosphatic-clast and siltstone-clast conglomerate horizons, rhythmically alternating siltstone and silty shale beds, and intense bioturbation at the base. However, aside from *Zoophycus,* there is very little bioturbation throughout the middle and upper parts.

Intraformational Phosphates

Phosphate within the Permian Johnston Canyon Formation is found as pellets and nodules in a series of interbedded siltstones, sandstones and shales (figure 7). This zone has a limited lateral distribution, being confined to the area south of Banff and the westernmost sections (figure 9 in pocket). Sections 365 (Mt Ishbel), 229 (Lizard Range), 231 (Weight Creek) and 221 (Mt. Broadwood) all have phosphate grades greater than 13 percent P_2O_5 for a minimum 1 m thickness (Appendix 6). Low-grade phosphate rocks and a number of unassayed nodule zones (1-6 percent P_2O_5) exist in the Kananaskis area (Section 306, 307 and 308). The region around Mt. Broadwood, Lizard Range, and the Weight Creek-Brule Creek areas (Area I and II, figure 9) would seem to have the best potential for phosphate exploitation within the zone (Appendix 6). Extensive, as yet untested, outcrops of Johnston Canyon Formation are likely present to the southeast of Mt. Broadwood in the Wigwam River-Macdonald Range area. This area may show further extension of the zone.

The Intraformational Phosphates consist mainly of diagenetic nodules, intraclasts, quartz-cored pellets and, less commonly, patches of phosphate cement. The nodules are usually composed of phosphate cement with numerous clastic quartz grains "floating" in the cement.

The grain size and mineralogy of material within the nodule is identical to that outside the nodule, suggesting slow replacement of original quartz overgrowth cement with francolite cement, leaving the clasts apparently floating. Hematite and/or manganese rims are sometimes present part way around the nodule. Intraclasts are often found as thin (10 cm) horizons showing scour bases and are composed largely of aggregates of quartz-cored pellets or structureless pellets. Some intraclasts are composed of detritus-free francolite cement. Siltstones and very fine-grained sandstone, both being well sorted and angular, are the typical host rocks for these phosphorites. Carbonate has apparently replaced clay minerals in these fine-grained rocks. Pelletal phosphorites have been reported by several companies studying this stratigraphic zone (Cominco Ltd., J. Hamilton, pers. comm.).

Upper Phosphate

The Upper Phosphate zone occurs at the top of the Johnston Canyon Formation in those areas where younger Permian strata have been removed, leaving the Johnston Canyon in direct contact with the Triassic Sulphur Mountain Formation. The zone is expressed as slightly phosphatic cemented sandstones, and sandstones containing phosphate nodules. While individual nodules may assay quite high (Section 303, appendix 6), the overall grade of the nodule-bearing zone is low (1-6 percent P_2O_5). This zone has only been recognized in the Banff and Kananaskis areas (figure 9) and may, in fact, be equivalent to the Ranger Canyon Basal zone discussed in a later section of this report.

The Upper Phosphate Zone is, as mentioned previously, likely equivalent to the Ranger Canyon Basal Phosphate. However, where the former zone has been identified, no overlying Ranger Canyon Formation is present and the Upper Phosphate directly underlies the Triassic Sulphur Mountain Formation. The main petrographic phosphates lithotypes are francolitic cements—though structureless and oolitic pellets, bones and shells, nodules and intraclasts can all be found to a lesser degree.

The host rock is generally a very fine-grained sandstone, whose clasts generally appear to be floating in the phosphate cement. Most of the clastic quartz shows pitted and etched surfaces, suggesting dissolution and corrosion. It appears that these sandstones have had their original cement replaced by phosphate cement, and in so doing have had their surfaces pitted by an active chemical environment. Little evidence remains to suggest what the original cement may have been, except perhaps an earlier phase of phosphate or a siliceous cement. An early siliceous cement is suggested by the presence of numerous partially and wholly phosphatized sponge spicules and chert and quartz clasts. Echinoderm and other unidentified fossils are also present.

Calcite has replaced phosphate in some places throughout most samples. Pelletal phosphates within the Upper Phosphates are generally in the 0.2 to 0.3 mm size range, are rounded, well sorted and organic rich. In contrast to the cement areas, they often appear dark brown in plain polarized light. Nodules that are present in otherwise unphosphatized sandstones contain quartz detritus apparently much smaller than the host lithology. This phenomenon, however, may be due to the dissolution process alluded to earlier. Pyrite is very common in these nodules as an accessory mineral. Intraclasts tend to look very much like reworked and transported phosphate cement described earlier in the paragraph. Intraclasts are found in well-sorted, fine-grained, otherwise non-phosphatic sandstone and tend to be a minor component in the rock.

Telford and Ross Creek formations

The Telford and Ross Creek formations are preserved mainly in the Telford Plate in southeastern British Columbia (MacRae and McGugan, 1977). Phosphates are only scantily known in these formations. The Telford Formation conformably overlies the Johnston Canyon and consists of resistant, thickly bedded, sandy, oolitic/pelletal, fossiliferous carbonates (MacRae and McGugan, 1977). The Ross Creek Formation consists of recessive weathering, thin bedded siltstones, shaly siltstones, carbonates and cherts. Pelletal and nodular phosphate zones (up to 24 percent P_2O_5) have been noted throughout the formation, though no thicknesses have been recorded (McGugan and Rapson, 1972).

The contact between the Telford and Ross Creek formations is thought to be paraconformable, with a thin chert conglomerate marking the contact (MacRae and McGugan, 1977). The upper contact of the Ross Creek with the Ranger Canyon Formation appears to be paraconformable and locally disconformable, with the contact being marked by the Ranger Canyon Basal Phosphate Zone.

The Ross Creek Formation is only exposed in the Telford Thrust Sheet, west of the Elk Valley, in the Fernie Basin area between Fernie and latitude 50° (figure 9; MacRae and McGugan, 1977). Phosphate nodules and pellets have been reported from this formation (MacRae and McGugan, 1977); however, no analytical data are available, and the phosphate potential is still largely unknown.

Ranger Canyon Formation

Three phosphate zones have been identified within the Middle to Upper Permian Ranger Canyon Formation: the Basal, Intraformational and Upper zones (figure 7). The Intraformational Zone has been identified only in the Banff area in westernmost sections. Here it consists mainly of thin, lenticular, nodular or channel-type phosphate zones, with individual beds untraceable over any distance. The Upper Zone is found at the Ranger Canyon/Mowitch contact over a wide geographical area (figure 10 in pocket).

The Ranger Canyon Formation has a very wide lateral extent, extending from the Fernie Basin area in southeastern British Columbia, northward to the British Columbia/Alberta border in Willmore Wilderness Park. Stratigraphic equivalents are known to occur as far north as the Yukon Territories (Fantasque Formation) and southward in the United States (Rex Chert Formation; MacRae and McGugan, 1977). Westward, the Ranger Canyon Formation is not present in the Main Ranges, and, eastward, it is unrecognizable throughout most of the easternmost exposures of the Front Ranges. The formation is thickest in westernmost sections (figure 10).

Lithologically, the Ranger Canyon consists of resistant, cliff-forming, blue-gray, massively bedded cherts, cherty sandstones, sandstones and siltstones. Dolomites, gypsum and phosphatic conglomeratics are also present to a lesser degree.

North of the North Saskatchewan River, the Ranger Canyon Formation is overlain sharply and conformably (and farther north, disconformably) by the Mowitch Formation. South of the river, the Ranger Canyon Formation is disconformably and sharply overlain by the Triassic Spray River Group. The base of the Ranger Canyon Formation is marked in most regions by the Basal Phosphate Zone. This zone is, in turn, unconformably underlain by either undifferentiated Carboniferous, Johnston Canyon, Ross Creek or (rarely) Kananaskis formations, depending on the specific location (see figure 10).

Sedimentary and biogenic structures have largely been destroyed within the Ranger Canyon Formation by pervasive silicification. The trace fossils *Rosselia, Planolites beverleyensis*[9] and an unidentified J-shaped vertical burrow are occasionally found within or immediately below the Basal Phosphate Zone. The most common feature observed is wavy and lenticular bedding. Cut and fill structures within the Basal Phosphate are common, having been eroded into the underlying formation, with observed relief of up to 1.0 m (plate 8). Parallel laminations, current ripples, small-scale cross stratification and heavy mineral laminations are also seen in these apparently channel fill deposits. The largest such channel is 3 m wide and 1 m deep.

Basal Phosphate Zone

Description and Occurrence: The Basal Phosphate Zone is one of the most widespread phosphate-bearing stratigraphic zones in Alberta. This zone is found directly below the massive, cliff-forming Ranger Canyon Formation (figure 7, plate 9) and extends from Willmore Wilderness Park south to the Fernie Basin area (figure 11 in pocket). However, many of the easternmost exposures of the Ranger Canyon Formation are not phosphatic at this stratigraphic position (figure 10).

Grade/thickness combinations, in general, improve in an east to west manner (figure 12 in pocket). However, this generality is breached in three locations: northern Jasper Park-Willmore Wilderness Park, southern Jasper Park-North Saskatchewan River, and the Crowsnest Pass area. In these localities, better grade/thicknesses exist for the eastern localities (see appendix 7 for all grade/thickness values).

The Basal Phosphate Zone consists mainly of breccio-conglomerates supported by phosphatic cement or matrix. Clasts are frequently either chert or dolomite, fairly well rounded or very angular, and are up to 1 m in size. One area around the southeast corner of Jasper Park contains a clast-supported, well-rounded, imbricated, flat phosphate pebble conglomerate with a medium to coarse sand matrix at the zone. The Zone has been recognized as far north as the Tuchodi River,

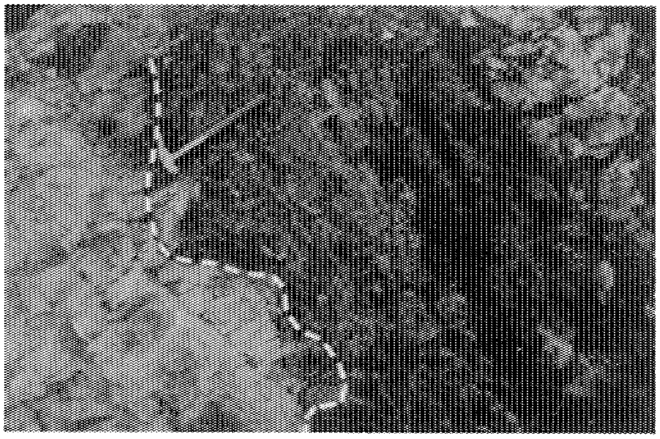

Plate 8. Base of Ranger Canyon Formation (dark colored) showing 30-cm deep scour surface into underlying (light colored) Tunnel Mountain Formation (?). Highway 11 - Roadcut Section 71.

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[9] Trace fossil identification by G. Pemberton, University of Alberta.

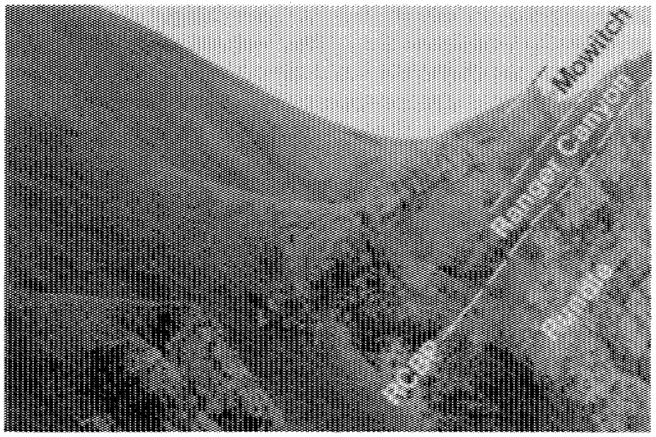

Plate 9. Typical exposure of Ishbel Group in Alberta, represented by Ranger Canyon and Mowitch formations and Ranger Canyon Basal Phosphate Zone (RCBP). Recessive weathering Sulphur Mountain Formation overlies Mowitch Formation. Monoghan Creek - South Ridge, Section 113. Scale: Ranger Canyon Formation is about 20 m thick.

northeastern British Columbia (58°28′N/123°58′W) by Bamber et al. (1968) as being a "...thin, irregular bed of shale containing numerous nodules and ? pebbles of phosphatic material."

Four localities (figure 11) are important in the future development potential of this horizon.

1. West Central Willmore Wilderness Park (Area I, figure 11) - Most localities have phosphate-bearing rocks with one locality having phosphatic rocks.
2. North Saskatchewan River (Area III, figure 11) - One area south and one north of the North Saskatchewan River are in the phosphatic rock group of deposits. Most other exposures in this area between the National Parks include phosphate-bearing rocks.
3. Crowsnest Pass Area (Area VII, figure 11) - A single section (210) in this area had phosphatic rocks (12-18 percent P_2O_5 in a 2 m thickness). However, as all of the Permian is condensed in this area to about 3 m, there is some doubt as to whether this showing does in fact belong to the Basal Zone. The anomalous thickness at this location suggests that the phosphate was deposited in a preexisting channel and does not represent a typical thickness for the area. This idea is supported by sections north and south of section 210 that show a thinner deposit.
4. Southeastern British Columbia, Telford Creek area (Area VI, figure 11) - A single section (232) in the Telford Thrust Sheet showed phosphatic rocks. The areal extent shown on figure 11 is approximate, being based on thickness (but not grades) given by MacRae and McGugan (1977). The zone may be present along the west side of the Elk Valley, north toward Kananaskis Park; however, such an occurrence is not known.

The phosphate is expressed in most areas as a cement that binds a chert breccia or conglomerate. It is also found cementing siltstone or fine-grained quartzose sandstones. In the band of deposits along the southern boundary of Jasper Park and in the North Saskatchewan River area (Area III, figure 11), the phosphate is expressed as reworked phosphate pebbles in a medium- to coarse-grained sand matrix, including the previously described cement. In all cases, it is dark black.

Petrography: The Ranger Canyon Basal Phosphate Zone was the zone most extensively studied, as it appeared to have the best potential for future development. Phosphate within the zone is francolitic cement. Pelletal varieties generally constitute less than 10 percent of the lithotypes, and within this group the structureless varieties are more abundant than the oolitic and nucleated forms. Laminated phosphate is rare. Intraclasts, nodules and phosphatized fossils together constitute about 20 percent of the lithotypes. Phosphate pebbles were deposited as a bimodal phosphate pebble conglomerate occuring in the central region of the study area (Area III, figure 11). These pebbles are detritus free and clast supported in a well-sorted, medium sand matrix. They are flattened, elliptical and show imbrication, and are up to 2 cm long.

The breccio-conglomerates hosting the phosphate cements tend to have unordered fabrics. They are often, though not always, cement supported, show no grading and are polymodal. Clasts are rounded to angular, sometimes within the same rock (plate 10). Clast composition consists of chert, dolomite, sandstone and, less commonly, phosphates. Clast size varies from 1 to 50 cm. The matrix of these conglomerates consists mainly of sand-size chert, quartz, sponge spicules, phosphate pellets and other minor accessory minerals.

Sandstone host rocks tend to be fine grained and well sorted, with pitted quartz and chert clasts. The clasts are floating, and are cemented with phosphate. This sandstone-hosted, fine clastic facies tends to be concentrated in the southwestern part of the study region.

Dolomites are also a host rock, but only in a small area in the southwestern part of the region. In dolomite, phosphate cement is preferentially found in silty quartz laminae or aggregates that contain higher porosity than the very fine grained dolomite.

Francolite often forms crusts or rinds of fibrously

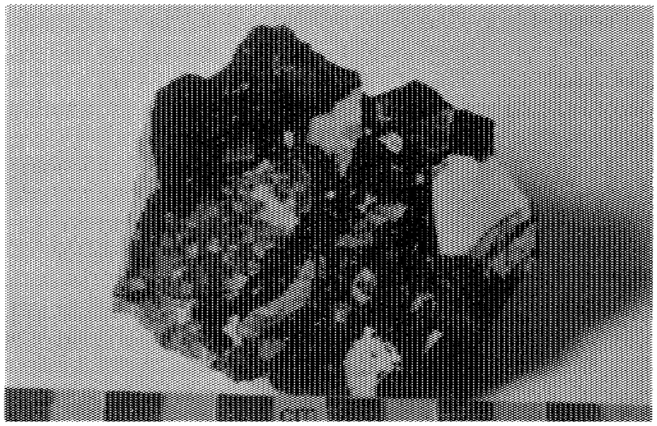

Plate 10. Ranger Canyon Basal Phosphate hand specimen showing a typical chert/dolostone breccia cemented by dark black phosphate. Scale in centimetres. Two O'Clock Creek, Section 1.

radiating crystals around quartz grains, pellets and other material. Most of the pellets are organic rich, structureless and nearly isotropic under crossed polars (plate 3). Ooids are often recrystallized to francolite. Pellets show a platelet-like, layered structure under the scanning electron microscope.

Diagenetic processes seem to have occurred in the following order: early phosphate replacement of sponge spicules and spicular cherts, some recrystallization of early phosphate to francolite cement, replacement of phosphate cements by calcite and to a lesser degree dolomites, and, finally, pore fillings of chert and some chert replacement of cements. Fluorite has also replaced spicule remains, and was probably contemporaneous with the phosphate replacement.

Intraformational Phosphate Zone

Phosphate is known from within the Ranger Canyon Formation at four localities in and around the western portions of Banff National Park (figure 10, appendix 7). The phosphate invariably occurs within a sandstone lithology as cement, phosphatic debris or nodules. The Intraformational Phosphate Zone is petrographically very similar to the Basal Phosphate Zone.

Upper Phosphate Zone

Phosphate is located at the unconformable contact between the Ranger Canyon Formation and the overlying Sulphur Mountain Triassic Formation. This phosphatic bed has a wide areal distribution, extending from Willmore Wilderness Park to southeastern British Columbia.

Grade/thickness combinations within this zone are not well developed with only one locality—Section 363—having phosphatic rocks. Moreover, this locality is in Banff National Park and is therefore not available for development. Nodule-bearing sandstone with high individual nodule assays are present in the Kananaskis area (Section 304, 305, appendix 7). All other occurrences of this zone include phosphate-bearing rocks.

The Upper zone is usually expressed as a phosphate-cemented chert pebble conglomerate, a reworked phosphate pebble conglomerate, a phosphate-cemented sandstone or a nodule-bearing sandstone. The Upper Phosphate Zone is marked by nodules, reworked phosphate pebbles, structureless pellets, bones and several types of cement. Petrographically, this zone is very similar to the Basal Phosphate Zone. Host rocks for the phosphates are either conglomerates or fine-grained sandstones.

Mowitch Formation

The Mowitch Formation is thought to disconformably overlie the Ranger Canyon over most of the study area, though some regions show apparent conformable contacts (plate 9). The Mowitch is lithologically very uniform, consisting of fine- to medium-grained, non-calcareous, thin to thickly bedded, pale yellow brown and slightly resistant, sub-angular quartz sandstones. Minor siltstone and shale beds occur toward the top of the formation. Silicified, lenticular cherty horizons are found scattered throughout the Mowitch, and in some sections in Willmore Park it becomes very difficult to distinguish the Mowitch from the Ranger Canyon, particularly when no erosional surface appears between the two.

Sedimentary structures observed in the Mowitch include massive planar bedding, minor cross stratification, heavy mineral laminations, cut and fill structures near the top of the formation, silicified gypsum knots, vugs, contractions features and minor concretions. Biogenic structures found in the lower Mowitch show vertical carrot shaped (escape?) burrows, whereas toward the top of the formation, *Zoophycus* and *Spirophycus* are the dominate trace fossils.

The upper contact with the Triassic Sulphur Mountain Formation is frequently marked by an upper phosphate zone and is generally thought to be disconformable. However, in some places (Sections 149 and 122), there is evidence to indicate that the contact may be conformable. At section 149, the grain size decreases upward to a silty platy shale and then to an argillaceous siltstone of the lower Sulphur Mountain Formation, seemingly without a break. The lower contact with the Ranger Canyon Formation has been discussed; however, in a few localities in Willmore Park (Section 97, 116 and 117), the Mowitch overlies undifferentiated Carboniferous strata. In these instances, the Basal Phosphate Zone marks the contact. As in the Ranger Canyon Formation, an intraformational phosphate zone is also recognized within the Mowitch.

Basal Phosphate Zone

A phosphate pebble, or phosphate-cemented chert pebble conglomerate, occurs in a zone at the base of the Mowitch Formation in three localities within Willmore Wilderness park (Sections 97, 116 and 117, figure 10). In all three localities, the Mowitch Formation directly and disconformably overlies Carboniferous age carbonates. This zone may be equivalent to any, some or all of the unconformity-type phosphate zones previously discussed. All showings of this zone are in the class of phosphate-bearing rocks only (appendix 7).

Intraformational Phosphate Zone

The Mowitch Formation is known to be slightly phosphatic; in two localities (Sections 146 and 151) north of Jasper National Park, the phosphate-bearing zones reach 6 percent P_2O_5 over 1 m (appendix 8). The phosphate occurs as patchy cement within the predominant sandstone lithology, and as cement within intraformational conglomerates.

Upper Phosphate Zone

Six localities in the northern and central regions have a phosphate pebble conglomerate at the contact between the Mowitch and the Triassic, Sulphur Mountain Formation (appendix 8). Although most P_2O_5 values for this zone exceed 10 percent, corresponding thicknesses seldom exceed 20 cm.

The Upper Phosphate Zone consists of phosphate pebbles, pellets, bones and shells in a fine to very fine grained, poorly sorted, angular calcite/clay cemented sandstone. These pebbles are up to 3 cm long and are composed of francolite cement around fine-grained quartz sand. Some reworked pebbles appear to be compositionally identical to phosphatic sandstones found in the Ranger Canyon Basal Phosphate Zone. These pebbles are in a matrix of clastic quartz, pellets, bones, phosphatic shells and detrital hematite. Other pebbles appear to be aggregates of structureless pellets or phosphatized sponge spicule (formerly cherts?). Replacement features include pellets and spicules being replaced by francolite-type cement, and calcite replacing original clay cement. The Upper Phosphate Zone is likely a secondary reworked phosphate occurrence.

Condensed Ishbel Formation Phosphate

In the easternmost Front Ranges and Foothills regions, all deposits from the Permian, and in places some of the Pennsylvanian deposits, are reduced to a thin (<1 m) chert-carbonate conglomerate. This conglomerate locally contains phosphate pebbles and phosphate cement. In this study, ten stratigraphic sections of the condensed Permian conglomerate have phosphate-bearing rocks associated with them (appendix 8). P_2O_5 contents range from 2 to 14 percent, although thicknesses rarely exceed 0.5 m.

Sulphur Mountain Formation

Phosphate rocks within the Triassic Spray River Group are largely confined to the various members of the Sulphur Mountain Formation, although minor occurrences are also known from most members of the Whitehorse Formation (figure 13). The Sulphur Mountain Formation has been divided into four main members by Gibson (1974). These are the Phroso, Vega, Whistler and Llama (figure 13). This formation is an easterly derived, fine-grained clastic wedge sequence that thickens from east to west. It consists largely of a recessive-weathering sequence of gray to rusty brown dolomitic calcareous siltstones, and to a lesser degree sandstones, silty limestones, dolomite and shale (Gibson, 1974). The best economic potential exists in the Whistler Member (in the Cline-North Saskatchewan Rivers area) and the Llama Member (in the Kananaskis Range). At the stated localities, both members have weighted P_2O_5 percent contents in the 2 to 6 percent range for a minimum 1 m thickness.

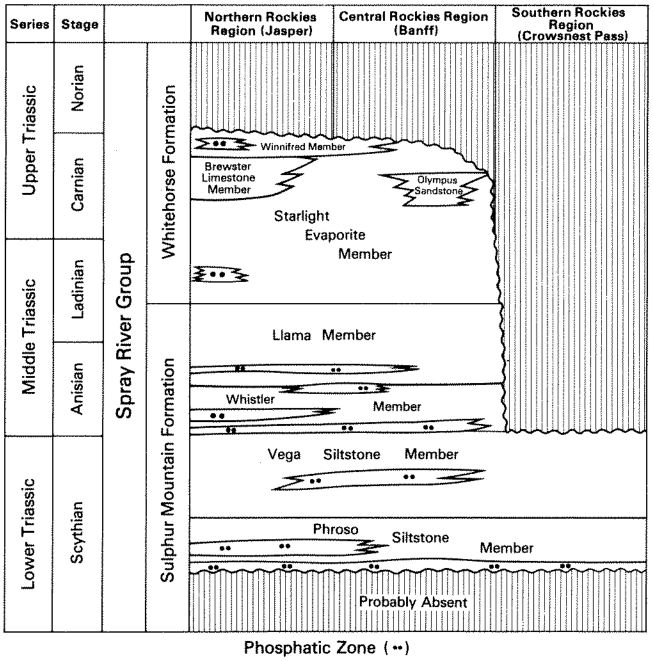

Figure 13. Nomenclature and stratigraphic correlation of the Spray River Group, Front Ranges of Alberta (modified from Gibson, 1974).

Lower Phroso Member Phosphates

The Phroso Member is characterized by thin to fissile bedded, recessively weathering, reddish brown, dolomitic and carbonaceous siltstones, argillaceous siltstones and silty shales. The basal 10 m or so is frequently marked by organic-rich, very recessive weathering, dark-gray-to-black silty shales. The base of this recessive unit is often phosphatic. Of six sections examined (96, 99, 192, 211, 241 and 391, appendix 1), representing the entire study area, only section 211 showed anomalously high P_2O_5 values (1.40 percent/2.0 m).

Phroso Member Intraformational Phosphates

Intraformational conglomerates consisting of reworked phosphate pebbles and shell beds are found sporadically within the Phroso Member (Sections 32, 147, 172 and 189). Sections 32 and 189, which were both sampled, lie in the easternmost Front Ranges, or outliers thereof. Two horizons at Section 32 contain phosphatic material—an upper one consisting of a 5-cm phosphate pebble bed (not sampled) and a lower one consisting of a 10-cm phosphatic shell horizon assaying 18.90 percent P_2O_5. Section 189 contains a single 5-cm phosphate pebble conglomerate bed, which assayed at 2.00 percent. This zone seems to be confined to the northern and north-central Rockies, and is not continuous nor mappable.

Vega Member Phosphates

The Vega Member is a sequence of rusty brown weathering, slightly more resistant (relative to Phroso), medium- to thick-bedded dolomitic siltstones that are rhythmically interbedded with very thin bedded to fissile siltstones. The Vega-Whistler contact is conformable but it is possibly a diastem. The Vega Member probably represents several lenticular, discontinuous zones.

Phosphate is found in the Vega Member primarily as fish debris and, secondarily, as scattered, reworked pebbles. Showings are not confined to any one zone and have been reported by Gibson (1965, 1968a, 1968b, and 1974) from 12 sections throughout the northern and southern parts of the study area.[10] No analyses are available, and most occurrences are less than 5 cm thick.

Whistler Member Phosphate

The Whistler Member is a recessive weathering sequence of thinly bedded, carbonaceous and argillaceous silty dolomites and dolomitic siltstones. Lighter gray dolomite laminations are typically seen interbed-

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[10] Sections: 83, 84, 167, 170, 172, 174, 238, 244, 246, 249, 251 and 269. Appendix 1.

ded with silty shale beds. The lower contact with the Vega Siltstone Member is marked by the Lower Phosphate Zone (figure 13), and the upper contact with the Llama Member by the first appearance of medium to thickly bedded siltstones. Wavy, lenticular and flaser-type bedding are the most common structures seen. Biogenic structures do not seem to be present. A few ammonites have been recovered (Gibson, 1974), although the member as a whole is sparsely fossiliferous. The phosphate consists mainly of oolitic pellets and ooliths, some pebbles and scattered bone remains. It is concentrated in the lower and upper zones of the member primarily in westerly sections. A third, middle zone is present in a few sections. All the analytical data for the Whistler Member phosphate are summarized in appendix 9.

The lower zone is known to be present from Willmore Wilderness Park to as far south as the Red Deer River. Although the zone is regionally more extensive than the other Whistler phosphatic zones, it seems to lack substantial grades and/or thicknesses. Section 174, Mount Greenock, has the thickest exposure of phosphate (20 cm); however, no analyses are available.

The middle zone has been identified at Section 126, in the Snake Indian River area, Jasper National Park, and possibly from Sections 79, 80 and 82 in the Cline-North Saskatchewan River area. The zone has very limited economic potential by itself; however, in combination with upper or lower zones in a continuous sequence, it may have some value.

The phosphate in the upper zone is found mainly as quartz-cored pellets and intraclasts in dolomite cement, with some quartz/feldspar matrix. This zone seems to have its best economic potential in the Cline-North Saskatchewan River area, where beds of up to 50 cm of 10.40 percent P_2O_5 are found (section 45).

Three sections in the upper zone showed substantial phosphate concentrations (Sections 79, 52, and 45; appendix 9). All three are in the Cline-North Saskatchewan River area where the zone seems to increase in grade and thickness to the west. Two other localities (Sections 99 and 380, figure 18) north and south of the Cline-North Saskatchewan River valley have some minor amounts of phosphate.

Phosphates of the Spray River Group are best developed in the Whistler Member of the Sulphur Mountain Formation. Petrographic examination of 12 samples from the Whistler phosphorites shows a predominance of the nucleated and oolitic pellets, and *Lingulid(?)* shell fragments (plate 11). Structureless pellets, bones, intraclasts and cements occur less frequently. The phosphates usually occur in a non-burrowed, very finely crystalline, well-laminated silty dolomite or, less commonly, a dolomitic siltstone. Phosphate pellets are usually subrounded, moderately to well sorted, loosely packed and 0.10 to 0.40 mm in size. They often contain cores or nuclei of detrital quartz, zircons, dolomite or shell fragments.

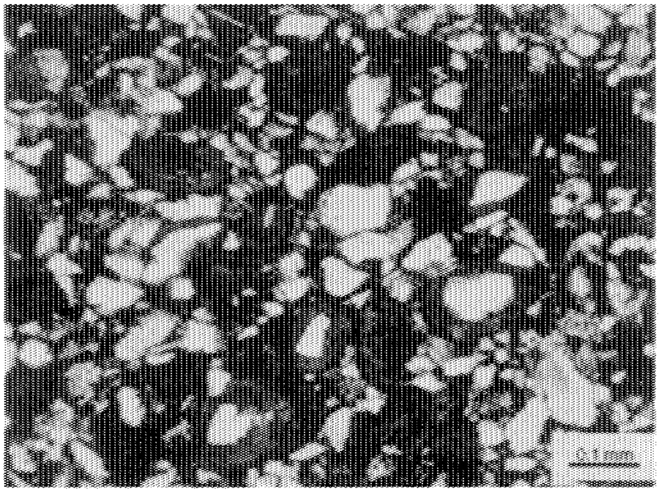

Plate 11. Pellets cored with quartz, minor structureless pellets, set in dolomitic siltstone of the Whistler Member, Sulphur Mountain Formation. Plain light.

Llama Member Phosphates

The Llama Member is a resistant, cliff-forming sequence of thin to thickly bedded, yellow brown, silty sandy dolomite and dolomitic siltstones. The overlying contact with the Whitehorse Formation is generally sharp. Some intraformational dolomitic-clast conglomerates, as described by Gibson (1975), probably correspond to the Llama Member as identified in this study (figure 13).

Phosphate is concentrated in the lower, and to a lesser extent, the upper portions of the Llama Member. It is normally expressed as fossil shell remains and pebbles. Such phosphates are rarely found within a single bed but are scattered throughout several metres of strata. One exception seems to be in the Kananaskis Range (Section 242, appendix 1), where concentrated phosphate pellet beds are interbedded with non-phosphatic sandstones over a 2.35 m interval (weighted P_2O_5 average = 1.56 percent).

Only two of the phosphatic beds were sampled (Mobil Oil Canada, 1966), yielding weighted grade/thicknesses of 5.2 percent P_2O_5/0.7 m or 3.67 percent P_2O_5/1.0 m. Many other beds in this 2.35 m interval contain phosphate pellets; more-detailed sampling may yield better grade/thickness values. The zone is found throughout the Kananaskis Range where twenty other occurrences have been reported[11] by Gibson (1965, 1968a, 1968b, 1974), although no assay results are available.

Whitehorse Formation

Scattered occurrences of phosphatic material are present in the Starlight Evaporite and Winnifred Members of the Whitehorse Formation.

Nine phosphate locations are known from within the Starlight Evaporite Member.[12] All occurrences include phosphatic *Lingula* shells scattered through the member. Phosphate is found in the Winnifred Member at six

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[11] Sections: 60, 83, 84, 85, 86, 87, 99, 147, 164, 165, 166, 167, 170, 171, 172, 173, 174, 175, 176 and 320.

[12] Sections: 1, 161, 162, 164, 166, 171, 173, 174 and 175.

localities, all within the Northern Rockies region.[13] They are all in thin and lenticular beds. There, the phosphate occurs as *Lingula* shell fragments and as scattered pellets.

Fernie Formation

Description

Phosphate in the Jurassic Fernie Formation is best developed within the Basal Fernie Phosphate Zone, Nordegg Member and Nordegg Equivalent (figure 14). Phosphate is also present, to a lesser extent, in the Rock Creek Member. Low-quality, small phosphate deposits are found in the Red Deer Member and the Poker Chip Shales.

The Jurassic Fernie Formation consists of 70 to 376 m of marine shales, limestones and sandstones. The formation thickens from east to west, in general. It is found throughout the Front Ranges, primarily in major intermontane valleys, its topographic expression being a result of the recessive nature plus the stratigraphic/structural control (figure 3, plate 12). The Fernie Formation has been divided into several members and beds (Frebold, 1957) (figure 14). Fernie strata unconformably overlie Triassic strata in most areas; however, in southern Alberta they overlie the Pennsylvanian Tunnel Mountain Formation. The Fernie crops out in a fairly narrow band extending from the Crowsnest Pass area northward to beyond the study area in Willmore Wilderness Park (figure 15 in pocket). It extends eastward into the subsurface, where it thins, both depositionally and by post-Jurassic erosion.

The regional stratigraphy of the Lower Jurassic portion of the Fernie Formation is seen in a series of columnar sections (figure 16 in pocket). The areal extent of Lower Jurassic phosphatic and phosphate rock is confined to westernmost exposures of the formation (figure 15).

The Basal Fernie, Nordegg Member and Nordegg Equivalent phosphate zones are all of Sinemurian age, and all are considered to be lateral facies equivalents of each other (figure 14, plate 13).

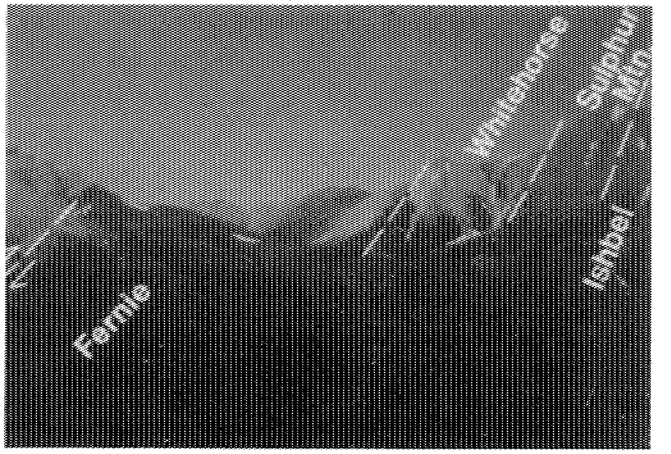

Plate 12. Typical structural/stratigraphic/topographic setting of phosphate-bearing units in the Cordilleran Front Ranges. Intermontane recessive areas - Fernie Formation. Major thrust at the rock/treeline contact - extreme left. Willmore Wilderness Park, Alberta.

Plate 13. Nordegg Member of the Lower Fernie exposed at Whitehorse Creek, Section 13 near Cadomin, Alberta. Eastern shelf facies. Woman's head is at the top of the Whitehorse Formation, pack is within the phosphatic zone. Section grades upward into thickly bedded cherty limestones.

Sinemurian age strata consist of two main lithofacies: an eastern shelf facies (carbonate-chert) and a western basin facies (fine-grained clastic phosphatic rocks—figure 16). The eastern shelf facies is represented by the Nordegg Member in outcrop (Nordegg Formation in the subsurface), and consists of up to 50 m of medium to thickly bedded limestones, cherty and sandy limestones, chert, sandstones, dark carbonaceous shales, breccia beds and coquina beds. The western basin facies (Nordegg Equivalent and Basal Fernie Phosphate Zone) consists of up to 10 m of thinly interbedded carbonaceous/calcareous shales and limestones, mudstones and pelletal phosphates, and up to seven thin bentonite seams. Sedimentary structures are generally lacking in Sinemurian age strata, and individual bed contacts are generally sharp. Graded and poorly sorted homogenous sandstone beds are occasionally present within these predominantly shale sequences of the western basin facies. The pelletal phosphorite beds are generally structureless, with occasional phosphate intraclast horizons being present. Biogenic structures also also generally lacking, with a few unidentified horizontal burrows present in the Nordegg, one occurrence of a burrow with a *Thalassinoides* morphology in the Basal Fernie Phosphate and one

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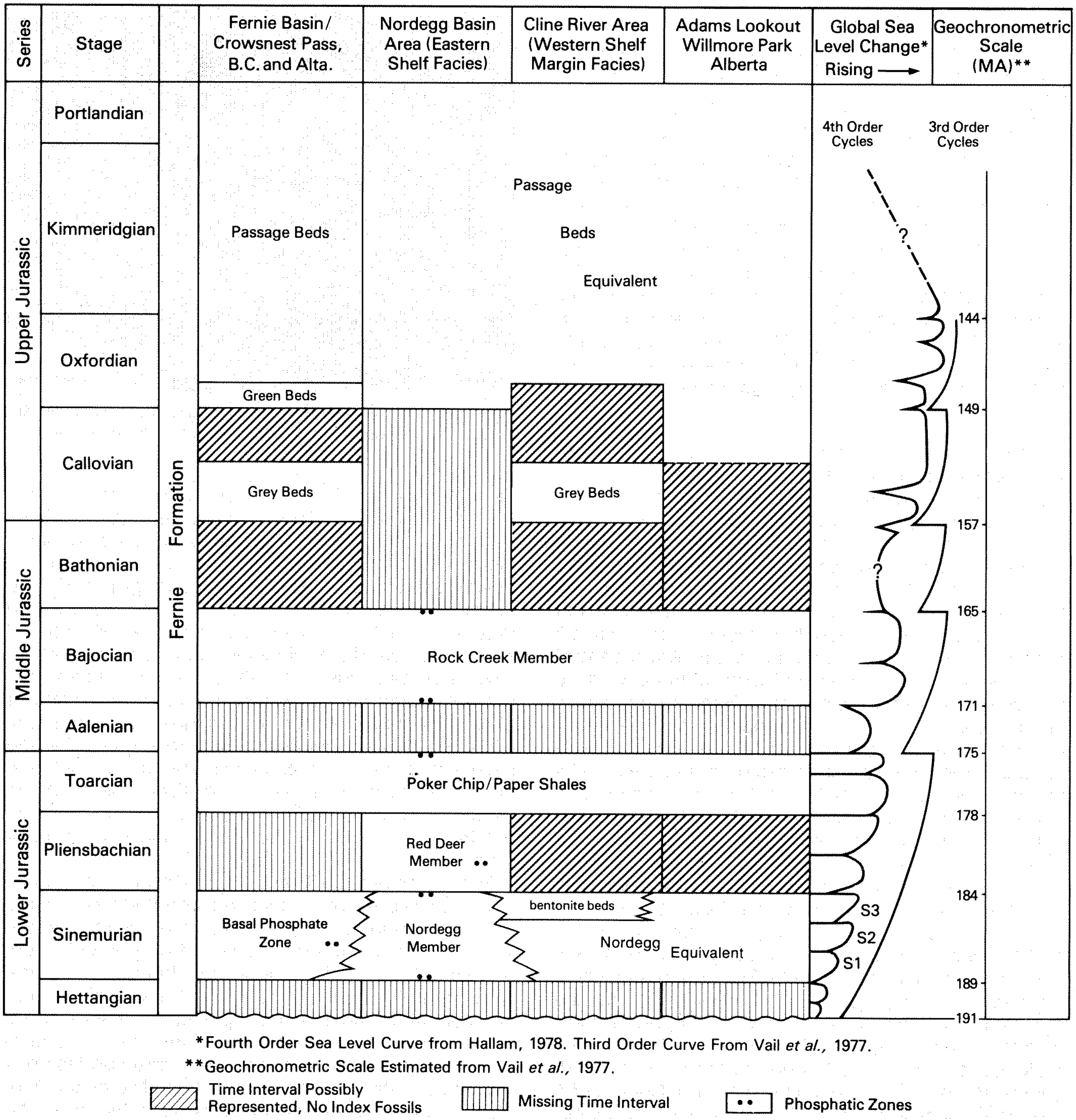
[13] Sections: 147, 164, 165, 166, 172 and 173.



*Fourth Order Sea Level Curve from Hallam, 1978. Third Order Curve From Vail *et al.,* 1977.

**Geochronometric Scale Estimated from Vail *et al.,* 1977.

Figure 14. Age, nomenclature, sea level rises, and lithologies—Fernie Formation, Alberta and southeastern British Columbia (modified from Frebold, 1957).

Paleodictyon trace.[14] Hard-bodied invertebrate fossils are abundant in the Sinemurian strata (Frebold, 1957). Ribs, miscellaneous bones and vertebrae (*Ichthyosaurous*?, pers. comm. C.R. Stelck) are also particularly abundant in the Lower Sinemurian.

The lower contact with Triassic, or in some cases Permo-Pennsylvania strata, is invariably sharp and disconformable. The upper contact with the Poker Chip Shales or the Red Deer Member is sharp where the entire Sinemurian is condensed to the Basal Phosphate Zone. However, where the Nordegg or Nordegg Equivalent is developed, the upper contact is more gradational. In the absence of reliable index fossils, this contact was taken to coincide with the uppermost occurrence of chert or the disappearance of multiple bentonite seams.

Petrography - General

The mineralogical characteristics of Jurassic age phosphates are different from those of the other geological periods discussed, based on their chemical

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[14] Identification of *Paleodictyon* by G. Pemberton, pers. comm.

characteristics. Lucas et al. (1980) describe the mineralogy of phosphates by certain chemical properties and ratios (e.g. CaO/P_2O_5, F/P_2O_5, CO_2, Na_2O, F, MgO).

The Jurassic phosphates more closely approach pure fluorapatite in their CaO/P_2O_5 ratios, CO_2 and Na_2O contents (table 2) and approach francolite in their F/P_2O_5 ratio, CaO, P_2O_5, F and MgO contents. Thus, the Lower Jurassic phosphates would seem to overall more closely approach a carbonate-poor francolite.

The Middle Jurassic phosphates more closely resemble pure fluorapatite in their CaO/P_2O_5 ratios, CO_2, F and Na_2O. Conversely, this same group more closely approximates francolite in their F/P_2O_5 ratio, CaO, P_2O_5 and MgO contents. The high CO_2 content in the Middle Jurassic phosphates would tend to make them slightly more francolitic in mineralogy than the Lower Jurassic forms.

Petrography - Basal Fernie Phosphate Zone

There are three main types of phosphate expression in the Basal Phosphate zone: pelletal phosphorites, coarse clastics hosting phosphates (conglomerates and sandstones), and phosphatic shales.

The pelletal phosphorites are the most economically important and consist mainly of the structureless pelletal petrographic lithotype (plate 1). The nucleated and oolitic varieties are generally present in less than 20 percent abundance, although in the north-central deposits (figure 15, Areas II and III) the abundance rises to nearly 35 percent in some cases. Nodules, intraclasts and phosphatic bone material make up the remainder of the phosphate material in these pelletal phosphorites. Most structureless pellets in the pelletal phosphorites are from 0.05 to 0.50 mm in size (mean value about 0.13 mm), well to moderately well sorted, subrounded to rounded, and very loosely packed. More densely packed varieties are found in Area I, Fernie Basin (figure 15), particularly in the south, where pellets are very densely packed with some showing plastic-like boundary adjustments. Lowell (1952) has suggested that this feature suggests early compaction of pellets while in a gel-like or plastic state. Pellets appear bleached, due to weathering, at some localities but most are not. Scanning electron microscope micrographs show pellets to be composed of very thin (50-100 nm) platelets of francolite. Other pellets show an anhedral, very finely crystalline, francolite (plate 14). Cook (1972) describes similar fluorapatite hexagonal crystallites from the Duchess Deposit in Queensland, Australia. Most pelletal phosphorites from the present study have a quartz silt matrix, and recrystallized sparry calcite-cement. Pelletal phosphates from Areas II and III (figure 15) tend to have more calcite cement and more silty matrix than those in Area I. These impurities are reflected in an overall lower grade of phosphorites (8-15 percent P_2O_5 generally) in those areas (i.e., Areas II and III) as compared to the Fernie Basin region (Area I). Dolomite, clay and barite cements are occasionally found in these pelletal phosphorites but are not common.

Nucleated pellets far outnumber oolitic pellets and are generally cored with a clastic quartz grain. Many of these nucleated pellets are clastic quartz with a thin rim of francolite material. Mineral replacement within these pelletal phosphorites is dominated by calcite replacement. Calcite is seen to replace phosphate pellets, quartz grains and occasionally feldspar grains. Calcite replacement of phosphate accounts for much of the lowering of grade at some locations. The pellets themselves show very little evidence of having been anything else other than phosphate. Although they are generally organic matter-rich, they rarely contain any micro or other fossil remains that might suggest a fecal origin. Likewise, little evidence is present to suggest that the pellets may have been calcium carbonate at one time, and were subsequently phosphatized. Most of the pellets likely formed authigenically from phosphorous-rich interstitial waters in muds below the water/mud interface.

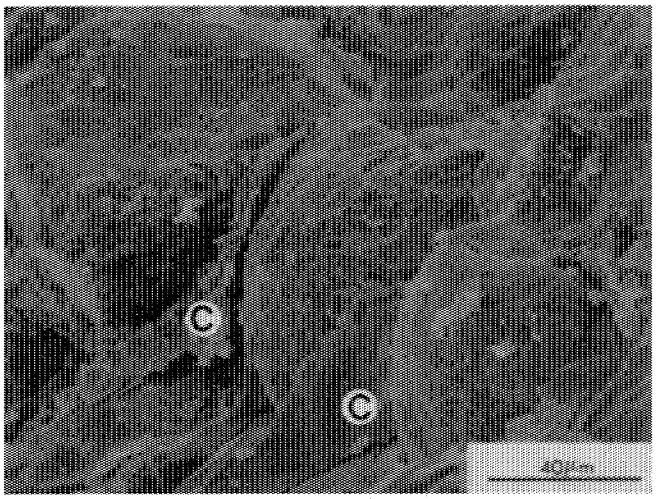

Plate 14. Scanning electron micrograph of three Basal Fernie Phosphate Zone pellets. Calcite (C) cements the pellets.

In the eastern shelf facies, the Basal Fernie phosphate zone is, in many places, represented by a thin (30 cm) phosphate-bearing sandstone or conglomerate. The petrographic nature of this unit is apparently very dependent upon the underlying formation. In the Crowsnest Pass area, underlain by the very clean Tunnel Mountain sandstones, the phosphatic sandstone is a well-sorted, well-rounded, medium-grained, quartzose sandstone that contains mostly structureless pellets, intraclasts, nodules or pebbles and some bone remains. Structureless pellets predominated over the other phosphate lithotypes and generally occupy less than 10 percent of the rock by volume. In the Livingstone Range, where the underlying formation is the subangular siltstones of the Sulphur Mountain Formation, the phosphate consists of structureless pellets and intraclasts in a poorly sorted, subangular to rounded, very fine grained sandstone. This relationship of the underlying formation to the type of phosphatic sandstone seem to hold true northward, where the Whitehorse Formation underlies the Basal Fernie zone and dolomite intraclasts are often present. In the Jasper region and northward, westernmost Basal Fernie sections often show phosphate intraclasts and pebble-rich conglomerates. Intraclasts and some phosphate peb-

Table 2. Microprobe determined compositions of carbonate fluorapatites in phosphorites - this study - by petrographic lithotype and geological period.

	Petrographic Lithotypes					Geological Period				
	Pellets (n = 20)[1]	Bones (n = 5)	Shells (n = 7)	Intraclasts (n = 8)	Cement (n = 9)	Dev./Miss. (n = 16)	Permo-Penn (n = 6)	Triassic (n = 7)	Lower Jurassic (n = 19)	Middle Jurassic (n = 3)
F	4.147	4.343	3.494	3.955	4.273	3.367	4.277	4.168	4.079	3.998
Na_2O	0.439	0.816	0.580	0.397	0.482	0.517	0.540	0.959	0.333	0.224
MgO	0.731	0.474	0.837	0.649	0.575	0.815	0.558	0.658	0.698	1.070
Al_2O_3	0.734	0.292	1.385	1.339	0.555	0.1675	0.343	0.640	0.925	2.187
P_2O_5	35.574	36.842	32.619	33.484	37.477	33.734	36.764	36.947	33.532	36.181
S	0.816	0.728	0.460	0.589	0.5888	0.297	0.683	0.918	0.691	0.820
Cl	0.0	0.0	0.0	0.154	0.018	0.0	0.052	0.009	0.007	0.0
K_2O	0.123	0.021	0.607	0.379	0.139	0.750	0.074	0.145	0.218	0.277
CaO	49.987	51.886	44.675	48.386	51.653	44.644	51.615	51.319	48.034	50.292
TiO_2	0.052	0.0	0.055	0.180	0.032	0.0	0.015	0.086	0.111	0.166
V_2O_5	0.025	0.0	0.015	0.075	0.051	0.018	0.018	0.062	0.050	0.0
MnO	0.064	0.053	0.051	0.072	0.072	0.051	0.053	0.124	0.056	0.056
FeO[2]	1.186	0.103	2.327	1.082	0.523	3.344	0.474	0.194	1.009	2.519
ZnO	0.657	0.107	0.161	0.071	0.084	0.144	0.059	0.184	0.075	0.0
CO_2[3]						0.99	1.33	2.19	1.96	3.00

[1] n = number of samples

[2] Total Fe, As FeO

[3] CO_2 determinations by XRD

bles are generally rich in silt-size clastic quartz and dolomite material. Phosphate cements are generally not present in the zone; however, some of the phosphate pebbles within these conglomerates show evidence of previous cementation by phosphates. Several episodes of phosphate precipitation, erosion and transportation are therefore indicated. All the phosphate found within these sandstones and conglomerates appears to be reworked and transported material.

Phosphatic shales are the third most common expression of the zone, and in this case the source of phosphatic material is often very difficult to discern. This is due to the very fine grained nature of the material and is further masked by high organic contents. The most common phosphate petrographic lithotype is the elongated pellets, typically set in a very argillaceous, well-laminated, unburrowed calcareous shale. These pellets tend to have many of the characteristics of the pelletal phosphorites; however, some pronounced differences are present. The elongate pellets are sometimes smaller in size (mean value approximately 0.07-0.10 mm), are not well sorted and have a typically elongated to lensoidal shape. These pellets appear to be precursors to the more rounded pellets, and perhaps formed as a phosphatic gel in this argillaceous setting as suggested by Lowell (1952).

Petrography - Nordegg and Nordegg Equivalent

The base of the Nordegg Member contains a series of organic, phosphatic shales and argillaceous limestones, with the phosphate generally in the form of phosphatic bone or shell debris. This fossil material is frequently replaced by sparry calcite, some fossils having been completely replaced by calcite.

Phosphate within the middle to upper Nordegg Member is best developed in cherty sandstones. The phosphate occurs as structureless and nucleated pellets, in part replaced by chert or calcite. Both varieties seem to be present in roughly equal abundance, throughout the member. Most of the nucleated variety have quartz cores, a thin pyrite layer and an enveloping phosphate layer. Phosphate nodules are also present, though not abundantly so. Chertification has been extensive in the Nordegg Member, masking many of the primary lithologies and perhaps many of the primary phosphate petrographic textures.

The top of the Nordegg Member contains the *Oxytoma* phosphate zone and consists mainly of phosphate pebbles in a conglomerate, structureless pellets in a well-sorted, quartzose sandstone, or phosphatized fossil shell debris.

Occurrences - Basal Fernie Phosphate Zone

In most eastern exposures, where Sinemurian age strata are preserved, this zone is represented by a thin (<1 m) phosphatic, pebbly sandstone or conglomerate. Concentrations of phosphatic fossils are also found in some localities. In western localities of the Fernie Basin, Cascade River Valley (Banff Park) and the North Saskatchewan River region (Areas I, II and III, respectively; figure 15), phosphate is pelletal and found within the lower 5 m of the contact. These latter three regions have the best phosphate potential in terms of grade/thickness combinations for the entire Fernie Formation.

Within Area I, the phosphate potential seems to be best in the southernmost outcrops of the zone and apparently diminishes northward up the Elk Valley toward Kananaskis Park and eastward toward Crowsnest Pass. It should, however, be noted that the data distribution in the northern Elk Valley is very limited. Pelletal phosphate rock in the southern Fernie Basin area gradually changes to a low-grade phosphatic sandstone in the northern Elk Valley-Kananaskis area and to phosphate-bearing shale north of Kananaskis Park in the Ribbon Creek areas (figure 16).

In Area II (figure 15), along the Cascade River Valley in Banff National Park, pelletal phosphates in the zone reaches a maximum grade/thickness of 14.1 percent/m, and the zone appears to be in the phosphatic rock class (appendix 10). No internal trends are apparent except that pelletal rock becomes phosphatic sandstone northward, and phosphatic shale southward.

Area III extends from the northwest border of Banff National Park, northward to the North Saskatchewan River. Here, the phosphate potential is believed to be consistently in the 6 to 12 percent P_2O_5 range for a minimum 1 m thickness; thus, the rocks are phosphatic. Pelletal phosphate is found at the contact and as high as 16 m above the contact (Section 385).

Area III (figure 15), excluding the portions in Banff Park, has the best potential for future phosphate development in Alberta. The only land use restriction in place at the present time is the Eastern Slopes Land Use Management Policy which places Area III in a "Prime Protection Zone." Area II is entirely within Banff National Park and Area IV within Jasper National Park. Area I, in the Fernie Basin of British Columbia, has the best geological potential for future development and currently is free of any land-use constraints. The Fernie Basin area may contain over 2 billion tonnes[15] of subsurface phosphates, as the basin is a large synclinal structure with surface outcrops on the east and west flanks. If this subsurface phosphate is continuous throughout the Fernie Basin, it would represent a vast resource for possible future in situ recovery programs.

The Fernie Formation and the basal zone within it, occupies a structural/stratigraphic/topographic position that is quite favorable to open pit mining. The formation is usually found in intermontane valley areas, at relatively low elevations, with dips somewhat flatter than those found in the mountain range areas, and is overlain by Middle and Upper Jurassic Fernie Formation soft shales (figure 3). On the other hand, due to the incompetent nature of the Fernie Formation, local structural folding, faulting, and near-surface creep can complicate mining conditions. Structural thickening of the zone by faulting is known to exist in the vicinity of Section 205 (north of Crowsnest Pass), and possibly in the Lizard Range (near Section 207).

Occurrences - Nordegg and Nordegg Equivalent

The cherty limestones and calcareous bedded cherts that form the Nordegg Member are often underlain by an organic-rich, phosphate-bearing black shale zone. These are commonly in the 1 to 4 percent range and are up to 3 m thick; however, none have a grade/thickness combination sufficient to place them in the phosphatic rock category. The middle to upper Nordegg Member is known to contain disseminated phosphate debris, and at one locality (Section 5, appendix 10), phosphate nodules. While thicknesses of the phosphate-bearing zones can exceed 17 m, corresponding grades never exceed 4 percent P_2O_5. However, the Nordegg Member is not phosphate-bearing in a regional sense. The top of the Nordegg Member is frequently marked by a fossil hash horizon containing the pelecypod *Oxytoma cygnipes,* an index fossil for the Sinemurian (Frebold, 1957). A phosphate pellet-bearing sandstone, or pebbly conglomerate, is often found immediately above or in the place of the *Oxytoma* bed. The Nordegg Member shows the best grade/thickness combination observed for this zone at Section 23 (appendix 10), reaching 6.87 percent/m. All other sections contain phosphate-bearing rocks only.

Red Deer Member Phosphate Zone

Phosphate has been identified in the Red Deer Member primarily in Banff National Park and east of the Park (figure 15). The Red Deer Member is lithologically very similar to the overlying Poker Chip shales and the underlying Sinemurian age strata. Frebold (1969) has identified the Red Deer Member only from fossil evidence, and only in a limited area. Only one occurrence (Section 385), contains substantial amounts of phosphate (8 percent P_2O_5 over 0.70 m). The phosphate occurs as pellets and is tentatively assigned to the Red Deer Member based on stratigraphic position, with no definite fossil evidence being present. All other occurrences are in the phosphate-bearing rock group.

Poker Chip Phosphate Zone

Some intervals within the Poker Chip shale beds are known to be phosphate-bearing to a slight degree (1-5 percent P_2O_5). Only one specific zone could be identified in more than one section, i.e. at the top of the member a phosphate-bearing sandstone or phosphate conglomerate is found in places (Sections 9, 190). Section 190 has the best grade (22.30 percent/0.10 m); however, Section 407 is worthy of note as numerous phosphate zones are found over a 2.74 m interval within the member, yielding an average grade of 5.12 percent (Appendix 10).

The Pliensbachian Red Deer Member and the Toarcian Poker Chip Shales have a wide areal extent, generally larger than the Nordegg and Nordegg Equivalent strata. In many eastern exposures, the Poker Chip Shales directly overlie Triassic or Permo-Pennsylvanian strata. The upper contact of the Poker Chip Shales is sharp and distinct, with the dark, organic, calcareous interbedded limestones and shales of the Poker Chip Shales abruptly replaced by non-calcareous, rusty weathering (pyritic), fissile shales of the Rock Creek Member. Lithologically, the Poker Chip Shales constitute a uniform series of very thin to thinly interbedded dark organic shales and microcrystalline limestones. Sedimentary and biogenic structures are generally not present. Invertebrate fossils are very abundant.

Rock Creek Phosphate Zone

Within the Middle to Upper Jurassic, phosphate is present only within the coarse clastic facies of the Rock Creek Member as an upper and lower zone. This clastic facies of the Rock Creek Member is found throughout

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[15] Based on a crude rectangular shape of 74 x 12 km, assuming a 1 m thickness of Basal Fernie Zone over the entire area.

the Middle Fernie in the Front Ranges and into the subsurface. The upper contact with Bathonian or Callovian age strata is not distinct and is based, lithologically, on a transition from reddish brown weathering shale to light gray weathering shale. Lithologically, the Rock Creek Member, shaly facies, consists of dark gray to black, reddish brown weathering pyritic fissile shales with some interbedded, arenaceous belemnite-rich limestones. The coarse clastic facies of the Rock Creek Member consist of interbedded sandstones, siltstones and some shales. The correlations from Sections 324 to 367 and 286 to 283 (figure 17, in pocket) illustrate how both westward and eastward increase in sandstone versus shale can occur. Springer et al. (1964) found the Rock Creek Member, in general, to become more argillaceous in a westward direction, and more arenaceous in an eastward direction, based on subsurface data. Phosphate is found most commonly as nodules, though occasionally oolitic pellets, at the uppermost and lowermost contacts of the coarse clastic facies of the Rock Creek Member. The Upper Zone is found predominantly in the northern region, whereas the Lower Zone predominates in the south (figure 17).

Invertebrate fossils are very common within the coarse clastic facies of the Rock Creek Member (Frebold, 1957). Biogenic structures include *Gyrochorte, Rhizocorallium* and *Planolites montanus*[16], all from the Cruziana ichnofacies. *Belemnites* are the most common fossil in the Rock Creek Member and are often found concentrated in calcareous, arenaceous horizons as "Belemnite Battlefields" (plate 6).

Lower Phosphate Zone: Phosphate is commonly found near the base of the Rock Creek Member (figure 17). The Rock Creek Member consists of shales and sandstones, with the Lower Zone being associated with the lowermost sandstone and shales in the member. Phosphate is expressed as nodules, pellets or unidentified debris generally found in a calcareous sandstone. Phosphate-bearing zones tend to be less than 2 m thick with corresponding grades less than 6 percent P_2O_5 (appendix 10). A normalized 1 m interval yields grades in the 2 to 7 percent range. Sections 220 (Lodgepole Creek, British Columbia) and 417 (Nordegg) are the only occurrences that can be classified as phosphatic rocks. Sections of the Lower Zone, a few kilometres south of Nordegg, are also known to be in the phosphatic rock class (J.M. Hamilton, Cominco Ltd., pers. comm.), but are reported to contain large amounts of pyrite.

Upper Phosphate Zone: Phosphate, as nodules and less commonly pellets, is found at the uppermost sandstone in the Rock Creek Member (figure 17). Nodules usually make up less than 20 percent, by volume, of a given bed. Seven occurrences of the Upper Zone are known in a region extending from the Jasper area (Section 181) south to the Crowsnest Pass (Section 196). All are in the easternmost Front Ranges or Foothills Belt, and all are phosphate-bearing rocks only (appendix 10).

Petrography: The Rock Creek Member phosphate-bearing zones consist primarily of phosphate nodules and more rarely structureless, nucleated and oolitic pellets. Nodules are by far the most common lithotype, and obtain sizes of 8 to 10 cm. The nodules are diagenetic, showing clear evidence of having grown in place. These nodules are frequently found in an iron-rich—often siderite or pyrite—fine-grained, carbonate-rich, moderately well sorted, sub-angular to sub-rounded sandstone. Belemnites, ammonites and pelecypods abound within these nodule zones, and some of these fossils appear to have been replaced by apatite. Glauconite is sometimes present as a minor mineral. The phosphatic material within the nodules is a mixture of cements and recrystallized fibrous francolite cement. Nodules often have shell fragments that have been replaced by phosphate, and may have acted as nucleation sites for diagenetic phosphate precipitation. The pelletal phosphorites often consist of forams, bryozoans(?), algae and small pelecypod shell fragments that have been replaced by phosphate (plate 15). Several layers of phosphate have apparently been added to many pellets, giving them an oolitic texture. Pyrite is often seen at the cores of pellets as fine laminae within non-fossil type pellets. Calcite replacement of phosphate pellets or oolites is indicated by "ghost" outlines of the former structures. The Rock Creek Member phosphates are therefore seen as resulting from early diagenetic phosphatization of fossil material and the formation of diagenetic phosphate nodules.

Miscellaneous occurrences

A number of other phosphate showings are present in Alberta; however, very little is known about them. These miscellaneous occurrences are discussed below:

Athabasca Group - Precambrian Helikian: Thin (<10 cm) phosphorites have been reported from the Precambrian Upper Wolverine Point Formation, Athabasca Group by J. Wilson (1985). The phosphate is found within a series of tuffaceous sediments and is expressed as a gray to colorless, zoned fluorapatite with low birefringence. No bulk chemical analysis is

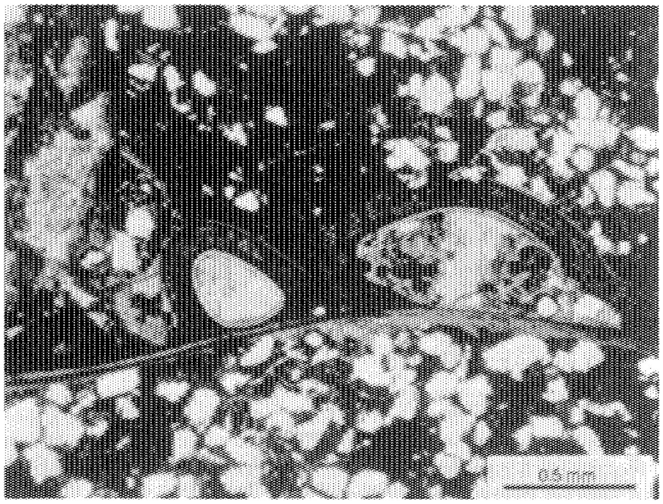

Plate 15. Gastropod shell completely phosphatized by francolite. Rock Creek Upper Phosphate Zone, Fernie Formation. Plain light.

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[16] Trace fossil identification by G. Pemberton, University of Alberta.

available; however, microprobe analysis on the phosphate cement revealed 40.55 percent P_2O_5, 4.3 percent F, 1 percent Na^+, Mg^+, Al, 0.3 percent V, Mn and Fe, based on two sample points only.

Christie (1981b) has reported oolitic, cement and fracture-fill type phosphates also from the Wolverine Point Formation of the Athabasca Basin. Grades of up to 30 percent P_2O_5 within intraformational conglomerates have been discovered by Eldorado Nuclear Ltd. (Christie, 1981b); however, most zones seem to be less than 0.5 m thick (up to 1 m is occasionally present) with corresponding grades around 10 percent P_2O_5.

Flume Formation - Upper Devonian: A 30-cm thick, pelletal phosphate zone has been reported from the Flume Formation at Kakwa Lake, British Columbia (B. Chatterton, pers. comm.).[17] Kakwa Lake is approximately 8 km west of the Alberta border, northwest of Willmore Wilderness Provincial Park (Latitude 54°, Longitude 120°10′). This same zone may be present in the Western Main Ranges of Willmore Park.

Shaftesbury Formation - Upper/Lower Cretaceous: Phosphate, in the form of densely packed fish scales, is reported to occur within the well known stratigraphic marker horizon known as the "Fish Scale" horizon on the east side of the Birch Mountains in northeastern Alberta (R. Green, pers. comm.) (figure 1). The bed is 30 cm thick and lies within a thick sequence of shales, with the Fish Scales marking the Upper/Lower Cretaceous boundary. No grades are available. The Fish Scale horizon is known to be very widespread throughout most of Alberta.

Dunvegan/Shaftesbury Formation: Phosphatic, uraniferous black shales are reported to be present near the Shaftesbury-Dunvegan Formation contact in the Birch Mountains of northeastern Alberta (J. Stewart, First Nuclear Corporation, pers. comm.). Surface samples collected by First Nuclear revealed up to 3.94 percent P_2O_5, 0.027 percent U_3O_8, 0.2 percent vanadium and up to 11.90 percent carbon. The bed thickness is unknown; however, gamma-ray log expressions suggest several tens of metres. This zone outcrops along the eastern edge of the Birch Mountains and extends into the subsurface to the west where it is overlain by younger Cretaceous strata and glacial deposits to an average thickness of 76 m.

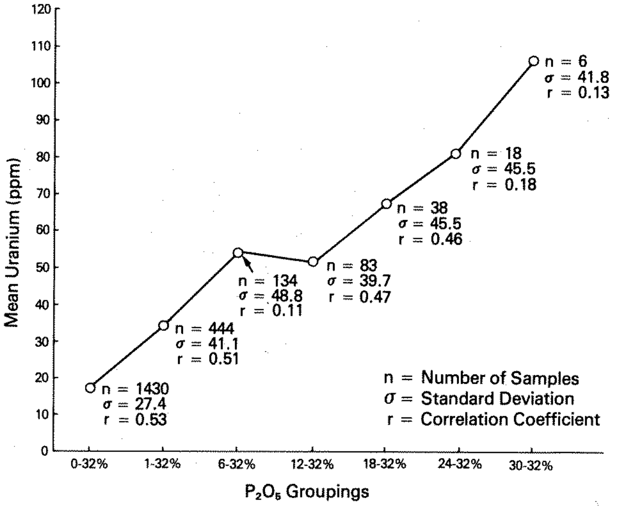

Figure 18. Mean uranium content and correlation coefficients in various classes of phosphatic rocks.

Smoky Group - Upper Cretaceous: The Clear Hills iron ore deposit in northwestern Alberta is reported to contain 1 to 2 percent P_2O_5 as finely disseminated phosphate grains (figure 1; Petruk et al., 1976). Opaline cement binds goethite-bearing ooliths, which compose the main ore. Apatite is also known to be incorporated into some of the concentric rings of the ooliths. The Clear Hills iron ore deposit varies from 1.5 to 9.1 m thick, grades 32 to 36 percent Fe and has total proven, probable and possible reserves of 1.1 billion tons (Bertram and Mellon, 1973). If this iron ore deposit is ever mined, phosphate might be produced as a byproduct.

Byproduct contents

Uranium

The uranium content of the rocks examined in this study was found to have a mean value of 34.3 ppm,[18] based on all samples with P_2O_5 contents of one percent or greater. For various groups of increasing grade, the mean uranium value rises with increasing P_2O_5 content (figure 18). The groups over 18 percent P_2O_5 show a range of uranium values, 67 to 107 ppm, that is comparable to the range of 60 to 130 ppm for "Free World" phosphorites (DeVoto and Stevens, 1980).

Scatter diagrams of uranium values versus phosphate values ($>1\%$ P_2O_5)[19] show a broad scatter of points in a crudely positive linear trend. The correlation coefficient (R), based on ^{10}log transformed data, indicates that roughly 28 percent (R^2) of the variability in uranium content is accounted for by the linear phosphorus-uranium relationship.[20] Several different grade groups were formed to see if this correlation could be improved (figure 18). The R value is highest (0.53) in the group containing 0 to 32 percent P_2O_5 and drops to no linear relationship (at 95 percent confidence) for the 6 to 12 percent, 12 to 18 percent, and 24 to 32 percent P_2O_5 groups. Similarly, R values of 0.21 to 0.22 are present in the 12 to 32 percent and 18 to 32 percent P_2O_5 groups.

It is therefore apparent that the phosphorus-uranium relationship is very strong in the entire sample population regardless of P_2O_5 content and in the 18 to 32 percent range. A somewhat weaker correlation ($r = 0.35$) is present in the 1 to 6 percent P_2O_5 group. The foregoing analysis suggests that roughly 72 percent of the variability in uranium content in the 1 to 32 percent P_2O_5 suite of samples is being controlled by some factor(s) other than P_2O_5 content.

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[17] University of Alberta, Geology Department, Professor of Paleontology.

[18] n = 444, std.dev. = 41.1, min. = 0.5, max. = 295.1.

[19] Taken to the ^{10}log to normalize the otherwise positively skewed data.

[20] All of the following correlation coefficients in this section are based on ^{10}log transformed data. This transformation results in near normal distributions for P_2O_5, U and V.

The phosphorus-uranium relationship was further explored with respect to stratigraphic position or zone. The best correlation is shown by the phosphate of the Johnston Canyon Formation (table 3); over 70 percent of the variability in uranium content is accounted for by the linear positive phosphorus-uranium relationship ($r = .83$). It appears, therefore that positive linear correlations between uranium and phosphorus are not predictable. Gaushin et al. (1974) concluded that a strong positive correlation of phosphorus-uranium on a global scale was not possible, although a particular region may show strong tendencies.

Data on uranium values found within phosphate zones can be found in Appendices 2 to 10, inclusively. Mean values for the formations studied show the Exshaw and Fernie to have the highest values (table 4). Figure 19 shows an isopleth map of uranium content in the Exshaw Formation, and suggests an increasing uranium content in an east to west direction, within the Exshaw Formation.[21] One anomalously high value occurs south of the Athabasca River, and likely represents a very localized enrichment.

Explaining the presence of anomalously high (relative to crustal averages) quantities of uranium in association with phosphate has been a long-standing problem. While this, and most other studies, have been able to show some degree of linear relationship between uranium and carbonate fluorapatite (via P_2O_5 content), most commonly some of the variability in uranium content cannot be accounted for by its association with P_2O_5.[22] Starinsky et al. (1982) suggested that uranium content in phosphates increased with increasing diagenesis.

Uranium shows a positive linear correlation with vanadium, particularly in the low P_2O_5 class ranges, reaching a maximum of $R = 0.70$ for 1 to 6 percent P_2O_5 samples. This relationship becomes less strong in the high P_2O_5 class ranges (e.g., $R = 0.47$ for 18 to 24 percent P_2O_5). All samples taken as a whole yield R values of 0.49; for phosphatic rocks (>1 percent P_2O_5), $R = 0.58$. It can be concluded, therefore, that some of the uranium in phosphates in this study seems related to vanadium, though the chemical or mineralogical association is unknown.

The form that uranium takes in phosphorites has been debated at length. However, the present general consensus seems to be that the uranylion (UO_2^{+2}) can be adsorbed onto carbonate fluorapatite crystals, or the tetravalent form U^{+4} can substitute for Ca^{2+} in the crystal lattice (Sheldon, 1959; Starinsky et al., 1982). Autoradiography, S.E.M. X-ray mapping, and fission track methods all failed to locate discrete uranium-bearing mineralogies within this group of phosphorites. This suggests that the uranium in the phosphorites of this study is adsorbed onto or incorporated into the apatite, as found with most other phosphorites. Gaushin et al. (1974) suggested a maximum of 1-2 atoms of uranium/1000 unit cells of carbonate fluorapatite. Values exceeding this range were attributed to the redeposition of phosphate into sea water. Nearly all samples examined in the present study fall into this "normal" range of atoms/1000 unit cells as described by Gaushin et al. (1974).

The origin of uranium in phosphorites has long been thought due to dissolved uranium in sea water. More recently, Starinsky et al. (1982) have shown that uranium is derived from organic matter breakdown associated with early diagenetic interstitial mud-formed phosphates. Many of the phosphates in the present study are deemed to be organic rich, based on color and petrographic appearance. Much of the uranium in the phosphorites may be associated with organic matter, as some authors have suggested (Gindy, 1978).

Table 3. Correlation coefficients of phosphorus-uranium by formation or zone within Alberta and British Columbia phosphates.

Zone or Formation[1]	Correlation Coefficient[2] (r)	Number of Samples
Fernie Formation	.5261	229
Basal Fernie Zone	.4260	64
Whitehorse Formation	.1413[3]	3
Sulphur Mountain Formation	.3116[3]	13
Mowitch Formation	.7931	23
Ranger Canyon Formation	.7800	62
Ranger Canyon Basal Zone	.7364	39
Johnston Canyon Formation	.8372	26
Kananaskis Formation	.7771	17
Tunnel Mountain Formation	.4821[3]	9
Rocky Mountain Supergroup	.7083	97
Exshaw Formation	.1913[3]	34
Exshaw-Whole[4]	.5102	256

[1] All formations or zones based only on samples with >1% P_2O_5, unless otherwise noted.

[2] All correlation coefficients are at .05 (95%) confidence level.

[3] Null hypothesis $Ho = 0$ accepted at .05 confidence level, i.e. no linear correlation.

[4] All samples regardless of P_2O_5 contents.

Vanadium

Vanadium is found to have a slight negative linear correlation with P_2O_5 when all phosphate grades (>1 percent P_2O_5) are considered ($r = -0.03$, $n = 428$).[23] This correlation coefficient is not significant at 0.01 or 0.05 confidence levels, i.e. there is likely no negative linear relationship between these two elements. A slightly negative linear correlation ($r = -0.10$, significant at 0.01 and 0.05 confidence levels) is present in all samples regardless of P_2O_5 content, i.e. 0 to 32 percent P_2O_5. No further groupings of P_2O_5 grades, as was done

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[21] It is of some interest to note that Campbell (1980) reports a mean uranium value for the Exshaw Formation (based on subsurface cores) of 10 ppm (std.dev. = 2, n = 155). In the present study, a mean value of 14.4 ppm (std.dev. = 17.7, n = 224) was found for non-phosphatic Exshaw samples. From these results it appears that very little uranium leaching or enrichment of surface outcrops has occurred.

[22] Mott and Drever (1983) found correlation coefficients of 0.29-0.45 for P_2O_5 versus U in the Green River Formation, Wyoming. Thompson (1953), in studying the Phosphoria Formation, found R values of 0.12-0.92 for the phosphorus/uranium relationship.

[23] All of the following analysis were performed on data transformed to $^{10}\log$.

Table 4. Mean uranium, vanadium and fluorine values in phosphate rocks of Alberta-B.C.—via geological formations.

Age	Formation or Group	Mean U[1]	N	Std. Dev.	Mean V[2]	N	Std. Dev.	Mean F[3]	N	Std. Dev.
Jurassic	Fernie	42.6	242	46.8	255	239	433	4.0036	16	0.6214
Triassic	Whitehorse	7.7	3	0.6	60	3	69	-	-	-
	Sulphur Mountain	16.7	13	9.9	148	13	209	4.1321	7	0.2425
	Mowitch	14.9	23	11.4	87	23	48			-
Permian	Ranger Canyon	19.9	64	21.3	78	67	45	4.2611	19	0.2491
	Johnston Canyon	24.3	26	24.0	67	26	53			
Penn.	Kananaskis	14.9	17	16.2	46	17	29	-	-	-
	Tunnel Mountain	6.9	9	2.9	46	8	23	-	-	-
Dev./Miss.	Exshaw	57.8	34	49.9	446	34	698	3.0888	8	1.1338
Precambrian	Athabasca Group	-	-	-	-	-	-	4.3145	2	0.0502

[1] All values in ppm for rocks with 1% P_2O_5. Neutron Activation method.
[2] Values in ppm for rocks with 1% P_2O_5. Wet chemical method.
[3] Values in percent (%) based on spot analysis of selected phosphate minerals. Microprobe method.

for uranium in the previous section, could produce any positive or negative linear correlations that were significant to at least 0.05 confidence levels. Scatter diagrams do not indicate any other type of non-linear relationship.

The phosphorus/vanadium relationship, when considered by formation, yields some linear correlations (table 5). The Fernie Formation phosphates seem to have a low negative linear correlation, where as the Mowitch and Ranger Canyon Formation phosphates seem to have a mildly positive linear correlation.

Mean vanadium values in the Phosphoria Formation of southeastern Idaho are reported by Gulbrandsen (1977) to be 800 ppm vanadium. Mean values for the formations in the present study range from 46 to 446 ppm (table 4). Gulbrandsen (1967) states that the vanadium is associated with the organic matter in the phosphates and not the apatite. Love (1967) reports vanadium values up to 2 percent V_2O_5 in organic-rich, non-phosphatic(?) zones within the Phosphoria. Organic matter was not analyzed in the present study; however, those parts of the Exshaw and Fernie Formations that usually appear to be organic-rich and with a grade of less than one percent P_2O_5 have mean V values of 607 and 227 ppm with maximum values of 4000 and 2800 ppm, respectively. Clearly, vanadium is present in substantial amounts, and is more likely related to organic matter than to phosphorus concentration. This appears to be the case for most phosphatic rocks, based on the foregoing statistical treatment.

Vanadium contents for phosphate zones are in Appendices 2 to 10.

Table 5. Correlation coefficients of P_2O_5 versus vanadium, by formation, in Alberta-B.C. phosphates.

Formation	Correlation Coefficient	N	Significant at 0.02 level
Fernie	−0.1779	226	yes
Sulfur Mountain	−0.1729	13	no
Mowitch	+0.7002	23	yes
Ranger Canyon	+0.5707	65	yes
Johnston Canyon	+0.2539	26	no
Kananaskis	+0.3173	17	no
Tunnel Mountain	+0.5273	8	no
Exshaw	−0.1908	34	no

Fluorine

Fluorine was analyzed in 21 representative samples of phosphate rock of 53 analysis points by the electron microprobe. The mean fluorine value for all phosphate samples analyzed is 4.0855 percent (Std.Dev. = 0.5124, n = 53). The fluorine content, with respect to phosphate petrographic lithotypes, shows a fairly tight clustering and high mean values in the carbonate fluorapatite cements, bones and fluorapatite cement groups, with broader ranges and lower mean values for the pellet, laminated phosphate and intraclast groups. With respect to age, fluorine is most variable in the Devonian-Mississippian and Lower Jurassic, and least variable in the Precambrian, Permian, Triassic and Middle Jurassic. The Permian phosphorites are composed mainly of carbonate fluorapatite cement and show the least scatter of fluorine values. Conversely, the Jurassic and Devonian-Mississippian phosphorites consist largely of the pellet lithotypes, and both show the largest variation and lowest mean values in fluorine contents (see Macdonald, 1985). F/P_2O_5 ratios are very consistent at a mean value of 0.12 for all data. F/P_2O_5 and CaO/P_2O_5 ratios are slightly lower in the Exshaw Formation and the Athabasca Group.

Fluorine in the Phosphoria Formation phosphorites is reported to be in the range of 2.20 to 4.40 percent (Gulbrandsen, 1967). The presence of fluorine is generally attributed to its incorporation into the fluorapatite crystal lattice. However, in the present study, some fluorine is present as fluorite in some of the Permian phosphorites.

Rare earth elements

The rare earth element (REE) content of phosphorites in this study was determined in four composite samples by Neutron Activation - Gamma Spectrometry. These four samples are believed to represent REE compositions in phosphorites of Devonian-Mississippian, Permo-Pennsylvanian, Triassic and Jurassic ages.

The average REE contents of the samples analyzed are all above the average values for worldwide phosphorites (table 6). In particular, the Fernie Group shows values for the elements Dy, Ho, Tm and Yb that are twice as high as the average. No depletions with respect to average REE contents are seen in any of the phosphorites of this study.

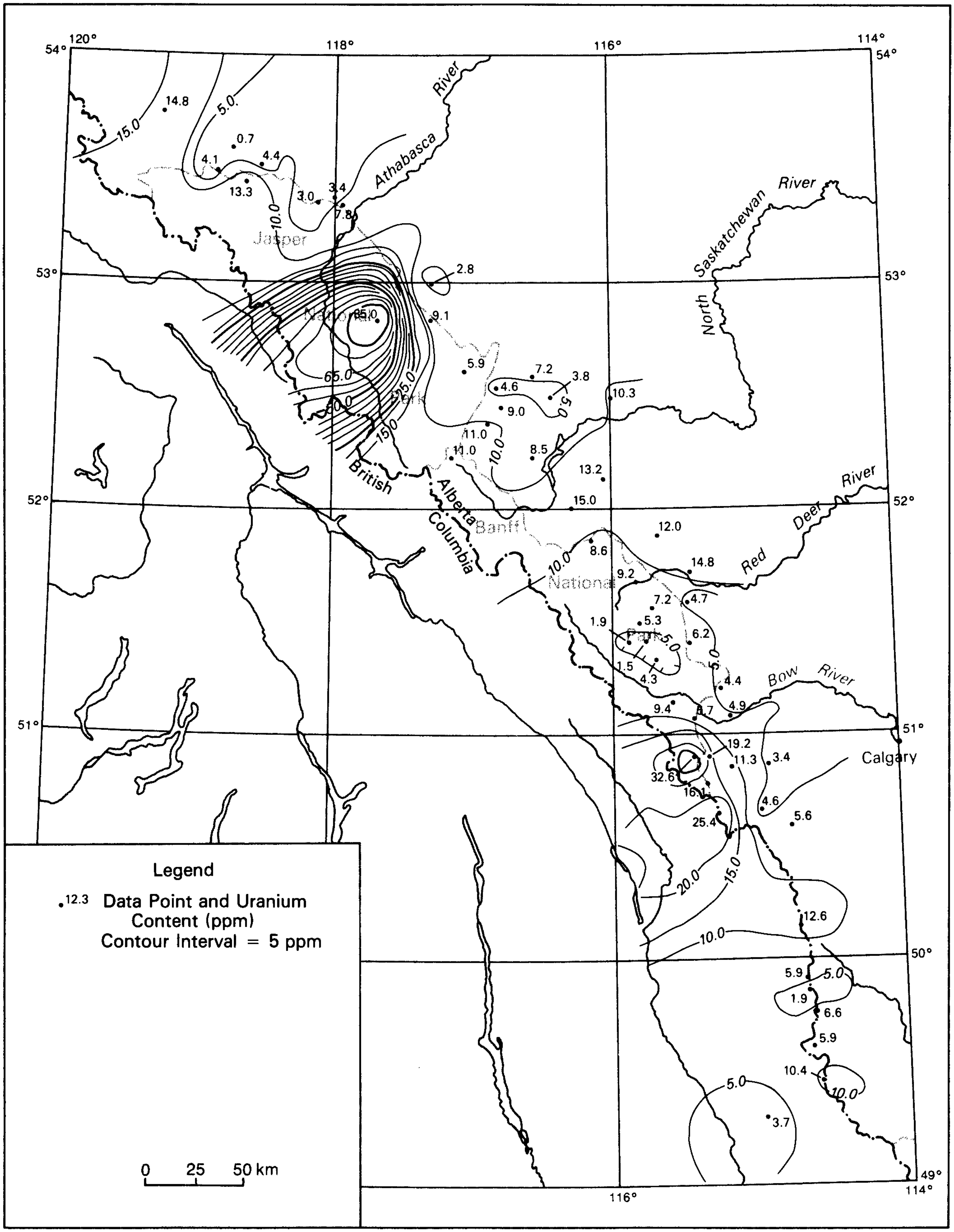

Figure 19. Isopleth map of uranium content (ppm) in the Exshaw Formation (weighted averages).

Table 6. Rare earth elements (REE) content in phosphorites of this study and average values obtained by Altschuler (1980).

	Average Phosphate (this study) n=28	Average Phosphate[1] n=18	Average[1] Shale n=36	Breakdown by Formation of "average - this study"			
				Exshaw[2] n=4	Sulphur Mtn.[3] n=4	Rocky Mtn.[4] n=10	Fernie[5] n=10
La[8]	180.0+	133.0	45.0	188.0+	143.0+	188.0+	201.0+
Ce	156.0+	104.0	91.0	193.0+[6]	172.0+	103.0	157.0+
Pr	100.0	21.0	10.7	100.0	100.0	100.0	100.0
Nd	139.0+	98.0	41.4	162.0+	83.0	149.0+	160.0+
Sm	30.9+	20.0	7.2	36.0+	18.6	30.5+	38.8+
Eu	6.9+	6.5	1.4	7.3+	4.2	7.6+	8.6+
Gd	-	12.8	6.0	-	-	-	-
Tb	3.9+	3.2	1.0	4.5+	2.3	3.4+	5.3+
Dy	35.0+	19.2	5.8	38.0+	20.0+	28.0+	53.0++[7]
Ho	7.5+	4.2	1.6	7.2+	5.0+	6.5+	11.3++
Er	-	23.3	3.8	-	-	-	-
Tm	1.9+	1.2	0.6	1.6+	1.4+	1.3+	3.2++
Yb	17.0+	12.6	3.6	13.0+	10.0	13.0+	30.0++
Lu	2.0+	2.7	0.7	1.6	1.1	1.3	4.0+

[1] Altschuler, 1980.

[2] Exshaw Formation - Devonian/Mississippian.

[3] Sulphur Mountain Formation - Triassic.

[4] Rocky Mountain Supergroup - Permo-Pennsylvanian.

[5] Fernie Formation - Jurassic.

[6] + values above "average phosphorites of Altschuler".

[7] + + values above "average phosphorites of Altschuler" by 2 times.

[8] All values in ppm via Neutron Activation - Gamma Ray method.

Altschuler et al. (1967) reported the REE content and its potential for development in both the Phosphoria Formation of the western United States and Florida deposits. They suggested that, based on present (i.e., 1967) production rates of phosphoric acid in the U.S.A., approximately 6000 to 7000 tons of REE could be recovered annually from phosphates. They further outlined the resources of REE, based on then current phosphate reserves, to be approximately 2.0 million tons for the U.S.A. Subsequently, Altschuler (1980) determined the average REE composition for worldwide marine phosphorites, and in general, found enrichments[24] above the average shale to occur for the following elements: La, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu. None of the remaining REE described by Altschuler (i.e., Ce and Pr), showed depletion relative to average values. Altschuler et al. (1967) did, however, describe a cerium depletion in several phosphate occurrences worldwide, which is characteristic of sea water.

Trace elements

The trace element composition in phosphorites of this study (table 7), compared with average values (Altschuler, 1980), shows a wide variation. Altschuler (1980) described enrichments in Ag, Ca, Mo, Pb, Se, Sr, U, Y and Zn, and depletions in B, Co, Ga, Hg, Li, Sn, Ti and Zr within worldwide phosphorites, with other trace elements being in normal abundance. The present study (table 7) shows enrichments in Ag, As, Cd, Mo, Ni, Se, U, Zn and Zr, and depletions in Mn and Ti, with most other elements analyzed in near normal amounts. Some of the differences between enrichment/depletion elements within this study compared with world averages has to do mainly with the Exshaw Formation. The Exshaw phosphorites show radically different quantities of several elements (i.e., As, Cd, Mn, Mo, Ni, Se, V and Zn; table 7) compared with the other formations. Thus, the Exshaw has had the effect of skewing the average values. Campbell (1980) similarly found anomalously high values of uranium, nickel and zinc within subsurface samples of the Exshaw Formation, in particular near the base.

Cd, U, Y, lanthanides, Sr, Pb and Zn are all known to be able to substitute crystallochemically for calcium in the apatite lattice. Ag, Se, Mo, As, Ni, V, Zn, Cr, Cu, Cd and Sb are all known to be associated with organic complexing or adsorption within phosphorites (Altschuler, 1980). Depleted and normal elements are generally explained by their association with clay minerals, or by having too large or too small ionic radii to fit into the apatite lattice. The relative abundance of various elements in seawater, compared to shale seems to have little bearing on their abundance in phosphorites (Altschuler, 1980).

Economic geology of Alberta phosphates

Resource parameters

The main parameters used to define the resource potential throughout this study are grade and thickness. As earlier defined in the methods section, there are three basic groups of phosphates: phosphate rock, phosphatic rock, and phosphate-bearing rock. Tables 8 to 10 outline grade and thickness for the various formations and phosphate zones. Figures 8, 9, 11 and 15 illustrate the occurrence, in a geographic sense, of the three basic classes of phosphates.

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[24] Enrichment was defined by the author to be 2 x "normal" abundance.

Table 7. Major, minor and trace elements in phosphorites of this study and average values obtained by Altschuler (1980).

Trace/ Minor[3]	Average[1] Shale	Altschuler (1980) Average[1] Phosphate	Average[1] Enrichment Depletion	Exshaw n = 4	Rocky Mtn n = 10	Sulphur Mtn n = 4	Fernie n = 10	Average Phosphate[2] (this study) n = 28
Ag	0.07	2.0	30.0 +	3.0	2.0	2.0	2.0	2.0?
As	13.0	23.0	N	156.0	13.3	14.6	24.5	52.1 +
Ba	580.0	350.0	N	694.0	477.0	1220.0	1521.0	978.0N
Cd	0.3	18.0	60.0 +	63.0	16.0	14.0	26.0	30.0 +
Co	19.0	7.0	3.0 –	23.9	24.4	12.2	18.0	19.6N
Cr	90.0	125.0	N	105.0	192.0	48.0	113.0	115.0N
Cu	45.0	75.0	N	100.0	100.0	100.0	100.0	100.0
Ga	19.0	4.0	5.0 –	30.0	30.0	30.0	30.0	30.0
Mn	850.0	1230.0	N	58.0	238.0	335.0	112.0	186.0 –
Mo	2.6	9.0	4.0 +	114.0	25.0	46.0	46.0	58.0 +
Se	0.6	4.6	8.0 +	27.7	8.9	8.5	9.2	13.6 +
Sn	6.0	3.0	2.0 –	100.0	100.0	100.0	100.0	100.0
Sr	300.0	750.0	2.0 –	484.0	370.0	471.0	753.0	520.0N
Ti	4600.0	640.0	7.0 –	1500.0	500.0	1900.0	1500.0	1600.0 –
U	3.7	120.0	30.0	44.9	30.8	26.5	35.5	34.4 +
V	130.0	100.0	N	333.0	121.0	212.0	65.0	183.0N
Zn	95.0	195.0	2.0 +	1610.0	63.0	195.0	230.0	525.0 +
Zr	160.0	70.0	2.0 –	375.0	344.0	380.0	392.0	73.0 +
Others								
Sb	-	-	-	55.1	1.04	3.38	1.28	15.2
Br	-	-	-	3.0	3.2	4.5	5.6	4.1
Cs	-	-	-	3.0	1.3	1.7	1.9	2.0
Au	-	-	-	0.008	0.005	0.008	-	
Hf	-	-	-	1.97	3.42	6.03	3.84	3.82
Ir	-	-	-	0.02	0.01	0.02	0.01	-
Rb	-	-	-	53.3	12.0	30.0	25.2	30.1
Ta	-	-	-	1.02	1.8	0.80	0.66	1.07
Th	-	-	-	7.75	1.94	9.45	7.85	6.75
W	-	-	-	87.0	270.0	85.0	110.0	138.0
Majors								
Al	-	-	-	3.26	0.55	1.87	1.93	1.90
Ca	-	-	-	13.5	21.5	19.2	21.7	19.0
Fe	-	-	-	3.42	0.86	0.80	1.30	1.60
Mg	-	-	-	0.52	1.2	4.0	0.65	1.59
K	-	-	-	2.4	1.0	1.2	1.0	0.0
Na	-	-	-	0.40	0.24	0.53	0.31	0.37
S	-	-	-	ND	ND	ND	ND	-

N - Normal

[1] Altschuler (1980), Enrichment(+) = 2 x average shale, depletion (–) = 1/2 or less average shale

[2] (+) = Enrichment 2 x "average phosphorite", (–) = depletion 1/2 or less "average phosphorite" (Altschuler, 1980)

[3] All values in ppm, except Majors - in % by neutron activation - gamma ray counting

Resource calculations

The phosphate resources for the Exshaw, Johnston Canyon, Ranger Canyon and Fernie Formations are presented in tables 8 to 10. These formations are deemed to have the best overall resource potential. The following is a list of conditions, assumptions and techniques used in the resource calculations:

1. All of these figures are NOT estimates of economically recoverable phosphate. None of these deposits are economically recoverable under present economic conditions.
2. These figures represent first attempts to show how much phosphate is present in situ. The geological assumptions are based on an on-strike and downdip continuity of phosphate beds with respect to grade and thickness, no structural complications (i.e., thickening of pinching out of beds), and no regard for topographic setting. Further, economic considerations were not considered, such as: price expectations, technological costs, pollution control, tax charges, transportation access and charges, marketability of product, availability of capital, and manpower.
3. Gross t (300 m) is based on the outcrop length (km) within a given area, times 1 or 2 m thickness —depending on class description—times a 300 m dipslope distance. Three hundred metres is considered to be a maximum amount by either open pit or underground methods.
4. Gross t (50 m) - same as in Gross t (300 m) except a more conservative estimate of 50 m of downdip ore is taken.
5. Phosphate-bearing rocks were not included in the resource calculations.
6. Specific gravity of phosphate rock was considered to

Table 8. Resource estimates for the Exshaw Formation, Alberta and British Columbia.

Area	Phosphate Class	Outcrop Length (km)	Gross Tonnes (x 10^6) 300 m	50 m	Number of Data Points
Crowsnest Pass	Phosphatic Rock	13.3	10.4	1.7	3

be 12 ft^3/t or 0.33984 m^3/0.9078 t (Sheldon, 1963).

7. Example of calculation - Outcrop Length (O.L.) = kilometres measured from map and rounded off to nearest whole number (x 1000 to yield metres)
Thickness (T) = metres.
Downdip Length (D) = 300 or 50 metres
Volume (V) = O.L. x T x D cubic/metres
t = V x 0.9078/0.33984 t.

Macdonald (1985) described the phosphate resources of Alberta and British Columbia in a more detailed grade/thickness classification scheme, which normalizes all raw data values to a minimum of 1 or 2 m thicknesses.

Exshaw Formation

The Exshaw Formation phosphate resources are mainly confined to the Crowsnest Pass region, within the Lower and Middle phosphate zones. This area is entirely within the Alberta Government's Eastern Slopes Management Protection area classed as "Prime Protection Area." No mineral exploration or development is permitted. Resource estimates for the Exshaw appear in table 8.

Ishbel Group

The Johnston Canyon Intraformational phosphates and the Ranger Canyon Basal phosphates were the only two horizons within the Ishbel Group deemed to have phosphate resources worth calculating (table 9). Based on the present data, there is estimated to be a maximum of 334 million t of in situ Permian phosphate rocks, mostly in the phosphatic rock class (6-18 percent P_2O_5 minimum 1 m thickness). Thirty-one percent of this in situ resource lies in areas politically amenable to exploitation with 90 percent (of the 31%) in the Fernie Basin area (B.C.) and 10 percent within Alberta. Of the remaining 69 percent found in restricted land use areas, 46 percent (of the 69%) lies in the Eastern Slopes Prime Protection Zone of Alberta, 14 percent in Kananaskis Provincial Park and 40 percent within Banff and Jasper National Parks.

Fernie Formation

The Basal Fernie phosphate is the only zone with economic potential for the foreseeable future. A crude estimate has been established of the amount of in situ phosphate rock present (table 10), but it must be stressed that these numbers are only approximations and do not indicate how much phosphate rock could be economically produced.[25] These estimates are best used in comparing one potential development area to another.

The Fernie Basin area, British Columbia, has the largest resource potential in terms of grades, thicknesses and potential tonneages (table 10). In Alberta, 59 percent of the available resource lies within the two national parks, 38 percent within the Eastern Slopes Prime Protection Zone, and only 3 percent within a potentially exploitable area. This potentially exploitable area lies in the Crowsnest Pass, where no actual data on the zone are available for the Alberta side. Calculations are based on data from British Columbia, about 2 km north of the Alberta border at the abandoned Crow

Table 9. Summary of in situ phosphate resource for the Ishbel Group.

Zone	Area	Geographical Situation[1]	Rock Class	Outcrop Length (km)	Gross Tonnes (x 10^6)		N*
					300 m	50 m	
JCIP	I - Figure 9	FB-B.C.	PIR	35	56.1	9.3	2
JCIP	II - Figure 9	FB-B.C.	PIR	20	16.0	2.7	2
JCIP	III - Figure 9	BNF-Alta	PIR	17	27.2	4.5	1
Total JCIP					99.3	16.5	
RCBP	II - Figure 11	FB-B.C.	PIR	26	20.1	3.5	1
RCBP	I - Figure 11	DP-Alta	PIR	6	9.6	1.6	1
RCBP	III - Figure 11	KNP-Alta	PIR	40	32.1	5.3	2
RCBP	IV - South - Figure 11	BMP-Alta	PIR	40	32.1	5.3	1
RCBP	IV - North - Figure 11	PPZ-Alta	PIR	21	16.8	2.8	1
RCBP	V - South - Figure 11	PPZ-Alta	PIR	114	91.4	15.2	4
RCBP	V - North - Figure 11	JNP-Alta	PIR	40	32.1	5.3	2
Total RCBP					234.2	39.0	
Permian Phosphate Totals					333.5	55.5	

[1] Abbreviations used: FB - Fernie Basin; BNF - Banff National Park; DP - Development Permitted in Alberta; KNP - Kananaskis Provincial Park; PPZ - Prime Protection Zone, Alberta; JNP - Jasper National Park; PR - phosphate rock; PIR - phosphatic rock; RCBP - Ranger Canyon Basal phosphate; JCIP - Johnston Canyon Intraformational phosphate.

* Number of stratigraphic data points used in calculating area.

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[25] At the present time, no phosphate rock in Canada is produced economically.

Table 10. Resource estimates for the Basal Fernie Phosphate, Alberta and British Columbia.

Area	Land[1] Status	Class[2] Average	Outcrop Length (km)	Gross Tonnes (x 10^6)		N*
				300 m	50 m	
IV-Fig.20	JNP-Alta	PIR	40	32.0	5.3	1
III-Fig.20	PPZ-Alta	PIR	120	6.0	15.9	4
III-Fig.20	BNP-North	PIR	4	7.0	4.5	1
II-Fig.20	NBP-South	PIR	114	1.0	15.0	8
I-Fig.20	DP-Alta	PIR	10	8.0	1.3	1
I-Fig.20	FB-B.C.	PIR	74	59.0	9.8	3
I-Fig.20	FB-B.C.	PR	9	14.4	2.4	1
I-Fig.20	FB-B.C.	PIR	201	323.0	53.7	7
I-Fig.20[3]	FB-B.C.	PR	(201)	(161.1)	(26.8)	7
Totals			602	650.4	108.0	27
				(488.4)	(81.1)	

[1] Land Status Symbols: JNP-Jasper National Park; BNP-Banff National Park; PPZ-Prime Protection Zone; DP-Development Permitted (some restrictions); FB-Fernie Basin.

[2] Class: PR-phosphate rock; PIR-phosphatic rock.

* N: number of stratigraphic sections used in calculations.

[3] Same area as previous line, recalculated based on (18% P_2O_5 or over at least 1.0 m).

Phosphate mine. Many of the resource block areas shown in table 10 are very low grade ores. In terms of 18 percent P_2O_5/m grade material or better, there is an estimated 29 to 175 million t present in the Fernie Basin area. This of course depends on whether the most or least optimistic figure is used for downdip projection of the phosphate beds. It should be remembered that the 1981 consumption of imported phosphate rock in Canada was only 3.6 million t of high grade rock.

Summary of resources

As can be seen from tables 8 to 10 and appendices 2 to 10, the majority of phosphate resources in Alberta and southwestern British Columbia appear to be in the phosphatic to phosphate-bearing rock classes. The Basal Fernie phosphates in the Fernie basin area are the only rocks that can be classed as Phosphate Rock, (i.e., greater than 18 percent P_2O_5 and 1.0 m or greater thickness).

Areas for future prospecting

The Fernie Basin in southwestern British Columbia has the best potential for future phosphate prospecting. In particular, the Basal Fernie zone in the southern part of the basin is the most promising area and zone. The Johnston Canyon Intraformational phosphates in the Fernie basin also warrant closer inspection. Within Alberta, most of the best phosphate prospecting areas have been sterilized through land use management decisions (National, Provincial Parks and Prime Protection zones). If development were permitted within the prime protection zones of the Eastern Slopes, the area north and south of the North Saskatchewan River (Area III, figure 15) in the Basal Fernie zone would have some potential.[26] The Crowsnest Pass area also has some low-grade phosphatic-rock class deposits within the Exshaw Formation.

Depositional models of marine phosphates

Introduction

In order to speculate on the origin of phosphate deposits, it is necessary to have an understanding of the phosphorus cycle and the currently accepted models of phosphate deposition. All Alberta phosphate deposits are of marine origin; consequently, models discussed in this section pertain particularly to marine deposition.

Phosphorus cycle

The deposition of sedimentary marine phosphates is, presently, thought to depend on the phosphorus cycle (Sheldon, 1981). As phosphate deposition basically involves the chemical precipitation of apatite, it is likely that geochemical processes are fundamental conditions. Seven variables in the phosphorus cycle influence the deposition of phosphates.[27]

1. A supply of phosphorus, derived from erosion.
2. Storage and accumulation of oceanic phosphorus.
3. Upwelling of stored phosphorus to shallower levels.
4. Concentration of phosphorus at the ocean floor from organic material, derived from biota that flourished in upwelling zones.
5. Correct chemical conditions to induce apatite precipitation.
6. Apatite precipitation by biogenic, diagenetic and/or primary sea floor precipitation.
7. Concentration of phosphate to form high-grade deposits.

Phosphorus deposition in oceans and lakes

The phosphorus cycle begins with the chemical erosion of rocks and soil containing phosphorous minerals. This is followed by dissolution of the phosphorus into solution (as organic and inorganic compounds), and then transport via rivers and groundwater to oceans and lakes where the phosphorus is deposited. An amount equivalent to about half that contributed by dissolved phosphorus is added by volcanic activity and sea floor spreading.

Phosphorus reservoirs

Surface ocean waters normally tend to become depleted in phosphorus by living organisms. Apatite is very soluble in cold, deep water; thus, deep ocean

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[26] Although grade/thicknesses in this area for this zone are still only in the 6 to 12 percent P_2O_5 range over 1 m.

[27] The following section is based largely on the work of Sheldon (1981) and Cook (1976).

basins tend to become sinks, enriched in dissolved phosphorus. Deep ocean vertical circulation is a slow process, and is only speeded up by changing sea levels (major transgressions or regressions), tectonic displacement of continental blocks, ocean currents, and changing wind patterns. Such turnover brings about upwelling and precipitation of apatite on the sea floor.

Cook and McElhinny (1979) identified a cyclic pattern of phosphate deposition during the Phanerozoic. Sheldon (1980) suggested that this cyclicity was related to the development of deep ocean phosphorus sinks, and their eventual turnover during later time periods. Thus, some geological periods were favorable for the accumulation and storage of phosphorus in solution, and others were more favorable for the deposition of phosphorus as apatite.

Deep oceanic turnover to shallow water

In order to tap the vast amounts of phosphorus available in the ocean basins, some mechanism must be evoked to circulate the well-stratified waters. This mechanism is oceanic mixing, which is mostly accomplished through winds and currents. It is known to take place in a number of different settings, the most often sited being:

1. In ocean currents that flow parallel to coastlines and are reinforced by prevailing winds.
2. In ocean currents flowing up to and over a high submarine topographic feature; this is called "dynamic upwelling."
3. In the Trade Wind belt, at low latitudes (0-25°).

Upwelling is seen as the essential process whereby a steady supply of phosphorus-bearing waters can be delivered from deep water to shallower (relatively) accumulation sites. The upwelling theory is more difficult to apply when the depositional environments are very shallow water (e.g., estuarine, fluviatile or tidal flat settings (Cook, 1976)).

Concentration of phosphorus at the ocean bottom

A net result of upwelling or oceanic mixing is a proliferation in the upwelling area of plankton, diatoms and other biota, all utilizing the phosphorus in their life processes. Upon death, these organisms settle to the sea floor. There, sulfate and iron reduction are instrumental in breaking down organic material and releasing phosphorus. Much of this interstitial phosphorus is returned to the water column during early diagenesis; however, some remains in the sediment and becomes highly concentrated.

Apatite solubility and chemistry

Apatite precipitation can be described by the following reaction:

$$SP = [Ca^{+2}]^5[PO_4^{-3}]^3[F^{-1}] \rightleftharpoons Ca_5\,(PO_4)_3F\ 5\,Ca^{+2} + F^{-1}$$

When the concentration of the PO_4^{-3} ion is increased to the point where the solubility product (SP) is exceeded, apatite precipitates, or the reaction proceeds to the left. The PO_4^{-3} concentration is pH dependent. The pH, in turn, is primarily influenced by dissolved CO_2, which forms carbonic acid and lowers the pH. PO_4^{-3} also combines with other elements to form a number of complex ions. The ion $MgHPO_4$ is probably one of the most important in reducing the overall concentration of PO_4^{-3}, thereby inhibiting the precipitation of apatite.

The SP of this reaction also increases with decreasing temperature and increasing pressure. The same temperature/pressure effect also increases the partial pressure of CO_2, thereby decreasing the pH of the water.

Current oceanographic studies combined with paleooceanographic work suggest that the ocean is, and was, probably close to saturation or slightly under saturated with apatite, during the Phanerozoic. However, very few, if any, modern-day examples exist of apatite precipitating directly out of the water column, onto the sea floor. Instead, it has been found that interstitial sediment pore waters are highly concentrated with respect to apatite (Sheldon, 1981). It is therefore in that zone, immediately below the sediment/oceanic water contact, that most researchers see apatite concentrations having formed in the past (Sheldon, 1981; Cook, 1976).

Apatite precipitation and concentration

Apatite is precipitated in three basic ways: as primary biogenic material, by diagenetic precipitation in ocean floor sediments, and by primary precipitation at the sediment-water interface.

Biogenic material includes shells of some brachiopods, bones and teeth of vertebrates, fish scales, conodonts, and mollusc kidney stones. All this material, of which apatite is a major component, is precipitated within life forms and can form discrete phosphate-rich beds upon accumulation.

Interstitial pore waters in modern sediments are found to be supersaturated with apatite, leading many researchers to suggest diagenetic precipitation. Phosphate pellets and nodules are subsequently found within modern muds (Burnett, 1977), as is apatite as a replacement of calcite and dolomite in carbonate rocks, and as a replacement of calcareous shell fragments. Many ancient deposits are attributed to diagenetic phosphate precipitation.

Although no modern deposits of primary precipitated phosphates have been found—and modern sea water chemistry suggests that they may not exist—there still remains a large body of evidence from ancient deposits that says this type of precipitation did occur in the past (Cressman and Swanson, 1964; Sheldon, 1963; Cook, 1976). Two types of phosphate in particular are said to be indicative of primary precipitation: oolites with cores of quartz, and finely laminated, bedded phosphorites (Sheldon, 1981). Disagreement still exists, however, with other workers (Cook, 1976) suggesting a diagenetic replacement of carbonate precursors for both quartz-cored oolites and bedded phosphorites.

The concentration of phosphates precipitated below the sediment-water interface requires winnowing, reworking or weathering in order to form high-grade deposits.

Models of deposition - general

Ten primary factors are thought to be the most important in developing any model explaining phosphate sedimentation (Burnett and Sheldon, 1979):

1. Paleogeographical and paleoclimatic setting.
2. Paleooceanography: currents, chemical characteristics, etc.
3. Plate tectonic setting.
4. Local tectonic setting.
5. Type of phosphate deposited.
6. Associated sediments—vertical and lateral facies changes.
7. Sedimentation rate.
8. Diagenesis.
9. Sediment transport and reworking.
10. Weathering.

Conceptual genetic models are perhaps the most all-encompassing, as they usually include the ten primary factors. Nine basic genetic models of phosphate deposition are in use today (table 11). Details of these models can be found in Cook (1976), Sheldon (1981), and Christie (1979).

Models of phosphate deposition —Alberta and southeastern British Columbia occurrences

Exshaw Formation

The Exshaw Formation represents a widespread black shale unit, genetically though not time correlative with many similar units throughout North America. The North American tectonic setting, in Early to Middle Devonian time, was one of transcurrent movement in the Appalachian area, resulting in the onset of the Acadian Orogeny (Morel and Irving, 1978). By Middle to

Table 11. Summary of phosphate depositional models.

Model Type	Oceanic Currents	Depositional Area	Lithologic Associations	Inferred Water Depth	Petrographic/ Textural Types	Plate Tectonic Setting	Associated Fauna	Examples
West coast shelf margin	upwelling along west coasts	shelf margin	chert, black shale	hundreds of metres	pellets, minor oolites	Geosynclinal sub- or obducting plate boundaries	Pelagic	Phosphoria Fm. USA Sechura deposits, Peru Fernie Fm., Fernie Fm., W. Canada
East-west shelf margin	upwelling along south side of east-west coasts	shelf	chert, black shale	?	?	?	Pelagic?	Iran, Morocco, Columbia, Cambrian deposits of China
East coast shelf margin	Dynamic upwelling?	shelf margin	Mg-rich clays glauconites dolomite	?	?	?	Pelagic?	Varswater, S. Africa Hawthorn Fm., USA
Epicontinental Platform	Dynamic upwelling	Flanks of anticlines and within synclines	Carbonates sandstones	shallow water (tens of metres)	pellets, nodules, microsphorite	not important	shallow water	London Paris Basins
Insular	not important	Islands - Equatorial regions	Corraline limestones	Subaerial exposure	guano	not important	terrestrial	Naru Ocean Islands
Unconformity	?	Continental or very near shore	Conglomerates sandstones	very shallow	cements minor pellets	not important	very shallow water	Permian, Alberta
Fossil and shell beds								parts of Phosphoria, Fm., Upper Exshaw, Alberta
Tidal Flat Estuarine		Tidal muds of estuaries	shale, dolomite sandstone, siltstone	very shallow	microsphorite oolites		very shallow water	Part of Sulphur Mountain Fm. Alberta, SW Africa
Reworked	Fluvial or marine currents	Fluvial systems	conglomerates, sandstones	very shallow	pebbles intraclasts			Florida, parts of Permian, Alberta

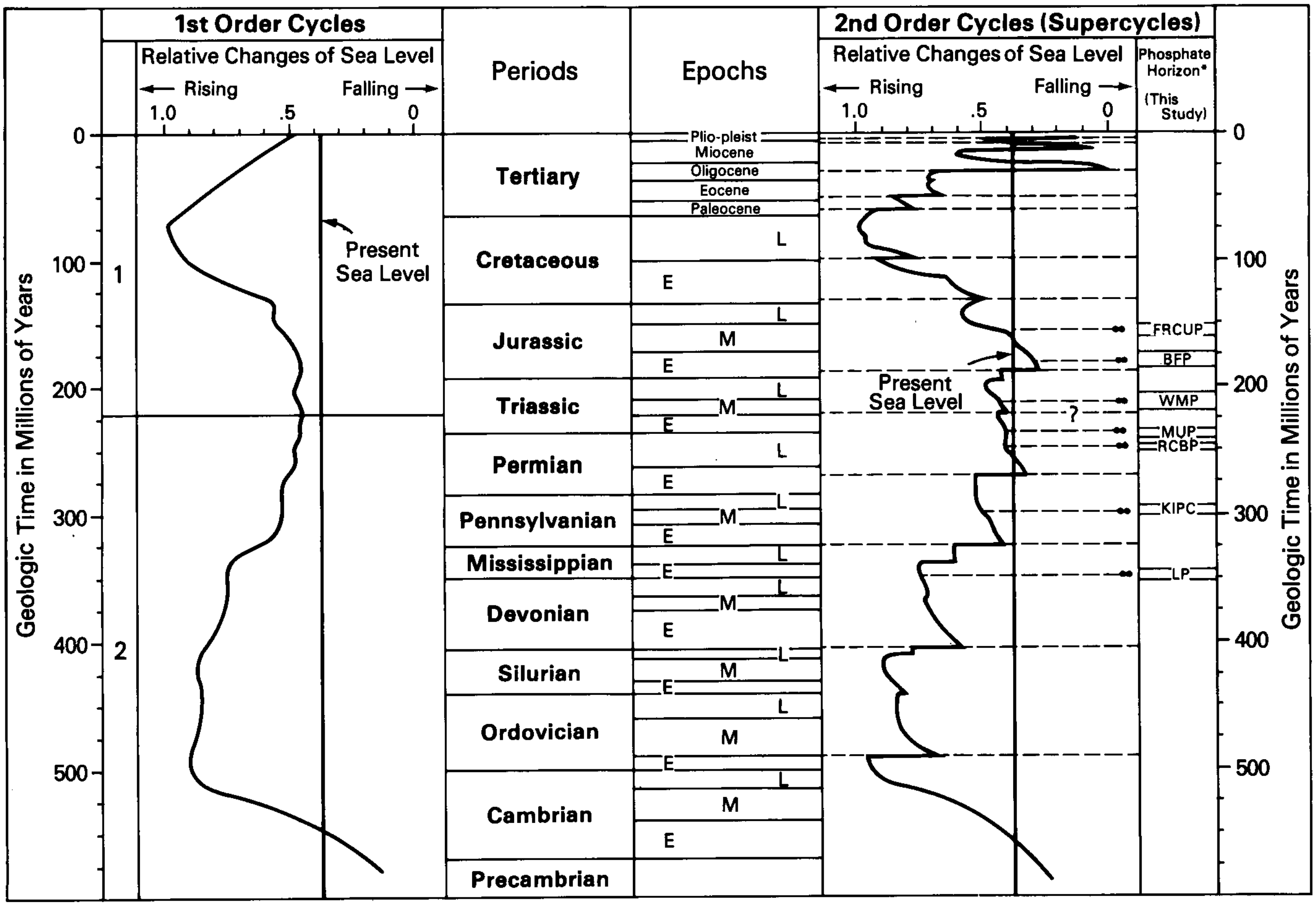
Late Devonian time, this transcurrent movement had developed into a spreading center and "Atlantic Two" (Morel and Irving, 1978) was born.

The tectonic activity that gave rise to the Acadian Orogeny was accompanied by a worldwide rise in sea level—a transgressive event that is classed as a second-order cycle (Vail et al., 1977; figure 20). That resulted in a gradual flooding of the North American continent (Laurasia) in a south to north fashion. Thus, the Marcellus Shale in New York is Middle Devonian in age, while the Exshaw Formation in the study area is from the Upper Devonian to Early Mississippian. Both, however, are genetically related.

In Western Canada, it appears likely that northwestern Montana and the Peace River Arch were mildly positive features, though possibly not subaerially exposed (McCrossan and Glaister, 1964). Strongly negative basinal areas at this time included parts of northeastern British Columbia, the Alberta Trough (as evidenced by thickening of several westernmost Exshaw sections in the study; figure 6), and an area near Butte, Montana.

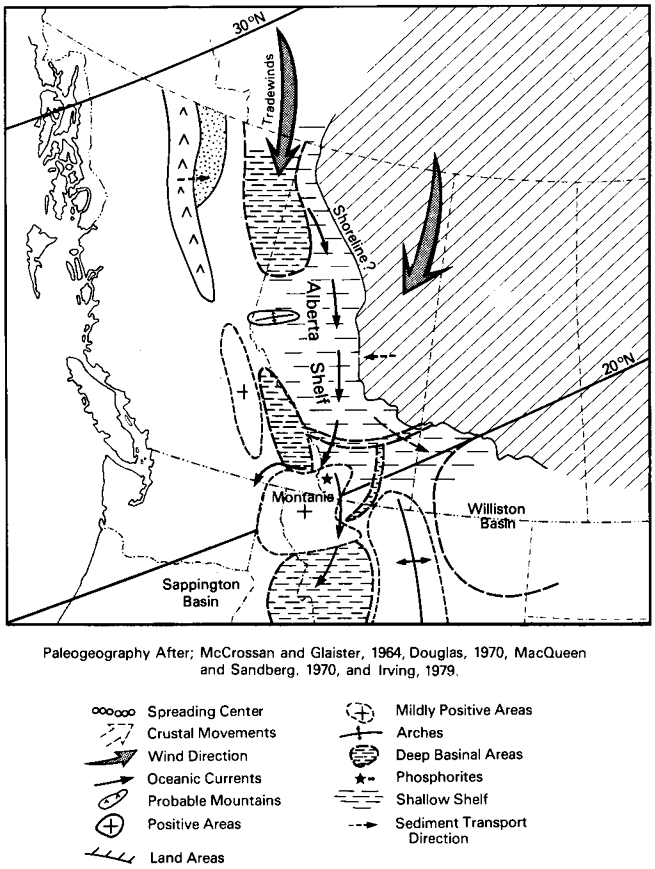
The paleogeographic setting in Western Canada was reconstructed based on the aforementioned tectonic elements, the works by Ettensohn and Barron (1981) and Irving (1979) (figure 21). This study area lay at about 20° to 24°N latitude and was dominated by the Trade Winds.

After the Palliser Wabamun carbonates were deposited in Famennian time, there is some facies evidence to support a minor, short regression of the sea in late Famennian time (McCrossan and Glaister, 1964). This is supported in this study by findings of possible paleosols and abundant hematite in the Basal Sandstone. The Exshaw everywhere sharply overlies the Palliser, and the Basal Sandstone is found throughout a very large part of the study area. These two characteristics are common to many of the other North American genetic equivalent black shale units. The presence of a thin (millimetres to one metre) phosphatic, bone, pebble sandstone at the base of this cycle—regardless of the time—is very widespread (Ettensohn and Barron, 1981). This sandstone, and others like it, probably represent a thin transgressive sandstone, being the on-



*FRCUP - Fernie Rock Creek Upper Phosphate
BFP - Basal Fernie Phosphate
WMP - Whistler Member Phosphate
MUP - Mowitch Upper Phosphate
RCBP - Ranger Canyon Basal Phosphate
KIPC - Kananaskis Interformational Phosphate Conglomerate
LP - Lower Phosphate Zone - Exshaw Formation

Figure 20. First- and second-order global cycles of relative sea level during Phanerozoic time and phosphate zones in Alberta and British Columbia (modified from Vail et al., 1977).



Paleogeography After; McCrossan and Glaister, 1964, Douglas, 1970, MacQueen and Sandberg. 1970, and Irving, 1979.

Figure 21. Paleogeographic setting of Western Canada, Late Devonian to Early Mississippian time.

ly evidence of a possible Late Famennian regressive sequence. A rapid transgressive phase and a rapid return to quiet water conditions is suggested by the basal bentonite bed immediately overlying the Basal Sandstone in many locations.

The Exshaw Formation is highly organic rich and most authors agree that stagnant, euxinic, reducing conditions must have existed. This is indicated by the high organic content, the thin, evenly bedded nature, abundant pyrite and the paucity of fossils. Macqueen and Sandberg (1970) suggest a series of extremely shallow, stagnant marine or brackish lagoons, formed by gentle downwarping in the previously shallow Palliser sea. It appears that there is a series of northeast-trending sills in this study (figure 6); this may lend support to the shallow water lagoon theory. Shallow water conditions are definitely indicated in the Crowsnest Pass and southeastern British Columbia regions.[28]

At section 226 (figure 5), a highly restricted, sponge spicule accumulation, equivalent to the algae-sponge unit of the Sappington Formation, directly overlies a phosphatic shaly equivalent of the Basal Sandstone. The Middle Phosphate Zone overlies this, though not directly, and together they suggest an area of upwelling oceanic water, probably at shallow depths. This is supported by the paleogeographic map (figure 21) that shows southward currents flowing parallel to the coastline, impinging on the slightly positive Montania and being diverted westward or southward over Montania. Both these conditions are known to produce upwelling. In either case, the result should be the same: a continued supply of PO_4^- for living organisms (e.g., sponges) to thrive on. This, then, is the first important step in the formation of phosphates.

Petrographic evidence shows the phosphates from north of the Crowsnest Pass to be elongated pellets with an argillaceous matrix, suggesting they formed diagenetically within near surface muds. South of the Crowsnest Pass, the phosphates are typically more rounded pellets and are matrix free, suggesting shallower water and possibly formation above the sediment/water interface by intermittent suspension.

Phosphate beds are not thick anywhere in the Exshaw. As the transgression continued and the waters continued to deepen, the upwelling processes likely became less efficient, and phosphate precipitation ceased. The Upper Phosphate Zone that caps the Upper Limestone in two localities marks the end of the minor regressive phase, within the larger, second-order cycle, Devonian-to-late-Mississippian transgressive event (figure 20). The Upper Phosphate is a mixture of reworked phosphate material and may be a transgressive lag deposit.

Spray Lakes/Ishbel Groups

The Pennsylvanian Spray Lakes Group phosphates are not important economically. However, they are thought to have formed in a manner similar to the Permian Ishbel Group phosphates, which are of more economic significance. Only the latter group will be discussed in detail.

The close of the Mississippian period saw a global drop in sea levels (figure 20), which was likely a reflection of the collision of Gondwana and Laurasia, closing "Atlantic II" (Morel and Irving, 1978). Throughout the Pennsylvanian, the relative sea level rose until the middle of the Early Permian, when sea levels were suddenly lowered. Sea levels fluctuated near present-day levels throughout the Permian, and only began to rise substantially during the Triassic. Continental plate movement is believed to have been fairly minimal throughout the Permo-Pennsylvanian (Morel and Irving, 1978).

In the Alberta Trough/Arch areas, the history of sea level rise and fall was more complex. The Early Permian transgression (figure 20) saw the progradation and deposition of eastern-derived clastics onto the Interior Platform shelf, into the Alberta Trough and possibly along the eastern flanks of the western belt island (figure 22).[29] The presence of this western island likely precluded any very deep water sedimentary environments; thus, shelf-marginal to shelf deposits were probably more common.

Climatic conditions throughout the Permo-Pennsyl-

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[28] Thick carbonates overlie the Palliser Formation in southeastern British Columbia and are likely related to the Sappington Formation. They may have developed on or around the slightly positive Montania.

[29] The Telford and Ross Creek Formations consist largely of carbonates, likely developed along this island (McCrossan and Glaister, 1964).

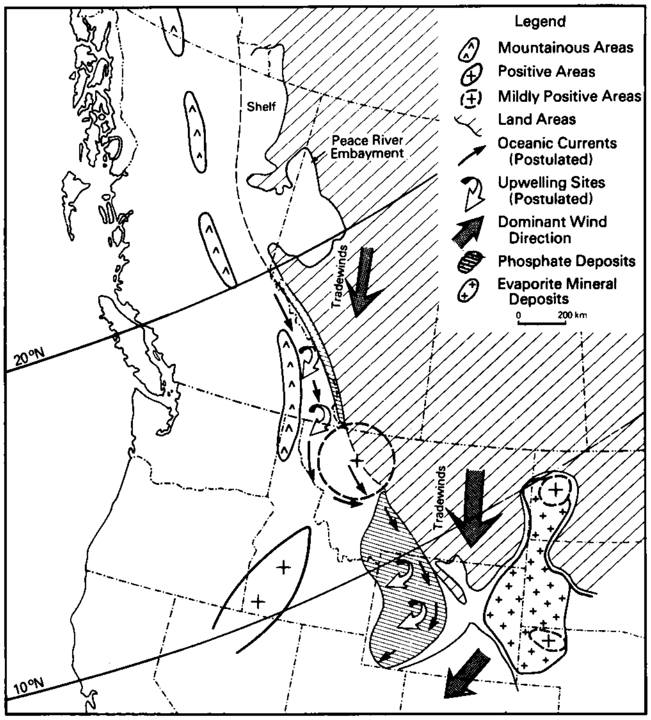

Figure 22. Paleogeographic reconstruction of the Permian (Guadalupian) in Western Canada.

vanian in this area are thought to have been hot and dry, as evidenced by an inferred low paleolatitude, and aeolian dune, evaporite and redbed sequences in the western United States. Clastic sedimentation was also thought to be very minimal, from low-lying continental areas. The paleographic setting of the present study area, and farther south to northern Utah, were ideal for coastal upwelling brought on by Trade Winds blowing parallel to the paleocoastline (figure 22) during the Permian (Guadalupian). Upwelling would have been even more likely to occur if, as has been well documented in the western United States Phosphoria Formation (Sheldon, et al., 1967), coastal currents encountered an east/west barrier and were diverted seaward (figure 22), producing divergent upwelling. This seems to have been possible in the southern parts of the Alberta Trough and Arch.

If Montania was a positive feature, currents may have been diverted seaward (west) or up and over Montania, producing dynamic upwelling. Whether Montania was a land area or a mildly positive area can only be speculated on, as no Permian rocks have been preserved in this area. However, given the known land positions in Alberta and southwest Montana, it is more reasonable to assume an intervening land area, than an oceanic one.

Johnston Canyon phosphate model

The Johnston Canyon Formation comprises the oldest known Permian strata and consists largely of dark interbedded shales, siltstones, cherts and some phosphorites. This assemblage would suggest a fairly deep outer shelf to shelf-margin depositional environment. Such an argument is supported by the following evidence:

1. There are abundant *Zoophycus* trace fossils, which most ichnologists put into the *Zoophycos* ichnofacies assemblage—a depositional environment in the slope-to-basin transition area (Howard, 1978; Chamberlain, 1978).[30]
2. Aside from *Zoophycus* traces, very few other trace fossils were observed or have been reported, again supporting a deeper water environment, slope-to-basin position.
3. Organic rich shales, cherts and fine-grained siltstone lithologies, suggest deeper, poorly oxygenated waters.
4. Phosphate pebble zones show basal scour and some suggestion of upward grading, perhaps indicating a turbidite origin from a more shelf position.
5. Abundant phosphate nodules in the Intraformational Phosphate Zone suggest, from modern analogues, a fairly deep water environment. Most modern phosphate nodules are found at the edge of the continental shelf or the upper slope region (Bentor, 1980).
6. Pelletal phosphate horizons have been reported (Cominco Ltd., J. Hamilton, pers. comm.), though not seen by this author. They would probably have formed in an outer shelf area, as this is the environmental interpretation given to the Permian Phosphoria pelletal phosphorites (Sheldon et al., 1967).

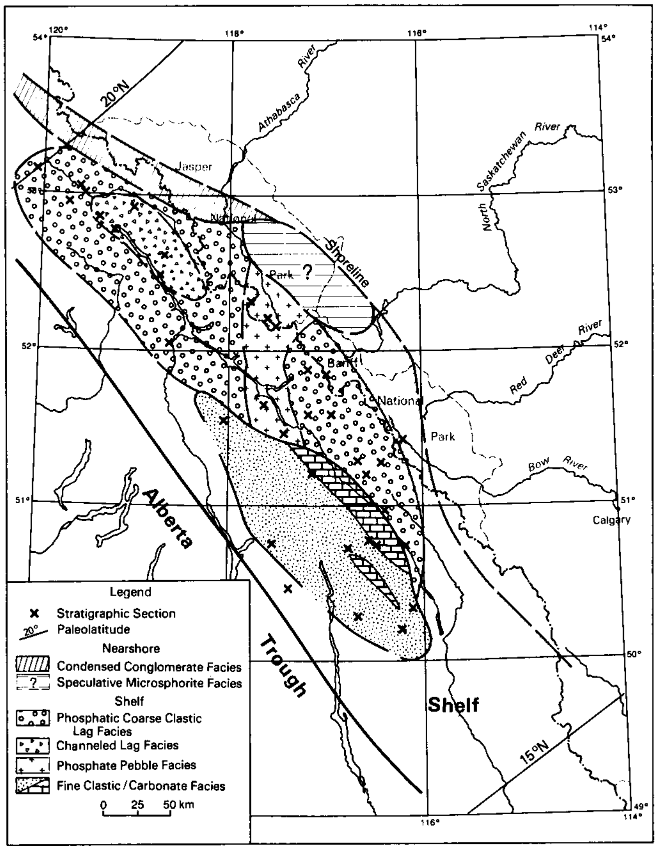

Figure 23. Palinspastically restored lithofacies map of the Ranger Canyon Basal Phosphate zone.

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[30] The presence of a single trace fossil is not enough to place it into any one ichnofacies; rather, a large assemblage is required.

Ranger Canyon phosphate model

In the Lower Guadalupian, the ocean gradually retreated and produced a long period of widespread regional erosion, now marked by the Basal Phosphate Zone. Erosion removed Guadalupian to Pennsylvanian age strata and was probably accompanied by uplift and tilting, as shown by an angular unconformity between the Johnston Canyon and Ranger Canyon formations in southwestern British Columbia (McGugan and Rapson, 1962).

The phosphate zone is represented over most of the study area by a poorly sorted, matrix-to-clast supported, phosphate-cemented chert pebble-to-boulder conglomerate (coarse clastic facies, figure 23). Within the Basal Phosphate, a number of other subfacies occur, the second most common being the fine-grained, well-sorted phosphate cemented sandstone. Commonly, the fine-grained sandstone facies directly overlies or grades laterally into very fine grained dolomites. The dolomite facies often contains patchy areas of phosphate cement or scattered nodules. A fourth facies comprises reworked phosphate pebbles and is found in the central and northern regions.

The origin of the coarse clasts facies is not certain. The trace fossil assemblage immediate below the conglomerates is very sparse, but where observed, the fossils are from the *Cruziana* ichnofacies (i.e., between fair and storm weather wave base [pers. comm. G. Pemberton]). Rapson-McGugan (1970) suggests that the conglomerates are a lag deposit, produced in part by dessication in a subtidal environment. This would appear to be a good explanation for a large part of the area. As the Wordian Sea retreated westward, progressively older, subtidally formed breccias would be exposed to the east. Many of the sections of the Basal Phosphate conglomerate show facies channel features such as 1 to 2-m deep, 3-m wide scour surfaces; various types of cross-bedding; some incomplete fining upward sequences; gray-green shale-filled channels and well-rounded chert boulders (up to 30 cm) in a medium- to coarse-grained sandstone; cut-and-fill structures; and parallel-laminated sandstones.

Although some of these channel-type deposits are possibly tidal in origin, it is not unreasonable—given the strong suggestion of a subaerially exposed shelf —to suggest that some of these channels were fluvial. A region in the northern part of the study area (figure 23, Channel Lag Facies) shows many fluvial features. Some cut-and-fill, cross-stratified, channel deposits were also observed farther south (Section 384); however, here the deposits are almost certainly marine, as vertical burrow trace fossils are also present. Likely, the phosphate was not deposited into the host conglomerates during the ensuing transgressive phase and prior to progradation of the Ranger Canyon clastics.

The combined fine sandstone/dolomitic facies (figure 23) may represent reworked shallow shelf environments. The Basal Phosphate Zone is 3 m thick at the very maximum, and most sections are less than 1 m. In the ensuing transgression, extensive reworking and removal of much of these low-stand deposits occurred. The etching of quartz, and the cement-supported nature of the fine sandstones, strongly suggest that some siliceous replacement by phosphate occurred probably in an alkaline environment (Rapson-McGugan, 1970).

Have et al. (1982) described phosphatized limestones and dolomites from Curacao that have very similar petrographic lithotypes to the Permian sand/dolomite phosphates facies. Bushinsky (1935) described phosphate-cemented sandstones containing sponge remains from the USSR, suggesting formation in a shallow marine basin, likely by phosphatization processes.[31] It is quite likely that, for the study area, both authigenic and replacement processes were occurring, perhaps at slightly different times.

The phosphate pebble facies (figure 23) consists of phosphatized sponge spicules and/or reworked microsphoritic material. Laminated phosphate (microsphorite facies - figure 24) may have been deposited in a lagoonal area, very close to the land. Periodic storms may have ripped up the phosphate and rounded it into flat pebbles, which were then transported seaward in the tidal channels. Folk (1973) and McBride and Folk (1977) describe some very similar flat pebble conglomerates composed of radiolarian cherts, and sometimes phosphate, that were deposited in tidal channels.

Phosphate may have been deposited within any of the host lithologies in one or both of two ways:

1. As the Mid-Guadalupian transgression advanced, upwelling waters along the coastline (figure 22) led to prolific flourishing and subsequent death of plankton. PO_4^- would be concentrated in the bottom sediments (i.e., the sand/dolomite facies). Phosphate would then have precipitated authigenically between the still-loose interstitial pore spaces of the sands.

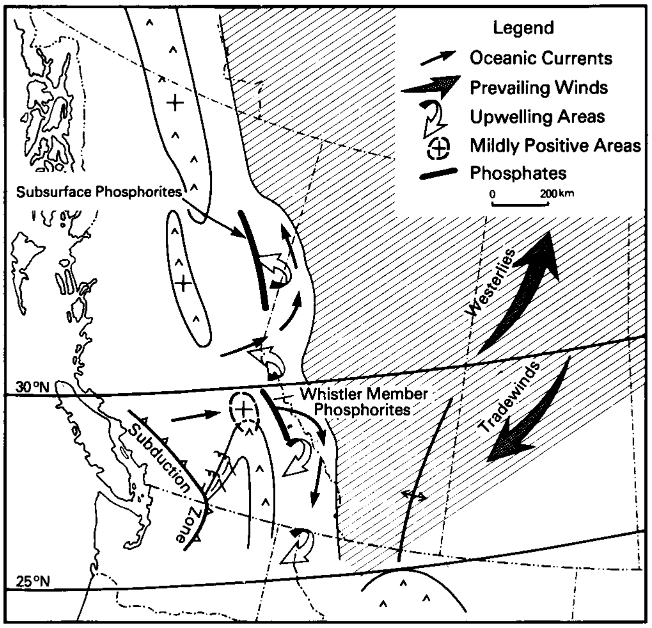

Figure 24. Paleogeographic reconstruction of the Middle Triassic in Western Canada.

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[31] This author's interpretation of Bushinsky's work.

2. Phosphate could also have precipitated as a replacement mineral during early diagenesis (i.e., by phosphatization).

Mowitch Formation phosphate model

A return to higher sea levels, combined with uplift in northern regions, brought the progradational Mowitch sands into the northern, and possibly as far down as the central, regions (figure 10). The depositional environment postulated by McGugan et al. (1968) is basically a continuation of the one put forth for the Ranger Canyon Formation. The Mowitch Formation was apparently not as heavily silicified as was the Ranger Canyon, and the predominant massive sandstone lithology is everywhere apparent.

The available evidence suggests a shallow shelf environment for the lower Mowitch, with a gradual deepening of the depositional environment for the upper Mowitch. A deepening is indicated by the *Zoophycus/Spirophycus* trace fossil assemblage, and finer siltstone to shale lithologies, at least in the westernmost sections. Some of these same western sections appear to be unbroken sequences right up into the silty shales of the Triassic Sulphur Mountain Formation. Most other eastern sections in the shelf-margin to shelf positions, show a break at the top of the Mowitch marked by the Upper Phosphate Zone. This last sea level lowering corresponds to a worldwide lowering at the end of the Paleozoic (figure 20), thought to have been brought on by glaciation in the southern continents (McCrossan and Glaister, 1964).

The Upper Phosphate Zone consists mainly of reworked phosphate pebbles that, compositionally, look identical to the in situ Ranger Canyon Basal Phosphates, sand/dolomite-type facies phosphate. It is likely that a similar environment of deposition existed in Mowitch Upper Phosphate time, and that these phosphatized sandstones were later ripped up, rolled into pebbles, transported and deposited during the Triassic transgression.

Spray River Group

Phosphates are not abundant throughout most of the Triassic Spray River Group. Those present consist mainly of *Lingulid* type phosphatic brachiopod shells (Gibson, 1974), thin phosphate pebble intraformational conglomerates and some pelletal varieties in the Whistler Member. Phosphorites are also known from the Middle Triassic in the subsurface of northwestern British Columbia (McCrossan and Glaister, 1964). The Sulphur Mountain Formation, in which all of these horizons are found, is considered by Gibson (1974) to have been deposited in a shallow water, neritic environment, parts of which formed coalescing delta complexes along the Alberta Arch and into the Alberta Trough.

Following a long period of erosion brought on by a low sea level stand (figure 20) during the Permian, the onset of the Lower Triassic was marked by a second-order global rising of sea level throughout the Lower Triassic. The Whistler Member marked the beginning of another (third-order?) global sea level rise at the start of the Middle Triassic (figure 20). This transgressive event is marked at the base of the Whistler by the Lower Phosphate Zone. It is likely that the preceding regressive event did not subaerially expose the Lower Triassic sediments, but rather this represented a stillstand or non-depositional time. During this stillstand, time phosphogenesis may again have had a chance to exceed clastic deposition.

The phosphatic material present in the Lower Phosphate Zone varies from nucleated and oolitic pellets, to pebbles, bones and phosphate-cemented siltstones. This assemblage would indicate an oxygenated, fairly active wave, shallow water environment of deposition. This is in sharp contrast to the oxygen-deficient environment envisaged by Gibson (1974), although he conceded that numerous fine, light gray silty dolomite laminations would represent more-oxygenated conditions. From a paleographic view (figure 24) the Whistler Member phosphates were within a favorable paleolatitude/shoreline position for upwelling to have occurred.

It may be possible to speculate that the Whistler represents an intertidal or subtidal flat deposit along some shallow water area to the west (figure 24). Evidence to support this would be (a) the apparent fluctuating oxygenated environmental conditions; (b) the nucleated phosphate pellets; (c) thickening of the Whistler Member westward and facies change eastward into the dolomitic siltstones of the Llama Member; and (d) the finely laminated silty dolomite lithology of the Whistler.

Intertidal-deposited phosphorites have been described by Birch (1980) from the South African coast and show many similarities to the Whistler Member phosphates. Many of these African phosphate varieties are nucleated and oolitic pellets, some phosphate-cemented siltstones also being present. Birch considers the pelletal phosphates to have been deposited authigenically at the water/sediment interface, while the phosphate in the phosphate-cemented siltstones is thought to have precipitated directly out of the water column or interstitial waters.

The Upper Phosphate Zone shows an almost identical assemblage of phosphate lithotypes as the Lower Zone that were probably formed in a very similar manner. Progradation of the Llama Member clastics and a corresponding drop in sea level (Gibson, 1974) ended the Whistler phosphogenic episode.

The other occurrences of phosphate in the Whitehorse Formation are almost always as phosphatic brachiopod shells—*Lingulid* and *Orbiculid* types (Gibson, 1974). Gibson considers these brachiopods to inhabit shallow marine brackish to near brackish water in intertidal to subtidal environments.

Fernie Formation

Nordegg Member phosphate model

The main phosphorite deposits within the Fernie Formation seem to have formed during Lower Sinemurian Nordegg Member time. On a global scale, the early Jurassic was the time that Pangea began to break apart and the present-day Atlantic Ocean developed. Rifting, that occurred between eastern North America and northwest Africa, is thought by Hallam (1978) and others to have brought on a major second-order cycle of sea level rising throughout the Jurassic (figure 14).[32]

A long period of post-Triassic erosion lasted through to the end of the Hettangian, at which time the Lower Jurassic third-order cycle of transgression began (figure 14). The fourth-order cycle, (S1 of figure 14), was likely a rapid transgression throughout the study area. Evidence for this includes black organic rich shales (deep stagnant water), often found at the base of the Nordegg Member; development of unnucleated, non-oolitic phosphorites immediately above the unconformity;[33] grain flow or similar deep-water mass-flow deposits very low in the section; and deep-water trace fossils, *Paleodictyon,* found very near the unconformity. The regressive phase, between cycles S1 and S2 (figure 14), is recorded in the Nordegg Member, which shows an upward shallowing lithofacies assemblage. The thin Sinemurian phosphatic sandstone bed, termed Transgressive Sandstone Facies (figure 25, and figure 16 Section D-D′), was deposited during one of the S1, S2 or S3 sea level rises. The Upper Sinemurian followed a final sea level rise (S3, figure 14) and the multiple bentonite beds were deposited. In the northern region, these bentonite beds (figure 16) attest to increased volcanic activity to the west and probable westerly winds. Only one Upper Sinemurian bentonite bed has been noted in the southern region, suggesting that this region was still in the Trade Wind belt (figure 16, Section B-B′).

Continental plate tectonic movement became quite rapid during the Jurassic. By the Middle Jurassic, the paleolatitude for the southern part of the study area had shifted from 30°N to about 40°N. This plate movement may have ended ideal phosphogenic conditions.

The Lower Sinemurian was evidently a time of extensive volcanism. Bentonites and the organic-rich shales found below the Nordegg Member in the central and eastern study area suggest that very quiet, stagnant, reducing conditions were established early in the western area of the shelf.[34] The Nordegg equivalent, found in the western sections, was probably deposited in a slope-to-shelf margin (figure 25). Resultant lithologies include black shales, thin cherts, pelletal phosphorites and phosphatic mudstones, grain flow deposits (sandstone) and bentonites. The pelletal phosphates must have been deposited in this shelf-margin facies as they are always found in the extreme western sections. A shelf-margin position is not so certain for the southern-most pelletal phosphorites, because no shelf sediments equivalent to the Nordegg Member are preserved (figure 25). In this area, western pelletal phosphorites are laterally equivalent to the eastern transgressive sandstone. The pelletal phosphates appear to be in an extremely likely area for upwelling to have taken place. The likelihood of upwelling would seem to diminish northward as the dominant oceanic current direction became north flowing and the westerly winds blew from the ocean onto the continent (figure 26). This is reflected in the lithofacies map (figure 25), where phosphate in the Phosphatic Shelf Margin facies (north of about paleolatitude 33°N) is poorly developed, thin and generally low grade. The pelletal phosphates likely formed in fairly deep, quiet, reducing conditions, below effective wave base. This is indicated by the absence of any cross-stratification, the dark, organic-rich nature of the pellets, the lack of burrowing[35] and an overlying bentonite seam. Hard-bodied invertebrates, including ammonites, are evidence that perhaps only the bottom muds were reducing and that the overlying water column was, at least in part, oxygenated. Some of the pelletal phosphates are quartz silt free, while most have some quartz silt matrix, suggesting that some areas were winnowed slightly by bottom currents. The pellets likely formed authigenically below the water/sediment interface, with mild bottom currents sweeping away argillaceous material, but not being strong enough to remove silt-size material.

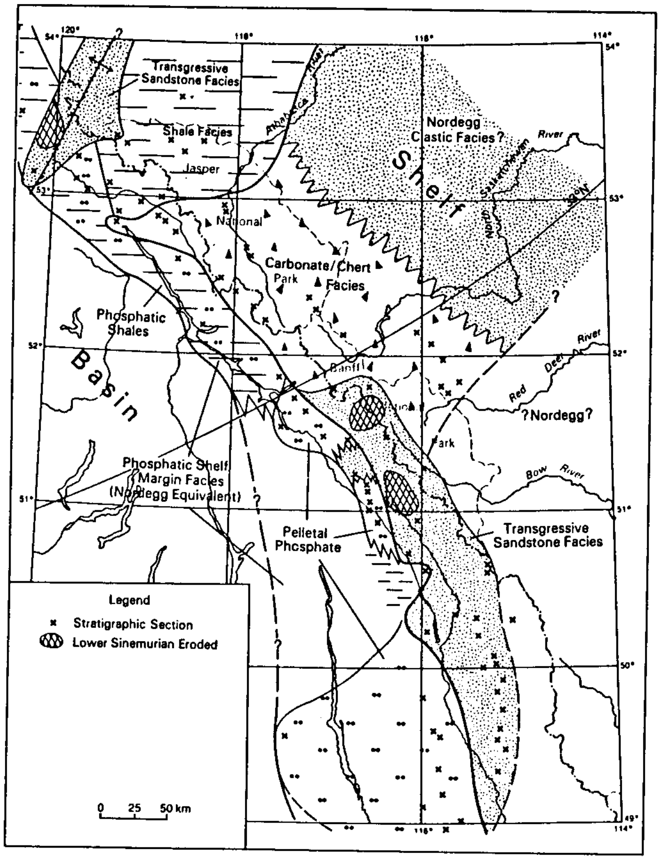

Figure 25. Palinspastically restored lithofacies map of the Lower Sinemurian Fernie Formation, Alberta and southeastern British Columbia.

Rock Creek Member phosphate model

The Bajocian sea is thought to have risen (third-order

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[32] This rifting was likely responsible for the major first-order cycle of sea level rise from Jurassic to Upper Cretaceous time.

[33] This suggests that the pellets were not formed in a shallow water environment by rolling wave action.

[34] The Nordegg Member in the eastern subsurface area was not studied in detail. Rather, the discussion is based mostly on the work of McCrossan and Glaister, and is therefore general.

[35] The only trace fossil seen in the pelletal phosphates was a single, large (2-cm wide) *Thalassinoides*-type burrow at the Fernie/Spray River contact.

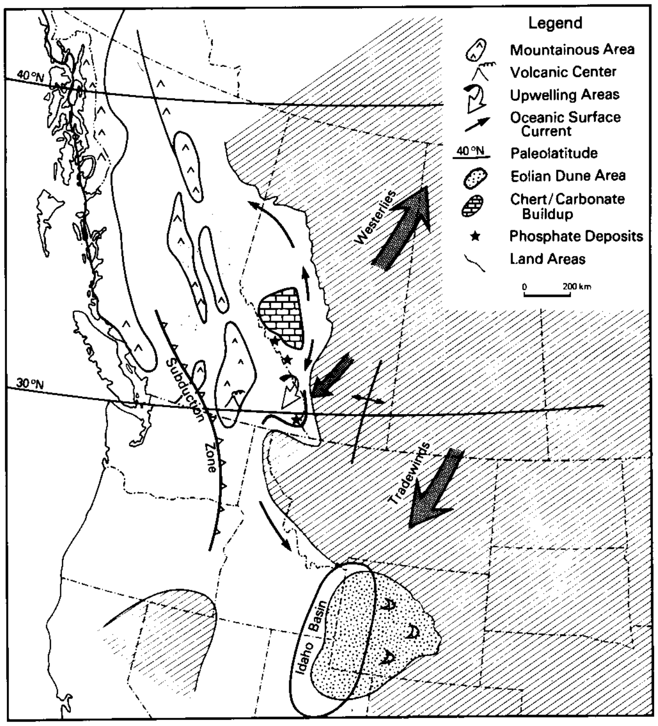

Figure 26. Paleogeographic reconstruction of the Lower Jurassic (Lower Sinemurian) in Western Canada.

cycle, figure 20) quite rapidly and to also have fallen quite rapidly (Vail et. al., 1977). The Bajocian sea was widespread, extending into the Williston Basin and south into the northwestern United States (Frebold, 1957). Two fourth-order cycles are recognized within the Bajocian third-order rise, with an intervening sea level drop (Hallam, 1978). This sea level drop separating the two fourth-order cycles likely resulted in deposition of the Rock Creek Member—sensu stricto, mainly sandstones. The Lower Phosphate Zone may be more a reflection of the first fourth-order cycle in the Bajocian, with sea levels rising and phosphatization of bottom sediments into nodules taking place as a result of fresh supplies of deep "ocean sink" phosphorus being brought to shallow levels (Sheldon, 1980). The Rock Creek Member, as a sandstone facies, varies considerably throughout the study area. In the Crowsnest Pass area (figure 17, Section 202), it is massive, structureless and contains a very sparse marine invertebrate fauna. In this region, the Rock Creek Member coarse clastic facies may represent shelf sand deposits. By contrast, the Rock Creek Member sandstones in the Kananaskis/Banff area are very thin, but continuous over a large area. The Rock Creek Member sandstones in the easternmost-central area (figure 17, Section 324) are distinctly heavily oxidized, structureless and contain no fossils. These sandstones may have been deposited as either beach deposits, subaerially exposed barrier islands or coastal dune deposits. The sandstones of the Rock Creek Member in the central to northern areas attain their maximum clastic development in this area (figure 17, Sections 190, 13 and 26). The basal portions show either offshore deeper water shales progressively shallowing upward with the increasing abundance of bioturbation, thin sandstone units or interbedded sandstones and shales showing distinct evidence of tidal influences such as starved ripples, flaser bedding, etc. (Section 190, figure 17). The upper sandstone sequences are typically 5 to 10 m thick, mostly show low-angle cross and parallel stratification and are almost always bioturbated. Trace fossils collected indicate a *Cruziana* ichnofacies assemblage, i.e. deposition between fair and storm weather wavebase in a shelf setting (pers. comm. G. Pemberton). These sandstone units show sharp upper and lower bases and are interbedded with ironstone-bearing gray shales. The central and northern Rock Creek sandstone sequence fits into a sublittoral sheet sand setting as described by Johnson (1978). Fine to very fine grain size, interbedded shales, some coarsening up sequences, lack of abundant high angle cross-stratification and erosional marked pebble conglomerate beds would all tend to support a sheet sand model that has perhaps been influenced by storm and wave action. The sequences may, of course, be a gradation of sheet sands at the base to barrier island-type model near the top. This seems likely in Section 13 where a possible rooted zone, fossil log and pebble conglomerates all appear on the uppermost sandstone. Marion (1983) considers the subsurface Rock Creek clastics were deposited "on a gently sloping, storm-dominated shallow marine shelf and were derived from the east." Stronach (1984) suggests that the Rock Creek clastics are tidally emplaced. The phosphate zone at the top of the Rock Creek lies at the very top of these shelf sandstone sequences and is common in both belemnites and phosphate nodules. The phosphate nodules likely grew diagenetically sometime after the emplacement of the belemnite-bearing sandstones and appear related to the second fourth-order Bajocian sea level rise (figure 14).

Conclusions

From this study, a number of conclusions can be drawn regarding phosphate in Alberta and southeastern British Columbia.

1. Although 16 geological formations, ranging in age from Helikian to Upper Cretaceous, are known to contain phosphate, only four are considered to have important economic potential. These four are: Devonian-Mississippian Exshaw Formation, the Johnston Canyon and Ranger Canyon Formations (of the Permian Ishbel Group), and the Jurassic Fernie Formation. Well over 95 percent of the phosphate deposits in Alberta are within the two national parks, one provincial park, and one wilderness area; the remainder lie in Alberta's Eastern Slopes Management

Policy Prime Protection Zone. Presently, the only developable area that contains phosphates is the Crowsnest Pass region of Alberta.

2. The Exshaw Formation has its best potential for phosphate exploitation in the region north of the Crowsnest Pass. Although individual phosphate beds may grade to greater than 20 percent P_2O_5 when considered over at least a minimum mineable thickness of one metre, diluted grades are in the 6 to 12 percent P_2O_5 range. There is an estimated 1 to 10 million t of in situ Exshaw phosphate in the 6 to 12 percent P_2O_5 range north of the Crowsnest area. The Exshaw is in very difficult mining conditions and all geologically favorable areas are within the "Eastern Slope Prime Protection Zone".
3. The Permian Ishbel Group has its best phosphate potential within the Ranger Canyon Basal Phosphate and the Johnston Canyon Intraformational Phosphate zones.

   The Johnston Canyon Formation, Intraformational Zone, is confined to the westernmost Front Ranges south of Banff and has the best potential for development in the southwest Fernie Basin area. Here the grade/thickness combination exceeds 13 percent P_2O_5 over at least 1 m, and is not subject to land-use restrictions. Most of the Intraformational Phosphate strata exposed in Alberta is within Banff National Park or Kananaskis Provincial Park. A maximum of about 99 million t of phosphates, with grades likely in the 12 to 18 percent P_2O_5 range over at least 1 m, are present in all areas for this zone. About 27 of the 99 million t are in Banff National Park, the remainder are in the Fernie Basin, British Columbia.

   The Ranger Canyon Basal Phosphate Zone extends from Willmore Wilderness Park south to the Crowsnest Pass area. In most localities, the phosphate bed is 20 to 100 cm thick with grades varying from 5 to 15 percent P_2O_5. Taken over a minimum of 1 m, most of the zone grades in the 6 to 12 percent P_2O_5 range. An estimated 224 million t of 6 to 12 percent P_2O_5/m is present. Of that, 204 million t is present in Alberta and the remainder is in British Columbia. However, none of the 204 million t in Alberta is in land-use areas where mineral development is permitted.
4. The Basal Fernie Phosphate Zone, within the Jurassic Fernie Group, is estimated to contain 254 million t of 6 to 12 percent P_2O_5/m within Alberta, of which a possible 8 million t are in potentially exploitable land-use areas. British Columbia is estimated to contain 396 million t of 6 to 24 percent P_2O_5/m (or 343 million t of $>$18 percent P_2O_5/2 m) in the Fernie Basin area. Grades and thicknesses, in general, tend to be leaner to the north, in Alberta, and richer to the south, toward the United States border in the Fernie Basin. The Fernie Basin area may contain over 2 billion t[36] of subsurface phosphates, as the basin is a large synclinal structure with surface outcrops on the east and west flanks. If this subsurface phosphate proves to be continuous throughout the Fernie Basin, it would represent a vast resource potential—perhaps to be recovered, in situ, in the future.
5. The mean uranium content in phosphates encountered during this study is 34.3 ppm, with a maximum value of 295.1 ppm. Uranium values are highest (40-60 ppm) in the Fernie and Exshaw phosphates, and lowest (6-7 ppm) in the Tunnel Mountain and Whitehorse formations. The phosphorus/uranium relationship is weakly linear and is best developed in all samples regardless of P_2O_5 content and in the group of phosphates containing 12 to 32 percent P_2O_5 ($r = 0.53$ and 0.21, respectively). At best, only 28 percent of the variability in uranium content in these phosphorites can be attributed to P_2O_5 content. Uranium and phosphorous show a stronger positive linear correlation when considered by stratigraphic horizon, with correlation coefficients rising to 0.7 or 0.8 for Permian phosphates.
6. Vanadium is found to have a slightly negative linear correlation with phosphorus content when all phosphatic rocks are considered ($r = -0.3$). The Ranger Canyon shows some positive linear correlation between phosphorus and vanadium ($r = 0.57$). Vanadium values in phosphorites vary from 46 to 446 ppm. Vanadium values up to 2600 ppm are present in non-phosphatic, organic-rich shales of the Exshaw and Fernie formations.
7. Fluorine in phosphate minerals of this study has a mean value of 4.0855 percent. Values seem to be highest in the lithotypes, phosphate cement and bones, and lowest in the pellet, microsphorite and intraclast lithotypes. Fluorine values show the most variability in the Exshaw and Lower Fernie formations and least variability in the Sulphur Mountain, Ishbel and Middle Fernie.
8. Rare earth elements are present in phosphorites of this study in above average abundances when compared with other worldwide phosphorites. In particular, the elements La, Ce, Na, Sm, Eu, Tb, Dy, Ho, Tm, Yb and Lu are all found in abnormally high amounts.
9. Trace elements in the phosphorites of this study compare similarly with other worldwide phosphorites with enrichments of the elements Ag, As, Cd, Mo, Ni, Se, U, Zn and Zr.
10. The mineralogy of the phosphorites in this study is transitional between pure carbonate fluorapatite (also called francolite) and pure fluorapatite. Dahllite is also present in very small amounts, usually as bone and teeth remains.
11. A variety of phosphate petrographic lithotypes have been identified, including pellets (cored and uncored, oolitic, elliptical and structureless varieties); cements (including microsphorite, fluorapatite and francolite cementing sandstone, siltstones and conglomerates); intraclasts; reworked pebbles; nodules and phosphatic fossil material.
12. Most of the phosphate occurrences in the study area seem to be related to worldwide sea level changes throughout the Paleozoic and Mesozoic. Most phosphorites are found at unconformities or within early transgressive sequences. Other conditions that seem to be required are a low ($<40°N$) paleolatitude. All the major deposits in this study are within such a range. Bottom currents winnowing

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[36] Based on a crude rectangular shape of 74 x 12 km, assuming a 1 m thickness over the entire area.

away muds further serve to concentrate the precipitated phosphate, while later diagenetic effects, such as the calcite replacement of phosphate, tend to dilute the eventual phosphate deposits.

13. The Exshaw Formation phosphates are thought to have formed in fairly shallow water shelf conditions, with upwelling being produced from the slightly positive Montania landmass and from a favorable paleolatitudinal/geographical continental position.
14. Most of the Rocky Mountain Supergroup phosphates are found at well-established unconformities throughout the Permian and Pennsylvanian. Most of these unconformities are thought to be sea level stands that were low, such as when the shelf was subaerially exposed. Phosphate was deposited during the next transgressive sea level rise during shallow water shelf conditions. Phosphate was likely precipitated authigenically within interstices of sands and dessicated breccio-conglomerates. There is also evidence to support phosphatization of sponge spicules and perhaps an early phase of phosphate cement. The paleolatitude/geographical setting was nearly ideal, at least during the Permian, to promote phosphogenesis. Phosphate within the Johnston Canyon Formation likely formed in deeper shelf marginal positions.
15. The phosphates within the Spray River Group are best developed in the Whistler Member of the Sulphur Mountain Group. The Whistler Member phosphates are primarily pellets and are thought to have formed during Middle Triassic transgression. An intertidal or subtidal depositional environment adjacent to a western land mass is suggested.
16. The structureless pelletal phosphates of the lower Fernie Group were deposited in a shelf marginal position, primarily during lower Sinemurian time. The Lower Sinemurian saw the beginning of a major global second-order cycle of sea level rise that lasted throughout the Jurassic. Upwelling along the western coastline was promoted by a low paleolatitude (30°N) and possibly an emergent Montania landmass to the south. Eastern, shoreward facies equivalents of the interbedded shale and pelletal phosphorites are a thick sequence of cherty carbonates and clastics deposited on the continental shelf. The pellets themselves are not thought to be derived from fecal or phosphatized carbonate/shale, but are thought to have formed authigenically in the interstitial muds below the sediment/water interface. Over much of the study area, the Sinemurian is represented by a thin regressive phosphatic lag deposit and represents reworked and probably more shelf-positioned phosphates.
17. Phosphates in the Middle Fernie, Rock Creek Member, seem to be associated with a sheet sand sequence brought on by a Middle Jurassic sea level lowering. Phosphate nodules and phosphatized fossils show clear evidence of having formed diagenetically by phosphatization processes. The study area was not within the ideal paleolatitudinal position during the Rock Creek time (Bajocian) and the reason for phosphatization at this time is still problematic.

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Appendix 1. Locations of stratigraphic sections used in this study.

Section	Reference	Latitude Longitude*	Palinspastic position	NTS sheet	Section name
1	Alberta Geological Survey	52 850 115 2750	51 5900 115 4600	83B3E	Prairie Creek
2	Alberta Geological Survey	52 500 115 5400	51 5000 116 3300	83B4E	Ram River-West of Falls
3	Alberta Geological Survey	52 450 115 5900	51 4700 116 4400	83B4E	Ram River-First Ranges
4	Alberta Geological Survey	52 675 115 5675	51 4800 116 3300	83B4W	Lynx Creek-Headwaters
5	Alberta Geological Survey	52 2075 115 4550	52 1000 116 300	83B5W	Brazeau Range-South
6	Frebold-1957	52 1575 115 3350	52 500 115 5400	83B5E	Fall Creek
7	Alberta Geological Survey	52 5900 117 2100	52 3600 118 200	93C14W	Whitehorse Creek
8	Alberta Geological Survey	52 5900 117 2100	52 3600 118 200	83C14W	Whitehorse Creek
9	Alberta Geological Survey	52 5850 117 1950	52 4100 117 5000	93C14W	McLeod River
10	Alberta Geological Survey	52 5875 117 1975	52 3900 117 4600	83C14W	McLeod River
11	Alberta Geological Survey	52 5875 117 1975	52 3900 117 4600	83C14W	McLeod River
12	Alberta Geological Survey	52 5775 117 2000	52 3900 117 5100	83C14W	McLeod River-South
13	Alberta Geological Survey	52 5875 117 2275	52 4200 117 5400	83C14W	Whitehorse Creek
14	Alberta Geological Survey	52 5950 117 1950	52 3800 117 4000	83C13E	Cadomin Quarry
15	Alberta Geological Survey	52 175 116 550	51 3800 116 5800	83C1E	Hummingbird Creek-South F
16	Alberta Geological Survey	52 200 116 520	51 3700 116 5000	83C1E	Hummingbird Creek-South F
17	Hudson Bay Oil and Gas-1965	52 325 116 1375	51 3700 117 100	83C1E	Ram Range
18	Hudson Bay Oil and Gas-1965	52 1325 116 1500	51 4100 117 100	83C1E	First Ram Range
19	Alberta Geological Survey	52 1325 116 3100	51 4400 117 2100	83C2E	Goat Creek-Headwaters
20	Hudson Bay Oil and Gas-1965	52 1475 116 2725	51 4500 117 2400	83C1W	First Range
21	Alberta Geological Survey	52 380 116 2525	51 2900 117 2900	83C1W	Two O'Clock Creek
22	Alberta Geological Survey	52 428 116 2610	51 3500 117 3700	83C1W	Two O'Clock Creek
23	Alberta Geological Survey	52 2950 116 25	52 2000 116 1900	83C8E	Nordegg
24	Alberta Geological Survey	52 2950 116 125	52 1700 116 1500	83C8E	Nordegg
25	Alberta Geological Survey	52 3517 116 3515	52 1900 117 800	83C10E	Blackstone River-West
26	Alberta Geological Survey	52 3525 116 3525	52 1800 117 700	83C10E	Black Stone River-North
27	Alberta Geological Survey	52 3520 116 3500	52 1800 117 600	83C10E	Blackstone River-East
28	Frebold-1957	52 3975 116 4100	52 2300 117 1100	83C10E	Chungo Creek Gap
29	Hudson Bay Oil and Gas-1965	52 5625 117 475	52 3700 117 3700	83C14E	Red Cap Mountain
30	Alberta Geological Survey	52 2966 116 2700	52 1300 117 100	83C9W	Bighorn Range
31	Alberta Geological Survey	52 2775 116 2175	52 1100 116 5300	83C08W	Bighorn Range-South
32	Alberta Geological Survey	52 2775 116 2150	52 1000 116 5500	83C8W	Wapiabi Gap
33	Alberta Geological Survey	52 3000 116 2633	52 1200 117	83C8W	Wapiabi Gap
34	Alberta Geological Survey	52 3400 116 3400	52 1600 117 500	83C10E	Smith Creek
35	Alberta Geological Survey	52 1625 116 3333	51 5500 117 1400	83C7E	Goat Creek-Headwaters
36	Alberta Geological Survey	52 1975 116 3900	51 5200 117 3100	83C7E	Bighorn River-Headwaters
37	Alberta Geological Survey	52 2700 116 4800	51 5500 117 3600	83C7W	Job Creek
38	Alberta Geological Survey	52 2650 116 4550	52 300 117 2600	83C7W	Job Creek-North Fork
39	Alberta Geological Survey	52 25 116 1800	51 2700 117 2000	83C1W	Siffleur River Ridge
40	Alberta Geological Survey	52 1350 116 1525	51 5500 117 200	83C01W	Crooked Creek-Headwaters
41	Alberta Geological Survey	52 300 116 1700	51 3700 117 1300	83C1W	Whiterabbit Creek Ridge
42	Alberta Geological Survey	52 600 116 1875	51 3900 117 1400	83C1W	Whiterabbit Creek-North R
43	Alberta Geological Survey	52 1075 116 3200	51 4000 117 4200	83C2E	Coral Creek Mouth
44	Alberta Geological Survey	52 675 116 2850	51 3300 117 3000	83C1W	Elliot Peak South
45	Alberta Geological Survey	52 700 116 2850	51 2400 117 4300	83C1W	Elliot Peak-South
46	Alberta Geological Survey	52 833 116 350	51 4300 116 4000	83C1E	Onion Creek-Ram Range
47	Alberta Geological Survey	52 1000 116 1050	51 4800 116 5600	83C1E	North Ram River
48	Alberta Geological Survey	52 1100 116 1700	51 5200 117 200	83C1W	Ram Range-North
49	Alberta Geological Survey	52 1100 116 1700	51 5200 117 200	83C1W	North Fork-North Ram River
50	Alberta Geological Survey	52 1375 116 3425	51 3800 117 3700	83C2E	Mt. Stelfox
51	Alberta Geological Survey	52 1600 116 4075	51 3600 117 5600	83C7E	Coral Creek-Headwaters
52	Alberta Geological Survey	52 1550 116 4150	51 3100 117 5200	83C7E	Coral Creek-West Ridge
53	Alberta Geological Survey	52 2225 116 5600	51 3500 118 600	83C7W	Mt. McDonald
54	Alberta Geological Survey	52 2275 116 5375	51 3800 118 600	83C7W	Obstruction Mountain
55	Alberta Geological Survey	52 5900 117 4000	52 3500 118 2100	83C13E	Rocky River-Jacques Lake
56	Alberta Geological Survey	52 5366 117 2933	52 3000 118 1000	83C13E	Deception Mountain-Rocky
57	Alberta Geological Survey	52 5333 117 2933	52 2700 118 700	83C13E	Blackface Mountain
58	Alberta Geological Survey	52 5000 117 2200	52 2500 117 5900	83C14W	Medicine Tent River
59	Alberta Geological Survey	52 5050 117 2066	52 2500 118	83C14W	Deception Mountain Pass

* Four spaces are used to denote the minutes; the first two represent the actual minutes, and the next two represent an estimate of the fraction to the next minute. For example, 52 850 is 52 degrees, 08 minutes, and .50 minutes estimated (i.e., 30 seconds). Similarly, 115 2750 is 115 degrees, 27 and ½ minutes.

Appendix 1. (continued)

Section	Reference	Latitude Longitude	Palinspastic position	NTS sheet	Section name
60	Alberta Geological Survey	52 5000 117 2200	52 2500 118	83C14W	Deception Creek
61	Alberta Geological Survey	52 5000 117 2200	52 2500 118	83C14W	Deception Mountain
62	Alberta Geological Survey	52 4633 117 2617	52 1000 118 1400	83C14W	Rocky River-Headwaters
63	Alberta Geological Survey	52 4700 117 2800	52 1200 118 1900	83C14W	Alpland Creek-Headwaters
64	Alberta Geological Survey	52 4325 117 0750	52 2000 117 5000	83C11E	Southesk Pass
65	Alberta Geological Survey	52 4375 117 1000	52 1800 117 4800	83C11E	Southesk Cairn
66	Alberta Geological Survey	52 3500 117 400	52 100 117 4700	83C11E	Southesk River
67	Alberta Geological Survey	52 3666 117 400	52 1200 117 4600	83C11E	Mt. Southesk
68	Alberta Geological Survey	52 3775 117 0	52 1400 117 4000	83C11E	Mt. Dalhousie
69	Alberta Geological Survey	52 3775 117 50	52 1400 117 4000	83C11E	Southesk River-East
70	Alberta Geological Survey	52 3775 117 50	52 1400 117 4000	83C11E	Mt. Dalhousie
71	Alberta Geological Survey	52 1400 116 2725	51 4700 117 2700	83C1W	Highway 11-Roadcut
72	Alberta Geological Survey	52 1350 117 1000	51 1700 119 300	83C3E	Sunwapta Pass
73	Alberta Geological Survey	52 2650 116 1975	52 900 116 5000	83C8W	Bighorn Range-Southend
74	Alberta Geological Survey	52 3225 116 5025	52 1100 117 3500	83C10W	Opabin Creek-East
75	Alberta Geological Survey	52 3225 116 5175	52 1000 117 3500	83C10W	Opabin Creek-West
76	Alberta Geological Survey	52 5000 117 4200	52 200 118 5100	83C13E	Medicine Lake
77	Alberta Geological Survey	52 4700 117 4050	52 400 118 4100	83C13E	Maligne River
78	Alberta Geological Survey	52 4675 117 4050	51 5900 118 5000	83C13E	Maligne River
79	Hudson Bay Oil and Gas-1966	52 1900 116 3900	51 5200 117 3300	83C7E	Bighorn River-Headwaters
80	Hudson Bay Oil and Gas-1966	52 1650 116 3400	51 4700 117 2900	83C7E	Littlehorn Creek-Headwater
81	Telfer-1933	52 5675 117 5750	52 700 119 400	83C13W	Grisette Mountain
82	Hudson Bay Oil and Gas-1966	52 1500 116 3200	51 4800 117 2600	83C2E	Whitegoat Creek
83	Gibson-1974	52 2800 117 200	51 3900 118 1200	83C7W	Mt. Olympus
84	Gibson-1968a	52 4700 117 3300	51 5800 118 4200	83C14W	Helmet Mountain
85	Gibson-1968a	52 5050 117 2250	52 2500 118	83C14W	Deception Mountain
86	Gibson-1968a	52 4400 117 800	52 1900 117 4800	83C11E	Mt. McBeath
87	Gibson-1968a	53 0 117 4300	52 3400 118 2000	83C13E	Rocky River
88	Mcgugan and Rapson-various	52 2725 116 5725	51 5400 118	83C07W	Arete Mountain
89	Gibson-1968a	53 0 118 0	52 1800 118 5700	83C13W	Colin Range-North
90	Mcgugan and Rapson-various	52 2900 116 5400	52 100 117 4700	83C07W	Valley Head Mountain
91	Alberta Geological Survey	53 2825 118 1625	53 2100 118 3000	83E08W	Wildhay River
92	Alberta Geological Survey	53 2825 118 1625	53 2100 118 3000	83E08W	Wildhay River
93	Alberta Geological Survey	53 2850 118 1675	53 2100 118 3000	83E8W	Rock Lake
94	Alberta Geological Survey	53 2950 118 1050	53 2400 118 2000	83E8E	Hoff Range-Wildhay River
95	Alberta Geological Survey	53 3900 118 3800	53 2500 118 5400	83E10E	Berland Range-North
96	Alberta Geological Survey	53 4750 119 2900	53 2000 120 300	83E14W	Muddywater River
97	Alberta Geological Survey	53 4775 119 3000	53 2000 120 600	83E14W	Llama Mountain
98	Alberta Geological Survey	53 4900 119 2900	53 2000 120 60	83E14W	Llama Mountain
99	Gibson-1968a	53 4900 119 2900	53 2000 120 600	83E14W	Llama Mountain
100	Alberta Geological Survey	53 5275 119 5650	53 1300 120 3600	83E13W	Mt. Cote
101	Alberta Geological Survey	53 5625 119 5975	53 3100 120 3000	83E13W	Cote Creek-Headwaters
102	Alberta Geological Survey	53 4550 119 3125	53 1000 120 800	83E13E	Muddywater River Ridge
103	Alberta Geological Survey	53 4500 119 3200	53 800 120 1400	83E13E	Muddywater River Ridge
104	Alberta Geological Survey	53 4350 118 3500	53 4000 118 3900	83E10E	Adams Lookout
105	Alberta Geological Survey	53 4475 118 3733	53 4100 118 4200	83E10E	Adams Lookout
106	Alberta Geological Survey	53 3400 118 2900	53 2200 118 4600	83E9W	Minny Ridge
107	Alberta Geological Survey	53 3250 118 2400	53 2200 118 4400	83E9W	Zebra Mountain
108	Alberta Geological Survey	53 3250 118 2400	53 2200 118 4600	83E9W	Zebra Mountain
109	Alberta Geological Survey	53 3050 118 2000	53 1900 118 4000	83E9W	Shrew Creek
110	Alberta Geological Survey	53 3100 118 2050	53 1900 118 3700	83E9W	Seep Creek-Headwaters
111	Alberta Geological Survey	53 3125 118 1250	53 2300 118 2600	83E9W	Collie Creek-Headwaters
112		53 4300 118 5875	53 2300 119 2100	83E10W	Lancaster Creek
113	Alberta Geological Survey	53 3275 118 5433	53 200 119 3700	83E10W	Monoghan Creek-South Rid.
114	Alberta Geological Survey	53 3225 118 5500	53 200 119 3800	83E10W	Monoghan Creek Ridge
115	Alberta Geological Survey	53 3275 118 5425	53 200 119 3700	83E10W	Monoghan Creek Ridge
116	Alberta Geological Survey	53 3275 118 4200	53 600 119 1500	83E10E	South Berland-Headwaters
117	Alberta Geological Survey	53 3850 118 5633	53 1000 119 2900	83E10W	Rocky Pass
118	Alberta Geological Survey	53 3850 118 5625	53 1000 119 2900	83E10W	Rocky Pass Lake
119	Alberta Geological Survey	53 3850 118 5033	53 2000 119 1400	83E10W	Muskegg River-Headwaters
120	Alberta Geological Survey	53 3517 118 4850	53 600 119 2300	83E10W	North Berland River-Headw
121	Alberta Geological Survey	53 3750 118 3483	53 2700 118 4900	83E10E	Planet Creek Headwaters

Appendix 1. (continued)

Section	Reference	Latitude Longitude	Palinspastic position	NTS sheet	Section name
122	Alberta Geological Survey	53 500 118 125	52 3800 118 4400	83E1E	Talbot Lake
123	Alberta Geological Survey	53 950 118 200	52 4700 118 4000	83E1E	Snake Indian River Bridge
124	Alberta Geological Survey	53 1450 118 1100	52 5100 118 4700	83E1E	Shale Banks
125	Alberta Geological Survey	53 1500 118 950	52 4800 118 5200	83E8E	Shale Banks-Creek East
126	Alberta Geological Survey	53 1550 118 925	52 5000 118 4700	83E8E	Shale Banks Creek
127	Walasko-1962	53 975 118 1675	52 3600 119 600	83E01W	Mt. Thornton
128	Alberta Geological Survey	53 300 118 400	52 3200 118 4700	83E1E	Morro Peak
129	Alberta Geological Survey	53 275 118 400	52 3200 118 4700	83E1E	Morro Peak
130	Alberta Geological Survey	53 450 118 875	52 3200 119	83E1E	Esplande Mountain
131	Alberta Geological Survey	53 1750 118 1625	52 5300 118 5100	83E8W	Snake Indian Falls
132	Alberta Geological Survey	53 2133 118 950	52 5900 118 4800	83E8E	Bosche Range-North
133	Alberta Geological Survey	53 2350 118 1350	52 5900 118 5100	83E8E	Bosche Range-North
134	Alberta Geological Survey	53 2380 118 1450	53 118 5000	83E8E	South Rock Lake
135	Alberta Geological Survey	53 2350 118 1350	52 5900 118 5100	83E8E	Bosche Range-North
136	Alberta Geological Survey	53 2050 118 3375	52 4900 119 1600	83E7E	Mt. Kelsey
137	Alberta Geological Survey	53 2050 118 3575	52 5000 119 1800	83E7E	Mt. Kelsey
138	Alberta Geological Survey	53 2725 118 2800	53 119 400	83E7E	Daybreak Peak
139	Alberta Geological Survey	53 2725 118 2800	53 119 400	83E7E	Daybreak Pass
140	Alberta Geological Survey	53 2217 118 280	53 1200 118 1800	83E8E	Mt. Kephala
141	Alberta Geological Survey	53 2250 118 150	53 1400 118 1500	83E8E	Mt. Kephala
142	Alberta Geological Survey	53 2400 118 250	53 1700 118 1600	83E8E	Soloman Creek
143	Alberta Geological Survey	53 2400 118 250	53 1700 118 1500	83E8E	Soloman Creek
144	Alberta Geological Survey	53 2750 118 800	53 2100 118 2200	83E8E	Wildhay River-South Fork
145	Alberta Geological Survey	53 2750 118 800	53 2000 118 2000	83E8E	South Tributary-Wildhay R
146	Alberta Geological Survey	53 2575 118 4375	52 5400 119 2800	83E7E	Vega Peak
147	Alberta Geological Survey	53 2550 118 4400	52 5400 119 2800	83E7E	Vega Peak
148	Alberta Geological Survey	53 2875 118 5450	52 5500 119 4400	83E7W	Mt. Perce
149	Alberta Geological Survey	53 2825 118 5475	52 5500 119 4500	83E7W	Sunset Peak
150	Alberta Geological Survey	53 3000 118 3533	53 200 119 800	83E7E	Persimmon Range-South
151	Alberta Geological Survey	53 2425 118 3125	52 5700 119 600	83E7E	Mowitch Creek Cabin
152	Alberta Geological Survey	53 2500 118 2950	52 5800 119 300	83E8W	Mowitch Creek-Mouth
153	Alberta Geological Survey	53 2525 118 3675	52 5400 119 1600	83E7E	Mowitch Creek
154	Alberta Geological Survey	53 4400 119 2000	53 1500 119 5200	83E11W	Wolverine Creek Ridge
155	Alberta Geological Survey	53 4425 119 1850	53 1600 119 5200	83E11W	Wolverine Creek
156	Alberta Geological Survey	53 3775 119 950	53 119 4900	83E11W	Kvass Creek Headwaters
157	Alberta Geological Survey	53 3550 119 650	52 5900 119 4800	83E11E	Hardscramble Creek
158	Alberta Geological Survey	53 3625 119 50	53 400 119 3900	83E11E	Monoghan Creek-North Rid.
159	Alberta Geological Survey	53 3775 119 750	53 600 119 4600	83E11W	Kvass Creek-South
160	Alberta Geological Survey	53 2550 118 4250	52 5400 119 2300	83E7E	Vega Peak
161	Hudson Bay Oil and Gas-1965	53 2600 118 400	53 1900 118 1500	83E8E	North Tributary-Wildhay R
162	Hudson Bay Oil and Gas-1965	53 3250 118 1500	53 3000 118 1900	83E9E	Collie Creek-Headwaters
163	Hudson Bay Oil and Gas-1965	53 3650 118 3250	53 2300 118 4900	83E10E	Planet Creek
164	Gibson-1968a	53 3250 119 50	52 5900 119 4800	83E11E	Monoghan Creek
165	Gibson-1968a	53 3550 118 5600	53 400 119 3600	83E10W	Sulphur River
166	Gibson-1968a	53 2675 118 4600	52 5800 119 2800	83E7W	Sulphur River-Headwaters
167	Gibson-1968a	53 3925 118 5900	53 1000 119 3000	83E10W	Rocky Pass
168	Alberta Geological Survey	53 3400 118 5000	53 500 119 2300	83E10W	South Sulphur River Cabin
169	Alberta Geological Survey	53 4175 119 1200	53 1400 119 4500	83E11E	Kvass Creek-North
170	Gibson-1968a	53 3100 118 4300	53 200 119 1200	83E10E	South Berland River-Headw
171	Gibson-1968a	53 3300 118 1800	53 2600 118 2900	83E9W	Mumm Creek-Headwaters
172	Gibson-1968a	53 3500 119 800	52 5800 119 5200	83E11E	Hardscramble Creek
173	Gibson-1968a	53 3800 119 700	53 600 119 4600	83E11E	Kvass Creek-South
174	Gibson-1968a	53 700 118 600	52 3900 118 5400	83E1E	Greenock Mountain
175	Gibson-1968a	53 2250 118 1250	52 5900 118 5000	83E8E	Moosehorn Creek Lake
176	Gibson-1968a	53 3200 118 2100	53 2000 118 3800	83E9W	Seep Creek-East Fork
177	Alberta Geological Survey	53 2950 118 1075	53 2200 118 2400	83E8E	Mumm Creek
178	Alberta Geological Survey	53 2000 117 5600	53 1200 118 900	83F5W	Oldhouse Creek
179	Alberta Geological Survey	53 2100 117 5850	53 1500 118 900	83F5W	West Fork-Soloman Creek
180	Alberta Geological Survey	53 1425 117 4725	53 700 118	83F4W	Folding Mountain
181	Alberta Geological Survey	53 1375 117 4650	53 600 117 5900	83F4W	Drystone Creek
182	Telfer-1933	53 250 117 2675	52 4800 117 5200	83F3W	Luscar Mountain
183	Frebold-1957	53 1050 117 5100	52 5800 118 900	83F4W	Fiddle River

Appendix 1. (continued)

Section	Reference	Latitude Longitude	Palinspastic position	NTS sheet	Section name
184	Alberta Geological Survey	53 2025 117 5925	53 1200 118 900	83F05W	Boule Roche
185	Alberta Geological Survey	53 1975 117 5750	53 1000 118 1500	83F05W	Boule Roche
186	Telfer-1933	53 1150 117 5250	52 5400 118 2100	83F04W	Pocahontas
187	Telfer-1933	53 225 117 2550	52 4500 117 5900	83F03W	Luscar Mountain
188	Alberta Geological Survey	53 375 117 5950	52 3600 118 4000	83F4W	Emir Mountain
189	Alberta Geological Survey	53 1075 117 5025	52 5600 118 800	83F4W	Fiddle River
190	Alberta Geological Survey	53 925 117 4800	52 5600 118 800	83F4W	Fiddle River-South
191	Alberta Geological Survey	49 3725 114 3850	49 3100 115 4700	82G10E	Highway 3-Roadcut
192	Alberta Geological Survey	49 5900 114 2300	49 5000 115 1400	82G16W	White Creek
193	Alberta Geological Survey	49 5900 114 2300	49 5000 115 1500	82G16W	White Creek
194	Douglas-1958	49 5900 114 2300	49 5100 115 1300	82G16W	White Creek
195	Alberta Geological Survey	49 5175 114 2100	49 4400 115 1100	82G16W	Oldman River Gap
196	Alberta Geological Survey	49 5175 114 2100	49 4400 115 1200	82G16W	Oldman River Gap
197	Alberta Geological Survey	49 4475 114 2250	49 3600 115 1300	82G9W	Daisy Creek Summit
198	Alberta Geological Survey	49 4475 114 2200	49 3700 115 1300	83G9W	Daisy Creek Summit
199	Western Warner Oil-1965	49 4400 114 3800	49 4200 115 4800	82G10E	Allison Peak
200	Alberta Geological Survey	49 5175 114 4000	49 4700 115 4700	82G15E	Racehorse Creek-Summit
201	Alberta Geological Survey	49 3725 114 2050	49 3000 115 1400	82G9W	Rock Creek Summit
202	Alberta Geological Survey	49 3725 114 2050	49 2800 115 1100	82G9W	Rock Creek Summit
203	Western Warner Oils-1965	49 4250 114 3450	49 3900 115 4300	82G10E	Crowsnest Mountain
204	Western Warner Oils-1965	49 5650 114 4100	49 5400 115 5100	82G10E	Tornado Pass
205	Alberta Geological Survey	49 3975 114 4200	49 3500 115 5200	82G10E	Crow Mine
206	Alberta Geological Survey	49 3750 114 4150	49 3400 115 5200	82G10E	Crowsnest Pass
207	Kenny-1977	49 3250 115 1100	49 3400 117 2300	82G6W	Lizard Creek
208	Telfer-1933	49 2200 114 4200	49 1100 115 4800	82G7E	Flathead River
209	Western Warner Oils-1965	49 3350 114 3450	49 2800 115 4300	82G10E	Mt. Ptolemy
210	Alberta Geological Survey	49 3400 114 4000	49 2300 115 4900	82G10E	Tent Mountain
211	Alberta Geological Survey	49 3400 114 4000	49 2300 115 4900	82G10E	Tent Mountain
212	Western Warner Oils-1965	49 4250 114 3825	49 3900 115 4800	82G10E	Deadman Pass
213	Alberta Geological Survey	49 2900 114 2450	49 2000 115 1600	82G8W	Adanac Mine
214	Telfer-1933	49 3950 114 3825	49 3400 115 4700	82G10E	Phillips Pass
215	Alberta Geological Survey	49 4025 114 2500	49 3200 115 1600	82G9W	Grassy Mountain
216	Alberta Geological Survey	49 3725 114 4150	49 3300 115 5000	82G10E	Crowsnest Pass
217	Alberta Geological Survey	49 2950 114 2450	49 2000 115 1500	82G8W	Adanac Mine
218	Alberta Geological Survey	49 2775 114 4200	49 2100 115 5000	82G7E	Barnes Lake
219	Alberta Geological Survey	49 1825 114 5775	49 200 116 200	82G7E	Mt. Broadwood
220	Alberta Geological Survey	49 1900 114 5550	49 600 116	82G7E	Lodgepole Creek
221	Alberta Geological Survey	49 1800 114 5675	49 300 116 300	82G7E	Mt. Broadwood
222	Alberta Geological Survey	49 2775 114 4150	49 600 116 4100	82G7E	Flathead Pass
223	Alberta Geological Survey	49 5450 114 5075	49 4900 116	82G15W	Fording River
224	Alberta Geological Survey	49 3925 114 4400	49 3500 115 5300	82G10E	Highway 3-Roadcut
225	Alberta Geological Survey	49 5450 114 4075	49 5100 115 5000	82G15E	Mt. Erris
226	Alberta Geological Survey	49 4675 114 3800	49 4500 115 4700	82G15E	Racehorse Pass
227	Telfer-1933	49 3125 114 3950	49 800 116 3800	82G10E	Corbin
228	Alberta Geological Survey	49 2800 114 3550	49 1800 115 4200	82G7E	Flathead Range-South
229	Kenny-1977	49 2800 115 700	49 200 117 1000	82G6E	Lizard Range
230	Kenny-1977	49 5225 114 5625	49 4800 116 5900	82G15W	Brule Creek
231	Kenny-1977	49 5700 114 5800	49 5200 117 100	82G15W	Weight Creek
232	Telfer-1933	49 3775 114 5675	49 3800 116 5100	82G10W	Mt. Hosmer
233	Mcgugan and Rapson-various	49 4600 115 275	49 4000 117 10	82G14E	Cummings Creek
234	Mcgugan and Rapson-various	49 4875 114 4100	49 2600 116 3600	82G15E	Alexander Creek-Headwater
235	Mcgugan and Rapson-various	49 5500 114 5075	49 5400 116 5400	82G15W	Fording River
236	Mcgugan and Rapson-various	49 3250 115 1100	49 1100 117 1600	82G11E	Lizard Creek
237	Gibson-1968b	49 5125 114 4675	49 4725 116 5300	82G15W	Mt. Salter
238	Gibson-1968b	49 4775 114 5950	49 4000 117 525	82G15W	Cummings Creek
239	Gibson-1968b	49 1475 114 5400	49 115 5400	82G2W	Lodgepole Creek-South
240	Alberta Geological Survey	50 4300 115 600	50 2500 116 1000	82J11E	King Creek
241	Alberta Geological Survey	50 4050 115 500	50 2200 116 800	82J11E	Elpoca Mountain
242	Mobil Oil-1966	50 4700 115 1600	50 2300 116 2900	82J14W	Mt Chester
243	Alberta Geological Survey	50 5600 115 900	50 4100 116 500	82J14E	Ribbon Creek
244	Hudson Bay Oil and Gas-1965	50 3200 114 4900	50 1600 115 3500	82J10W	Highwood Range
245	Alberta Geological Survey	50 3850 115 150	50 2700 115 5200	82J11E	Elpoca Mountain

Appendix 1. (continued)

Section	Reference	Latitude Longitude	Palinspastic position	NTS sheet	Section name
246	Hudson Bay Oil and Gas-1965	50 3400 114 5000	50 1800 115 3900	82J10W	Gibralter Mountain
247	Alberta Geological Survey	50 3850 115 150	50 2000 116 200	82J11E	Elpoca Mountain Gap
248	Alberta Geological Survey	50 3850 115 150	50 1600 116	82J11E	Elpoca Mountain Group
249	Hudson Bay Oil and Gas-1965	50 3600 115 300	50 1500 116 700	82J11E	Elk Range Fire Tower
250	Alberta Geological Survey	50 5400 115 2000	50 2800 116 3200	82J14W	Spray Lake
251	Hudson Bay Oil and Gas-1965	50 4600 115 700	50 2300 116 300	82J14E	Mt. Evans-Thomas Creek
252	Alberta Geological Survey	50 4425 115 750	50 2700 116 1100	82J11E	Walker Creek
253	Hudson Bay Oil and Gas-1965	50 650 114 4300	50 300 115 5200	82J2E	Mt. Lyall
254	Alberta Geological Survey	50 3975 115 450	50 2000 116 800	82J11E	Whiteman Creek
255	Hudson Bay Oil and Gas-1965	50 4825 114 5350	50 3400 115 4300	82J15W	Nihahi Ridge-South
256	Alberta Geological Survey	50 750 114 2275	50 100 115 1600	82J1W	Mt. Livingstone
257	Hudson Bay Oil and Gas-1965	50 475 114 2000	49 5500 115 1200	82J1W	Livingstone Range
258	Hudson Bay Oil and Gas-1965	50 1000 114 2450	50 300 115 1800	82J1W	Mt. Livingstone-North
259	Norris-1965	50 2350 114 3675	50 900 115 2600	82J07E	Mt. Head Ranger Station
260	Hudson Bay Oil and Gas-1965	50 1950 114 3275	50 1200 115 2500	82J7E	Mt. Burke
261	Kenny-1977	50 2000 114 5700	49 5300 116 4500	82J7W	Mt. Bleasdell
262	Hudson Bay Oil and Gas-1965	50 4725 114 5000	50 3700 115 2100	82J15W	Forgetmenot Mountain
263	Alberta Geological Survey	50 900 114 2950	50 100 115 2200	82J1W	Savanna Creek
264	Alberta Geological Survey	50 925 114 2950	49 5500 115 1900	82J2E	Savanna Creek
265	Alberta Geological Survey	50 1075 114 2650	49 5700 115 1600	82J1W	Mt. Livingstone
266	Norris-1965	50 1375 114 3125	50 115 2000	82J02E	Plateau Mountain
267	Alberta Geological Survey	50 1750 114 3450	50 300 115 2400	82J7E	Cataract Creek
268	Douglas-1958	50 3300 114 3500	50 1900 115 2700	82J10E	Sullivan Creek Headwaters
269	Hudson Bay Oil and Gas-1965	50 5000 115 1300	50 2700 116 1500	82J14E	Fortress Mountain Ski Hill
270	Alberta Geological Survey	50 2800 114 3500	50 1800 115 500	82J7E	Trap Creek
271	Alberta Geological Survey	50 2850 114 3850	50 1400 115 2700	82J7E	Trap Creek
272	Douglas-1958	50 3000 114 4100	50 1600 115 3200	82J7E	Puriform Mountain
273	Alberta Geological Survey	50 4300 114 4350	50 3300 115 1300	82J10E	Volcano Ridge
274	Alberta Geological Survey	50 3900 114 3550		82J10E	
275	Alberta Geological Survey	50 3575 114 5150	50 2100 115 4100	82J10W	Gibralter Mountain
276	Alberta Geological Survey	50 3575 114 5150	50 2100 115 4100	82J10W	Gibralter Mountain
277	Alberta Geological Survey	50 4300 114 5900	50 2700 115 3900	82J10W	Little Elbow River-Headw
278	Alberta Geological Survey	50 4300 114 5900	50 2400 115 5500	82J10W	Little Elbow River-Headw
279	Alberta Geological Survey	50 4150 114 5850	50 2600 115 4700	82J10W	Tombstone Mountain
280	Alberta Geological Survey	50 3600 114 4600	50 2200 115 3600	82J10W	Sheep River
281	Alberta Geological Survey	50 3375 114 5600	50 1400 115 5500	82J10W	Mist Mountain
282	Alberta Geological Survey	50 3325 114 5575	50 1400 115 5800	82J10W	Mist Mountain
283	Alberta Geological Survey	50 5425 114 4550	50 3900 115 2000	82J15W	Canyon Creek
284	Alberta Geological Survey	50 4750 114 5250		82J15W	
285	Alberta Geological Survey	50 5200 114 5600	50 3800 115 4500	82J15W	Nihahi Ridge-North
286	Alberta Geological Survey	50 5175 115 650	50 3700 115 5800	82J14E	Evans-Thomas Creek
287	Alberta Geological Survey	50 5175 115 625	50 3800 116 300	82J14E	Evans-Thomas Creek
288	Alberta Geological Survey	50 5200 115 600	50 3600 116	82J14E	Evan-Thomas Creek
289	Alberta Geological Survey	50 5150 115 1025	50 2900 116 800	82J14E	The Wedge
290	Alberta Geological Survey	50 5125 115 1450	50 3300 116 1500	82J14E	Mt. Kidd
291	Alberta Geological Survey	50 5075 115 1250	50 3450 116 1500	82J14E	Fortress Mountain
292	Alberta Geological Survey	50 4700 115 2050	50 700 117 300	82J14W	Mt. Burstall
293	Alberta Geological Survey	50 3900 115 1600	50 100 117	82J11W	Three Isle Lake
294	Alberta Geological Survey	50 4000 114 5900	50 2600 115 5700	82J10W	Mt. Rae
295	Alberta Geological Survey	50 4150 115 750	50 1300 116 1700	82J11E	Kananaskis River Canyon
296	Alberta Geological Survey	50 5625 115 2400	50 3200 116 3500	82J14W	Goat Range
297	Alberta Geological Survey	50 5450 115 2600	50 3200 116 3900	82J14W	Mt. Turbulent
298	Harker and McLarn-1958	50 5925 115 750	50 4300 116 400	82J14E	Mt. Lorette
299	Alberta Geological Survey	50 4000 115 475	50 2200 116 800	82J11E	Whiteman Creek
300	Gibson-1968b	50 1950 114 5675	49 5600 116 5200	82J7W	Mt. Bleasdell
301	Hudson Bay Oil and Gas-1966	50 3550 115 275	50 1500 116 800	82J11E	Elk Range Fire Tower
302	Hudson Bay Oil and Gas-1966	50 4500 115 650	50 2300 116 300	82J14E	Mt. Evans-Thomas
303	Mobil Oil-1966	50 5425 115 1675	50 3400 116 1900	82J14W	Mt. Bogart
304	Mobil Oil-1966	50 4925 115 1750	50 2500 116 2700	82J14W	Mt. Galatea
305	Mobil Oil-1966	50 4725 115 1550	50 2400 116 2600	82J14W	Mt. Chester
306	Hudson Bay Oil and Gas-1966	50 4500 115 1125	50 1700 116 2000	82J14E	Mt. Lawson
307	Hudson Bay Oil and Gas-1966	50 4450 115 1325	50 2000 116 2400	82J11E	Mt. Kent-North

Appendix 1. (continued)

Section	Reference	Latitude Longitude	Palinspastic position	NTS sheet	Section name
308	Hudson Bay Oil and Gas-1965	50 4225 115 1075	50 1400 116 2000	82J11E	Mt. Kent-South
309	Mcgugan and Rapson-various	50 600 115 75	50 400 116 5200	82J03E	Mt. Peck
310	Norris-1965	50 450 114 4325	49 5300 115 5000	82J02E	Beehive Mountain
311	Mcgugan and Rapson-various	50 1700 115 300	50 1700 117	82J06E	Connor Lake
312	Mcgugan and Rapson-various	50 4700 115 975	50 2800 116 1300	82J14E	Highway 40-Roadcut
313	Mcgugan and Rapson-various	50 4075 115 150	50 2200 116 200	82J11E	Tombstone Mountain
314	Alberta Geological Survey	50 5600 115 900	50 4000 116 300	82J14E	Ribbon Creek
315	Alberta Geological Survey	50 900 114 4300	50 400 115 5400	82J2E	Mt. Gass
316	Frebold-1957	54 1200 119 4900		83L4W	Stinking Springs
317	Alberta Geological Survey	51 5350 116 1025	51 3700 116 5900	82N16E	Ram Falls-Headwaters
318	Alberta Geological Survey	51 5325 116 1025	51 3100 117 2700	82N16E	Ram River-Headwaters
319	Alberta Geological Survey	51 5200 116 900	51 3000 116 5900	82N16E	Whiterabbit Creek-Headw
320	Hudson Bay Oil and Gas-1965	51 5800 116 050	51 3600 116 4700	82N16E	Wampum Peak-North
321	Alberta Geological Survey	51 5875 116 950	51 3800 117 100	82N16E	Headwaters-Whiterabbit Cr.
322	Alberta Geological Survey	51 5875 116 0950	51 3500 116 5600	82N16E	Whiterabbit Creek-Headw
323	Alberta Geological Survey	51 5566 116 700	51 2900 117 200	82N16E	Indian Lookout Pass
324	Alberta Geological Survey	51 5800 115 1500	51 5000 115 3600	82O14E	Clearwater River
325	Hudson Bay Oil and Gas-1965	51 3825 115 3525	51 1600 116 2400	82O12E	Dormer Mountain
326	Alberta Geological Survey	51 5400 115 2100	51 4700 115 4300	82O14W	Limestone Mountain South
327	Alberta Geological Survey	51 4450 115 3250	51 3000 116 2200	82O12E	Bighorn Creek Falls
328	Alberta Geological Survey	51 4450 115 3250	51 2800 116 2200	82O12E	Bighorn Creek Falls
329	Hudson Bay Oil and Gas-1965	51 5175 115 3275	51 3100 116 1700	82O13E	Limestone Creek-Headwater
330	Alberta Geological Survey	51 4400 115 2900	51 2600 116 1600	82O12E	Eagle Creek
331	Hudson Bay Oil and Gas-1965	51 5775 115 5000	51 3700 116 3400	82O13W	Washout Creek
332	Alberta Geological Survey	51 4400 115 2900	51 2600 116 1500	82O11W	Eagle Creek
333	Telfer-1933	51 2850 115 4125	51 800 116 3400	82O5E	Cuthead Creek-Headwaters
334	Alberta Geological Survey	51 4350 115 2700	51 2300 116 1200	82O11W	James Pass
335	Alberta Geological Survey	51 3400 115 2600	51 1900 115 5900	82O11W	Sheep Creek
336	Alberta Geological Survey	51 3400 115 2600	51 1975 116 75	82O11W	Sheep Creek
337	Alberta Geological Survey	51 600 115 1900	50 4600 116 1400	82O3W	Cougar Canyon
338	Telfer-1933	51 3600 115 4750	51 1400 116 4000	82O12W	Snow Pass
339	Alberta Geological Survey	51 150 115 1500	50 4400 116 900	82O3W	Pigeon Creek
340	Alberta Geological Survey	51 200 115 1500	50 4800 116 1200	82O3W	Pigeon Creek
341	Alberta Geological Survey	51 550 115 1000	50 4800 115 5700	82O3E	Type Section-Exshaw Form.
342	Alberta Geological Survey	51 4800 115 5200	51 2300 116 3800	82O13W	Forbidden Creek
343	Alberta Geological Survey	51 4850 115 3050	51 3000 116 1700	82O13E	Bighorn Creek-Headwaters
344	Alberta Geological Survey	51 5750 115 4650	51 3900 116 3500	82O13W	Washout Creek-Headwaters
345	Alberta Geological Survey	51 1025 115 1325	50 5600 116 300	82O3E	S. Ghost River-Headwaters
346	Alberta Geological Survey	51 1325 115 1525	50 5700 116 400	82O3W	S. Ghost River-Headwaters
347	Alberta Geological Survey	51 1325 115 1525	50 5900 116 400	82O3W	Saddle Peak
348	Alberta Geological Survey	51 1275 115 1375	50 5400 116 200	82O3E	Saddle Peak
349	Alberta Geological Survey	51 413 115 2550	50 4200 116 2400	82O3W	Mt. Rundle Gap
350	Alberta Geological Survey	51 1700 115 1850	51 200 116 900	82O6W	Mt. Costigan
351	Alberta Geological Survey	51 1700 115 1850	51 200 116 900	82O6W	Mt. Costigan
352	Alberta Geological Survey	51 1700 115 1850	51 325 116 725	82O6W	Mt. Castigan
353	Alberta Geological Survey	51 2050 115 2850	51 300 116 2200	82O6W	Mt. Aylmer
354	Douglas-1958	51 2050 115 2850	51 300 116 2000	82O6W	Mt. Aylmer
355	Alberta Geological Survey	51 2300 115 2700	51 800 116 1900	82O6W	Ghost River Headwaters
356	Alberta Geological Survey	51 2475 115 2725	51 500 116 2200	82O6W	Mt. Oliver
357	Alberta Geological Survey	51 3525 115 2850	51 1500 116 2200	82O11W	Otuskwan Ridge
358	Alberta Geological Survey	51 3550 115 2925	51 1800 116 1800	82O12E	Otuskwan Ridge
359	Alberta Geological Survey	51 3550 115 2925	51 1800 116 1800	82O12E	Otaskwan Ridge
360	Alberta Geological Survey	51 5550 115 2675	51 4800 115 4700	82O14W	Limestone Mountain
361	Harker and McLarn-1958	52 0 115 2850	51 4600 115 5500	82O14W	Limestone Mountain
362	Alberta Geological Survey	51 875 115 3450	50 4400 116 4600	82O4E	Sulphur Mountain
363	Alberta Geological Survey	51 800 115 4133	50 3000 117 2600	82O4E	Brewster Creek
364	Alberta Geological Survey	51 300 115 3025	50 4600 116 2700	82O4E	Sulphur River
365	Alberta Geological Survey	51 1600 115 4600	50 5000 116 5600	82O5W	Mt. Ishbel
366	Alberta Geological Survey	51 1725 115 3200	51 116 2700	82O5E	Cascade River Crossing
367	Alberta Geological Survey	51 2150 115 3900	51 100 116 3300	82O5E	Vermilion Range
368	Alberta Geological Survey	51 2050 115 4150	50 5500 116 5400	82O5E	East of Forty Mile Creek
369	Alberta Geological Survey	51 2175 115 3500	51 300 116 3000	82O5E	Stoney Creek

Appendix 1. (continued)

Section	Reference	Latitude Longitude	Palinspastic position	NTS sheet	Section name
370	Alberta Geological Survey	51 2475 115 5325	50 5000 117 4200	82O5W	Badger Pass
371	Alberta Geological Survey	51 2450 115 4725	50 4700 117 3500	82O5W	Flints Park Cabin
372	Alberta Geological Survey	51 2475 115 4850	50 4500 117 3600	82O5W	Cascade River-Headwaters
373	Alberta Geological Survey	51 2450 115 4000	51 117 300	82O5E	Cuthead Creek-South
374	Alberta Geological Survey	51 2550 115 3950	51 400 116 3200	82O5E	Cuthead Creek-North
375	Alberta Geological Survey	51 3100 115 4325	51 1000 116 3400	82O12E	Wigmore Creek
376	Alberta Geological Survey	51 2975 115 4850	51 400 117	82O5W	Panther River-Headwaters
377	Alberta Geological Survey	51 3300 115 4350	51 1300 116 3700	82O12E	Panther Mountain Gap
378	Alberta Geological Survey	51 3400 115 4300	51 1200 116 3400	82O12E	Panther Mountain Gap
379	Alberta Geological Survey	51 4025 115 5825	51 1500 117 1000	82O12W	McConnell Creek
380	Alberta Geological Survey	51 3650 115 4800	51 1600 116 4900	82O12W	Snow Peak
381	Alberta Geological Survey	51 3925 115 5000	51 1900 116 4300	82O12W	Mt. White
382	Alberta Geological Survey	51 4075 115 5000	51 2100 116 4300	82O12W	Mt. Tyrrell
383	Alberta Geological Survey	51 4325 115 5425	51 2200 116 4500	82O12W	Divide Creek
384	Alberta Geological Survey	51 3825 115 4175	51 1800 116 3000	82O12E	Gable Mountain
385	Alberta Geological Survey	51 4550 115 5300	51 2900 116 4700	82O13W	Forbidden Creek-Summit
386	Alberta Geological Survey	51 4575 115 5375	51 2300 116 4100	82O13W	Forbidden Creek-Headwaters
387	Alberta Geological Survey	51 5400 115 5475	51 3500 116 4100	82O13W	North of Peters Peak
388	Alberta Geological Survey	51 5450 115 5400	51 3800 116 4400	82O13W	North of Mt. Peters
389	Alberta Geological Survey	51 5400 115 5475	51 3500 116 4100	82O13W	North of Peters Peak
390	Alberta Geological Survey	51 5700 115 4650	51 4200 116 3600	82O13W	Washout Creek-Headwaters
391	Alberta Geological Survey	51 1000 115 1750	50 5400 116 1300	82O3W	Mt. Stewart
392	Alberta Geological Survey	51 1000 115 1750	50 5400 116 1300	82O3W	Mt. Stewart
393	Telfer-1933	51 3075 115 4775	51 1100 116 3800	82O12W	Panther River-Headwaters
394	deSchmid-1916	51 850 115 3750	50 4400 116 4900	82O4E	Sundance Canyon
395	Alberta Geological Survey	51 1375 115 3100	50 5800 116 2500	82O3E	Lake Minnewanka Damsite
396	deSchmid-1916	51 1100 115 3675	50 4900 116 3500	82O4E	Mt. Norquay
397	Mobil Oil-1965	51 3900 115 2725	51 2100 116 1400	82O11W	Mouth of Dogrib Creek
398	Hudson Bay Oil and Gas-1966	51 4975 115 4100	51 3200 116 2800	82O13E	Skelton Creek
399	Alberta Geological Survey	51 875 115 3333	50 4800 116 3200	82O4E	Bow Falls
400	Alberta Geological Survey	51 1466 115 3066	50 5700 116 2500	82O4E	Minnewanka Highway
401	Alberta Geological Survey	51 1425 115 3025	50 5700 116 2700	82O4E	Lower Cascade River
402	McGugan and Rapson-various	51 5100 115 5900	51 3000 116 4900	82O13W	Mt. Peters
403	Gibson-1974	51 700 115 3100	50 4700 116 3200	82O4E	Sulfur Mountain
404	Alberta Geological Survey	51 5300 115 4050	51 3200 116 2400	82O13E	Timber Creek
405	First Nuclear Corp.-1981	49 0500 114 3425		82G2E	Cabin Creek
406	First Nuclear Corp.-1981	49 0700 114 4150		82G2E	Cabin Creek-North
407	First Nuclear Corp.-1981	49 0700 114 4600		82G2E	Bighorn Creek
408	First Nuclear Corp.-1981	49 0750 114 4000		82G2E	Cabin Creek-West

Appendix 2. Lithologic and chemical analysis data—Exshaw Formation, Basal Sandstone Member.

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
76	Shale	0.45	7.78	271	127.1	3.50	1.75	2
120	Sandstone	0.10	4.10	110	13.0	0.41	0.21	1
160	Sandstone	0.10	4.50	60	13.0	0.45	0.23	1
191	Shale	0.30	4.00	2600	129.3	1.20	0.60	2
200	Sandstone	0.10	6.30	340	168.0	0.63	0.32	1
225	Sandstone	0.03	8.67	400	80.0	0.26	0.13	1
226	Shale	0.30	1.40	380		0.42	0.21	1
280	Sandstone	0.10	2.20	440	71.0	0.22	0.11	1
285	Sandstone	0.10	1.90	120	34.0	0.19	0.10	1
315	Shale	0.25	2.96	212	74.4	0.74	0.37	1
334	Sandstone	0.10	3.70	60	53.0	0.37	0.19	1
341	Sandstone	0.03	5.00	33	53.3	0.15	0.08	1
378	Sandstone	0.08	2.25	163	23.8	0.18	0.09	1

* - number of samples

Appendix 3. Lithologic and chemical analysis data—Exshaw Formation, Middle and Lower Phosphate Zones.

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
24	Sandstone	0.30	1.33	320	66.3	0.40	0.20	2
59	Phosphate	0.10	26.50	190	122.0	2.65	1.33	1
191	Mudstone	0.90	1.40	335	6.2	1.26	0.63	3
199	Shale	0.60	15.90		0.0	9.54	4.77	2
214	Shale	0.87	10.16		0.0	8.84	4.42	3
226	Phosphate	3.00	6.30	97	7.5	6.30	6.30	2
228	Shale	0.20	10.20	125	6.6	2.04	1.02	3
293	Shale	1.00	1.60	640	31.4	1.60	0.80	1
382	Sandstone	0.10	2.30	130	151.0	0.23	0.12	1

* - number of samples

Appendix 4. Lithologic and chemical analysis data—Tunnel Mountain Interformational Phosphate.

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
38	Conglomerate	1.50	1.73	40	4.8	1.73	1.30	1
194	Sandstone	0.20	6.00	50	38.0	1.20	0.60	1
206	Conglomerate	0.01	0.08	20	5.3			1
232	Conglomerate	0.20						1
264	Conglomerate	0.06	9.00	40	12.0	0.45	0.22	1
266	Conglomerate	0.61						1
267	Sandstone	0.05	4.20	60	12.0	0.21	0.10	1
276	Conglomerate	0.10	13.90	50	28.0	1.39	0.60	1
317	Conglomerate	1.00						1
395	Conglomerate	0.50						1

* - number of samples

Appendix 5. Lithologic and chemical analysis data—Kananaskis Formation, Phosphate Zones.

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
Interformational Phosphates								
210	Conglomerate	2.00	0.72	30	3.3	0.72	0.72	2
221	Conglomerate	0.30						1
222	Sandstone	0.75	4.10	33	35.7	3.08	1.54	3
227	Sandstone	0.98	29.27†					1
235	Conglomerate	0.20						1
252	Conglomerate	0.10	0.20	40	4.0	0.02	0.01	1
281	Sandstone	1.10	9.33	57	33.7	9.33	5.13	2
288	Siltstone	0.80	3.90	50	26.1	3.12	1.56	2
295	Sandstone	0.40	3.40	20	13.5	1.36	0.68	1
301	Conglomerate	0.30						1
303	Sandstone	3.66						1
312	Conglomerate	0.10						1
353	Conglomerate	0.50						1
373	Conglomerate	0.60	0.71	30	5.1	0.43	0.21	2
389	Conglomerate	0.30	13.80	30	10.0	4.14	2.07	1
392	Sandstone	0.50						2
Intraformational Phosphates								
210	Sandstone	1.00	8.40	140	53.4	8.40	4.20	1
267	Sandstone	2.00	3.80	70	12.5	3.80	3.80	1
332	Sandstone	8.00	1.30	40	1.4	1.30	1.30	1
381	Chert	0.40	4.20	30	4.0	1.68	0.84	1

* - number of samples

† - assay of nodules only

Appendix 6. Lithologic and chemical analysis data—Johnston Canyon Formation, Intraformational and Upper Phosphate Zones.

		Weighted values						
Section	**Host lithology**	**Thickness (m)**	**P_2O_5 %**	**Vanadium (ppm)**	**Uranium (ppm)**	**P_2O_5 % (1 m)**	**P_2O_5 % (2 m)**	**N***
Interformational Phosphates								
221	Sandstone	7.90	4.86	42	12.0	15.60†	9.71†	9
229	Phosphatic rock	4.08	8.57			16.69†	8.57	5
229†	Phosphatic rock	0.83	20.10					
230	Phosphatic rock	1.83	7.18			7.18	6.57	4
231	Phosphatic rock	0.94	16.86			15.85	7.92	3
288	Sandstone	0.10	4.90	170	41.0	0.49	0.24	1
295	Siltstone	1.60	1.66	3	1.8	1.66	1.33	2
295†	Siltstone	0.20	5.90	29	14.9			1
304	Sandstone	0.23	30.00‡					1
306	Sandstone	0.10						1
307	Sandstone	0.30						1
308	Sandstone	0.61						1
365	Sandstone	3.51	7.77			7.77	7.77	2
365†	Siltstone	1.08	13.73			13.73	7.44	
394	Shale	0.03	30.66			0.92	0.46	1
Upper Phosphate Zone								
278	Sandstone	1.50	2.59	100	6.3	2.59	1.94	1
281	Sandstone	0.90	1.93	55	9.1	1.74	0.87	3
290	Sandstone	0.35	4.42	82	18.5	1.55	0.77	3
303	Sandstone	0.33	30.00			9.90	4.95	1
304	Sandstone	0.41						1
353	Sandstone	0.60	2.36	76	5.6	1.42	0.71	2
369	Sandstone	0.50	3.90	180	24.2	1.95	0.97	1

* - number of samples
† - recalculated from original data
‡ - assay of nodules only

Appendix 7. Lithologic and chemical analysis data—Ranger Canyon Formation, Basal, Intraformational and Upper Phosphate Zones.

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
Basal Zone								
21	Phosphate bearing	0.20	22.60	100	60.9	4.52	2.26	1
35	Phosphate bearing	0.45	15.51	60	11.3	6.98	3.49	2
38	Sandstone	0.60	14.30	70	15.5	8.58	4.29	3
41	Conglomerate	0.60	7.90	50	19.1	4.74	2.37	1
43	Conglomerate	0.50	23.00	146	85.7	11.50	5.75	1
48	Conglomerate	0.10	21.10	80	16.3	2.11	1.05	1
53	Conglomerate	0.65	3.78	40	14.8	2.46	1.23	1
62	Conglomerate	0.10	4.50	60	14.2	0.45	0.22	1
64	Conglomerate	0.40	28.30	240	44.9	11.32	5.66	1
66	Conglomerate	0.20	4.30	50	3.9	0.86	0.43	1
68	Conglomerate	0.20						1
71	Conglomerate	0.15	2.53	60	7.1	0.38	0.19	1
75	Conglomerate	1.00	7.68	80	16.6	7.68	3.84	1
77	Conglomerate	0.70	11.90	80	39.1	8.33	4.16	1
81	Nodules	0.24						1
90	Conglomerate	0.20						1
100	Sandstone	0.40	4.60	180	34.5	1.84	0.92	2
102	Conglomerate	0.20	15.20	140	34.7	3.04	1.52	1
113	Conglomerate	0.50	3.40	70	8.7	1.70	0.85	1
122	Conglomerate	0.30	0.06	10	5.8	0.02	0.01	1
127	Conglomerate	0.30						1
128	Sandstone	0.35	14.85		63.0	5.20	2.60	1
146	Conglomerate	0.60	5.80	50		3.48	1.74	1
149	Conglomerate	0.10	11.10	100	47.2	1.11	0.55	1
151	Conglomerate	0.20	14.10	90	25.9	2.82	1.41	1
157	Conglomerate	1.00	3.80	30	15.9	3.80	1.90	1
158	Conglomerate	0.35	23.31	131	17.3	8.16	4.08	1
210	Conglomerate	1.50	17.10	120	77.5	17.10	12.82	1
232	Phosphate bearing	0.27	24.59	-	-	6.64	3.32	1
236	Conglomerate	0.20	-	-	-	-	-	1
240	Sandstone	0.15						1
295	Sandstone	0.40	22.60	210	112.0	9.04	4.52	1
301	Sandstone	0.30						1
304	Phosphate bearing	0.14	30.00			4.20	2.10	1
305	Sandstone	0.91	16.57			15.08	7.54	3
317	Conglomerate	0.40	19.60	140		7.84	3.92	1
321	Conglomerate	0.25	2.48	52	6.6	0.62	0.31	1
337	Conglomerate	2.00	2.20	60	10.6	2.20	2.20	1
342	Conglomerate	0.10	15.10	120	44.7	1.51	0.75	1
363	Conglomerate	0.20	8.60	40	12.9	1.72	0.86	1
365	Conglomerate	0.40						1
366	Conglomerate	0.25	3.92	140	7.6	0.98	0.49	1
371	Phosphate bearing	0.20	23.20	100	18.7	4.64	2.32	1
377	Conglomerate	0.25	4.00	20	8.6	1.00	0.50	1
379	Dolomite	1.00	7.60	180	18.8	7.60	3.80	1
381	Sandstone	1.50	1.91	53	6.0	1.91	1.43	4
389	Sandstone	0.10	2.40	40	6.3	0.24	0.12	1
393	Conglomerate	0.06	23.83			1.43	0.71	1
394	Shale	0.52	18.53			9.64	4.82	3
396	Sandstone	0.61	3.83			2.34	1.17	1
399	Conglomerate	0.10	1.80	30	1.4	0.18	0.09	1
402	Conglomerate	0.30						1
Intraformational Zone								
38	Sandstone	5.30	1.00	60	1.6	1.00	1.00	1
332	Sandstone	0.90	3.30	60	5.8	2.97	1.48	1
342	Sandstone	1.50	1.80	60	14.6	1.80	1.35	1
371	Sandstone	0.40	0.15	60	7.5			

Appendix 7. (continued)

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
Upper Zone								
62	Conglomerate	0.10	1.50	50	3.0	0.15	0.07	1
125	Conglomerate	0.40	7.40	60	21.0	2.96	1.48	1
155	Conglomerate	0.40	3.40	30	14.7	1.36	0.68	1
210	Sandstone	0.50	1.40	120	13.8	0.70	0.35	1
229	Sandstone	0.30	10.00			3.00	1.50	1
247	Conglomerate	0.30	5.50	80	14.6	1.65	0.82	1
252	Conglomerate	0.50	2.28	110	8.0	1.14	0.57	1
299	Sandstone	1.00	1.70	60	8.3	1.70	0.85	2
301	Sandstone	0.76						1
304	Sandstone	0.64	30.00†					1
305	Sandstone	0.70	28.70†					1
306	Sandstone	0.91						1
307	Sandstone	1.07						1
308	Sandstone	0.61						1
309	Conglomerate	0.30						1
332	Conglomerate	0.10	1.50	40	5.0	0.15	0.07	1
359	Conglomerate	0.50	2.76	50	14.2	1.38	0.69	1
363	Phosphate rock	1.50	6.70	80	9.1	6.70	5.02	1
365	Conglomerate	0.10						1
371	Conglomerate	0.20	0.35	20	1.5			1
377	Sandstone	0.75	5.42	66	6.8	4.07	2.03	2
381	Sandstone	0.30	2.80	50		0.84	0.42	1
389	Sandstone	0.30	2.30	100	7.0	0.69	0.34	1
421‡	Conglomerate	1.52						1
97‡	Conglomerate	0.70	4.55	100	20.0	3.19	1.59	1
116‡	Conglomerate	0.20	19.40	80	27.0	3.88	1.94	1
117‡	Conglomerate	1.00	3.69	98	6.3	3.69	1.84	2

* - number of samples
† - assay of nodules only
‡ - sections of Mowitch Formation basal phosphate - equivalent to Ranger Canyon basal phosphates

Appendix 8. Lithologic and chemical analysis data—Mowitch Formation, Upper Phosphate, Intraformational Phosphate and Ishbel Condensed Phosphate Zones.

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
Upper Phosphate								
421	Conglomerates	1.52						1
38	Sandstone	0.10	10.40	110	31.0	1.04	0.52	1
57	Conglomerate	0.20	2.10	80	14.5	0.42	0.21	1
61	Sandstone	0.20						2
116	Sandstone	0.10	18.60	210	45.0	1.86	0.93	1
133	Conglomerate	0.15	20.80	120	30.6	3.12	1.56	1
138	Conglomerate	0.20	12.70	170	22.5	2.54	1.27	1
Interformational Phosphate								
146	Conglomerate	0.20	16.80	130	26.5	3.36	1.68	1
151	Sandstone	10.50	5.10	40	5.6	5.10	5.10	1
Ishbel Condensed Phosphate								
8	Conglomerate	0.20	3.55	40	15.0	0.71	0.35	1
95	Conglomerate	0.50	3.80	80	7.4	1.90	0.95	1
105	Conglomerate	0.10	11.30	140	13.0	1.13	0.56	1
185	Conglomerate	0.07	5.28	114	7.1	0.37	0.18	1
186	Sandstone	0.39	4.74			1.85	0.92	3
187	Chert	0.09	14.55			1.31	0.65	1
264	Sandstone	0.35	3.20	20	7.4	1.12	0.56	1
267	Sandstone	0.10	4.70	40	8.0	0.47	0.23	1
271	Chert	2.00	2.00	25	2.8	2.00	2.00	1
302	Sandstone	0.10						1

* - number of samples

Appendix 9. Lithologic and chemical analysis data—Whistler Member Phosphate Horizons.

Section	Host lithology	Weighted values						
		Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
Upper Whistler Zone								
45	Siltstone	0.50	10.40	382	35.3	5.20	2.60	2
52	Sandstone	0.60	2.67	60	17.5	1.60	0.80	1
99	Conglomerate	0.02	1.24	83	3.3	0.02	0.01	2
380	Siltstone	0.50	0.89	68	4.8	0.44	0.22	1
Middle Whistler Zone								
126	Conglomerate	0.05	6.20	289	19.0	0.31	0.16	2
Lower Whistler Zone								
22	Siltstone	7.00	1.12	40	2.2	1.12	1.12	1
83	Siltstone	2.40	-	-	-	-	-	-
84	Dolomite	5.00	-	-	-	-	-	-
164	Conglomerate	0.30	-	-	-	-	-	1
166	Conglomerate	0.30	-	-	-	-	-	1
172	Siltstone	2.40	-	-	-	-	-	1
174	Phosphatic rock	0.20	-	-	-	-	-	1
318	Siltstone	0.30	0.90	50	5.7	0.27	0.14	1
Whistler Miscellaneous								
79	Phosphatic rock	0.47	-	-	-	-	-	-
80	Shale	3.65	5.90	-	-	5.90	5.90	1
82	Limestone	0.91	-	-	-	-	-	-
147	Siltstone	0.04	0.32	840	8.4	0.01	-	1
386	Phosphatic rock	0.20	25.40	40	18.0	5.08	2.54	1

* - number of samples

Appendix 10. Lithologic and chemical analysis data—Fernie Formation, Phosphate Zones.

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
Basal Fernie Zone								
5	Limestone	0.15						1
6	Limestone	2.10						1
19	Sandstone	0.50	14.02	70	39.6	7.01	3.50	3
23	Conglomerate	0.20	1.00	120	11.0	0.20	0.10	1
42	Phosphate	0.80	9.30	140	55.7	7.44	3.72	1
93	Conglomerate	0.15						1
103	Sandstone	0.15	14.13	100	36.0	2.12	1.06	1
112	Sandstone	0.15						1
114	Conglomerate	0.30	2.13	80	29.3	0.64	0.32	2
123	Conglomerate	0.10	7.80	40	23.0	0.78	0.39	1
134	Conglomerate	0.85	0.84	871	31.6	0.72	0.36	3
137	Sandstone	0.60	11.50	60	43.8	6.90	3.45	1
152	Sandstone	0.50	1.92	30	7.6	0.96	0.48	1
153	Sandstone	0.10	7.00	50	13.0	0.70	0.35	1
159	Sandstone	1.20	1.65	45	6.0	1.65	0.99	3
182	Conglomerate	0.09	11.55			1.04	0.52	1
188	Conglomerate	0.50	3.94	438	61.4	1.97	0.98	2
190	Conglomerate	0.02	5.00	150	120.0	0.10	0.05	1
193	Sandstone	0.65	1.64	61	6.1	1.07	0.53	2
196	Sandstone	0.70	0.82	40	5.5	0.58	0.29	1
197	Sandstone	0.40	3.55	30		1.42	0.71	1
405	Phosphate rock	3.25	21.33	76	73.7	31.40†	29.73†	13
202	Sandstone	0.30	8.80	80	40.0	2.64	1.32	1
408	Phosphate rock	2.75	11.95	163	38.4	19.29†	15.24†	11
205	Phosphate rock	1.42	20.64			21.24†	14.65	4
207	Phosphate rock	3.11	13.86			18.53†	13.86	5
208	Phosphate rock	1.10						1
406	Phosphate rock	2.00	16.41	162	49.9	20.49†	16.41	8
215	Conglomerate	0.15						1
407	Phosphate rock	4.00	10.37	400	138.8	21.99†	15.99†	16
217	Sandstone	2.20	2.92	300	38.8	2.92	2.92	2
218	Phosphate	2.90	7.96	112	10.1	10.68†	7.96	8
220	Phosphate	3.45	5.07	126	18.4	9.05†	5.07	6
223	Phosphate	2.09	8.70	90	29.0	9.02†	8.70	7
224	Phosphate rock	2.05	13.87	35	20.9	25.03†	13.87	6
254	Conglomerate	0.20	9.95	50	69.5	1.99	0.99	1
256	Siltstone	2.60	2.13			2.13	2.13	4
257	Sandstone	0.90						1
258	Sandstone	0.45						1
261	Phosphate	0.91	16.64			15.15	7.57	2
262	Sandstone	9.14						2
273	Sandstone	2.00	0.60	30	2.6	0.60	0.60	1
282	Sandstone	1.10	3.30	32	21.9	3.30	1.81	2
283	Conglomerate	0.50	0.74	20		0.37	0.18	1
323	Siltstone	1.30						3
324	Conglomerate	0.05	16.20	60	78.0	0.81	0.40	1
327	Conglomerate	0.60	2.90	160	38.8	1.74	0.87	1
333	Phosphate	0.60	7.11			4.27	2.13	4
335	Sandstone	0.30	4.20	60	19.6	1.26	0.63	1
338	Conglomerate	0.09	7.66			0.69	0.34	1
339	Conglomerate	0.21	15.90			3.34	1.67	1
346	Sandstone	0.80						1
367	Phosphate	1.50	1.43	5	2.4	1.43	1.07	4
374	Phosphate	0.75	17.61			13.21	6.60	4
375	Phosphate	2.15	9.20	44	18.4	14.10†	9.20	6
385	Phosphate	2.10	2.90	90	15.3	6.04†	2.90	2
400	Phosphate	0.60	18.08			10.85	5.42	2

* - number of samples used to calculate P_2O_5 % column

† - values recalculated from original data, not based on P_2O_5 % column

Appendix 10. (continued)

Nordegg Member, Lower Phosphate-bearing shales

		Weighted values						
Section	**Host lithology**	**Thickness (m)**	**P_2O_5 %**	**Vanadium (ppm)**	**Uranium (ppm)**	**P_2O_5 % (1 m)**	**P_2O_5 % (2 m)**	**N***
13	Shale	1.20	2.09	830	81.2	2.09	1.25	4
23	Shale	0.20	3.70	1000	59.0	0.74	0.37	3
169	Shale	1.50	2.30	880	37.1	2.30	1.72	1
177	Shale	1.30	1.65	286	38.9	1.65	1.07	2
183	Shale	3.00	1.84	180	71.9	1.84	1.84	1
190	Shale	0.80	1.95	237	56.2	1.56	0.78	5
324	Siltstone	0.15	1.06	120	9.3	0.16	0.08	1

* - number of samples

Nordegg and Nordegg Equivalent, Phosphate-bearing strata

		Weighted values						
Section	**Host lithology**	**Thickness (m)**	**P_2O_5 %**	**Vanadium (ppm)**	**Uranium (ppm)**	**P_2O_5 % (1 m)**	**P_2O_5 % (2 m)**	**N***
4	Limestone	0.50	1.58	60	2.0	0.79	0.39	1
5	Sandstone	4.00	3.90	40	9.5	3.90	3.90	1
13	Limestone	17.90	1.45	68	3.7	1.45	1.45	7
23	Chert	1.60	1.01	100	8.0	1.01	0.81	5
26	Limestone	6.00	3.14	40	4.0	3.14	3.14	1
101	Limestone	1.30	2.30	200	10.6	2.30	1.49	3
324	Limestone	3.60	1.13	68	3.9	1.13	1.13	2
326	Limestone	5.50	0.53	20	0.9	0.53	0.53	3

* - number of samples

Oxytoma Zone

		Weighted values						
Section	**Host lithology**	**Thickness (m)**	**P_2O_5 %**	**Vanadium (ppm)**	**Uranium (ppm)**	**P_2O_5 % (1 m)**	**P_2O_5 % (2 m)**	**N***
23	Phosphate	0.27	25.44			6.87	3.43	2
123	Limestone	0.20	4.00	65	105.5	0.80	0.40	2
137	Sandstone	5.20	3.10	91	11.3	3.10	3.10	2
324	Sandstone	0.30	6.80	20	8.6	2.04	1.02	1
367	Limestone	1.00	2.00	160	6.9	2.00	1.00	1

* - number of samples

Red Deer Member, Phosphate-bearing strata

		Weighted values						
Section	**Host lithology**	**Thickness (m)**	**P_2O_5 %**	**Vanadium (ppm)**	**Uranium (ppm)**	**P_2O_5 % (1 m)**	**P_2O_5 % (2 m)**	**N***
327	Limestone	0.20	4.10	100	36.9	0.82	0.41	6
335	Limestone	6.00	1.30	110	5.3	1.30	1.30	2
375	Limestone	2.00	1.00	510	7.9	1.00	1.00	1
385	Phosphate	0.70	8.00	80	37.1	5.60	2.80	1

* - number of samples

Appendix 10. (continued)

Poker Chip Shales, Phosphate Zone

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
9	Shale	0.30	4.50	400	63.6	1.35	0.67	1
111	Shale	2.98	1.20	150	14.8	1.20	1.20	1
190	Shale	0.10	22.30	800	30.3	2.23	1.12	1
405	Shale	0.25	2.20	200	24.4	0.55	0.27	1
406	Shale	0.25	1.20	200	16.8	0.30	0.15	1
407	Shale	2.74	5.12	436	105.2	5.12	5.12	11
254	Limestone	5.00	1.87	290	28.2	1.87	1.87	1
351	Limestone	1.50	1.00	190	12.7	1.00	0.75	1
367	Shale	4.50	1.40	170	8.9	1.40	1.40	1

* - number of samples

Rock Creek Upper Phosphate Zone

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
9	Sandstone	4.00	0.17	50	2.2	0.17	0.17	1
13	Sandstone	1.00	2.02	60	2.6	2.02	1.01	1
26	Sandstone	0.20	0.70	80	2.5	0.14	0.07	1
181	Sandstone	3.00	1.20	160	1.9	1.20	1.20	1
196	Sandstone	0.40	4.30	-	-	1.72	0.86	1
256	Sandstone	0.30	0.20	-	-	0.06	0.03	1
346	Sandstone	2.00	0.08	20	5.2	0.08	0.08	1

* - number of samples

Rock Creek Lower Phosphate Zone

		Weighted values						
Section	Host lithology	Thickness (m)	P_2O_5 %	Vanadium (ppm)	Uranium (ppm)	P_2O_5 % (1 m)	P_2O_5 % (2 m)	N*
42	Shale	6.00	2.90	260	15.7	2.90	2.90	1
181	Sandstone		12.20†					1
193	Sandstone	0.20	0.20	90	2.0	0.04	0.02	1
205	Sandstone	1.00	2.70	60	4.2	2.70	1.35	1
208	Sandstone	1.91	5.36			5.36	5.12	1
220	Limestone	1.00	6.10	110	13.9	6.10	3.05	1
245	Shale	4.40	1.10	120	6.2	1.10	1.10	1
262	Siltstone	1.52						1
275	Sandstone	0.45						1
283	Sandstone	1.10	2.03	31	6.0	2.03	1.12	2
286	Sandstone	1.40	1.56	58	4.4	1.56	1.09	3
335	Sandstone	1.70	2.20	240	6.8	2.20	1.87	1
351	Sandstone	2.00	2.70	110	5.7	2.70	2.70	1
367	Shale	1.90	2.20	110	6.4	2.20	2.09	4

* - number of samples
† - assay of nodules only

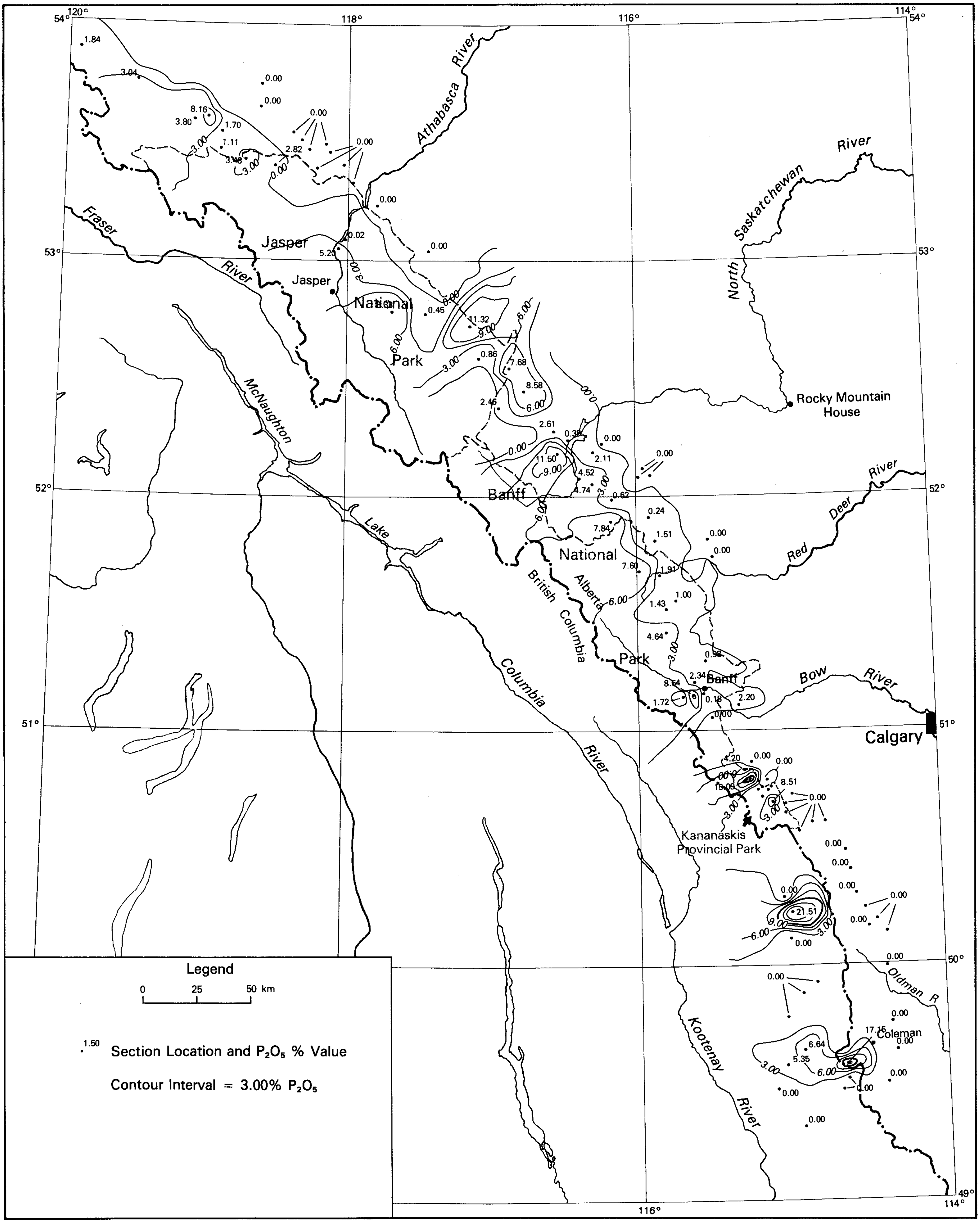

Figure 12. Isopleth map of P_2O_5 values in the Ranger Canyon Basal Phosphate Zone over 1.0 m thick

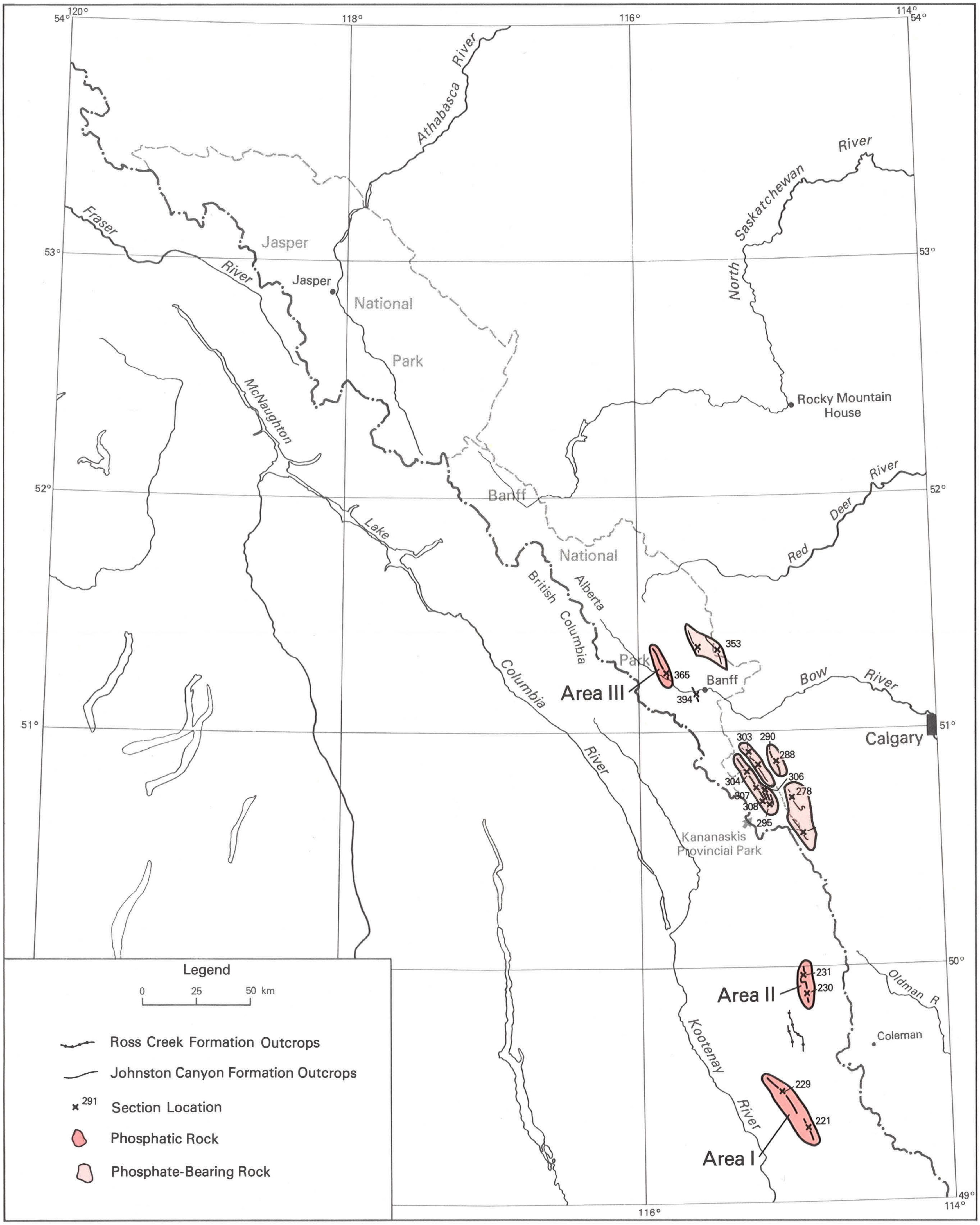

Figure 9. Johnston Canyon and Ross Creek formations—phosphate-bearing outcrops and phosphate potential

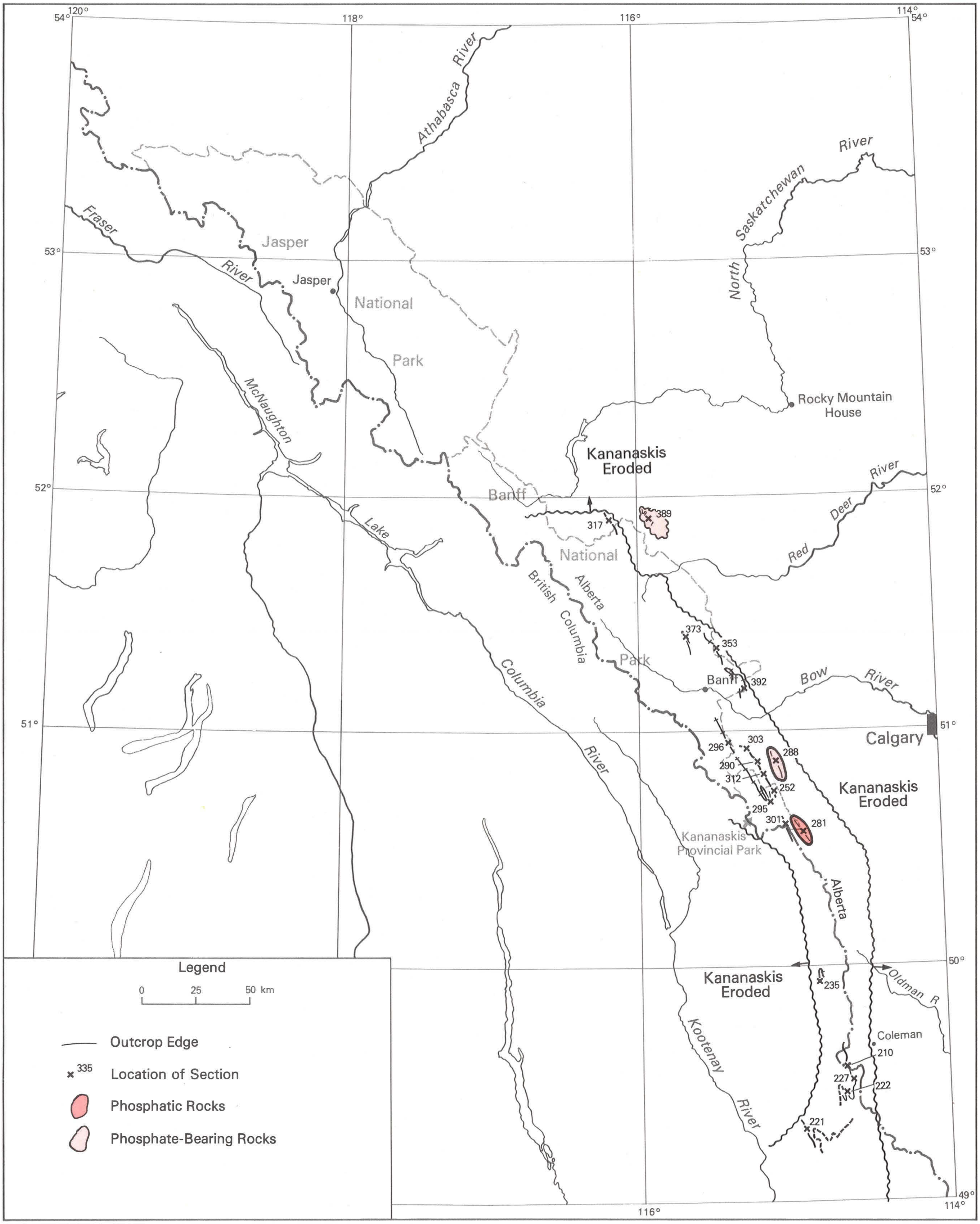

Figure 8. Kananaskis Interformational Phosphate conglomerate—location of outcrops and sections

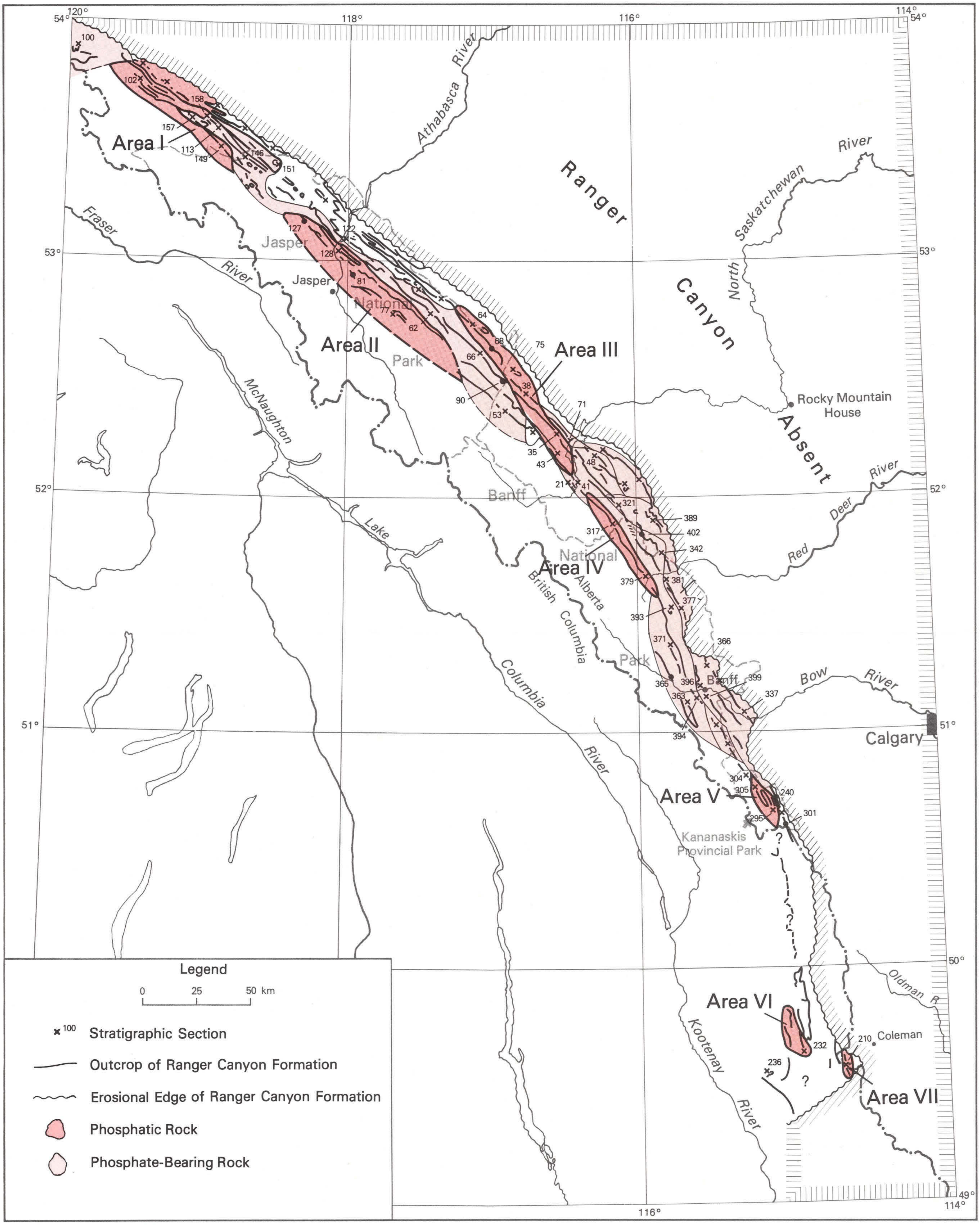

Figure 11. Ranger Canyon Formation, outcrops and phosphate potential in the Basal Zone

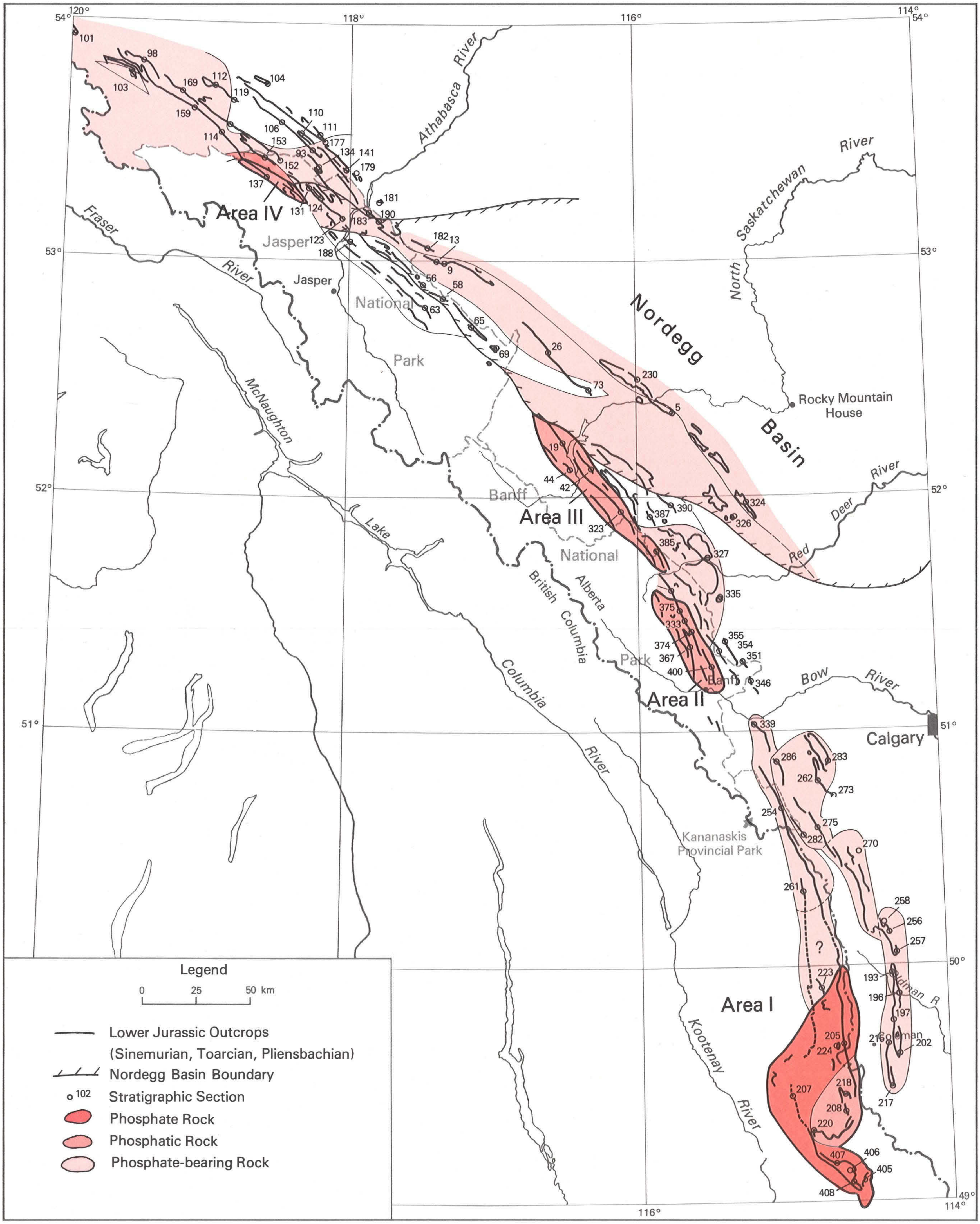

Figure 15. Lower Jurassic outcrops and phosphate potential—Fernie Formation

Figure 16. Stratigraphic columnar sections showing correlation between Lower Jurassic sections—Front Ranges and Foothills, Alberta and British Columbia

Footnotes

ϕ Position of section moved 60 km to southwest to facilitate better viewing.

* Position of section moved 60 km to southwest and vertical scale 2 x that shown. i.e. 25 mm = 8 metres.

⊗ True position of sections displaced to aid viewing.

Diagram based on Palliser Formation/Exshaw Formation contact.

Figure 5. Fence diagram illustrating correlation of Exshaw Formation units—palinspastically restored—and location of stratigraphic sections studied

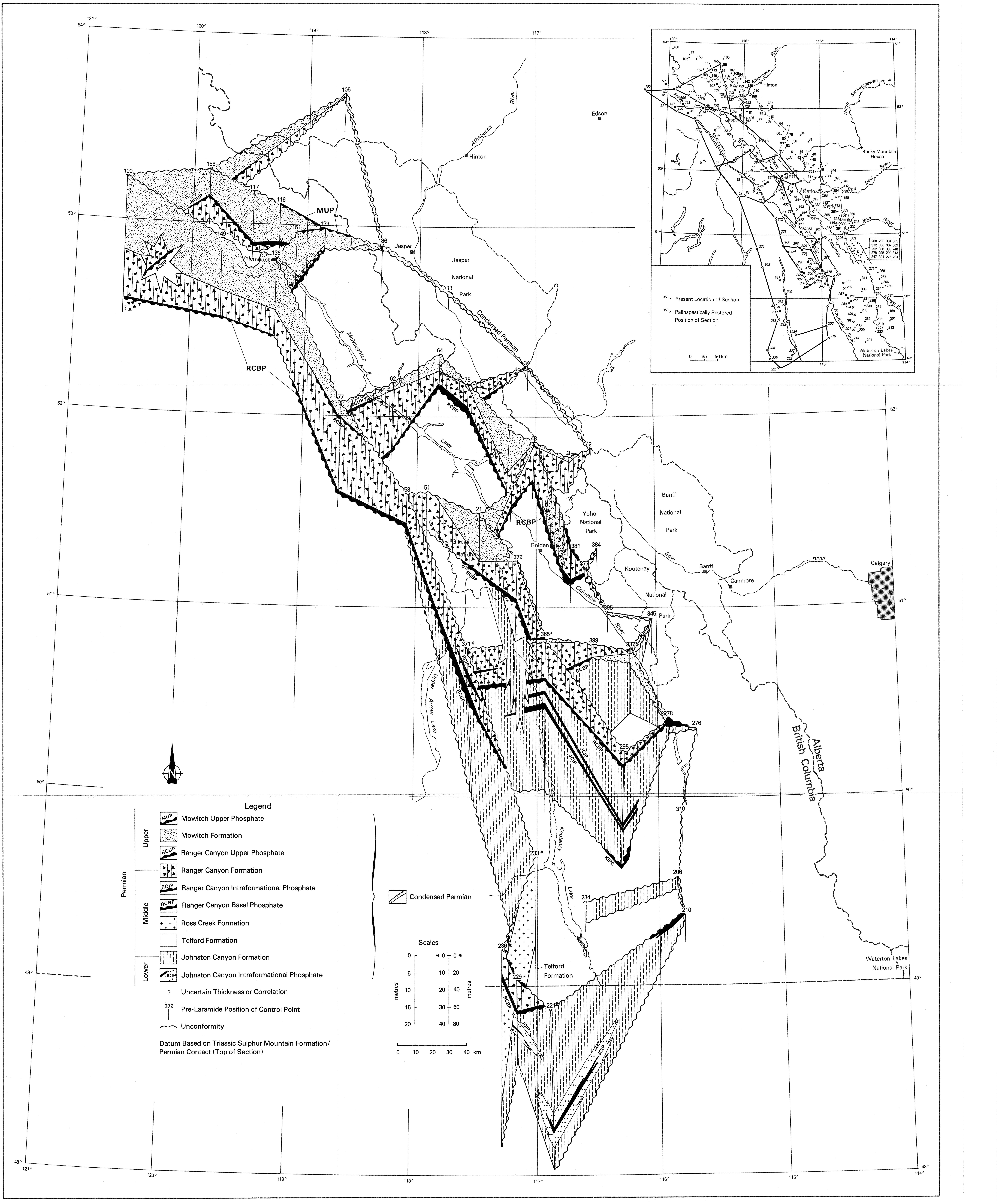

Figure 10. Fence diagram illustrating Permian stratigraphy and phosphate horizons—palinspastically restored—and Permo-Pennsylvanian stratigraphic section location map

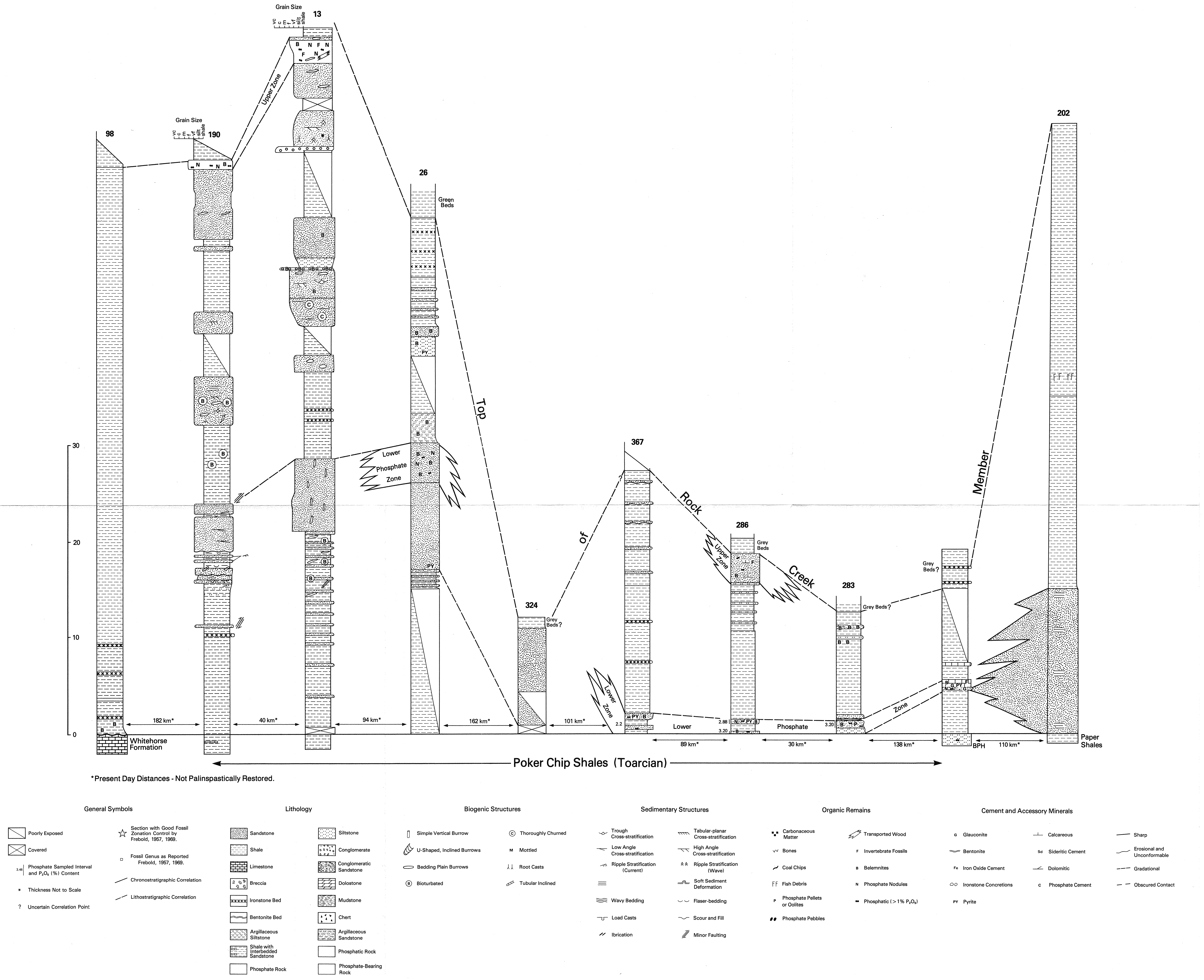

Figure 17. Stratigraphic columnar sections showing correlation of Rock Creek Member, Middle Jurassic Fernie Formation