ERCB/AGS Open File Report 2011-01

Review of Metallic Mineralization in Alberta with Emphasis on Gold Potential

Energy Resources Conservation Board

Alberta Geological Survey

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A.S. Rukhlov

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January 2011

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ISBN 978-0-7785-8633-3

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Rukhlov, A.S. (2011): Review of metallic mineralization in Alberta with emphasis on gold potential; Energy Resources Conservation Board, ERCB/AGS Open File Report 2011-01, 93 p.

Published in January 2011 by:
Energy Resources Conservation Board
Alberta Geological Survey
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Acknowledgments

I thank A.P. Beaton, D.R. Eccles, W.A.D. Edwards, B. Kafle, C.W. Langenberg, C. Pana, D.I. Pană, J.G. Pawlowicz, and G.J. Prior for useful discussions during the course of this project. I am grateful to R. Mussieux, Royal Alberta Museum, for sharing his knowledge and an insightful slideshow of southern Alberta and the Clark Range.

Thanks also go to D.K. Chao and K. Mckay for assistance with ArcGIS® applications, E.J. Waters for contributing some of the AGS databases at the early stage of the project, and D. Magee for kind help with some of the illustrations. Constructive reviews by D.I. Pană, D.R. Eccles, N. Atkinson, M. Grobe and F.J. Hein, and editorial work by G. Hippolt-Squair and B. Davie, RnD Technical, significantly improved this report.

Abstract

This report summarizes the history of metallic mineral exploration and the inventory of gold occurrences in Alberta, based on the publicly available data. It also examines the origin and potential of several distinct types of gold-bearing mineralization in terms of their origin and exploration potential, and compares these occurrences in Alberta with similar deposits elsewhere.

Numerous precious-metal mineral occurrences have been documented in Alberta. The exposed Precambrian crystalline basement in northeastern Alberta hosts more than 200 occurrences, some with significant exploration potential, of stratiform and intrusion-related, disseminated sulphides; magmatic-hydrothermal iron-oxide breccias/veins; and shear-hosted, quartz-vein precious and base metals. The depositional record of the Western Canada Sedimentary Basin (WCSB) in Alberta shows evidence of synsedimentary extensional faulting and orogenies associated with recurrent magmatic-hydrothermal activity during the last 1.5 billion years. Similar environments produced several types of world-class precious- and base-metal deposits elsewhere, including areas adjacent to Alberta. Dozens of sediment-hosted metallic showings of syngenetic, epigenetic and intrusion-related epithermal origin exist in the Alberta part of the Canadian Rocky Mountains and other parts of the WCSB in Alberta. Placer gold and platinum-group elements (PGE) occur in Cretaceous to modern alluvial deposits throughout the province.

Documented geochemical anomalies and mineral occurrences in Alberta show similarities to several metallic deposit types with significant to trace concentrations of gold. Modern and preglacial placers are currently the most prospective sources for gold in Alberta. Other potential deposit types may include

- granitoid intrusion– and/or shear-related quartz-carbonate vein Au-Ag-As (±Mo±W±Bi) and mesothermal Au-Ag-Cu-Pb veins;
- iron-oxide breccia/vein and unconformity-associated Cu-Au-Ag-U-REE[1] (±PGE±Ni±Co);
- volcanogenic–sedimentary-exhalative sulphide (VMS-SEDEX) Zn-Pb-Cu-Ag-Au-Co;
- stratiform black shale–hosted Ni-Mo-Zn-PGE (±Cu±Ag±Au±V±Cr±Co±U±Y±REE±P);
- alkaline intrusion–related, epithermal Au-Ag (±Cu±Zn±Pb±Mo±W);
- magmatic-hydrothermal Cu-PGE (±Au±Ag±Pb±Zn±Ni±Cr±Co±V);
- Kupferschiefer/redbed–type stratiform Cu-Ag (±Au±Pb±PGE±U); and
- epigenetic, sediment-hosted Au-Ag-PGE (±Cu±Mo±Pb±Zn±Ni) variety of the Mississippi Valley–type (MVT) deposits within the WCSB.

[1] rare-earth elements

1 Introduction

Since the beginning of exploration for metallic minerals in Western Canada in the late 1800s, no world-class deposits have been discovered within Alberta, whereas adjacent jurisdictions have had discoveries and development of significant metallic mineral deposits (e.g., Au-Ag-Cu-Pb-Zn in Montana, uranium in northwestern Saskatchewan, Pb-Zn-Ag historical producers in southeastern British Columbia and along the Great Slave Lake Shear Zone in the Northwest Territories).

That only a few metallic mineral deposits are known in Alberta is surprising, given that the province is underlain by favourable geology, has an extensive mineral exploration footprint in some areas, numerous geophysical, hydrological and well data, developed infrastructure throughout much of the province, and favourable regulatory regimes.

Despite the scarcity of discovered metallic mineral deposits, Alberta has been producing placer gold since the mid-1800s. Recently, placer gold and associated PGE are the only metals produced as byproducts of sand and gravel operations in Alberta. Natural Resources Canada (2010) has reported a production of up to 100.9 kg/year of gold in Alberta. Placer gold and platinum group minerals (PGM) are common in alluvial, glacial and preglacial conglomerate and sand and gravel deposits throughout Alberta (e.g., Allan, 1920, 1924; Halferdahl, 1965; Guisti, 1983; Godfrey, 1985; Edwards, 1990; Edwards and Scafe, 1996; Ballantyne and Harris, 1997; Leckie and Craw, 1997).

Extensive historical precious- and base-metal exploration and mining occurred in the Rocky Mountains and Foothills of southwestern Alberta from the late 1800s to the 1970s. Examples of these workings include the

- Oldman (Bearspaw), Baker Creek and Eldon MVT Pb-Zn-Ag-Cd-Cu prospects on the eastern flank of Mount Gass and on both sides of the Bow River valley within Banff National Park (e.g., Hedley, 1954; Evans et al., 1968; Holter, 1973, 1977; Salat, 1988; Pană, 2006);
- Spionkop Ridge, Yarrow and Grizzly creeks and Whistler Mountain redbed-type stratiform Cu-Ag prospects in the Clark Range area (e.g., Goble, 1972a, 1976; Collins and Smith, 1977);
- Carbondale River, and South and North Lost creeks SEDEX Pb-Zn-Ag showings near North Kootenay Pass (Carter and Irvine, 1971; Goble, 1975);
- Jura Creek black shale–hosted Zn-Ni-Mo polymetallic occurrence at the base of the Mississippian Exshaw Formation (Richards et al., 1994);
- Jutland Brook and La Coulotte Ridge alkaline intrusion–related epithermal Au-Ag-Cu occurrences along the Alberta–British Columbia border in the Clark Range area (Goble, 1974a, b); and
- Castle and Copper mountains (Silver City mines), Herbert Lake and Miette River quartz-carbonate vein Au-Ag-Cu-Pb-Zn past-producers and occurrences within Banff and Jasper national parks (Dawson, 1901; La Casse and Roebuck, 1978).

More recently, several polymetallic prospects in Alberta continue to attract exploration. These include

- the unconformity-type uranium mineralization at Maybelle River in northeastern Alberta (Jefferson et al., 2007);
- the Clear Hills ironstone Fe-Zn-V deposit in northwestern Alberta (Hamilton, 1980; Olson et al., 1999; Kafle, 2009); and
- the Burmis and Dungarvan Creek paleoplacer magnetite-ilmenite-rutile (±Au±PGE±V±W±Zr± REE±Sn) deposits in southwestern Alberta (Grant and Trigg, 1983; Dufresne and Kupsch, 2003).

In addition, there are at least two black shale–hosted V-Zn-Mo-Ni-U-Cu-Cd-Co-Ag (±Au±PGE) potential deposits, Buckton and Asphalt, in the Birch Mountains area of northeastern Alberta (Sabag, 2008).

Previous exploration and geological studies on the Precambrian shield in northeastern Alberta have identified more than 200 metallic mineral occurrences, some with significant exploration potential (e.g., Godfrey, 1986a; Dufresne et al., 1994; Olson et al., 1994; Langenberg and Eccles, 1996; McDonough, 1997). For the rest of the province, the depositional environments and tectonic evolution recorded by the Precambrian through Phanerozoic strata of the WCSB in the Rocky Mountain fold-and-thrust belt and the Interior Plains are similar to those of world-class metal-mining camps elsewhere (e.g., British Columbia, Yukon, Northwest Territories, Nevada, Montana, Idaho, China and Europe). Syndepositional rifting, recurrent magmatic-hydrothermal activity and orogenies, coupled with reactivation of ancient zones of strain in the crystalline basement and development of brittle faults, arches and other structures within the WCSB, favour the emplacement of diverse syngenetic and epigenetic base- and precious-metal deposits in Alberta (e.g., Olson et al., 1994; Eccles, 2000; Dufresne et al., 2001; Pană, 2006; Sabag, 2008).

Since publication of the previous provincial metallogenic report (Olson et al., 1994), numerous geological studies and considerable exploration have produced an enormous amount of mineralogical and geochemical information pertinent to gold potential in Alberta. These new and historical data need to be synthesized to identify realistic deposit models and future exploration targets in the province. Since gold exploration is driven by the high price of the metal (approximately $1100/ounce in April 2010), recent extraction technologies permit profitable mining of deposits with grades as low as 1–10 g/t Au (Butt and Hough, 2009), a level that approaches the grades of some of the known gold occurrences in Alberta.

This report reviews the history of metallic mineral exploration and summarizes the inventory of gold occurrences in Alberta, based on publicly available data. It also discusses the origin and exploration potential for several distinct types of gold-bearing mineralization in relation to similar deposits elsewhere.

2 Methodology and Format

2.1 Data Compilation

The Alberta gold inventory reviewed in this report is based on previous work by industry, government and universities. It includes metallic mineral occurrences, free gold grains recovered from heavy mineral concentrate (HMC) samples, and geochemical analyses with higher than background gold and/or pathfinder-element concentrations for various sample media, including bedrock, stream and lake sediments, soil, glacial deposits and water. The data were compiled from about 50 documents, including previous regional compilations and other government reports, industry mineral-assessment reports, monographs, journal papers, university theses and conference documents, crediting overall about 800 sources. An attempt was made to exclude logically inconsistent data (i.e., incorrect or insufficient information on sample location and data quality).

Throughout this report, element concentrations are quoted either in per cent by weight (wt. % or %), parts per million (ppm) or parts per billion (ppb); in some cases, these were converted from troy ounces per short ton (oz./ton) or pounds per short ton (lbs./ton). Proportions of minerals are in the units given in the original source (i.e., by weight or volume). All measurements were converted to metric units, with tonnages converted to metric tons (tonnes or t) where applicable. Neither AGS nor the author is responsible for quality of the data compiled from various sources in this report.

All occurrences were plotted on a summary map (scale 1:5 000 000) using the AEG Forest, 10th Degree Transverse Mercator projection with central meridian at 115°W and North American Datum 1983 (10TM83). The locations obtained from the Dominion Land Survey (DLS) system or from digitized small-scale maps may have location uncertainty up to several hundred metres. Figure 1 displays a

simplified base map of Alberta (after Alberta Sustainable Resource Development, 2007). The reader should refer to the cited original works for details on locations, samples and analytical methods.

The classification of metallic mineral occurrences is based on geochemical 'signature,' an association of elements exceeding the natural background concentrations that, in conjunction with tectonic setting, geological environment, host lithology and mineralogy, alteration, and mineralization style and nature (e.g., epigenetic vein versus syngenetic stratiform), may be characteristic of a specific deposit model. In some cases, identification of a deposit model could be complicated due to intense tectonometamorphic reworking and/or hydrothermal remobilization of primary mineralization, especially for many of the Precambrian shield occurrences (e.g., Langenberg and Eccles, 1996). Samples from soil, glacial deposits and stream and lake sediments that contain visible gold particles and/or geochemically anomalous gold concentrations were classified as placer-type occurrences.

The large amount of data compiled in this report allows metallogenic generalizations applicable to the present state of knowledge. As more data become available and are compiled and evaluated, along with revision of the deposit models, new reports will be published.

2.2 Mineral Occurrences and Geochemical Anomalies

In this report, a mineralized locale is referred to as a 'mineral occurrence' if the mineralization has been observed, and as a 'geochemical anomaly' if it is based solely on geochemical data. The meaning of the terms 'producer,' 'deposit,' 'prospect' and 'showing,' as used in compiled works, may be different from the definitions currently used by the Canadian Institute of Mining, Metallurgy and Petroleum (CIM). Evaluation of the tonnages and grades of mineral resources or reserves is beyond the scope of this report.

Identification of a geochemical anomaly, or simply a concentration of an element that is distinct from an ordinary range, depends on a measure of the natural background for a given material (e.g., Levinson, 1980; Reimann and Garrett, 2005; Rencz et al., 2006). Table 1 summarizes estimates of the representative chemical compositions for the major crustal materials (Condie, 1993; Wedepohl, 1995; Taylor and McLennan, 1995; Rudnick and Gao, 2004), which can be useful to screen anomalous values. However, because abundances of many elements vary significantly between different rock types, it is important to establish the upper limits of background variations or a threshold to separate true anomalies.

The threshold can be defined as a distance from the mean or median of distribution at which outliers may not be representative of the normal range (e.g., using the 95th percentile; Bednarski, 1996). Rencz et al. (2006) used the Tukey upper inner fence, defined as the 3rd quartile plus 1.5 times the inter-quartile range, to estimate the upper background limit for geochemical analyses of till samples. Using this method, the threshold and median concentrations of selected elements were calculated for major rock types in Alberta, based on the available geochemical analyses for drillcore, drill cuttings, outcrop and float rock samples from both government and industry reports (Table 2). The global threshold values, based on a large number of samples from the EarthChem (2010) databases, are included for comparison.

The thresholds are not well defined by the limited data for some elements and/or rock types. Moreover, ignoring the values below the minimum analytical detection limit that are reported as nulls in many of the datasets tends to increase the thresholds for some elements. Therefore, 'thresholds' that are based on

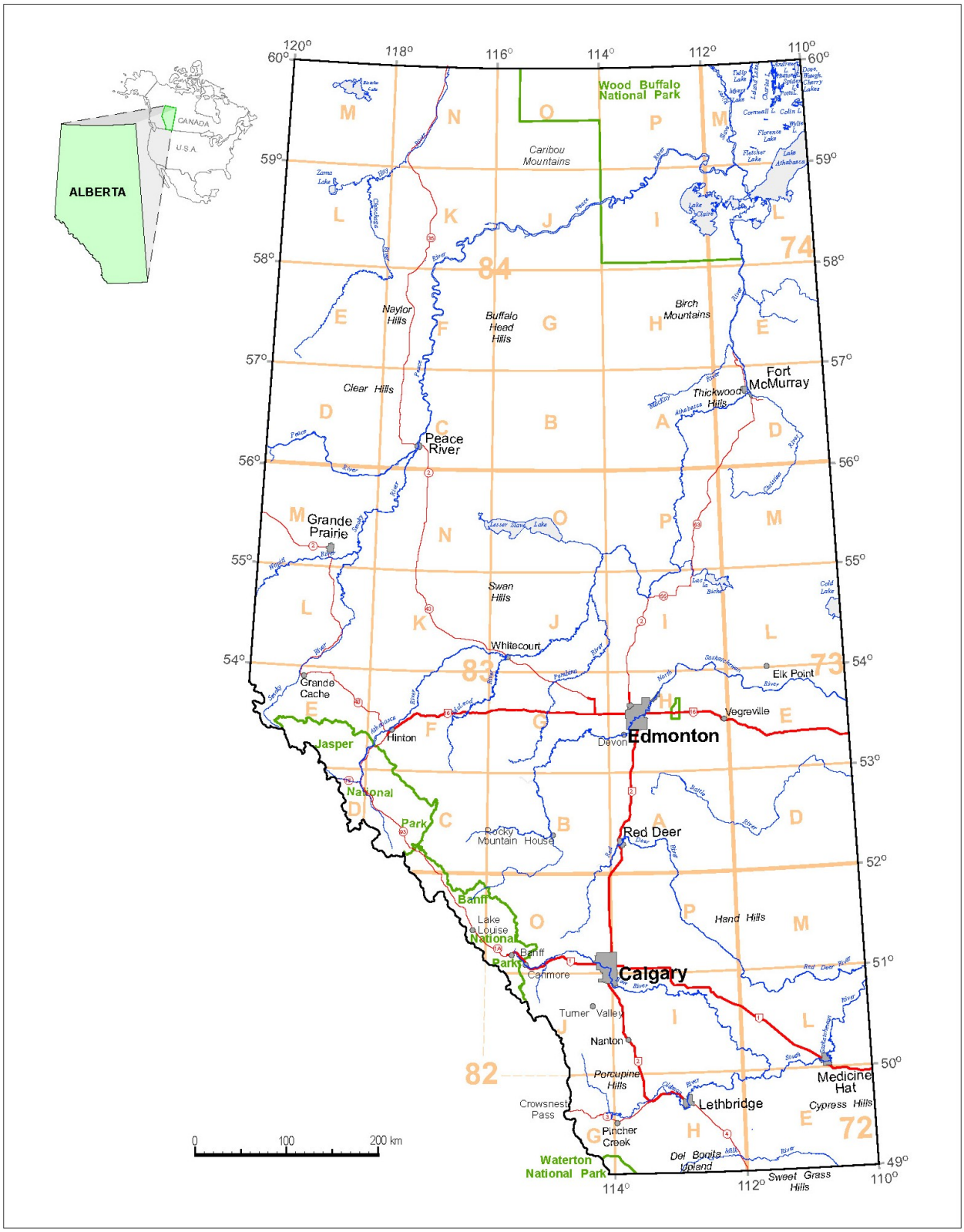

Figure 1. Simplified base map of Alberta; see Alberta Sustainable Resource Development (2007) for a detailed provincial base map at 1:1 000 000 scale.

Table 1. Average chemical compositions of crustal materials.

Reservoir	Upper Continental Crust				Grey-wacke	Sand-stone	NASC*	Marine Shale	Middle Continental Crust	TTG*	Granite*	Basalt*
Source	**3**	**5**	**4**	**2**	**3**	**2**	**2**	**1**	**5**	**2**	**2**	**2**
Ag (ppb)	55	53	50					70	48			
As	2	4.8	1.5					13	3.1			
Au (ppb)		1.5	1.8		4.8			2.5	0.7			
Ba	668	628	550	626	426	150	636	580	532	780	750	277
Be	3.1	2.1	3					3	2.3			
Bi (ppb)	123	160	127					430	170			
Cd (ppb)	102	90	98					300	61			
Ce	65.7	63	64	59.4	58	22.3	67	70	53	45	115	27
Co	12	17	10	18	15	3	26	19	22	12	6	40
Cr	35	92	35	112	88	30	125	90	76	35	18	182
Cs	5.8	4.9	3.7		2.2			5	2.2			
Cu	14.3	28	25		24			45	26			
F	611	557						740	524			
Fe (wt. %)	3.09	5.04	3.5	3.64	4.13	0.89	4.41	4.72	6.02	3.19	1.79	7.39
Ga	14	18	17		16			19	18			
Ge	1.4	1.4	1.6					1.6	1.13			
Hg (ppb)	56	50							7.9			
In (ppb)	61	56	50					100				
Ir (ppt)		22	20		50			80				
Li	22	24	20					66	12			
Mn	527	1000	600					850	1000			
Mo	1.4	1.1	1.5					2.6	0.6			
Ni	19	47	20	60	24	8	58	68	34	15	15	96
P	665	1500	700	524	567	87	567	700	1500	567	349	873
Pb	17	17	20	18	14.2	19	20	20	15.2	15	25	6
Pd (ppb)		0.5	0.5		0.4			4	0.8			
Pt (ppb)		0.5			0.4				0.85			
Re (ppb)		0.2	0.4									
Sb	0.3	0.4	0.2					1.5	0.3			
Se (ppb)	83	90	50					600	64			
Sn	2.5	2.1	5.5					6	1.3			
Ta	1.5	0.9	2.2	0.82		0.3	1.1	0.8	0.6	0.8	1.5	0.27
Te (ppb)								80				
Th	10.3	10.5	10.7	9.1	9	4	12.3	12	6.5	10	18	2.4
Tl	0.75		0.75					1.2				
U	2.5	2.7	2.8	2.4	2	1.1	2.7	3.7	1.3	2.3	4.5	1.2
V	53	97	60	86	98	15	130	130	107	70	20	252
W	1.4	1.9	2					1.8	0.6			
Y	20.7	21	22	25	26	6.8	35	26	20	25	45	32
Zn	52	67	71		76			95	69.5			
Zr	237	193	190	162	302	105	200	160	149	150	240	133

Concentrations of elements are in ppm unless otherwise indicated.

* Average Early Proterozoic basalt, Proterozoic granite and tonalite-trondhjemite-granodiorite (TTG), Phanerozoic cratonic sandstone, and North American shale composite (NASC) of Condie (1993).

References: 1, compiled values from Li (1991); 2, Condie (1993); 3, Wedepohl (1995); 4, Taylor and McLennan (1995); 5, Rudnick and Gao (2004).

Table 2. Geochemical background values for selected rock types in Alberta. Concentrations are in parts per million (ppm), except for Au, Pt, Pd, and Ir, which are in parts per billion (ppb). Values prefixed with the '<' symbol are below the minimum analytical detection limit. Ranges are for the data by different analytical methods. Values based on global data (EarthChem, 2010) are included in parentheses for comparison.

	Sandstone, Quartzite			Shale, Siltstone, Bentonite			Carbonates			Mafic and Alkaline Igneous Rocks			
	Median	Threshold[1]	Count[2]	Median	Threshold[1]	Count[2]	Median	Threshold[1]	Count[2]	Median	Threshold[1]	Count[2]	UCC[3]
Au (ppb)	0.6	**4.9–8**	506	2	**11–18**	2622	0.4	**2.5 – 6.3**	471	2.5	**15 (23)**	41 (504)	2
Ag	0.1	**0.9**	510	0.1	**1.6**	3301	0.1	**0.9**	419	<0.1	**0.3**	28	0.05
Zn	84	**343–446 (272)**	509 (4900)	129	**277–381 (385)**	3307 (8357)	18	**190–390 (713)**	419 (4636)	103	**232 (188)**	28 (6834)	70
Pb	12	**51 (60)**	344 (12472)	18	**34 (53)**	1785 (17690)	5	**32 (60)**	370 (7396)	16	**51 (32)**	23 (3348)	20
Cu	10	**27 (66)**	344 (16883)	31	**88 (148)**	1785 (21323)	10	**51 (70)**	370 (11779)	46	**257 (250)**	23 (8693)	30
Ni	24	**97 (65)**	516 (15878)	41	**95–198 (102)**	3445 (21421)	10	**62–123 (77)**	458 (10391)	4.5	**32 (270)**	28 (10022)	50
Mo	2.0	**9–14**	437	3	**59–82 (68)**	2971 (8207)	0.6	**6.5–20 (43)**	402 (3851)	1.0	**6.5 (10)**	25 (1044)	2
V	88	**931 (219)**	348 (18144)	226	**561 (281)**	1786 (21716)	8	**274 (219)**	370 (12920)	96	**316 (612)**	23 (7506)	100
Cr	62	**200 (153)**	346 (17056)	94	**166 (311)**	1779 (21644)	22	**201 (160)**	330 (11969)	40	**133 (658)**	23 (10024)	90
Co	11	**66 (30)**	348 (13359)	11	**28 (39)**	1786 (18009)	3	**23 (22)**	370 (7653)	6.0	**23 (88)**	23 (8878)	20
Cd	0.06	**1.3**	344	0.2	**5**	2009	0.1	**0.8**	373	<1.0	**1 (5)**	28 (238)	0.1
W	0.6	**4.3**	347	1.5	**4**	1780	0.8	**4.8**	370	3.0	**15 (6)**	23 (238)	2
U	2.8	**8.7 (38)**	303 (5126)	5	**27 (37)**	1744 (3533)	1.0	**11 (26)**	301 (2644)	0.5	**(2.0)**	(3180)	3
Th	7.3	**19 (19)**	303 (3592)	11	**18 (27)**	1744 (4646)	2.0	**20 (27)**	301 (1787)	1.3	**(6.3)**	(4113)	11
Ce	47	**113 (140)**	302 (3833)	71	**119 (186)**	1743 (6075)	58	**148 (155)**	145 (2419)	19	**(82)**	(6319)	65
As	17	**135**	343	19	**101**	1779	5.0	**27**	370	7.0	**29 (7.5)**	23 (937)	5
Sb	0.9	**4.6**	341	1.4	**11 (14)**	1773 (1881)	0.3	**5.2**	363	1.2	**13 (1.0)**	23 (1303)	0.4
Bi	0.4	**8.5**	304	0.3	**0.5**	221	0.1	**4.8**	367	0.5	**(2.9)**	(610)	0.2
Se	0.7	**6.3**	298	1.1	**12 (9.4)**	1742 (1401)	0.5	**12 (66)**	145 (799)	0.3	**(0.7)**	(56)	0.1
Ba	577	**1479**	347	900	**1968**	1780	87	**1416**	370	202	**1043**	23	630
Te	0.3	**1.1**	133	0.06	**0.22 (0.2)**	220 (406)	0.06	**0.2 (0.7)**	96 (134)	0.1	**(0.3)**	(72)	
Pt (ppb)	<5	**(10)**	125 (22)	<5	**(12)**	947 (164)	<5	**2.5 (12)**	85 (45)	7.5	**(30)**	(1578)	0.5
Pd (ppb)	<3	**(21)**	125 (14)	<4	**(13)**	947 (218)	<4	**7.5 (11)**	85 (61)	7.6	**(30)**	(1585)	0.5
Ir (ppb)	<5		165	<5		1516	<5		49	1.2	**(5.3)**	(193)	0.02

[1]Threshold (i.e. the upper limit of background variation) is set at 1.5 interquartile range above the 3rd quartile (Rencz et al., 2006).
[2]Count is the number of samples used to calculate the median and threshold.
[3]UCC is the average Upper Continental Crust after Condie (1993), Wedepohl (1995), Taylor and McLennan (1995) and Rudnick and Gao (2004).

populations dominated by mineralized samples due to ignoring of the 'normal' less-than-detection values are excluded from the compilation in Table 2.

Different analytical methods may contribute further bias between the compiled geochemical datasets. Although the calculated thresholds vary up to 200% between analytical methods, the significance of these variations cannot be evaluated for those compiled datasets that lack sufficient duplicate analyses by more than one analytical method.

In this report, element concentrations above the estimated thresholds are considered strongly anomalous, suggesting the presence of mineralization. Based on these criteria, the Alberta gold inventory uses the cutoff value of 6 ppb Au, along with the associated anomalous Ag, PGE and other element (e.g., Te, W, Mo) concentrations. Although the Au threshold based on a limited number of analyses for some of the Alberta materials (e.g., metamorphic and igneous rocks of the Precambrian shield) may seem higher, the 6 ppb Au cutoff is 2–3 times higher than the estimated median values for these rock types and the typical upper crustal concentration (Table 2).

The average preglacial sand and gravel deposit in Alberta contains about 3 ppb Au (Edwards and Scafe, 1996). Therefore, concentrations of 6 ppb Au or greater can be considered anomalous. When only visible gold grains were reported for stream sediments, samples containing even a single gold particle were included as placer occurrences in this compilation, consistent with the previous metallogenic assessments (Edwards, 1990; Eccles, 2000).

3 Geological Overview of Alberta

The largely drift-covered bedrock of Alberta (Figure 2) can be divided into two main domains: 1) the Canadian Shield and the late Paleoproterozoic to early Mesoproterozoic Athabasca Basin in the northeast; and 2) the Western Canada Sedimentary Basin (WCSB), which unconformably overlies the Precambrian crystalline basement throughout the rest of the province. The WCSB consists of thrusted and folded Proterozoic, Paleozoic, Mesozoic and Tertiary[†] strata within the Rocky Mountains and Foothills of the Canadian Cordillera in the southwest, and Paleozoic to Tertiary successions beneath the Interior Plains (Pettapiece, 1986) throughout much of the province. This section briefly summarizes the geology of the crystalline basement of the Alberta portion of the Canadian Shield and Athabasca Basin, and the WCSB.

3.1 Precambrian Basement and Athabasca Basin

Precambrian basement forms the western margin of the exposed Canadian Shield in the northeast, overlain by the late Paleoproterozoic to early Mesoproterozoic Athabasca Basin to the south, and dips gently beneath the Proterozoic and Phanerozoic rocks of the WCSB in the remainder of Alberta. The complex crystalline-basement assemblages comprise foliated granitoids and metamorphic tectonites of the western margin of the Churchill Structural Province. Geophysical, petrographic, geochemical and isotopic-dating studies of the crystalline basement, including shield mapping and well samples, have revealed tectonic assemblage of the crustal blocks separated by strike-slip or transfer faults beneath the Athabasca Basin and the WCSB (Figure 3; e.g., Ross et al., 1994; McDonough et al., 2000; Ross, 2002; Lyatsky and Pană, 2003; Pană et al., 2007). Ross and Stephenson (1989) subdivided these blocks into discrete tectonometamorphic domains that range in age from Archean (3.28 Ga) to Early Proterozoic (1.8 Ga).

[†] According to the International Commission of Stratigraphy, 'Tertiary' is an historical term. The terms 'Paleogene Period' (comprising the Paleocene to Oligocene epochs) and 'Neogene Period' (comprising the Miocene and Pliocene epochs) should be used. The author used the term 'Tertiary' because it was used in many of the works compiled and reviewed for this report.

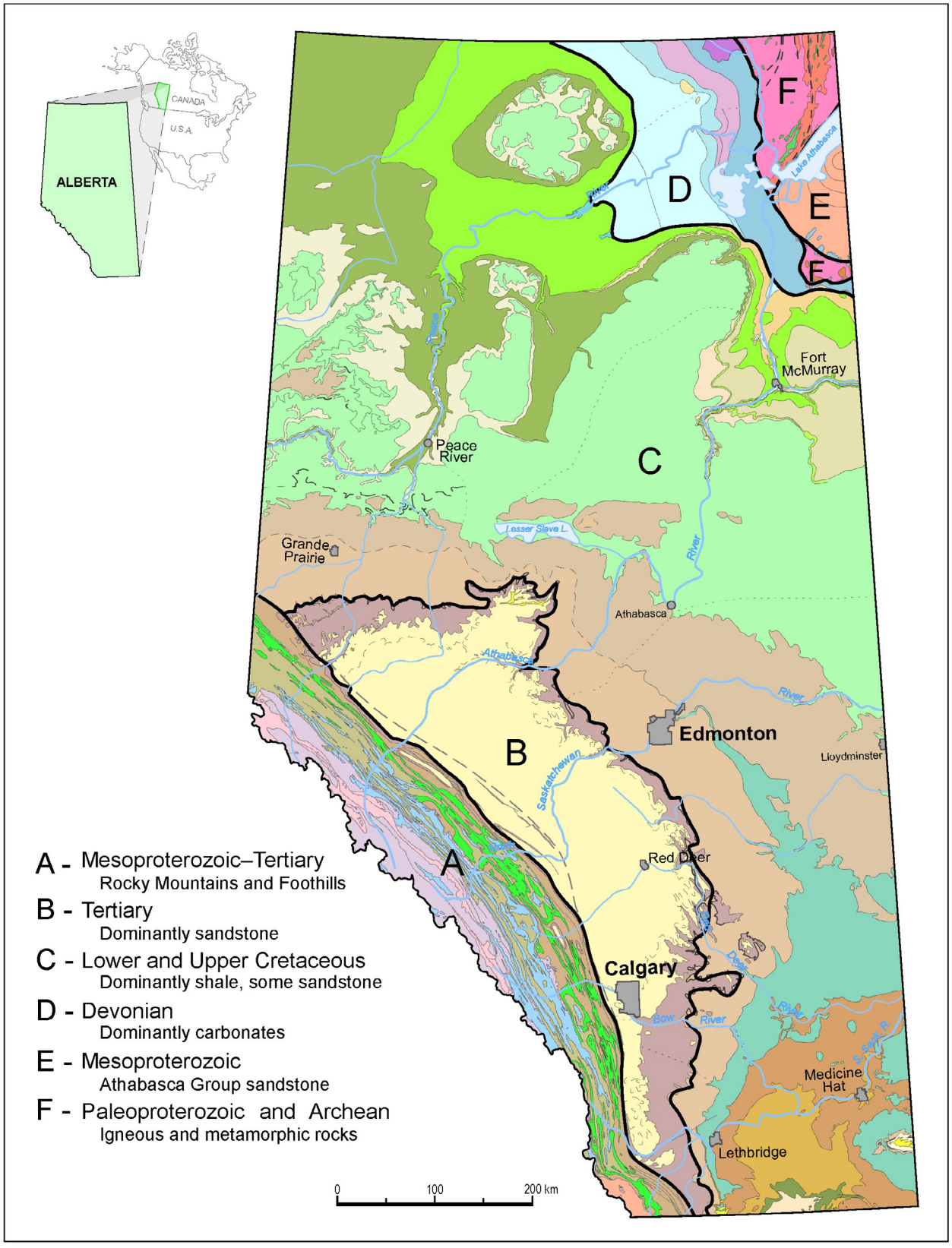

Figure 2. Simplified bedrock geology of Alberta (after Hamilton et al., 1999).

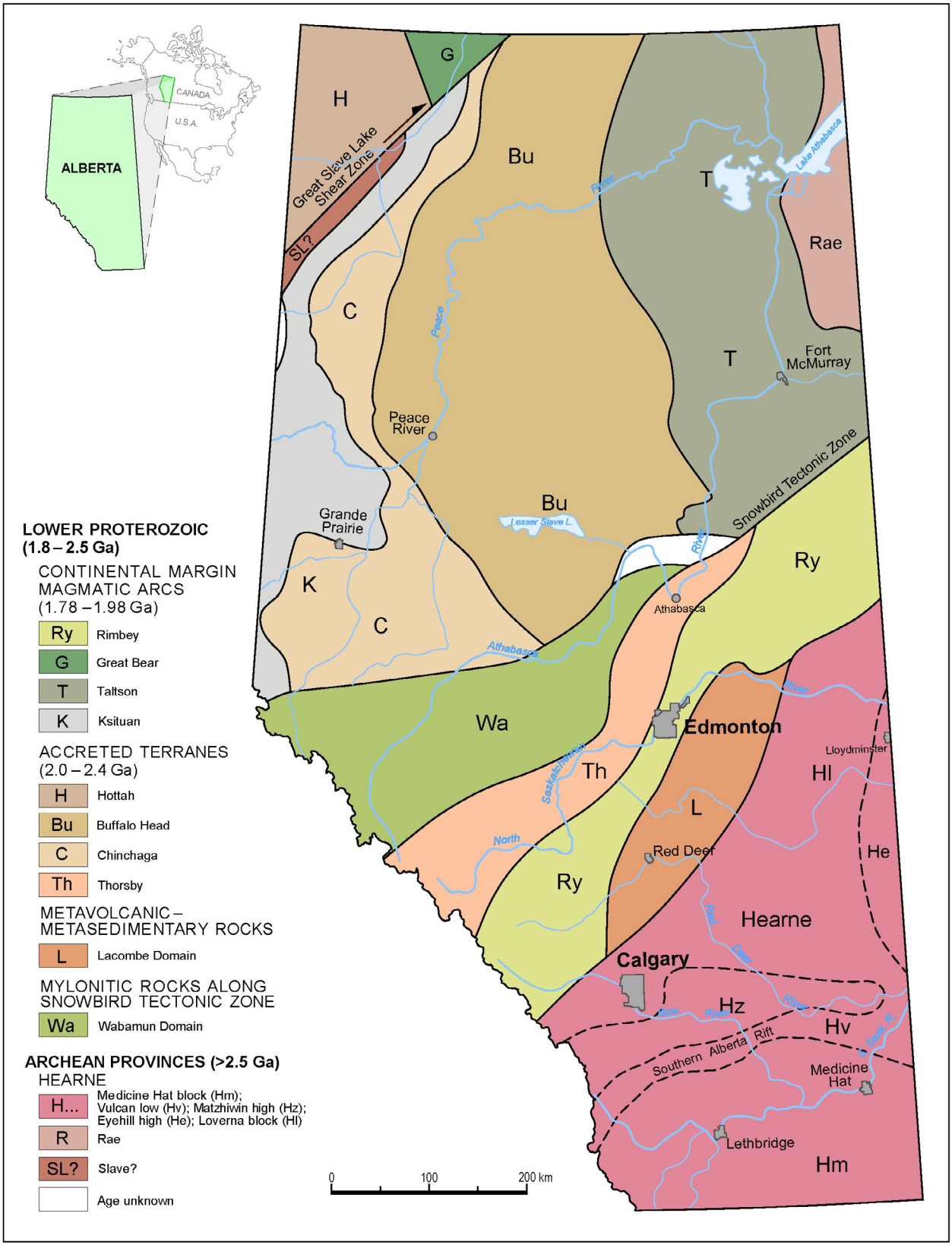

Figure 3. Major tectonic domains in the Precambrian crystalline basement (after Ross et al., 1994).

They include the Archean Rae Terrane and part of the Taltson magmatic zone (TMZ), exposed in the northeast, and a number of the Early Proterozoic terranes to the west and south beneath the WCSB (Figure 3). The Archean Slave Province to the northwest and the Hearne Province to the southeast are further subdivided into a number of discrete crustal blocks that are overlain by the WCSB (Ross et al., 1994).

The TMZ forms the southern segment of the approximately 3000 km long, north-trending, Paleoproterozoic (2.0–1.9 Ga) Thelon-Taltson orogenic belt (e.g., Hoffman, 1988; Ross et al., 1991, 1994; McDonough et al., 2000; Ross, 2002). Exposed as a 100 km wide belt between the Great Slave Lake Shear Zone in the Northwest Territories and Lake Athabasca in northeastern Alberta, the TMZ has been traced to the south beneath the late Paleoproterozoic–early Mesoproterozoic Athabasca Basin and the Phanerozoic WCSB, where it is truncated by the Snowbird Tectonic Zone (e.g., Hoffman, 1988; Ross et al., 1991). Small exposures of the TMZ also occur south of the Athabasca Basin in the Marguerite River area of northeastern Alberta. Pană et al. (2007) summarized the proposed tectonic evolution models for the TMZ, including

- accretion and closure of the ca. 2.13–2.09 Ga Rutledge River Basin, with the TMZ evolving from a continental magmatic arc to the core of the collisional Himalayan-type orogen between the Buffalo Head island arc to the west and the Rae craton to the east (e.g., Ross et al., 1991; McDonough et al., 2000; Ross, 2002);
- plate-interior evolution of the TMZ as a Tian Shan–type orogen in response to distant plate-margin compression west of the TMZ (e.g., Chacko et al., 2000); and
- intracontinental orogeny induced by a large-scale mantle downwelling with localized weakening and anatexis of the Rae crust due to regions of high radioactive heat production, followed by oblique crustal stretching and decompression melting within the TMZ (Pană et al., 2007).

In northeastern Alberta, the exposed TMZ of the Canadian Shield (Figure 4) encompasses the Taltson basement complex (TBC), considered to represent the northwestern margin of the Archean to Paleoproterozoic Churchill Province crust (Rae Terrane), intruded and reworked by ca. 1.97–1.93 Ga, moderately to strongly foliated granitoid plutons (e.g., Chacko et al., 2000; McDonough et al., 2000; McNicoll et al., 2000). The TBC forms a curving, generally north-trending belt of high- to medium-grade metamorphic tectonite comprising Archean (3.2–2.6 Ga) to Early Proterozoic (2.4–2.1 Ga) metaplutonic gneisses, interlayered with subordinate supracrustal gneiss and minor but widespread amphibolite, hornblendite and rare metagabbro (e.g., Godfrey, 1986b; McDonough et al., 2000; McNicoll et al., 2000; Pană, 2010a, b). The supracrustal gneiss and amphibolite have been inferred to represent metamorphosed remnants of the ca. 2.13–2.09 Ga Rutledge River Basin clastic sediments and ophiolites, respectively (e.g., McDonough et al., 2000; McNicoll et al., 2000).

The TMZ granitoid plutons postdating the TBC have been subdivided into two petrologically distinct age groups: 1) earlier, ca. 1.974–1.959 Ga, subduction-related (I-type), diorite–quartz monzonite–granodiorite complexes (Colin Lake, Wylie Lake–Fishing Creek and Andrew Lake) east of the TBC; and 2) later, ca. 1.960–1.934 Ga, collision-related (S-type) monzo-syenogranite complexes (Slave and Arch Lake) west of the TBC. In addition, there are smaller, variously foliated plutons of uncertain affinity emplaced within the TBC, including the ca. 1.933–1.919 Ga Charles Lake granite and the ca. 1.925 Ga Chipewyan and Thesis Lake quartz monzonite–syenogranite complexes (e.g., Godfrey, 1986b; Bostock et al., 1991; McDonough et al., 2000). Others suggested that the entire TMZ plutonic suite might have originated by the ultrametamorphism of the TBC crust (e.g., Chacko et al., 2000; Pană et al., 2007). Pană et al. (2007) proposed that the high- and medium-grade metamorphic tectonites of the Alberta portion of the Canadian Shield might reflect evolution from widespread granulite- and amphibolite-facies conditions to localized deformation along major strike-slip shear zones during syntectonic uplift and cooling of the TMZ.

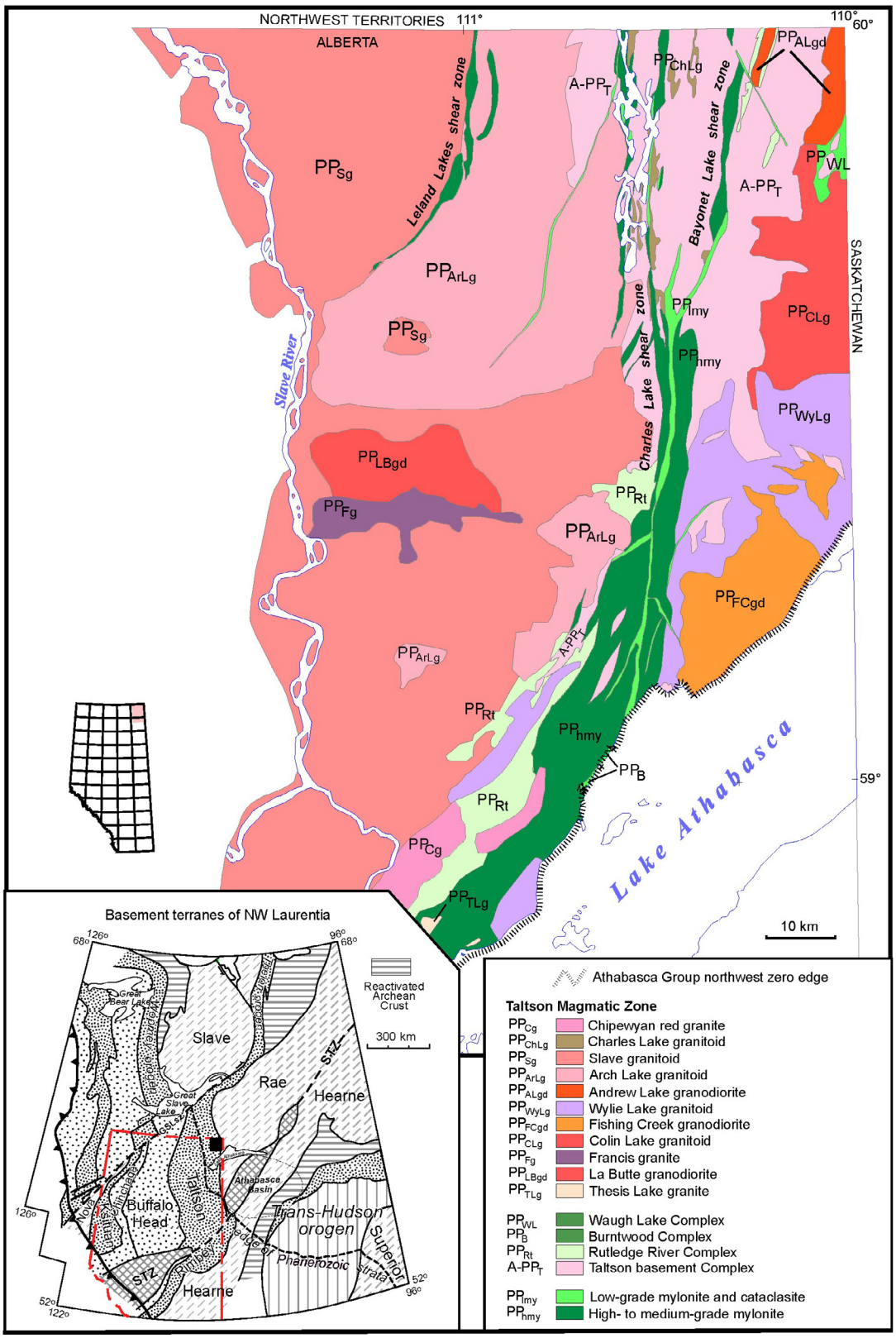

Figure 4. Simplified geology of the Precambrian shield in northeastern Alberta (after Pană, 2010b); index map compiled from Hoffman (1988) and Ross et al. (1994). See Pană (2010a) for a detailed map of the Precambrian shield in northeastern Alberta at a scale of 1:250 000.

Two low-grade metamorphic sequences, the Waugh Lake Complex southeast of Andrew Lake and the Burntwood Complex near the northern shore of Lake Athabasca, comprise variably sheared granitoid and gneiss interlayered with metasedimentary and metavolcanic (basalt and andesite) rocks, and phyllonite and hematite/limonite–cemented quartzofeldspathic rocks of uncertain origin, respectively (e.g., Pană, 2010a, b). McDonough and McNicoll (1997) interpreted the Waugh Lake Complex to represent a volcano-sedimentary sequence deposited in an intra-arc basin between 2.02 and 1.97 Ga and subsequently affected by the low-grade prograde metamorphism (e.g., Godfrey, 1986b; Langenberg and Eccles, 1996). The Burntwood Complex has been described either as correlative to the Waugh Lake Complex (Godfrey, 1986b) or as a lower stratigraphic unit of the Athabasca Group (McDonough and McNicoll, 1997). Pană et al. (2007) suggested that these low-grade metamorphic complexes might represent the retrogressed granitoid gneiss tectonically interlayered with the local sedimentary cover and minor igneous plugs within the upper structural levels of crustal-scale shear zones during the late stages of the TMZ syntectonic exhumation.

South of the Precambrian shield in northeastern Alberta, the crystalline basement is unconformably overlain by a succession of at least 2.1 km of predominantly fluviatile clastic and some lacustrine rocks of the Athabasca Group deposited in the ca. 1.76–1.50 Ga intracontinental Athabasca Basin (e.g., Collier, 2005). Pană and Olson (2009) recently summarized the details of the Athabasca Group stratigraphy and geochronology. The rapid changes in sequence thickness and basal lithology of the Athabasca Group may indicate syndepositional faulting that could control the unconformity-type uranium mineralization in the western Athabasca Basin (e.g., Ramaekers et al., 2007).

3.2 Western Canada Sedimentary Basin

The WCSB wedge unconformably overlies the Precambrian crystalline basement, tapering from very thick strata (up to 20 km for the Proterozoic successions alone) within the deformed belt of the Canadian Cordillera in the southwest to a zero edge along the Canadian Shield in the northeast (Figure 2). The WCSB stratigraphy reflects deposition in three different tectonic settings: 1) Mesoproterozoic intracontinental rift, 2) Neoproterozoic to Middle Jurassic passive continental margin, and 3) Middle Jurassic to Oligocene foreland basin.

The Proterozoic to Lower Cambrian successions of the WCSB exposed within the Rocky Mountain fold-and-thrust belt of the Canadian Cordillera are structurally deformed, imbricated and transported northeastward by Middle Jurassic to Eocene tectonism (e.g., Ross et al., 1989). These strata have been interpreted to record intermittent Mesoproterozoic and Neoproterozoic intracontinental rifting events, followed by the break-up of a Late Proterozoic supercontinent between 730 and 570 Ma, and subsequent development of the proto-Pacific passive margin of the North American craton (Ross et al., 1989; Hein et al., 1994; Colpron et al., 2002; Lydon, 2007).

The Mesoproterozoic Belt-Purcell Supergroup represents a ca. 1.50–1.32 Ga intracontinental rift filled by marine turbidites in the west and stratigraphically equivalent shallow-water carbonates and clastic rocks of the surrounding rift platform in the east, overlain by shallow-marine to lacustrine and fluviatile mudstones, carbonates and sandstones of a rift-cover sequence (e.g., Ross et al., 1989; Lydon, 2007). In southwestern Alberta, the Purcell strata include basaltic lava flows (up to 150 m thick) and are intercalated with rift-related, high-iron, tholeiitic to alkali olivine gabbro sills up to 25 m thick (e.g., Höy, 1989).

It has been proposed that the Mesoproterozoic history of Laurentia's northwestern margin might have involved crustal thickening (e.g., Reid and Greenwood, 1968; McMechan and Price, 1982). Isotopic evidence (K-Ar, Sm-Nd, Lu-Hf and U-Pb dates) suggests that the greenschist- to upper amphibolite–facies metamorphic rocks of the Belt-Purcell basin and its basement, exposed in the core of the Mesozoic Rocky Mountain fold-and-thrust belt in northern Idaho and southern British Columbia, may record at least two widespread Mesoproterozoic metamorphic events in northwestern Laurentia: 1) during the

postulated 1.5–1.4 Ga East Kootenay Orogeny, synchronous with the voluminous mafic magmatism; and 2) during the Grenville assembly of the Rodinia supercontinent at 1.1–1.0 Ga (e.g., Zirakparvar et al., 2010).

The Neoproterozoic Windermere Supergroup, including the Miette Group exposed in southwestern Alberta, unconformably overlies the Belt-Purcell Supergroup and is made up of coarse-grained siliciclastics (grit), diamictites, turbiditic argillites to fine-grained sandstones, and deep-water to platform carbonates (Ross et al., 1989). These strata record a transition from intracontinental rift basin with local glaciation to passive continental margin between ca. 770 and 570 Ma (Ross et al., 1989; Hein et al., 1994; Colpron et al., 2002).

The Windermere strata are unconformably overlain by conglomeratic or pebbly sandstones, quartzite and shale of the Early Cambrian Gog Group, which are interpreted to reflect deposition during a rapid thermal subsidence of the passive continental margin triggered by latest Proterozoic or earliest Cambrian rifting (e.g., Aitken, 1989; Devlin, 1989; Colpron et al., 2002).

Subsequent deposition on the western passive margin of North America produced an extensive Middle Cambrian to Middle Jurassic carbonate platform to the east and shale basins to the west. These strata comprise dominantly shallow-water carbonates interlayered with marine clastics exposed throughout the Rocky Mountains and Foothills, from the United States border to near Grande Cache in Alberta (Figures 1 and 2), and record periods of uplift and erosion marked by many disconformities and unconformities, reflecting extensional deformation along the Cordilleran miogeocline (e.g., Price, 1994).

During the Middle Jurassic to Eocene, the western edge of the North American craton was an active continental margin due to convergence with the adjacent oceanic lithosphere, resulting in oblique collisions with the accreted oceanic terranes (e.g., Price, 1994). This compressional tectonism transformed the passive margin strata into the Rocky Mountain fold-and-thrust belt to the west and formed the Cordilleran foreland basin, filled by Middle Jurassic to Oligocene clastic strata to the east (e.g., Porter et al., 1982; Wright et al., 1994; Price, 1994). The onset of the Columbian Orogeny (Middle Jurassic to Early Cretaceous) marked the transition from a passive continental margin to an active one with the deposition of the Jurassic Fernie Group turbidites in a narrow foredeep trough to the east of the rising orogen (Poulton, 1989). The eastward advancement of the Cordilleran deformation front and the development of the WCSB into a foreland basin continued during the subsequent Laramide Orogeny (Late Cretaceous to Paleogene) with deposition of westerly derived clastic detritus and volcanic rocks of the Late Albian Crowsnest Formation in southwestern Alberta, followed by isostatic recovery and erosion throughout the Tertiary (Price, 1994). The Laramide tectonism involved transpressional and transtensional deformation, with lateral transformations between dextral strike-slip faulting in the north and either thrust faulting and folding or extensional faulting in the south (Price, 1994).

To the east of the Rocky Mountain Foothills, the northwest-trending Alberta Basin forms a trough filled with the Phanerozoic strata of the WCSB, which underlies the Interior Plains and has its maximum thickness of 6 km in the axis of Alberta Syncline (Figure 5). Deposition in the Alberta Basin reflected several periods of extension and rifting and the tectonic evolution of the adjacent Cordilleran Orogen (Price, 1994; Cecile et al., 1997). Much of the southern Interior Plains is about 760 m above sea level (asl), with several highlands up to about 1530 m asl capped by preglacial sand and gravel deposits at Cypress Hills, Hand Hills, Porcupine Hills and Swan Hills (Figure 1; e.g., Edwards and Scafe, 1996).

Most of Alberta's surficial geology reflects the distribution of Quaternary glaciogenic sediments deposited by the Late Wisconsinan Laurentide Ice Sheet between 22 000 and 9 000 years ago (e.g., Fenton, 1984; Clague, 1989; Fulton, 1989; Klassen, 1989; Dyke et al., 2002). These sediments, composed mostly of till, contain fragments of igneous and metamorphic rocks derived from the Precambrian shield and carbonate rocks exhumed from the WCSB. Glaciofluvial sands and gravels are common deposits

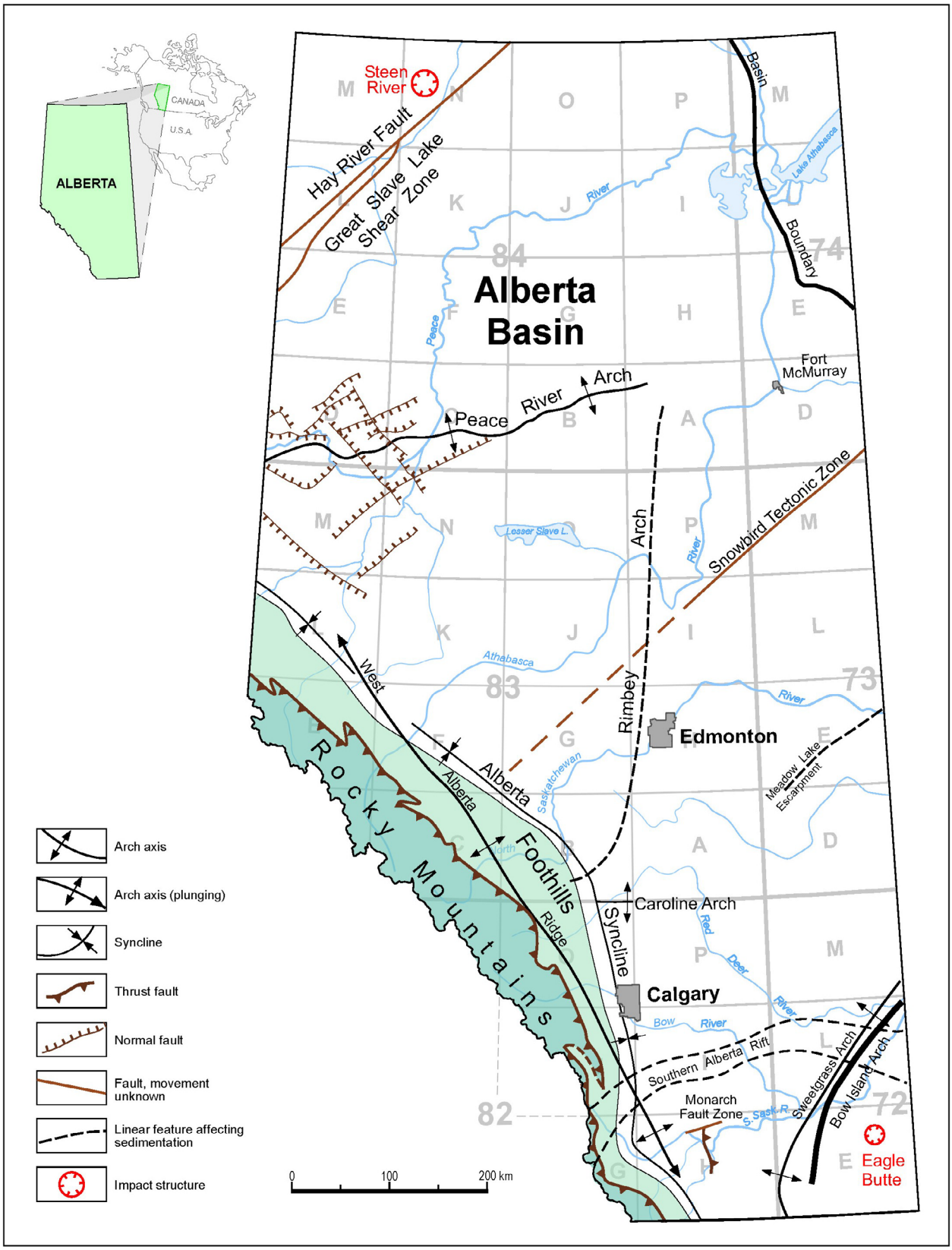

Figure 5. Major Western Canada Sedimentary Basin (WCSB) and basement structures in Alberta (after Dufresne et al., 1996; Ross and Eaton, 1999; Pană et al., 2001).

associated with regional deglaciation, particularly along the axes of large meltwater-channel systems (Christiansen, 1979; Clayton and Moran, 1982). The regional Quaternary stratigraphy of Alberta was reviewed by Fenton (1984).

4 Regional Structures

There are numerous summaries of Alberta tectonism and structural features in the literature (e.g., Lorenz, 1982; Cant, 1988; Podruski, 1988; O'Connell et al., 1990; Price, 1994; Wright et al., 1994; Ross and Eaton, 1999; Pană et al., 2001; Lyatsky et al., 2005; Mei, 2006). Geophysical studies have revealed the Archean to Early Proterozoic ductile orogenic structures and Middle Proterozoic to Recent brittle cratonic structures in the basement of the WCSB (e.g., Lyatsky et al., 1999). The major Precambrian structures include two transcurrent shear zones exposed in the Canadian Shield and traced in the Alberta subsurface, the Great Slave Lake Shear Zone (GSLSZ) and the Snowbird Tectonic Zone (STZ), and the Southern Alberta Rift in the subsurface (e.g., Kanasewich, 1968; Ross et al., 1994). Phanerozoic evolution of the WCSB involved both extensional and compressional tectonism along the continental margin. This overprinted the pre-existing zones of crustal weakness and resulted in several prominent structures: the West Alberta Ridge and Alberta Syncline in western Alberta, the Peace River Arch-Embayment in northwestern Alberta, the Meadow Lake Escarpment in central Alberta and the Sweetgrass Arch in southern Alberta (Figure 5). This section briefly describes the main structures.

4.1 Precambrian Structures

The GSLSZ is a northeast-trending, crustal-scale, dextral transcurrent shear zone that extends from the southeastern side of Great Slave Lake to the eastern edge of the Canadian Cordillera (e.g., Hoffman, 1987; Ross et al., 1994). Where exposed east of Great Slave Lake in the Canadian Shield, the GSLSZ is a zone of granulite to lower greenschist–facies mylonite belts up to 25 km wide and extending for more than 200 km along strike (e.g., Hanmer and Connelly, 1986; Hanmer, 1988). Magnetotelluric studies have traced this zone in the Alberta subsurface to a depth of 100 km in the upper mantle (Pană et al., 2001). The GSLSZ offsets the Thelon and Taltson Precambrian basement domains by up to 700 km, and may represent a continental transform during northeastward convergence, collision and indentation of the Archean Slave Terrane into the Rae Terrane between 1.98 and 1.92 Ga (e.g., Hoffman, 1987, 1988; Hanmer, 1988). The subparallel, brittle McDonald Fault Zone overprinted the northwestern margin of the GSLSZ by accommodating up to 125 km of additional dextral strike-slip after 1.86 Ga (Bowring et al., 1984).

The STZ is another northeast-trending transcrustal discontinuity, associated with gravity and aeromagnetic anomalies, that separates the Rae Terrane to the northwest and the Hearne Terrane to the southeast (Ross et al., 1989). The STZ cuts the TMZ at a high angle in the subsurface of east-central Alberta and has a sinuous projection to the southwest beneath the WCSB, extending for more than 2800 km from Hudson Bay to the Rocky Mountains (e.g., Hoffman, 1988). The STZ has been described as either

- an intracontinental transcurrent dextral shear zone that accommodated southward tectonic escape of a crustal wedge from a convergence zone between the Archean Rae and Hearne terranes after 1.92 Ga (e.g., Hanmer et al., 1995); or
- a reworked suture zone that marks ca. 1.9 Ga subduction and collision of the Hearne and composite Rae-Chesterfield blocks during the accretionary phase (Wathaman continental arc) of the Hudsonian Orogeny (e.g., Gibb and Walcott, 1971; Hoffman, 1988; Ross, 2002; Berman et al., 2007).

Three major, northerly trending, high- to low-grade shear zones (Warren, Allan and Andrew Lake shear zones) and their splays (Leland Lakes, Bocquene River, Goldschmidt Lake, Mercredi Lake, Charles Lake and Bayonet Lake) have been mapped in the Precambrian shield of northeastern Alberta (e.g., Pană and

Olson, 2009). They comprise a subparallel, curvilinear to braided system of anastomosing, subvertical zones of ductile mylonites, 50–3000 m wide, near the transition zone between the TMZ and the Archean Rae Terrane (Figure 4). These shear zones were active during Early Proterozoic indentation (Hoffman, 1988; McDonough et al., 2000; Pană and Olson, 2009). Based on deep seismic reflection, magnetic and gravity anomalies in the Precambrian basement, Kanasewich (1968) and Kanasewich et al. (1969) proposed a major east-trending Precambrian graben-like structure in southern Alberta, identified as the 'Southern Alberta Rift' (SAR), beneath 2.5 km of flat-lying Phanerozoic sediments. The SAR, traced for hundreds of kilometres from north of Medicine Hat in southern Alberta to southwest of Cranbrook in British Columbia, was interpreted to be filled by low-density, nonmagnetic strata, possibly representing the Mesoproterozoic Belt-Purcell Supergroup, with up to 5 km of vertical displacement along the faults within the structure (Figure 3; Kanasewich et al., 1969). The north- to northwest-trending rift-parallel and east- to northeast-trending transfer synsedimentary faults occur throughout the Belt-Purcell basin in southeastern British Columbia and southwestern Alberta (Lydon, 2007).

In a more recent compilation of aeromagnetic data, the SAR coincides with a prominent magnetic low, identified as the 'Vulcan low' basement domain, with a possibly contiguous southeast-projecting low (Ross et al., 1991). Based on U-Pb isotopic dating and Nd isotopic data for core samples of the Precambrian basement, Villeneuve et al. (1993) identified the Vulcan low as an Archean north-dipping subduction zone within the Churchill Province. The Paleoproterozoic titanite ages for the Vulcan low and the adjacent Archean Medicine Hat block to the south are interpreted to record a Proterozoic collisional event in these two domains (Villeneuve et al., 1993). This interpretation, however, "…does not preclude younger reactivation of this boundary to produce the southern Alberta aulacogen" (Ross et al., 1991).

4.2 Phanerozoic Structures

At least some of the Precambrian zones of strain or terrane boundaries in the crystalline basement have been reactivated during the Phanerozoic evolution of the WCSB (e.g., Skall, 1975; O'Connell et al., 1990; Burwash et al., 2000; Pană et al., 2001; Mei, 2006; Pană, 2006). Using the magnetic and seismic reflection data, Ross and Eaton (1999) distinguished two types of Phanerozoic faults: 1) 'intrabasement' or reactivated basement faults, and 2) 'suprabasement' faults unrelated to ancestral basement structures. The reactivated basement faults controlled the distribution of hydrocarbon traps and mineralization zones (e.g., Pine Point MVT-type Pb-Zn and Clear Hills Zn-V-Fe deposits) within the WCSB (e.g., Burwash et al., 2000; Hannigan, 2006; Pană, 2006).

4.2.1 Reactivated Faults

The brittle basement faults of the Hay River Fault Zone (HRFZ) propagate into the Phanerozoic cover of the WCSB, recording post–Middle Devonian dextral shearing along the GSLSZ that possibly accommodated stress build-ups during the Laramide Orogeny (Skall, 1975; Burwash et al., 1994; Pană, 2006). To the north, the Tathlina Fault Zone (TFZ) is parallel to the HRFZ-GSLSZ in the subsurface (Burwash et al., 1994). The northwest-trending Late Mississippian to possibly Permian Belloy (Dunvegan) Fault is coincident with the crustal break between the Proterozoic Ksituan and Chinchaga basement terranes (Wright et al., 1994). The low-angle Normandville (Tangent), Fahler and Kimiwan faults offset the Phanerozoic–Precambrian unconformity and mark an elongate zone of $\delta^{18}O$ depletion in the basement, identified as the 'Kimiwan isotope anomaly,' which might have originated due to hydrothermal alteration during ca. 1.76 Ga extension that overprinted an easterly dipping shear zone (e.g., Eaton et al., 1999; Burwash et al., 2000).

4.2.2 Paleozoic Arches and Hinges

The subsurface, east-northeast-trending Peace River Arch-Embayment (PRA-E) is a zone of recurrent structural disturbance within the basement and the overlying WCSB, up to 140 km wide, that extends about 750 km across northwestern Alberta to the Front Range in northeastern British Columbia (Cant,

1988; Hart and Plint, 1990; O'Connell et al., 1990). This zone is approximately collinear with the axis of the Athabasca Mobile Zone, which is characterized by basement shearing, retrograde metamorphism and metasomatism (Burwash and Krupička, 1969). The PRA-E recorded three phases of tectonic activity: 1) a Cambrian to Late Devonian topographic high on the passive continental margin (arch phase), 2) a Mississippian to Triassic subsidence resulting in a system of grabens (embayment phase), and 3) a Jurassic to Cretaceous downwarping (deep-basin phase) coeval with the Columbian and Laramide orogenies (e.g., Pană et al., 2001). Small-scale extensional faults within the PRA-E region indicate reactivation of the long-lived basement faults during the Late Cretaceous (Donaldson et al., 1998; Mei, 2006). Pană et al. (2001) summarized the proposed tectonic mechanisms for origin and development of the PRA-E, including

- basement uplift due to potassium enrichment or mantle plume;
- incipient rifting along basement faults;
- nonorogenic flexural deformation;
- interaction between foreland- and craton-basin bulges; and
- interplay of intraplate transfer zone and unusual crust rheology within the Winagami reflection sequence, a series of middle- and upper-crustal subhorizontal seismic reflections (Ross and Eaton, 1997), during the break-up of Rodinia and formation of the paleo-Pacific continental margin (e.g., Eaton et al., 1999).

The Kevin-Sunburst Dome, a part of the northwest-trending Sweetgrass Arch offset by the northeast-trending Pendroy and Scapegoat-Bannatyne dextral strike-slip faults, extends from Montana into southern Alberta and may represent a forebulge of the Laramide Orogeny (Lorenz, 1982; Lopez, 1995). The Carboniferous and Permian sediments wedge out against the eastern flank of the Sweetgrass Arch, with the estimated overall uplift of 600 m increasing during the Triassic (Podruski, 1988).

The Early–Middle Eocene regional extension that postdated the compressive Laramide deformation of the Cordilleran fold-and-thrust belt (e.g., Price, 1994) was temporally associated with the emplacement of the Eocene (ca. 54–50 Ma) Sweet Grass Hills mafic to felsic potassic igneous complex (NTS 72E; Figure 1) on the northeastern flank of the Sweetgrass Arch in northern Montana and southern Alberta (Figure 5; e.g., Dawson, 1884; Kjarsgaard, 1994; Lopez, 1995). To the north, the Sweetgrass Arch meets the southwest-plunging nose of the Late Paleozoic to Cenozoic Bow Island Arch, which separates the Alberta Basin from the Williston Basin to the southeast. The Bow Island Arch may have formed due to interaction between the Alberta foreland basin peripheral bulge and the edge of the Williston cratonic basin (Wright et al., 1994).

The northwest-trending West Alberta Ridge, along the eastern limit of the Rocky Mountains, was a topographic high possibly from the Late Cambrian to the Middle Devonian (Figure 5; Verrall, 1968; Wright et al., 1994). Its northeast-oriented hinge is roughly parallel to several regional structures: the Upper Devonian Cline channel, the axis of the Thorsby low basement block, the traced trend of the STZ in the subsurface, and the Bighorn tear fault (Verrall, 1968). Using three-component magnetovariation studies, Bingham et al. (1985) identified a conductive ridge, more than 50 km wide, in the upper crust beneath the Main Ranges of the Rocky Mountains, indicating uplift and possibly associated partial melting. Root (2001) has suggested that the West Alberta Ridge may represent a forebulge of the Paleozoic Antler Orogen. However, evidence for the extensional, rift-like setting to the west of the carbonate platform and recent tectonic reconstructions precluding any major compression along the western continental margin of North America during the Devonian–Mississippian make the existence of the Antler Orogeny in Western Canada highly unlikely (e.g., Pană et al., 2001).

The northeast-trending, 320 m high, sub–Middle Devonian Meadow Lake Escarpment (MLE) forms the erosional edge of the Ordovician Red River Formation in east-central Alberta (van Hees and North,

1964). The MLE lies above the Archean basement Hearne Terrane and may coincide with the Stanley Fault, mapped in the Canadian Shield to the northeast (Wright et al., 1994). The MLE may represent a hinge of the extensive Silurian to Early Devonian uplift, marking the southern depositional limit of the Middle Devonian Lower Elk Point Evaporite (Wright et al., 1994).

4.2.3 Other Structures

The Alberta Syncline follows the eastern Rocky Mountain Foothills front, marking the axis of the foreland basin with the thickest Tertiary successions (Wright et al., 1994). The Alberta Syncline was active during the Late Cretaceous to Early Tertiary tectonic loading in the Rockies (Leckie, 1989).

Local dissolution of the Devonian evaporites and carbonates over reef mounds produced the collapse structures reflected in the subsurface seismic and well data, and in the stratigraphic variations and topography above the sub-Cretaceous unconformity of the WCSB in northeastern Alberta (e.g., Wright et al., 1994). Karst features associated with stockwork fracturing, brecciation, dolomitization and mineralization of the Paleozoic carbonates are controlled by major thrusts (e.g., Lewis thrust) or by northwest-trending, postorogenic collapse or tear faults (e.g., Stephen-Cathedral and Fossil Gully normal faults) in the Rocky Mountains, and by pinnate fractures and joints associated with the Laramide brittle faults (e.g., HRFZ) overprinting the GSLSZ and STZ (e.g., Hannigan, 2006; Pană, 2006).

At least two large meteorite impact craters, marked by subcircular raised rims with associated faults, fractures and central uplift, occur in Alberta. The circular Steen River Impact Structure (SRIS) in northwestern Alberta (Figure 5) is 25 km in diameter. The SRIS is characterized by a central uplift of fractured and partly melted basement up to 1 km above the regional level, overlain by the tectonically disturbed Devonian strata (Burwash et al., 1994). A rim syncline locally downthrows the basement more than 500 m around the central uplift, with a raised rim a few tens of metres high contouring the crater. An irregular disturbed zone surrounds the crater, extending up to 30 km from its centre, with small-scale horsts and grabens offsetting the raised rim. The partially melted basement rocks gave a K-Ar age of ca. 95 Ma for the impact (Burwash et al., 1994). The Eagle Butte structure in southeastern Alberta (Figure 5) represents a buried Early Tertiary meteorite impact crater about 17 km in diameter. It has a central uplift up to 200 m above the regional surface, surrounded by a moat and fractured rim raised to a height of 120 m (e.g., Visser and Scott, 2005).

5 Previous Regional Metallogenic Studies and Mineral Exploration in Alberta

The history of gold and base-metal exploration in Alberta dates back to prospecting and mining in the Banff-Field corridor of the Canadian Rocky Mountains and Foothills (NTS 82O, N; Figure 1), and the first evaluations of alluvial placers in the mid-19th century (Hector, 1863; Dawson, 1886; Hoffmann, 1891, 1892; McConnell, 1891; Tyrrell, 1915). John Allan produced the first systematic account of Alberta's mineral resources in a series of reports that mark the foundation of the Alberta Geological Survey (e.g., Allan, 1920, 1922, 1924; Allan and Cameron, 1922). Since these pioneer works, there have been several regional metallogenic evaluations of Alberta by the government, industry and University of Alberta (e.g., Halferdahl, 1971; Holter, 1973, 1977; Morton et al., 1974a; Godfrey, 1985, 1986a; Edwards et al., 1991; Williamson et al., 1993; Olson et al., 1994). Halferdahl (1965) performed systematic assessment of gold in Alberta rivers. More recently, gold potential of modern alluvial and preglacial conglomerate and sand and gravel deposits was evaluated by Guisti (1983), MacGillivray et al. (1984), Edwards (1990), Harris and Ballantyne (1994), Horachek (1994), Ballantyne and Harris (1997), Leckie and Craw (1995, 1997), Edwards and Scafe (1996), Leckie et al. (1998) and Bednarski et al. (1998).

Godfrey (1986a) mapped several metallic mineral occurrences in the Alberta portion of the Canadian Shield. Edwards et al. (1991) compiled about 170 mineral assessment reports on the Precambrian shield, most detailing uranium exploration during the 1960s–1970s and only a few focused on base and precious

metals or REE. Numerous projects by the government and industry, including the Canada-Alberta Agreement on Mineral Development (1992–1995), Northern Resources Development (NRD), Targeted Geoscience Initiative 2 (TGI-2) and National Geochemical Reconnaissance (NGR) programs, evaluated Alberta's mineral potential and produced lithogeochemical and/or HMC data from bedrock, till, stream and lake sediments, and water samples (e.g., Fenton and Pawlowicz, 1993, 1998, 2001; Thorleifson and Garrett, 1993, 1997; Williamson et al., 1993; Fenton et al., 1994; Friske et al., 1994, 2003; Olson et al., 1994, 1999; Turner and McPhee, 1994; Bednarski, 1996; Dufresne et al., 1996, 2001; Eccles et al., 1998, 2001a, b; Pawlowicz et al., 1998; Eccles, 2000; Eccles and Pană, 2003; Rice and Zerbe, 2003; Prior et al., 2005, 2006; McCurdy et al., 2006, 2008; Hannigan, 2006; Pană, 2006; Plouffe et al., 2006, 2008; Kafle, 2009). Metallic mineral occurrences in the Precambrian shield of northeastern Alberta were studied by Langenberg et al. (1993, 1994), Dufresne et al. (1994), McDonough et al. (1994), Salat et al. (1994), Ianelli et al. (1995), Langenberg and Eccles (1996), McDonough (1997) and Pană et al. (2006).

Since the 1990s, there has been a resurgence of diamond- and metallic-mineral–exploration activity throughout Alberta due to the results of the above-mentioned studies, including the discovery of kimberlites and precious and base metals in northern Alberta, as well as an increase in metal prices during the last few years (e.g., Boulay, 1995; Stapleton and Kelly, 1995; Gutfreund and Bryant, 1996; Sabag, 1996a, b, 2002, 2008; Chin and Olson, 1998; Cieszynski and Keylor, 1999; Liddle, 1999, 2001; Richardson, 1999; Besserer and Balzer, 2000; Bladek, 2000; De Paoli et al., 2000; Dufresne and Copeland, 2000; Kropinak, 2001; Owens, 2001; Dufresne and Kim, 2002; Vanhill, 2002; Dufresne and Besserer, 2003).

The current land disposition in Alberta can be viewed on the Alberta Department of Energy website (Alberta Department of Energy, 2010). The remainder of the report reviews the history of precious-metal exploration, and theories of origin and potential for gold-bearing deposits in Alberta by deposit type or geological province.

6 Placer Gold in Alberta

Placer gold and platinum-group elements (PGE), along with other heavy minerals and rare diamonds, occur in modern alluvial and glacial deposits throughout Alberta (Figure 6; Selwyn, 1874; Hoffmann, 1891, 1892; McConnell, 1891; Tyrrell, 1915; Allan, 1920, 1924; Rutherford, 1937; Halferdahl, 1965; Guisti, 1983, 1986; MacGillivray et al., 1984; Godfrey, 1985; Edwards, 1990; Bi, 1993; Morton and Mussieux, 1993; Morton et al., 1993; Harris and Ballantyne, 1994; Bi and Morton, 1995; Ballantyne and Harris, 1997; Leckie et al., 1998).

6.1 Historical Perspective

Available records indicate that gold had been initially tested in Alberta's drainages by prospectors passing through the province to the gold fields of the Fraser River and the Cariboo in 1858 (e.g., Tyrrell, 1915). Placer-gold mining along the North Saskatchewan River in the Edmonton area (Figure 6) had started in 1860, initially by panning, then using rockers and sluices, and finally by dredging in 1894 (MacGillivray et al., 1984). Between 0.84 and 1.06 tonnes of gold were produced during the 100 years since 1887 (Tyrrell, 1915; Allan, 1920, 1924; MacGillivray et al., 1984). Activity peaked in 1898, when approximately 300 miners worked a 200 km stretch of the river centred on Edmonton and up to 12 dredges were in operation; 233.28 kg of gold were recovered between 1895 and 1897 (Morton and Mussieux, 1993; Edwards and Scafe, 1996).

In 1890, McConnell (1891) reported the discovery of potentially economic placer-gold concentrations along the Peace River (Figure 6). Hoffmann (1891, 1892) first described the association of platinum with placer gold in the North Saskatchewan River near Edmonton.

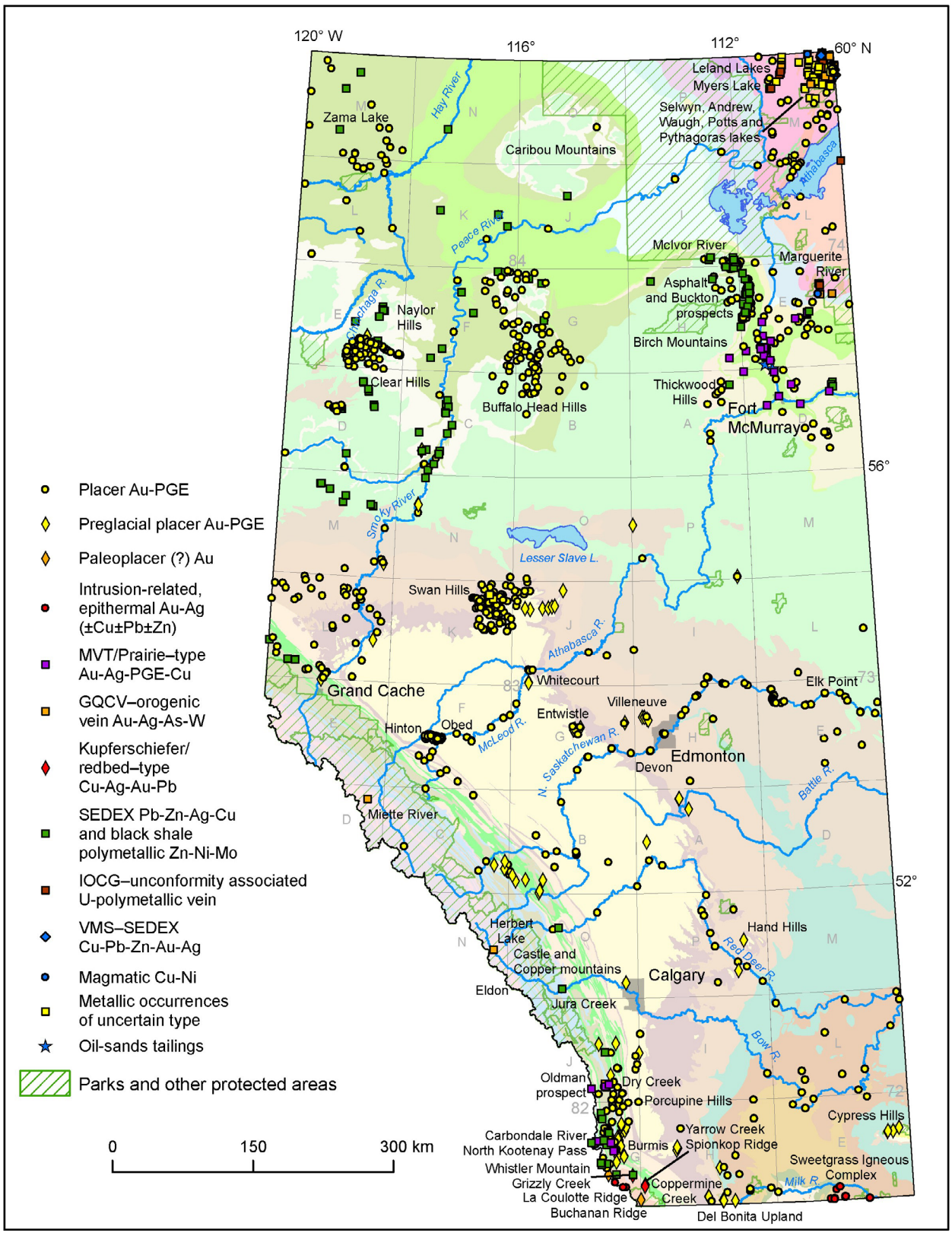

Figure 6. Locations of gold-bearing mineral occurrences in Alberta, based on compiled data.

Halferdahl (1965) reported volumetric concentrations of gold (in milligrams per cubic yard) from alluvial deposits at 124 sites along the main rivers in the province and concluded that "Few, if any, concentrations…would be considered high enough for economic recovery." However, the Edmonton region has experienced a resurgence in gold production during the past 30 years, with placer gold, gold-silver alloys, platinum-group minerals, diamonds and other heavy minerals being recovered as byproducts of sand and gravel operations (Godfrey, 1985; Edwards and Scafe, 1996; Ballantyne and Harris, 1997; Mudaliar et al., 2007). Natural Resources Canada (2010) reported the production of 55.4–100.9 kg of gold per year (revenue value of $0.959–2.223 million/year) during the last 7 years in Alberta.

During the 1990s, exploration in the Athabasca region of northeastern Alberta discovered abundant alluvial gold, locally coincident with enrichment of As-Ba-Cu-F in the stream-sediment heavy-mineral concentrates from the Firebag and Steepbank rivers, and at the confluence of the High Hill River and Sutton Creek northeast of Fort McMurray (NTS 74E; Figure 6). These anomalies, accompanied by elevated Zn-Cu-Pd-Rh-Au concentrations in the soils and lake sediments, appear to correlate with the northeasterly trending broad fault zone inferred from the discontinuous aeromagnetic profiles (Sabag, 2008). Southwest of Fort McMurray, lake and pond sediments along the Athabasca River terrace in the Thickwood Hills area (NTS 84A; Figure 6) contain anomalous Au, Cu, Zn, As, Mo and V spatially associated with the concretionary layer within the Lower Cretaceous Clearwater and Grand Rapids formations, and are coincident with the junction of two regional faults (Sabag, 2008).

Bednarski (1997) and McCurdy (1997) reported geochemical data from glaciogenic sediments and lake waters, respectively, in the areas underlain by the Precambrian crystalline basement and the Paleozoic sedimentary rocks along the Peace and Slave rivers to the west, in northeastern Alberta (Figure 6). The results of these surveys, evaluated in terms of statistical contour maps, indicated proximal sources for most of the glaciogenic sediment and revealed several geochemical anomalies, including gold, coincident with the known mineral showings in the Precambrian shield (Langenberg and Eccles, 1996). The highly anomalous concentrations of several elements in coarse to pebbly glaciofluvial gravel (samples 93BJB101, 93BJB116, and 93BJB120) and glaciolacustrine silt (sample 93BJB093) were interpreted to reflect distal upstream sources to the east and south along the Peace River, respectively (Bednarski, 1996).

The Birch Mountains area in northeastern Alberta has been a focus of extensive exploration for gold by several companies since the discovery of alluvial gold concentrations along at least 10 km of the McIvor River and at least 3 km upstream of the KRC[3] tributary from its confluence with the McIvor River (NTS 84I; Figure 6; Sabag, 1996a). Subsequent sampling confirmed the common presence of fine-grained alluvial gold in the heavy mineral concentrates from the sediments of the McIvor River (Sabag, 2002). Abundant alluvial gold, accompanied by cinnabar and base-metal sulphides, was also found downstream along the Pierre River (NTS 74E; Figure 6; Sabag, 1996b).

Chin and Olson (1998) discovered anomalous concentrations of up to 132 ppb Au and 2.0 ppm Ag in the silt fraction and up to 26 gold grains (as much as to 1 mm long) in panned concentrates of alluvial sediments along the Athabasca and McLeod rivers and smaller tributaries near Hinton, immediately east of the inferred limit of the Rocky Mountain deformed belt (NTS 83F; Figure 6).

Fenton and Pawlowicz (1998) carried out a reconnaissance till mineral and geochemical survey across northern Alberta and reported a number of local multi-element anomalies, the highest concentrations being associated with the subcrop of the mid-Cretaceous Shaftesbury Formation and in the Clear Hills and Naylor Hills areas (NTS 84D, E; Figure 6).

[3] unofficial place name cited in the mineral assessment report

Anomalous concentrations of up to 1030 ppb Au in the silt fraction and up to 1250 visible gold grains in HMC, corresponding to an estimated total-sample grade of up to 139 ppb Au, were discovered in alluvial deposits of the West Prairie River headwaters, Goose River and Atikkamek Creek, and in the Lightbulb Lake ridge area, together with anomalous As, Sb and Te contents in local bedrock in the Swan Hills area, northwest of Whitecourt in central Alberta (Figure 6; Dufresne and Copeland, 2000; Dufresne and Kim, 2002; Dufresne, 2005).

Dufresne et al. (2001) reported alluvial gold from 6 of 11 pan-concentrated stream-sediment samples (up to 4 grains per sample) collected from different streams and rivers draining the Birch Mountains (NTS 74E, 84H; Figure 6), including an irregular gold grain. Gold grains were also recovered from bedrock samples of sand from the Lower Cretaceous Pelican Formation and gravelly bone beds at the base of the Upper Cretaceous Second White Speckled Shale Formation (Dufresne et al., 2001).

In the Buffalo Head Hills and Caribou Mountains (NTS 84B, C, F, G, O; Figure 1), a total of 9, mostly detrital gold grains were recovered from 4 of 10 stream-sediment HMCs; the one exception was an authigenic gold grain (sample 95SH033-001) characterized by irregular shape and rough surfaces, suggesting a proximal bedrock source (Dufresne et al., 2001). This sample was from the known occurrence of pyrite-marcasite southeast of Wadlin Lake (NTS 84G; Figure 6), which was concentrated due to erosion of the Upper Cretaceous Dunvegan Formation sandstone that is rich in sulphide-bearing concretionary nodules (Hennessey and Wilson, 1968).

In the Peace River area of northwestern Alberta, Dufresne et al. (2001) reported 53 gold grains recovered from 7 stream-sediment panned concentrates. Two of the samples (95SH014-001 and 95SH027-001) contained 14 and 19 gold grains, respectively, with the largest gold particle measuring 1 by 2 mm (sample 95SH027-012).

Eccles et al. (2001b) reported up to 32 ppb Au in stream sediments collected from drainages of the exposed sub-Cretaceous unconformity between carbonates of the Upper Devonian Waterways Formation and sandstones and siltstones of the Lower Cretaceous McMurray Formation in the Fort McMurray area of northeastern Alberta. Microdisseminated precious and base metals were documented in these rocks by Abercrombie and Feng (1997), and Ballantyne and Harris (1997).

Friske et al. (2003) reported up to 130 ppb Au from stream sediments in the southern Buffalo Head Hills area (Figure 6), with ~66% of the heavy mineral concentrates containing >30 ppb Au (up to 2.23 ppm Au, 1.69 ppm Ag, 9.4% Ba, 0.16% Cr, 0.06% Zn and 0.06% Hg). Of the 154 stream-sediment HMCs analyzed, 56% yielded at least one visible gold grain, with up to 80 ppb Au estimated total concentration. About 15% of the gold-bearing samples contained pristine gold grains; in some samples, these accounted for up to 100% of the recovered gold grains, suggesting a proximal bedrock source within the Upper Cretaceous Shaftesbury Formation (Friske et al., 2003).

McCurdy et al. (2006) sampled stream silt from drainages in the northern and southwestern Buffalo Head Hills and reported up to 12 ppb Au, 270 ppb Ag and 0.16% Ba. The corresponding HMC samples yielded up to 1.5 ppm Au, 2.4 ppm Ag, 1.1% Ba, 0.41% Cr, 0.21% Zn, 302 ppm Ni, 280 ppm As and 109 ppm Cu, with about 64% of the 67 samples containing more than 30 ppb Au. Visible gold, including both reshaped and pristine grains, was detected in about 45% of all the HMCs, with total-sample concentrations of up to 114 ppb Au estimated from the total weight of the recovered gold grains and the sample weight.

Plouffe et al. (2006) discovered anomalous concentrations of sand-sized sphalerite (>1000 grains) and minor galena in glacial sediments over approximately 1200 km^2 in the Zama Lake–Zama City region of northwestern Alberta (NTS 84M, L; Figure 6). The HMC samples also yielded estimated total-sample

concentrations of up to 18 and 39 ppb Au, based on the size of the recovered gold particles (Plouffe et al., 2006, 2008).

6.2 Hypotheses of Origin

In modern Alberta placers, morphologically distinct gold grains often occur in association with various platinum-group minerals (PGMs), which is a globally rare phenomenon (Hoffmann, 1891, 1892; Guisti, 1983, 1986; Bi, 1993; Harris and Ballantyne, 1994; Bi and Morton, 1995; Ballantyne and Harris, 1997; Mudaliar et al., 2007). Guisti (1983) described Pt-Fe and Os-Ir alloy grains of up to 400 μm (microns) in size from the Groat Bridge locality in Edmonton. Harris and Ballantyne (1994) and Ballantyne and Harris (1997) examined PGM and gold concentrates from the North Saskatchewan River and concluded that the principal PGMs include

- Pt-Fe alloys forming platelets up to 400 μm in diameter, rods up to 600 μm long and spheres <100 μm that contain 10–32 wt. % Fe+Cu+Ni and minor or trace Os, Ir, Rh, Pd and Ru, with inclusions of chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4), native Os, cooperite (PtS), irarsite (IrAsS), hollingworthite (RhAsS), and unidentified Rh-S and Rh-Ir-As-S phases;
- Os-Ir-Ru alloys forming platelets similar in appearance to Pt-Fe alloys but more silvery in colour; and
- rare native Pt, hongshiite ([Pt,Fe]Cu) and sperrylite ($PtAs_2$).

Mudaliar et al. (2007) described deformed, rounded, flattened and abraded Pt-Ir grains associated with gold, pyrite, root-shaped native Pb (up to 1.2 cm), cerussite, barite, rare diamonds and other heavy minerals (ilmenite, hematite, magnetite, zircon, almandine, monazite, rutile and chromite) recovered as a byproduct from an alluvial sand and gravel pit at Whitecourt in central Alberta. The gold grains are 0.1–1.5 mm in size, have fineness ranging from 550 to 790 in cores and from 940 to 980 in rims, and contain up to 30 wt. % Ag and <0.19 wt. % Cu (Mudaliar et al., 2007).

Using petrographic, scanning electron microscope (SEM) and electron microprobe studies, Guisti (1983) identified three types of alluvial gold in Alberta:

- irregularly shaped, less flattened detrital grains (1%–5% of all studied grains) with scratches and preserved crystal faces
- flakey, scaly and occasionally drop-like, recrystallized grains (90%) with high fineness rims and sometimes enclosing other trapped grains
- fibrous new filaments, usually binding grains of other morphological types

Ballantyne and Harris (1997) described different assemblages of precious-metal grains recovered from drainages in northern Alberta:

- pristine, delicate intergrowths (20 μm) of Ag-sulphide and native Ag with attached complex gangue
- polycrystalline aggregates (up to 218 μm long) of both pristine and modified Au-Ag octahedra (with crystal-growth microlaminae and plane faces)
- large (>100 μm), pristine, Au-Ag alluvial grains with smooth surfaces, delicate appendages and embedded gangue of quartz, K-Al silicate and Ca-Fe-Mg carbonate, and surface Fe-oxide blotches

They also documented disk-shaped alluvial gold grains recovered from the Athabasca River and the Muskeg River north of Fort McMurray (Figure 6; Ballantyne and Harris, 1997), including

- Au-Ag grains (>50 μm) with sponge-like surface texture, possibly due to bacterial overgrowths, and thread-like Cu-Zn metal on the surface of an embedded quartz grain;

- Au and Au-Ag grains (up to 100 μm), the surfaces of which are covered with probable bacterial growths and mound-like appendages, along with a Cu-Zn metal flake (~50 μm) adhering to a pristine phyllosilicate(?) flake;
- mottled and multilayered Au grains with meandering crevasses and embayments, showing secondary gold growth cycles with an embedded quartz grain overgrown by Cu-Zn alloy(?); and
- elliptical to oblate alluvial Au with high purity, delicate appendages.

Several hypotheses have been proposed to explain the provenance of gold and co-occurrence of gold and PGM in Alberta placers:

- Selwyn (1874) and Morton et al. (1993) suggested that gold in modern Alberta drainages was derived by reworking of glaciogenic sediments in which gold was originally transported from the Precambrian shield exposed in northeastern Alberta. A diamond-indicator-mineral and geochemical survey of till and soil carried out in southern Alberta (Thorleifson and Garrett, 1993, 1997) showed that sediment consisting of material transported generally southwestward from the Canadian Shield by the Laurentide Ice Sheet can be distinguished from Quaternary sediments north and south of Calgary that contain abundant glacially transported material from the Cordillera.
- Tyrrell (1915) suggested a clinker deposit in the Cretaceous–Tertiary Edmonton Group as the source of the gold.
- Rutherford (1937) proposed that preglacial Saskatchewan Sands and Gravels (Leckie and Craw, 1997), subsequently considered as part of the Empress Group (Leckie, 2006), might have supplied the alluvial gold.
- The mesothermal veins in the Lower Cambrian strata near the Committee Punch Bowl area of the central Canadian Cordillera (NTS 83D; Figure 6) have been suggested as possible sources of Pleistocene gold placers in Alberta (Godfrey, 1985; Morton et al., 1993; Mudaliar et al., 2007). Based on the chemistry of the gold grains, the assemblage of associated minerals and the inclusions in the gold grains, Mudaliar et al. (2007) suggested that both mesothermal and low-sulphidization epithermal gold deposits may be the primary sources of the placer gold, with estimated transport distances ranging from 3 to 8 km, as indicated by flattening, rounding and rimming of the grains. However, neither mesothermal nor low-sulphidization epithermal gold deposits explain the coexistence of gold and PGMs in this placer deposit.
- Bi (1993) and Bi and Morton (1995) proposed an extraterrestrial origin for the Pt-Fe alloy grains with Os-Ir-Ru inclusions in Quaternary sediments of the Onoway area northwest of Edmonton and common magnetite-hematite spherules, including some with Ni-rich cores, in fluvial sediments throughout Alberta.
- Mudaliar et al. (2007) suggested that clastics of the Scollard Formation might be the source of placer PGEs sampling the sediment shed from the Cretaceous–Tertiary boundary during the Laramide Orogeny.
- Primary PGM enrichment is often associated with mafic–ultramafic intrusions of either Alaskan or Alpine ophiolite complex types. Mafic intrusions and lava flows within the Mesoproterozoic Purcell Supergroup in the Clark Range area of southwestern Alberta (NTS 82G, H; Figure 6) and near the Tulameen River in British Columbia (NTS 92H) could have supplied PGMs to the Alberta foreland basin (Morton et al., 1993). Minor PGEs are associated with the Eocene lamprophyres in southern Alberta (Kjarsgaard, 1994; A. Rukhlov and J. Pawlowicz, Metal potential of the Eocene Sweetgrass intrusive complex in southern Alberta and northern Montana: geochemical data release, work in progress, 2010). Erosion of these intrusions and the Cretaceous kimberlites in northern Alberta may contribute some PGEs to modern placers. The coincidence of gold and PGMs, along with mafic

silicate minerals, chromite and ilmenite, in modern drainages throughout the province may support this hypothesis.

- Godfrey (1985) argued that many Alberta placers are unlikely to have a single source of gold and that multiple sources, including reworked glacial sediments, other preglacial fluvial deposits and Cretaceous to Tertiary bedrock, might have contributed gold to the modern rivers in Alberta. Patyk-Kara et al. (2001) and Garnett and Bassett (2005) have shown that many gold placers elsewhere in the world are multigenerational and exhibit a high degree of reworking, with an increase in grade from older to younger deposits.
- Harris and Ballantyne (1994) and Ballantyne and Harris (1997) suggested Cretaceous–Tertiary conglomerates and gravels or other local bedrock sources of placer gold and PGM. Based on gold-grain morphology, chemistry and inclusions, and encrustations of Cu-Fe and Fe-sulphides, quartz and barite, Ballantyne and Harris (1997) proposed the Upper Cretaceous Shaftesbury Formation clastics and the Devonian carbonates as possible local bedrock sources for alluvial gold in northeastern Alberta. Abercrombie and Feng (1997) and Ballantyne and Harris (1997) documented the precious- and base-metal minerals in these bedrocks, lending further support to this hypothesis.

Horachek (1994) cited Alberta Research Council results that indicated up to 141 ppb Au for the modern alluvial placers along the North Saskatchewan River segment between Devon and Elk Point in central Alberta (NTS 83G, H, 73E; Figure 6). These placers are coincident with the Upper Cretaceous Scollard, Horseshoe Canyon and Belly River formations, which are intersected by the river in this area.

Possible proximal bedrock sources of alluvial gold have also been suggested for other parts of northern Alberta. The anomalously high concentrations of gold and other metals in stream sediments from drainages flanking the north, southwest and south sides of the Buffalo Head Hills, along with high acidity (pH 3.3) and up to 1 ppm Zn in the stream water, may indicate a local source within the Upper Cretaceous Shaftesbury Formation (Friske et al., 2003; Prior et al., 2005; McCurdy et al., 2006).

Based on morphology and low Ag contents, Dufresne et al. (2001) interpreted the gold grains recovered from drainages in the Peace River area of northwestern Alberta to be detrital and possibly derived from the local Cretaceous continental sandstone and preglacial sand and gravel deposits.

The distribution of placer-gold occurrences in the Swan Hills area (Figure 6) cannot be explained by contribution of detrital gold from the Swan Hills Tertiary gravels that cap the local topographic highs, but may instead indicate derivation from multiple local bedrock sources, including the Cretaceous–Tertiary sandstone paleoplacers and possibly hydrothermal vein or replacement-type gold (Dufresne, 2005).

Based on glacial-flow directions and topography in the Zama Lake area, Paulen et al. (2007) favoured a proximal SEDEX-like source, possibly in the Cretaceous shale, for the detrital sphalerite, galena and gold grains in the glacial drift. They rejected the possibility of glacial transport from the Pine Point MVT Pb-Zn deposits, located approximately 330 km to the northeast.

6.3 Future Potential

Alberta alluvial gold is often referred to as ‘flour gold’ due to its relatively small grain size, which ranges from 100 to 800 μm, with most grains being between 125 and 250 μm (Guisti, 1983; MacGillivray et al., 1984). Several studies pointed out that the highest concentrations of placer gold (>600 grains in panned concentrate) in modern alluvial deposits occur along a stretch of the North Saskatchewan River from Devon to north of Myrnam in the vicinity of Edmonton (Figure 6; Halferdahl, 1965; Guisti, 1983; MacGillivray et al., 1984; Edwards, 1990; Morton et al., 1993; Ballantyne and Harris, 1997). Elsewhere in Alberta, placer-gold occurrences with >10 ppb Au occur in the Peace, Athabasca, McLeod, Red Deer and Milk rivers (Figure 6; Halferdahl, 1965; Guisti, 1983; Edwards, 1990; Ballantyne and Harris, 1997;

Eccles, 2000). Placer gold has recently been produced as a byproduct of sand and gravel operations in Alberta (e.g., Mudaliar et al., 2007).

Fenton and Pawlowicz (2001) suggested that the Wapiti area (NTS 83L) in western Alberta has exploration potential for placer gold, based on samples of gravel, till and fluvial sediment containing up to 36 ppb Au. Regional geochemical sampling in the Peerless Lake area (NTS 84B) of northern Alberta revealed the presence of both abraded and irregular microscopic gold (up to 0.74 by 1.04 mm and up to 2–3 grains per sample) in stream sediment HMC, till, glaciofluvial, and preglacial samples (Eccles et al., 2001a).

The anomalous concentrations of placer gold in the Swan Hills area approach the minimum cut-off grade of 200 to 500 ppb Au required for stand-alone placer-gold operations (Dufresne, 2005). Other potential areas include alluvial placers in the Birch Mountains and Buffalo Head Hills areas and near Hinton (Chin and Olson, 1998; Dufresne et al., 2001; Friske et al., 2003; McCurdy et al., 2006).

7 Buried Placer or Paleoplacer Gold in Alberta

Paleoplacer gold (± PGM, magnetite, ilmenite, rutile and other heavy minerals) occurs in consolidated fluvial and marine-beach clastic sedimentary rocks of Mesoproterozoic (lower Purcell Supergroup), Early Cretaceous (Blairmore Group) and Late Cretaceous (Brazeau Group) ages in southwestern Alberta, and unconsolidated to lithified sand and gravel deposits of Tertiary to Pleistocene age throughout Alberta that predate Laurentide glaciation (e.g., Edwards, 1990; Horachek, 1994; Leckie and Craw, 1995, 1997; Ballantyne and Harris, 1997; Bednarski et al., 1998). Figure 6 shows the distribution of known paleoplacer-gold occurrences and geochemical anomalies in Alberta.

7.1 Historical Perspective

Olson et al. (1994) included in their metallogenic inventory an unsubstantiated paleoplacer-gold occurrence that had reportedly been discovered between 1901 and 1903 in quartzites of the Mesoproterozoic Purcell Supergroup on the northwestern flank of Buchanan Ridge in the Clark Range of southwestern Alberta (Goble, 1974b). If confirmed, this occurrence may be the oldest gold paleoplacer found in Alberta thus far; since it is now within Waterton Lakes National Park, there has been no follow-up exploration.

Leach (1912) and Allan (1931) described two magnetite-ilmenite-rutile paleoplacer deposits in southwestern Alberta: 1) Burmis (up to 10% TiO_2) in the Crowsnest Pass area, and 2) Dungarvan Creek, south of Pincher Creek. Exploration during the 1950s–1980s, involving trenching, drilling and metallurgical testing, estimated that the Burmis resource, comprising the Marasek, Milvain and Boutry deposits, ranges between 1.9 and 6.1 million tonnes of magnetite (e.g., Mellon, 1961; Grant and Trigg, 1983). More recent exploration identified a volume of 34 550 m^3 of magnetite-bearing rock corresponding to an NI43-101–compliant indicated resource of about 111 200 tonnes (t) with an average grade of 60 wt. % magnetic minerals for the Marasek deposit, which could supply the dense-media separation at Elkview coal mine for at least 5 years (Dufresne and Kupsch, 2003). Assays reported by Grant and Trigg (1983) indicate up to 150 ppb Au, 15 ppb Pd, 4.48 wt. % Ti, 1675 ppm V, 1583 ppm Zr, 1052 ppm Ce, 485 ppm Zn, 138 ppm W, 71 ppm Th and 22 ppm Sn in these paleoplacer deposits.

In 1980, Trigg, Woollett and Olson Consulting Ltd. reported up to 1.15 ppm Au with elevated concentrations of Zn, Ni, Co and V from sandstone samples of the Early Cretaceous Blairmore Group near Logan Creek, northeast of Canmore, but could not duplicate this result later (Olson et al., 1994). In his comprehensive compilation of placer gold in Alberta, Edwards (1990) quoted values up to 69 ppb (0.02 oz./ton) and 137 ppb (0.04 oz./ton) Au for the Early Cretaceous Blairmore Group conglomerate and the Crowsnest Formation volcanogenic conglomerate, respectively, from Highway 3 roadcut outcrops in the Crowsnest Pass (NTS 82G; Figure 1).

Olson et al. (1994) suggested a possible gold paleoplacer in conglomerates of the Upper Cretaceous Belly River Formation on the basis of up to 1.51 ppm Au from stream sediments and 78 ppb Au from soil samples, with no associated anomalous As, Sb or Hg contents, reported for the Anderson Creek area, which is about 15 km southeast of Hinton (NTS 83F; Figure 6; Fox, 1991).

Horachek (1994) evaluated paleoplacer-gold potential of conglomeratic sandstones and conglomerates, containing >60% volcanic clasts, of the Lower Cretaceous Cadomin and Mountain Park formations and the Upper Cretaceous Hoadley and Brazeau formations in the North Saskatchewan River watershed, based on 134 samples from 92 sites. Thirteen samples returned values above the background of 5 ppb Au, with the highest values ranging between 10 and 16 ppb Au from five samples, three of which were from Cadomin Formation conglomerate and other two (10 and 13 ppb Au) from Brazeau Formation conglomeratic sandstones or conglomerates.

Leckie and Craw (1995, 1997) analyzed 66 samples of sandstone matrix from the Lower Cretaceous Blairmore Group igneous-clast conglomerates from 11 sites in southwestern Alberta; 60 samples returned fire-assay gold values above the estimated local background of 2–5 ppb Au. The gold concentrations are 16–34 ppb at Coal Creek, 9–26 ppb (with 40 ppb Pt) at Rio Alto Ranch, 5–23 ppb at Corral Creek, 11–120 ppb at White Creek, 9–910 ppb at Bruin creek, 10–232 ppb at Castle River, 4–80 ppb at Vicary ridge, 5–21 ppb at the Frank Slide, 9–15 ppb at Ginger Hill, 7–22 ppb at Carbondale Hill and 5–19 ppb at Screwdriver Creek.

In addition to the fire-assay data, Leckie and Craw (1995) obtained anomalous metal concentrations by aqua-regia ICP for various units of the Blairmore Group:

- Crowsnest volcanics: 10 ppb Au, 220–249 ppm Cu, 216–222 ppm V, 135–156 ppm Zn, 61–66 ppm Pb and 7–11 ppm As
- Lynx Creek Member: 10 ppb Au
- Bruin Creek Member sandstone: 10–80 ppb Au and 0.4 ppm Ag
- igneous-clast conglomerates: 10–40 ppb Au, 4.7 ppm Ag, 669 ppm Pb, 100 ppm Zn and 260 ppm As

Leckie and Craw (1997) also analyzed 20 samples of sandstone matrix from basal conglomerate of the Early Cretaceous Cadomin Formation in the Crowsnest Pass area. All samples returned background gold values, except one from Oldman River outcrop that contained 17 ppb Au.

Edwards and Scafe (1996) identified 203 preglacial sand and gravel deposits of Tertiary to Quaternary age and 170 probable sites of preglacial origin in Alberta. They divided preglacial deposits into six groups based on their location, lithological similarity, paleocurrent data and gold content, reflecting the source of the deposits and the extent of the fluvial basin. For cross-group correlation, they further classified these preglacial deposit groups into the following four stratigraphic units according to their age and elevation, reflecting the erosional history of the plains (Edwards and Scafe, 1996):

1) Late Eocene–Early Oligocene Cypress Hills Formation and equivalents
2) Pliocene Hand Hills Formation and equivalents
3) Pleistocene(?) Upland Gravels
4) Pliocene to Early Pleistocene members of the Empress Group (Leckie and Craw, 1997; Leckie, 2006)

The lithified conglomerate of the Late Eocene–Early Oligocene Cypress Hills Formation in southeastern Alberta contains up to 15 ppb Au, with 9 of 22 analyzed samples of sandstone matrix yielding ≥6 ppb Au (Leckie and Cheel, 1989; Edwards, 1990; Leckie and Craw, 1997).

Leckie and Craw (1997) reported up to 21 ppb Au, with 10 of 16 samples returning ≥6 ppb Au, for screened sand matrix of the Miocene–Pliocene Swan Hills unconsolidated cobble/boulder gravels at Swan Hills and Deer Mountain in central Alberta, which possibly formed in a northeastward-flowing paleofluvial system, based on the paleocurrent data. The unconsolidated sand and gravel of the Late Miocene–Early Pliocene Del Bonita Upland in southern Alberta contained 20–69 ppb Au (Edwards, 1990; Bednarski et al., 1998).

Vanhill (2002) evaluated the unconsolidated preglacial sands and gravels on the west side of Athabasca River for gold using a 30 cm run sluice box, followed by panning of the sand-size fraction and weighing the separated gold. A small-scale operation near a large island in this area produced approximately 5670 g of fine-grained placer gold during the last 70–80 years (Vanhill, 2002).

7.2 Hypotheses of Origin

Edwards and Scafe (1996) studied clast lithology and paleocurrents of the preglacial sand and gravel deposits to determine the possible source stratigraphic units because these, along with the extent of the fluvial basin, determine the gold grades of buried placers in the Alberta Basin. They found that clasts of the Group 3 and/or 4 sand and gravel deposits comprise chert-pebble conglomerate, chert, quartzite, sandstone, ironstone/mudstone, argillite, cherty dolomite and limestone. These represent the Neoproterozoic Miette Group, Devonian and Carboniferous carbonates, Lower–Upper Permian Ranger Canyon Formation, Starlight Evaporite Member of the Upper Triassic Whitehorse Formation, Lower Cretaceous Cadomin Formation and Paleocene Paskapoo Formation in eastern British Columbia and western Alberta (Edwards and Scafe, 1996).

For the Group 6 sand and gravel deposits, the clast types include chert- and quartz-pebble conglomerates, chert, quartzite, sandstone, ironstone, shale, argillite, schist, granitoids, white and smoky quartz, vein quartz, and basaltic and other volcanic and metavolcanic rocks. These may have derived from the Proterozoic–Cambrian Misinchinka Group; Lower Cambrian Mahto, Stelkuz, Boya and McNaughton formations; Lower Ordovician Monkman Formation; Carboniferous–Permian fine-grained clastic rocks, chert, mafic volcanics and related ultramafic, mafic and rare granitoid intrusions of the Slide Mountain Assemblage; Lower to Upper Permian Fantasque Formation; Starlight Evaporite Member of the Upper Triassic Whitehorse Formation; Middle Cretaceous granodiorite–granite plutons of the Cassiar Suite; and Upper Cretaceous Dunvegan and Badheart formations in western Alberta and adjacent areas of British Columbia (Edwards and Scafe, 1996).

Sands and gravels of the Late Miocene–Early Pliocene Del Bonita Upland in southern Alberta represent the remnant of the north-northeasterly flowing paleochannels (Bednarski et al., 1998). Clast types include white and purple quartzite, sandstone, siltstone, red and green argillite, gritstone/arkose, chert, and amygdaloidal basalt, diabase and diorite. These may have derived from the Mesoproterozoic Belt-Purcell Supergroup intruded by the Mesoproterozoic gabbroic intrusions, Rock Creek Member of the Middle Jurassic Fernie Formation, Lower Cretaceous Cranbrook Formation, and dikes and sills of the Upper Cretaceous Blood Reserve Formation exposed in northwestern Montana (Edwards and Scafe, 1996; Bednarski et al., 1998).

The Late Eocene–Early Oligocene Cypress Hills conglomerates in southeastern Alberta are the remnants of the northeast-flowing braidplain paleochannels and potholes with interlayered debris-flow deposits and braided river sediments that scoured into the underlying Ravenscrag Formation (Leckie and Cheel, 1989; Leckie and Craw, 1997)

The Burmis and Dungarvan Creek paleoplacer deposits in southwestern Alberta comprise basal sandstone intercalated with magnetite-ilmenite-rutile beds of the Late Cretaceous Belly River Formation, which possibly formed in a beach environment along the margin of the Late Cretaceous Colorado Sea and

subsequently deformed during the Late Cretaceous and Tertiary thrusting and folding (Allan, 1931; Dufresne and Kupsch, 2003).

The lithified igneous-clast conglomerates of the Early Cretaceous (Albian) Blairmore Group in southwestern Alberta comprise several east-northeast-flowing paleochannels (Highwood, Sentinel, Bruin, Crowsnest, Carbondale and Vicary) up to 22 km wide and scoured up to 60 m deep into the underlying strata of the Early Cretaceous Mill Creek and Beaver Mines formations (Leckie and Craw, 1995, 1997). The conglomerates are crudely to well-stratified, parallel- or crossbedded, predominantly clast supported and poorly to well sorted, and contain rounded, imbricated pebbles and cobbles set in a medium- to coarse-grained sandstone matrix with silica-calcite-dolomite cement. The clasts comprise felsic to intermediate plutonic rocks and intermediate to mafic volcanic rocks (~50%), chert, quartzite and minor slate, low-grade schist and postmetamorphic quartz veins derived from the western Omineca Belt, approximately 250 km to the west (Leckie and Craw, 1995). The K-Ar dates for dacite, rhyodacite porphyry and granodiorite clasts range between 174 and 113 Ma, with most of the dates bracketed between 158 and 142 Ma, indicating the emplacement age of the magmatic source rocks in the Omineca Belt of British Columbia (Leckie and Craw, 1995).

The base of the Early Cretaceous (Neocomian–Aptian) Cadomin Formation contains highly indurated, basal pebble/cobble conglomerate with silica cement, possibly deposited in a north- to northwest-flowing braided river, with sediment transported from Precambrian quartzites and Paleozoic carbonates and clastics flanking the North American craton (Leckie and Craw, 1997).

Paleoplacer-gold chemistry and grain morphology provide some clues on the origin of these deposits. Ballantyne and Harris (1997) described compositionally zoned, flattened, native gold and gold-alloy grains (up to 1.2 mm in diameter) associated with PGMs from mineral aggregate operations on the Pliocene–Pleistocene Saskatchewan Sands and Gravels in the Edmonton region. The alluvial gold grains range from 550 to 950 in fineness, contain up to 40.7 wt. % Hg, 14.1 wt. % Pt, 8.0 wt. % Pd and 4.0 wt. % Ag, and show pristine bacterial gold growth (Ballantyne and Harris, 1997). Their surfaces are characterized by

- vertically multilayered pure Au mounds;
- delicate porous gaps;
- undulating and/or branching filaments;
- ultrafine (~5 μm scale), spheroidal and lace-like accumulations or 'budding hyphae' and their collapsed structures; and
- delicate Au-adsorbing overgrowths (bacterial colonies?) engulfing and bridging some grains.

Based on this morphological evidence, Ballantyne and Harris (1997) proposed an in situ bioaccumulation of pure gold on surfaces of fluvially transported gold particles in the Tertiary paleochannels.

The broadly rounded and irregularly shaped, detrital gold grains (up to 234 μm long) from the Early Cretaceous igneous-clast conglomerates at Bruin and Screwdriver creeks in southwestern Alberta (NTS 82G; Figure 6) have highly convoluted surfaces, irregular cavities, delicate apophyses and scaly gold coatings (1–10 μm size). Some grains are partially coated by limonite, silica and dolomite, indicating postdepositional solution and overgrowth in the conglomerate matrix (Leckie and Craw, 1997).

Several stratigraphic units in the Canadian Cordillera might have contributed paleoplacer gold in Alberta. Craw and Leckie (1996) suggested that the postmetamorphic quartz veins in the greenschist-facies Neoproterozoic rocks west of the Yellowhead Pass might have supplied detrital gold to the Swan Hills and Whitecourt Mountain sands and gravels.

Volcanic-clast conglomeratic sandstones and conglomerates of the Lower Cretaceous Cadomin and Mountain Park formations and the Upper Cretaceous Hoadley and Brazeau formations in the North Saskatchewan River watershed, and their equivalents in the Alberta Plains (i.e., basal strata of the Scollard, Horseshoe Canyon and Belly River formations), represent part of a clastic wedge that resulted from erosion of the more internal portions of the Rocky Mountains and gold-bearing Omineca Belt. Therefore, these stratigraphic units might have been favourable for placer-gold deposition (Horachek, 1994).

Leckie and Craw (1995, 1997) proposed that the Lower Cretaceous–Pleistocene gold paleoplacers in the Alberta foreland basin reflect the position of the drainage divide associated with the deformed belt to the west. They suggested three detrital gold depositional 'windows' in the Western Canada foreland basin: 1) an exposure of the Omineca Belt lode gold deposits due to the uplift; 2) a cut-off of source by lateral eastward-stepping of the drainage divide; and 3) the modern, still open 'window' (Leckie and Craw, 1997).

7.3 Future Potential

The Tertiary to Quaternary sand and gravel deposits are valuable sources of high-quality mineral aggregate, generating annual revenue of approximately $50 million, with an additional $1 million/year worth of gold recovered as a byproduct of washing the preglacial sand and gravel (Edwards and Scafe, 1996). Given the fact that gold is being economically recovered as a byproduct of sand and gravel deposits grading as low as 34 ppb Au (Edwards and Scafe, 1996), some of the paleoplacer occurrences with similar or higher grades in Alberta are potentially economic, depending on a number of factors (e.g., gold price, distribution of grade throughout a deposit, and size and morphology of gold grains). For example, stand-alone placer-gold operations in the Yukon require a minimum grade cut-off of about 300 ppb Au (Dufresne, 1987).

On average, the preglacial placers from central Alberta (Group 3/4) and northwestern Alberta (Group 6) have the highest gold grades, ranging from 18 to 20 ppb Au for total sand and gravel material and from 71 to 79 ppb Au for the sand fraction only (Edwards and Scafe, 1996). According to the compilation by Edwards (1990), the highest paleoplacer-gold concentrations occur in the unconsolidated Grimshaw Gravels (NTS 84C; 549 ppb Au) in northwestern Alberta and in the preglacial sands and gravels at the Heatherdown deposit (NTS 83G; 140 ppb Au) in the Onoway area and at the Villeneuve deposit (NTS 83H; 34–575 ppb, up to 3861 gold grains in HMCs) in the Edmonton area. Many other Tertiary–Quaternary sand and gravel paleoplacer occurrences associated with mineral aggregate deposits have grades >10 ppb Au: Calgary (NTS 82O; 69 ppb Au), Entwistle (NTS 83G; 69 ppb Au), Swan Hills (NTS 83J; 25 ppb Au), Whitecourt mountain (NTS 83J; 69 ppb Au) and Magnolia (NTS 83G; 34 ppb Au) in central Alberta; Fort McLeod (NTS 82H; 34 ppb Au), Nanton (NTS 82I; 34 ppb Au), Wintering Hills (NTS 82P; 50 ppb Au) and Magrath (NTS 82H; 69 ppb Au) in southern Alberta; and Smoky tower (NTS 83L; 69 ppb Au) and Halverson Ridge (NTS 84E; 69 ppb Au) in western Alberta (Figure 6; Edwards, 1990).

Anomalous concentrations of gold also occur in consolidated fluvial and marine-beach paleoplacers of Early–Late Cretaceous age in southwestern Alberta. For example, the Early Cretaceous Blairmore Group igneous-clast conglomerates and the Crowsnest Formation volcanogenic conglomerates in southwestern Alberta may host potentially economic gold concentrations (Edwards, 1990; Leckie and Craw, 1995, 1997). The well-known Burmis and Dungarvan Creek marine paleoplacer Fe-Ti deposits in southwestern Alberta (NTS 82G; Figure 6) may have potential for byproduct Au, PGEs, V, Zr, Ce, Zn, W, Th and Sn (e.g., Grant and Trigg, 1983).

Following up on an historical gold recovery on the west side of the Athabasca River (NTS 83P; Figure 6), Vanhill (2002) tested preglacial sands and gravels, likely members of the Empress Group, and reported

potentially economic concentrations of between 0.25 and 0.75 g/m^3 associated with "thin bands of black sands that contain enough fine gold to be seen by the naked eye" from "Test site No. 30 at Sandswamp Prospect No. 5." This occurrence is within a shallow (1–3 m below the surface) paleochannel 2 km south of the confluence of the Athabasca and Lesser Slave rivers, near Smith in central Alberta (Vanhill, 2002).

Interesting results were recently obtained by the Geological Survey of Canada (GSC) from the southern Buffalo Head Hills, where a preglacial gravel sample (RP04-BHH-04) returned 143 gold grains, the largest grain measuring 100 μm by 250 μm by 250 μm; the calculated concentration for the HMC was 2986 ppb Au (R. Paulen, pers. comm., 2009). More sampling is needed to evaluate the placer-gold potential of this preglacial gravel deposit.

8 Lode Gold in the Alberta Portion of the Canadian Shield

Table 3 summarizes examples of gold-bearing metallic mineral occurrences in the Precambrian shield.

8.1 Historical Perspective

Pană et al. (2006) and Pană and Olson (2009) have summarized previous work on the Precambrian shield. Langenberg and Eccles (1996) catalogued approximately 200 known metallic mineral occurrences (i.e., gold, uranium, base metals and rare-earth elements) in the Precambrian shield in northeastern Alberta (Figure 6).

Allan (1920) reported 21.6 ppm Au for the Precambrian granitic basement (336.8 m depth) penetrated by the Athabasca Oils Ltd. No. 1 well near Fort MacKay (approximately 8-2-96-11-W4) in 1911–1912. In the early 1960s, Scurry-Rainbow Oil Ltd. drilled four holes near the Athabasca Oils Ltd. No. 1 well to check for the gold mineralization. Three of the holes penetrated the basement, which showed minor pyrite with only traces of gold in the samples (Halferdahl, 1986; Dufresne et al., 1994).

During 1988, the Ells Gold No. 1 well was drilled on the west side of the Athabasca River (11-2-96-11-W4) near the Athabasca Oils Ltd. No. 1 well, terminating in quartz with abundant pyrite at 280 m depth, just below the sub-Phanerozoic unconformity (Dufresne et al., 1994; Olson et al., 1994). Assays of the drill cuttings (nine analyses) showed up to 1.1 ppm Au and 7.54 ppm Ag for one sample and 210 ppb Au for two others (Dufresne et al., 1994; Olson et al., 1994).

Halferdahl (1986) supervised drilling on the east side of the Athabasca River about 35 km south of the Athabasca Oils Ltd. No. 1 well, and reported up to 60 ppb Au and 2.6 ppm Ag for basement samples with chalcopyrite and malachite from two drillholes (Halferdahl, 1986). Graphite- and hematite-rich migmatitic granite at 882.1 m depth, 4.4 m below the sub–Athabasca Group unconformity, from a Golden Eagle Oil and Gas Ltd. well drilled on the south shore of Lake Athabasca near the Alberta-Saskatchewan border, returned up to 2.7 ppm Au, coupled with high Ag, U, Ni, Co, Zn and As (Wilson, 1987).

Originally, Godfrey (1958, 1986a) identified several arsenopyrite showings in the Pythagoras Lake, Hutton Lake, Bonny Lake, Waugh Lake and Potts Lake areas (NTS 74M; Figures 1 and 6) that contain up to 25 vol. % sulphides with 0.39% Ni and 10.3 ppm Ag. Subsequent work by AGS and GSC has led to the discovery of additional metallic mineral occurrences in the Precambrian shield of northeastern Alberta (Langenberg et al., 1993, 1994; McDonough et al., 1994; Salat et al., 1994; Ianelli et al., 1995; Pană et al., 2006), which were classified on the basis of geological setting, mineralogy and metal signature (e.g., Olson et al., 1994; Langenberg and Eccles, 1996; McDonough, 1997). The highest gold concentrations are associated with shear-related sulphide and/or quartz-vein showings, examples of which are summarized below.

Langenberg et al. (1993) and Salat et al. (1994) reported up to 340–416 ppb Au with 20.4 ppm Ag, 1.46% As, 0.1% Ni, 300 ppm Zn, 211 ppm Cr and 130 ppm Cu for the Northeast Waugh Lake gold showing

(NTS 74M/16). The showing comprises variable amounts of massive pyrite, pyrrhotite and arsenopyrite with rare chalcopyrite concentrated along sheared quartz-mica schists with quartz veins and quartz stockwork, and around a crosscutting microgranite dike.

Salat et al. (1994) examined the Doze Lake showing (NTS 74M/16), comprising sulphide-rich metasediments with numerous small quartz veins along the Waugh Lake Shear Zone, which returned 121–3212 ppb Au and 27–99 ppm Mo. Ianelli et al. (1995) reported up to 3.2 ppm Au for the Waugh Lake Group greenschist mylonite, whereas quartz-tourmaline veins cutting the Waugh Lake Group

Table 3. Gold occurrences of the Precambrian shield in northeastern Alberta.

Mineralization Type	Metal Association	Maximum Gold Grade	Host Geological Unit	Host Lithology	Geographic Area or Showing/Occurrence Name
Stratiform and shear zone–hosted sulphides (VMS-SEDEX ± magmatic Cu-Ni)	Au-Ag-As (±Bi±Mo±Ni±Cu±Zn±Pb±Cr)	3212 ppb	TBC; Rutledge basin; Waugh Lake Group	Greenschist shear and breccia zones with quartz veins and stockworks; mylonitized amphibolites interlayered with garnet-rich quartzite; supracrustal metasediments and bimodal metavolcanics	Doze, Potts, Waugh, Pythagoras-Lindgren, Selwyn, Myers, Whaleback, Florence, Flett and Doré lakes, and Marguerite River
Quartz-tourmaline veins (GQCV-type and RIRGS)	Au-W-Mo-As-Bi (±Ag±Cu±Pb±Zn)	157 ppb	Waugh Lake granitoids; Waugh Lake Group and felsic dikes	Quartz-tourmaline veins, stockworks and masses associated with syn- to late-orogenic granitoids and shear zones in metasediments	South Waugh Lake
Polymetallic pegmatite and iron-oxide breccia/vein (IOCG and unconformity-associated)	Cu-Au-Ag-U-REE (±Th±PGE±Ni±As ±Co±Mo±Pb±Zn±Cd±V±Y)	2700 ppb	TBC and Colin Lake granites and pegmatites along the Bonny Fault Zone; Wyllie Lake granitoids	Massive epidote-magnetite-hematite breccias (up to 50% Fe-oxides); brecciated, hematized and silicified gneisses, pegmatites and granitoids along shear and/or fault zones; Athabasca unconformity graphite- and hematite-rich regolith	West arm of Andrew Lake, Spider, Holmes, Hutton, Charles, Cherry, Twin and Small* lakes, Golden Eagle Oil and Gas well (890 m depth) and Maybelle River

Abbreviations: VMS, volcanogenic massive sulphides; SEDEX, sedimentary exhalative; GQCV, greenstone–hosted quartz-carbonate veins; RIRGS, reduced intrusion–related gold systems; IOCG, iron-oxide copper-gold; TBC, Taltson Basement Complex; REE, rare-earth elements; PGE, platinum-group elements.

* Unofficial name of a small lake located about 1.8 km to the northeast of Cherry Lake (NTS 74M/16; after Langenberg and Eccles, 1996).

metasediments returned up to 157 ppb Au, 455 ppm Mo, 1119 ppm W and 58 ppm As (Langenberg et al., 1993).

On the western shore of Waugh Lake, pyritic metasediments of the Waugh Lake Group yielded 20 ppb Au and 290 ppm Zn, with a chloritized shear zone within these rocks on the eastern shore of the lake containing 120 ppm Cu (Langenberg and Eccles, 1996). The pyrite-bearing Waugh Lake granitoids on the west-central shore of Waugh Lake returned up to 470 ppm Cr, 207 ppm Ni and 124 ppm Zn (Langenberg and Eccles, 1996).

In the Pythagoras-Lindgren lakes area (NTS 74M/16), Langenberg et al. (1993, 1994) and McDonough (1997) described millimetre-thick pyrite-pyrrhotite-arsenopyrite stringers along a gossanous band of

feldspathic quartzite and biotite schist that returned up to 116–603 ppb Au, 10 ppm Ag, 0.39% Ni, 0.36% As and 107 ppm Zn.

Langenberg et al. (1994) documented several sulphide occurrences with variable contents of base and precious metals along the Leland Lake Shear Zone. For example, the Myers Lake showing (NTS 74M/11), comprising pyrite-bearing amphibolite bodies (1–15 m wide and tens of metres long) within the mylonitized Slave Lake granitoids, contains up to 200 ppb Au and 60 ppm Cu (Langenberg et al., 1994). The Selwyn Lake mineralized zone, extending more than 2 km in a north-south direction along the western edge of the eastern branch of the Charles Lake Shear Zone, returned up to 20 ppb Au, 895 ppm Cu, 39–65 ppm Ni and 35–57 ppm Co (Langenberg and Eccles, 1996). The mineralization comprises massive pyrrhotite, pyrite, and minor chalcopyrite (up to 40% total sulphides) in greenschist-mylonitized amphibolite bodies (1–5 m wide), interlayered with silicified and chloritized high-grade biotite-hornblende (±garnet) quartzite and schists (Langenberg et al., 1993, 1994).

Dufresne et al. (1994) examined several pyrite and pyrrhotite occurrences hosted by the 2–4 km wide mylonite zone in the Marguerite River area, south of Lake Athabasca, which yielded up to 500 ppm Cr, 343 ppm Zn, 210 ppm Ni, 191 ppm Cu and 163 ppm V.

Langenberg and Eccles (1996) reported up to 770 ppb Au, along with >10% As, 6236 ppm W, 205 ppm Bi, 132 ppm Zn and 116 ppm Cu, for the South Potts Lake gold showing (NTS 74M/9). The showing comprises 2%–3% disseminated arsenopyrite and pyrite (up to centimetre size) along quartz-chlorite shears within a 0.5 m wide breccia zone, surrounded by a metre-wide silicification envelope. McDonough (1997) described stratiform and shear-related sulphide metallic occurrences in the Whaleback Lake, Florence Lake, Flett Lake and Doré Lake areas (NTS 74M; Figures 1 and 6). Elsewhere in the Alberta portion of the Precambrian shield, sulphide (pyrite-pyrrhotite±minor chalcopyrite) occurrences in gossanous basement paragneiss and other metasediments returned up to

- 79 ppb Au and 245 ppm Cu northeast of Charles Lake;
- 27 ppb Au, 232 ppm Cu and 188 ppm Zn on the east shore of Potts Lake;
- 24 ppb Au and 162 ppm Cu southeast of Spider Lake; and
- 24 ppb Au, 270 ppm Pb, 122 ppm Cu and 106 ppm Zn in metasediment bands within the Colin Lake granite on the eastern shore of Andrew Lake (Langenberg and Eccles, 1996).

About half of the known metallic mineral occurrences in the Precambrian shield of northeastern Alberta have elevated concentrations of uranium or thorium in pegmatites, breccias and metasediments along shear zones and fractures near the Athabasca unconformity (Olson et al., 1994; Langenberg and Eccles, 1996; Pană and Olson, 2009). Langenberg and Eccles (1996) evaluated several radioactive hematite-breccia and/or pegmatite polymetallic showings (NTS 74M/9, /16), some of which contain traces of gold:

- **Holmes Lake** (up to 33 ppb Au, 1187 ppm U, 258 ppm Pb, 208 ppm Zn, 159 ppm Ni, 139 ppm V and 283 ppm Ba), comprising white silicified and hematized pegmatite, locally containing bands of foliated biotite-feldspar quartzite and minor sulphides (mostly pyrite), interlayered with hematized, feldspar-porphyroblastic gneiss of the high-grade metasedimentary belt cut by the Bonny Fault.
- **Cherry Lake** (up to 21 ppb Au, 0.67% U, 232 ppm Pb, 150 ppm Zn, 114 ppm Th and 57 ppm Cu), comprising mylonitized, porphyritic to equigranular Colin Lake biotite-hornblende granite with slivers of highly deformed metasediments and pyrite in biotite layers, quartz veins around the mylonitic zone, and brecciated pegmatite.
- **Twin Lakes**, to the north of Cherry Lake (up to 11 ppb Au with 0.12% U, 182 ppm Th, 126 ppm Zn, 118 ppm Mo and 106 ppm Pb), comprising foliated and hematized, porphyritic Colin Lake biotite leucogranite with spots of radioactive massive hematite and numerous bands of brecciated and

hematized white muscovite pegmatite that contains abundant red feldspars and local entrainments of wispy biotite-rich layers.

- **Small lake** (up to 12 ppb Au with 0.59% U, 0.21% Th, 0.17% Mo, 0.11% Pb, 124 ppm Zn, 122 ppm Cu and 121 ppm V), comprising silicified high-grade basement paragneiss and schists intruded by the Colin Lake biotite granite and quartz-rich, biotite pegmatite breccia bodies with molybdenite and pyrite in mica-rich layers.
- **Carrot Lake**, about 2.5 km south of Andrew Lake (up to 5.7 ppm Ag with 1.8% U, 382 ppm Pb, 189 ppm Cu, 117 ppm Zn, 103 ppm V and 29 ppm Mo), comprising migmatized, tightly folded and locally sheared, porphyroblastic basement gneiss, amphibolites and pink foliated Colin Lake biotite granite to granite gneiss, crosscut by numerous silicified and hematized pegmatite bodies, with abundant red-pink feldspar, graphite and small veins and pods of uraninite(?) along fracture joints and small shear zones.
- **Northeast Charles Lake** (up to 704 ppm La, 1051 ppm Th, 362 ppm Ba, 146 ppm Zn, 107 ppm Pb and 72 ppm Mo), comprising tightly folded, high-grade rusty schists, quartzite and mylonitic gneiss, intruded by hematized white leucogranite with pink K-feldspar and pegmatite along the Charles Lake Shear Zone.
- **North and South Potts Lake** (up to 7–8 ppb Au, 0.56% Ce, 0.28% Th, 0.26% La, 0.26% Nd, 0.14% Ba, 384 ppm Sr, 202 ppm Sm, 115 ppm Pb, 98 ppm Cu and 49 ppm U), comprising interbanded basement gneiss, high-grade biotite-sericite, graphite and garnet schists, quartzite, granite and silica-rich, pegmatite breccia along the north-trending shear zone.
- **Hutton Lake** (25.1% Fe and 274 ppm V), comprising pegmatitic breccia with epidote-magnetite-hematite cement (up to 50 vol. % of total Fe-oxides) within the basement gneiss and leucogranite along a late brittle fault associated with the northwest-trending Bonny Fault.
- **West arm of Andrew Lake** (29.2 % Fe and 381 ppm V), comprising pegmatite breccia with magnetite-hematite cement within foliated leucogranite.
- **West of Andrew Lake** (up to 751 ppm La but no information on other elements), comprising hematized quartz breccia (red cataclasite) along the Bonny Fault.

In addition, the Marguerite River showing south of Lake Athabasca, comprising hematized megacrystic Wyllie Lake(?) granitoids, returned up to 0.33% Ce, 0.19% Th, 0.19% La, 0.12% Nd, 300 ppm U, 200 ppm Sm, 175 ppm Zn, 110 ppm Hf, 103 ppm Pb, 15 ppm Tb, 11 ppm Bi, 10 ppm Mo and 4.5 ppm Eu (Dufresne et al., 1994).

Several regional geochemical surveys by the GSC evaluated metal concentrations in glaciogenic sediment, lake sediment and water to identify new prospective exploration targets in the Precambrian shield of northeastern Alberta (Friske et al., 1994; Bednarski, 1996, 1997; McCurdy, 1997). Recently, Pană et al. (2006) examined some of the anomalously radioactive occurrences in the Holmes Lake area and reported up to 16 ppb Au, 395 ppm U, 215 ppm Pb, 210 ppm Th and elevated Mo, V, Zn and As concentrations.

8.2 Types of Mineral Occurrences and Hypotheses of Origin

8.2.1 Stratiform and Shear Zone–Hosted Sulphides

The arsenopyrite-pyrrhotite-pyrite occurrences, with an Au-Ag-As (±W±Bi±Mo±Ni±Cu±Zn±Pb±Cr±Ba) geochemical signature, are associated with gossanous or silicified breccia zones, quartz veins and extensive quartz stockworks in greenschist shear zones or faults within metasedimentary and metavolcanic rocks that are locally cut by mafic to felsic dikes (Langenberg and Eccles, 1996; McDonough, 1997). The mineralization is interpreted to be syn- to postkinematic, relative to the

greenschist-grade deformation, involving mobilization and redeposition of originally stratiform sulphides along the shear zones (Langenberg and Eccles, 1996; McDonough, 1997).

Langenberg and Eccles (1996) distinguished two types of sulphide occurrences in the Precambrian shield of northeastern Alberta: 1) predominantly Cu-Pb-Zn±Au mineralization in metasedimentary-metavolcanic assemblages with a felsic bulk composition; and 2) Cu-Au-Ni-Cr mineralization associated with mafic amphibolite to diorite bodies. McDonough's (1997) classification of sulphide occurrences is three-fold: 1) stratiform pyrite-arsenopyrite-gold mineralization (e.g., Pythagoras Lake, Potts Lake and Whaleback Lake) associated with the 2.13–2.08 Ga Rutledge River Basin pelitic gneisses; 2) shear zone–hosted pyrrhotite-pyrite Cu-Au mineralization (e.g., Selwyn Lake; NTS 74M, Figure 6) within 1.86–1.80 Ga greenschist mylonites; and 3) pyrite-pyrrhotite Cu-Au mineralization in sheared ultramafic–mafic amphibolite bodies (metre to kilometre scale) within the TBC gneisses.

Both 'stratiform' and amphibolite-hosted sulphides have been influenced by the later penetrative greenschist deformation (McDonough, 1997). For example, the Myers Lake and Selwyn Lake sulphide showings, containing variable gold concentrations, may represent mafic intrusion–related and/or volcanogenic massive sulphides remobilized by postemplacement shearing along the Leland Lake and Charles Lake shear zones, respectively (Langenberg and Eccles, 1996). Supracrustal metasediments and bimodal metavolcanics (e.g., Rutledge Basin pelitic gneiss and Waugh Lake Group) are a favourable setting for the VMS and SEDEX deposits, including the Broken Hill–type Pb-Zn-Ag±Cu±Au. The latter is characterized by high metamorphic grade, elevated metal to S ratios, spatial and temporal association with Fe-Si-Mn oxide exhalites, and bimodal volcanic/intrusive and mostly clastic sedimentary hostrocks (e.g., Goodfellow and Lydon, 2007). Some of the pyrite-pyrrhotite occurrences associated with lensoid ultramafic amphibolite bodies within the TBC gneisses may represent originally magmatic Cu-Ni-Au mineralization (McDonough, 1997).

8.2.2 Quartz-Tourmaline Veins

The auriferous quartz-tourmaline veins (1–10 cm wide and 10–15 m long) and massive, contorted layers (15–75 cm thick) with minor pyrite-arsenopyrite are spatially associated with the Waugh Lake granitoids (e.g., South Waugh Lake showing) that intrude the Waugh Lake Group quartzite and quartz-sericite schists (Langenberg and Eccles, 1996; McDonough, 1997). The quartz-tourmaline masses also form selvages, with up to 1%–2% pyrite, along the contacts of granitic dikes crosscutting these metasediments.

The geological setting and Au-W-Mo-As-Bi association of quartz-tourmaline veins and quartz-vein stockworks with arsenopyrite along the shear zones are similar to the Precambrian lode gold (Olson et al., 1994; Langenberg and Eccles, 1996) or greenstone-hosted quartz-carbonate vein (GQCV) type, according to the classification of Dubé and Gosselin (2007). The mineral occurrences associated with the syn- to late-orogenic granitoids may also resemble various types of intrusion-related mineralization, including reduced intrusion-related gold systems (RIRGS), characterized by the Au-Bi-Te-W metal assemblage, with proximal Au-W-As and distal Ag-Pb-Zn associations (e.g., Hart, 2007).

8.2.3 Polymetallic Pegmatite and Iron-Oxide Breccias

Iron-oxide breccias and hematized and silicified pegmatites with elevated U-Th-REE (±Au±Ag±Mo±base metals) occur along the shear and/or brittle fault zones and in association with the Athabasca unconformity (Olson et al., 1994; Langenberg and Eccles, 1996; Pană and Olson, 2009). Olson et al. (1994) proposed that the magnetite-hematite breccias associated with the Bonny Fault in the Andrew, Holmes and Charles lakes area (NTS 74M; Figures 1 and 6; Godfrey, 1958; Langenberg et al., 1993) might indicate a potential for the polymetallic iron-oxide copper-gold (IOCG) deposit type.

The IOCG group comprises several hydrothermal magnetite/hematite (±apatite) deposit types (e.g., Corriveau, 2007 and references therein): 1) Olympic Dam–type Cu-Au-U-REE (±Ag±Co±Ni), 2) Fe-

skarn Cu-Au, 3) Kiruna-type Cu-Au (±U±Co±Ni±Ag±As), and 4) Cloncurry-type Cu-Au (±Co±U±Ag±W±Bi). Numerous IOCG deposits and prospects (e.g., Corriveau, 2007) occur in the northwestern Canadian Shield within the Early Proterozoic Athapuscow aulacogen (Hoffman, 1973), in the east arm of the Great Slave Lake, and in the north-trending Great Bear Magmatic Zone of the Early Proterozoic Wopmay Orogen (Gandhi et al., 2001), between Great Slave and Great Bear lakes in Northwest Territories:

- Kiruna-type (e.g., Bell, Labelle Peninsula, Easter Island Dyke and Lux);
- Olympic Dam–type (e.g., Valnica, BBX-Aristifat breccia pipes and carbonate veins, Nod prospect and Damp breccia); and
- Cloncurry-type (e.g., Burke Lake zone, Duke showing, Hamp Lake and Tan magnetite-apatite-actinolite veins).

In northeastern Alberta, pegmatite-hosted uranium occurrences with high concentrations of Th, Mo (up to 1.4%) and REE (±precious and base metals) are associated with shearing and brecciation (e.g., Small lake, west arm of Andrew Lake and Spider Lake; Langenberg and Eccles, 1996). Pană et al. (2006) suggested that the anomalous metal concentrations were derived from the Early Proterozoic anatectic granitoids due to the hydrothermal activity along zones of late brittle strain adjacent to the main Bonny Fault.

The Athabasca unconformity–associated polymetallic uranium prospects in northeastern Alberta (e.g., Maybelle River) have similar characteristics to the classic Great Bear and Beaverlodge vein uranium deposits (Ruzicka, 1997; Jefferson et al., 2007; Pană and Olson, 2009). Pană and Olson (2009) concluded that shear/fault–controlled hydrothermal convection through a fertile granitoid basement sealed by the late Paleoproterozoic to early Mesoproterozoic Athabasca Group strata was the key mechanism in the origin of these deposits.

8.3 Future Potential

Langenberg and Eccles (1996) identified about 20 metallic mineral showings with significant concentrations of base and precious metals and/or radioactivity several times greater than the local background that may warrant future exploration. Regional, northerly trending, granulite to greenschist shear zones (Warren, Allan and Andrew Lake) and their splays (Leland Lakes, Bocquene River, Goldschmidt Lake, Mercredi Lake, Charles Lake and Bayonet Lake) control quartz-tourmaline vein Au-W-Mo-As-Bi occurrences that have characteristics similar to the GQCV-type and/or RIRGS.

Numerous stratiform and shear-hosted sulphide occurrences associated with ultramafic–mafic and intermediate intrusive, metavolcanic and metasedimentary rocks (e.g., Rutledge Basin pelitic gneiss, Waugh Lake Group, amphibolite bodies at Myers Lake and Selwyn Lake) may indicate favourable settings for VMS-SEDEX-BHT deposits. Shear zones within the supracrustal gneisses and amphibolite tectonic slivers in the TBC gneisses at Holmes, Split, Ashton, Potts, Alexander, Swinnerton, Whaleback, Florence, Flett and Dore lakes warrant further exploration for base and precious metals (Langenberg and Eccles, 1996; McDonough, 1997).

The polymetallic, iron-oxide pegmatite breccias associated with the Bonny Fault (e.g., Hutton Lake, west arm of Andrew Lake, Holmes Lake and Twin Lakes) should be further investigated, given the discovery of numerous IOCG deposits within the Great Bear Magmatic Zone and Athapuscow aulacogen in the Northwest Territories (Corriveau, 2007). Regional high-magnetic anomalies, coupled with elevated radioactivity (Sprenke et al., 1986; Charbonneau et al., 1997), may help delineate targets for future IOCG exploration in the Precambrian shield of northeastern Alberta. The Athabasca Basin unconformity has a potential for polymetallic uranium (±Ni±Co±Ag±Au±PGE±Cu±REE) deposits controlled by the basement shear/fault zones (Pană and Olson, 2009).

The statistical contour maps for As, Au, Co, Cr, Cu, Fe, Mo, Ni, Pb, Sb, U and Zn concentrations, based on a large number of glaciogenic sediment (Bednarski, 1997) and lake sediment and water samples (Friske et al., 1994; McCurdy, 1997) from northeastern Alberta, revealed several geochemical anomalies coincident with the known mineral occurrences and shear/fault zones, indicating prospective areas for future exploration. South of Lake Athabasca, the geochemical results reflect mainly the glaciogenic sediment, with a number of possible placer-gold deposits in the areas underlain by Athabasca sandstone. Lake sediments to the north of Johnson Lake (NTS 74E; Figure 6) returned anomalous Sb and Au concentrations, outlining an area underlain by granitoid rocks (McCurdy, 1997). North of Lake Athabasca, lake sediments and waters show anomalous U and Au concentrations coincident with the intersecting east- and north-trending shear/fault zones within the Slave granitoids and high-grade metasediments (McCurdy, 1997).

Although possibly displaced westward by glacial flow, some of the coincident glaciogenic and lake sediment geochemical anomalies may indicate proximal bedrock sources (Bednarski, 1997; McCurdy, 1997). The glaciogenic sediment geochemical maps show anomalous concentrations of >16 ppb Au (up to 24 ppb Au), relative to the average glacial sediment concentration of 2.4 ppb Au, sometimes associated with high As values (up to 128 ppm), in several areas:

- near Tulip Lake, just west of the lake sediment gold anomaly (McCurdy, 1997);
- southern part of Andrew Lake, just west of the gold showings on the eastern shore of Waugh Lake (Salat et al., 1994);
- Barrow and Ryan lakes; and
- east of Lapworth Point (Bednarski, 1997).

9 Lode Gold in the Rocky Mountain Fold-and-Thrust Belt of Southwestern Alberta

Table 4 provides examples of gold-bearing metallic mineral occurrences in the deformed belt of Proterozoic and Phanerozoic rocks that forms the Rocky Mountains and Foothills in southwestern Alberta (Figure 6).

9.1 Historical Perspective

The history of geological observations and mineral exploration in the Canadian Rocky Mountains dates back to Captain Palliser's expedition to the Canadian west (Hector, 1863) and other pioneer work (e.g., Dawson, 1875, 1886; McConnell, 1887). Discovery of placer gold at Wildhorse Creek in 1864 had started the Kootenay gold rush, which led to further prospecting in the region and discovery of several world-class Pb-Zn-Ag (±Au±Cu±Cd±Sn±Sb±Bi) deposits (e.g., Monarch–Kicking Horse, North Star and Sullivan) in southeastern British Columbia between 1884 and 1917 (e.g., Hedley, 1954; Lydon, 2007). Completion of the railway from Calgary to British Columbia aided mineral exploration and mining in the Banff-Field corridor during the late 1800s to early 1900s. Hoffmann (1885) found that pyrite-rich limestone (Middle Cambrian Cathedral Formation?) from the Ghost River area, near Devils Gap east of Banff National Park, assayed 25.0 ppm Ag. Dawson (1886, 1899, 1901) described several metallic mineral occurrences in that portion of the Alberta Rocky Mountains that is now within Banff National Park: 1) a number of copper sulphide occurrences associated with quartz veins cutting the Cambrian limestones at Copper Mountain; 2) quartz veins with galena, assaying 17.14 ppm Ag, in the Neoproterozoic Miette Group or Lower Cambrian Gog Group clastic rocks near Twin Lakes; 3) sphalerite at the headwaters of Cascade River, about 2.5 km west of Block Mountain, and downstream along the Cascade River; 4) sphalerite on the east flank of Storm Mountain; 5) bornite at the headwaters of the Panther River; and 6) chalcopyrite and chalcocite at the headwaters between Johnston and Cascade Creeks (NTS 82N, O; Figure 1).

Table 4. Gold occurrences of the Rocky Mountain fold-and-thrust belt in southwestern Alberta.

Mineralization Type	Metal Association	Maximum Gold Grade	Host Geological Unit	Host Lithology	Geographic Area or Showing/Occurrence Name
Marine and fluvial paleoplacer	Au (±PGE±Fe±Ti±V±Zr±REE ±Zn±W±Th±Sn)	910 ppb	Mesoproterozoic Waterton and Appekunny formations; Cretaceous Blairmore Group, Belly River and Brazeau formations	Quartzite; sandstone; igneous- and quartzite-clast conglomerates	Syncline Mountain, Buchanan Ridge (Waterton Lakes National Park), Bruin*, Coal and White creeks, Castle River, Burmis and Dungarvan Creek
Alkaline intrusion–related epithermal	Au-Ag-Cu-Pb-Zn (±Mo±W±As±Sb±Bi±Hg)	1370 ppb	Cretaceous Crowsnest Formation and alkaline intrusions within Proterozoic, Paleozoic and Mesozoic sedimentary hostrocks	Phonolite and alkali trachyte flows, pyroclastic and volcaniclastic deposits; strata adjacent to alkali trachyte, latite and phonolite dikes and sills	Iron Ridge, York and Star creeks (Crowsnest Pass), Jutland Brook and La Coulotte Ridge (Clark Range)
Sulphides in quartz-carbonate veins (meso-thermal and MVT)	Pb-Zn-Cu-Ag-Au	13 710 ppb	Mesoproterozoic Siyeh Formation; Neoproterozoic Miette Group; Early Cambrian McNaughton Formation; Middle Cambrian carbonates	Quartz-carbonate veins and stockworks within low-grade metasiliciclastic rocks; argillaceous limestones and calcareous shales	Blind Canyon (Clark Range), Miette River (Jasper National Park) and Twin Lakes, Herbert Lake, Baker Creek, Eldon, and Copper and Castle mountains (Banff National Park)
Magmatic–hydrothermal	Cu-PGE (±Pb±Zn±Ni±Co±Cr±Au± Ag±Mo±As±Bi)	1370 ppb	Mesoproterozoic syn-rift mafic intrusions and Purcell Lava; Neoproterozoic(?) dike	Tholeiitic and alkali olivine gabbro dikes and sills within the Belt-Purcell Supergroup strata; Crowfoot diabase dike	North Kootenay Pass and Yarrow Creek–Spionkop Ridge prospects (Clark Range), near Bow Lake (Banff National Park)
SEDEX	Pb-Zn-Cu-Ag (±Au±Co±Mo±PGE±Re± As±Sb±Bi±Se±Tl±Te)	24 ppb	Mesoproterozoic Siyeh and Sheppard formations	Laminated siltstones, dolomitic siltstones and argillaceous dolomites; quartzite with abundant pyritic spheres	North Lost and South Lost creeks, Carbondale River, South Drywood Creek, Spionkop Ridge, Table Mountain, Mount Gladstone (Clark Range)
Black shale polymetallic	Zn-Ni-Mo (±V±PGE±Re±Ag±Au±Cd ±U±Co±Cu±As±Sb±Se± Tl±REE)	15 ppb	Mississippian Exshaw Formation; Triassic Sulphur Mountain Formation; Jurassic Fernie Group	Black shale with bentonite, reworked tuff and phosphate-rich layers, calcareous concretions, and massive to disseminated sulphides	Jura Creek near Exshaw, Crowsnest Lake, east flanks of Mount Gass and Moose Mountain (Bragg Creek headwaters)
Redbed/ Kupferschiefer-type	Cu-Ag (±Co±Au±Pb±Mo±U)	514 ppb	Mesoproterozoic upper Appekunny, Grinnell, Siyeh, upper Sheppard and Roosville formations	Quartz arenites in redbed cycles; dolomitic argillite; silty dolomite–siltstone; oolitic sandstone	Spionkop Ridge, Yarrow and Grizzly creeks, Whistler Mountain, North Kootenay Pass, Victoria Peak

Several old Cu, Pb-Zn-Ag-Cu and Au mining sites occur in this sector of the Rocky Mountains in southwestern Alberta (La Casse and Roebuck, 1978):

- Until 1930, bedrock gold mining took place at a pothole near the south end of Herbert Lake, about 4.8 km northwest of Lake Louise, and at Baker Creek, about 12.9 km east of Lake Louise.
- Between 1885 and 1905, Ag-Pb and Cu were produced at 1) Silver City mines, located at the foot of Castle Mountain (also known as 'Protection Mountain' and 'Eisenhower Peak' for its southern part), about 1.6 km east of the junction of Highways 93 and 1A; 2) a minesite below Consolation Lakes, west of the Bow River, 12.9 km west of the junction of Highways 1 and 93; and 3) the Copper Mountain mine, south of Castle Mountain at the elevations of 2290–2440 m asl. The mining concentrated on quartz veins, containing massive galena, bornite, cuprite, enargite and secondary azurite and malachite that cut the Paleozoic carbonates.

Between 1888 and 1952, the Monarch–Kicking Horse mines, located west of Lake Louise along Highway 1A in adjacent southeastern British Columbia, produced Zn, Pb and Ag from dolomite stockworks and late quartz veins in carbonates of the Middle Cambrian Cathedral Formation (Paradis et al., 2007).

In addition, the Eldon Cu-Pb-Zn deposit on the east flank of Panorama Ridge and the Baker Creek Pb-Cu prospects on the west flank of Castle Mountain (NTS 82O; Figure 6) were explored and partially developed during the 1890s and early 1900s (Hedley, 1954; Evans et al., 1968). Smith (1963) described the Neoproterozoic Crowfoot diabase dike (58 m wide) cut by quartz-magnesite-calcite veins, up to 20 cm wide, with associated chloritization, pyrite and chalcopyrite, that are exposed in the Lake Louise–Jasper highway roadcut near the east end of Bow Lake.

However, little follow-up work has been done on these historical mine sites, prospects and occurrences because they are within Banff National Park. Dawson (1901) also reported occurrences of galena and gold (up to 13.71 ppm Au) in quartz veins cutting the Neoproterozoic Miette Group clastic strata (his 'Great Cambrian Series' rocks) west of Jasper in the Miette River valley of the Athabasca Pass area, now within Jasper National Park (NTS 83D; Figure 6).

South of Banff National Park, Dawson (1886) first reported copper mineralization in the Mesoproterozoic Purcell basaltic lavas and gabbro intrusions in the North Kootenay Pass area of southwestern Alberta. During the late 1880s and early 1890s, exploration focused on chalcopyrite veins associated with gabbro dikes and the Cu-Pb-Ag mineralization within the Mesoproterozoic Grinnell and Siyeh formations near the heads of Quartz and Mineral creeks in adjacent Montana, now in Glacier National Park (Goble, 1974c).

The resurgence of exploration activity between 1901 and 1903 due to the oil discovery at Oil City, now a national historic site in Waterton Lakes National Park, led to discovery of gold mineralization in quartzites of the Mesoproterozoic Appekunny Formation on the northwestern slope of Buchanan Ridge (NTS 82G; Figure 6; Goble, 1973a). At the same time, gold was mined from the Appekunny Formation on the east side of Goat Haunt Mountain in Montana, now in Glacier National Park (Goble, 1973a). Between 1900 and 1910, small-scale mining also took place on a gabbro dike with chalcopyrite veins within the top of the Appekunny Formation at Coppermine Creek (formerly Blakiston Brook) in the Clark Range, now within Waterton Lakes National Park, and on a gold showing on Chief Mountain in Glacier National Park (Morton, 1971; Goble, 1974c).

During 1910–1920, stratabound Cu-Ag mineralization was discovered on the northern side of Yarrow Creek, north of Waterton Lakes National Park. In 1935, C. Wise reported 70.63 ppm Au from a trench through a quartz-cemented alkali syenite breccia cutting the Mesoproterozoic Siyeh and Sheppard formations on the ridge between Commerce Peak and Sunkist Ridge in southeastern British Columbia, near the Alberta border (Morton, 1971; Goble, 1972c).

Hedley (1954) and Holter (1973, 1977) reported the Oldman (Bearspaw) Pb-Zn-Ag prospect, an intense network of irregular, flat-lying and vertically oriented calcite-dolomite veins crosscutting the top of the Late Devonian Palliser dolomitized limestone, which was discovered by hunters in 1912 on the east flank of Mount Gass, near the headwaters of the Oldman River (NTS 82J; Figure 6). Salat (1988) estimated that the Oldman deposit might contain 2.0–2.5 million tonnes grading 6% Zn, 1% Pb, 500 ppm Cd and 34.3 ppm Ag. Based on petrographic investigation of six mineralized samples from the Oldman prospect, Ecstall Mining Corp. reported 15%–45% sphalerite, 1%–35% pyrite and trace–15% galena in the form of disseminated grains (0.01–2.5 mm), intergrowths and granular clusters (up to 15 mm). Geochemical analyses of these samples indicated 0.24%–29.4% Pb, 0.28%–26.0% Zn, and up to 670 ppm Cd, 390 ppm Cu, 310 ppm Ge, 210 ppm Ag and 60 ppm Co (Graf, 1997).

During the 1960s and 1970s, several companies (McGregor Telephone and Power Construction Co. Ltd., Kennco Exploration (Western) Ltd., Akamina Minerals Ltd. [now Alcor Minerals Ltd.], Falconbridge Nickel Mines Ltd., Cominco Ltd., Denison Mines Ltd., Canford Engineering Ltd., Halferdahl and Associates Ltd., Geowest Services Ltd., Frances Creek Mines Ltd. and Kintla Explorations Ltd.) explored for base and precious metals in southwestern Alberta. Prospecting, mapping, geochemical surveys, trenching and drilling identified distinct styles of Au-Ag-Cu, Cu-Ag (±Au±Pb±U) and Pb-Zn-Ag (±Cu±Au±Mo) mineralization, some of significant lateral extent, at different stratigraphic levels in the Mesoproterozoic Purcell Supergroup in the Clark Range area (NTS 82G; Figure 6). A few assessment reports during this period that include gold assays show an enrichment in precious metals associated with some of the showings.

In 1967, Kennco Exploration (Western) Ltd. revisited the Cretaceous monzonite and undersaturated syenite and trachyte sills and dikes cutting the Mesoproterozoic Siyeh, Purcell Lava and Sheppard formations at Commerce Peak in southeastern British Columbia, about 2.4 km south of the Alberta border (Goble, 1974a; Goble et al., 1999). Halferdahl (1971) and Van Dyck (1971) reported 1.2–76 m thick alkali syenite and trachyte sill-like intrusions within Gateway Formation strata along the Continental Divide between the north end of Sunkist Ridge and Rainy Ridge in southwestern Alberta.

During 1972 and 1973, Kintla Explorations Ltd. conducted a follow-up exploration program focused on the Au-Ag (±Cu±Pb±Zn) mineralization associated with the widespread Cretaceous alkali-feldspar syenite and trachyte, and phonolite sills and dikes cutting the Mesoproterozoic Siyeh, Purcell Lava, Sheppard, Gateway and Roosville formations, and the Middle Cambrian Flathead Formation along the Continental Divide in southwestern Alberta: at Rainy Ridge, on the east ridge of Scarpe Mountain; on the northwest end of Sunkist Ridge at the headwaters of the West Castle River; on the north ridge of La Coulotte Peak; at the headwaters of Jutland Brook; and at Font Mountain (NTS 82G; Figure 6). These Cretaceous intrusions and the adjacent sedimentary rocks along the intrusive contacts in Alberta assayed 0.334–1.37 ppm Au, 5.14–32.68 ppm Ag and up to 0.43% Cu and 200 ppm Zn (Halferdahl, 1971; Goble, 1974a, b). Morton et al. (1974b) also mentioned numerous coarse-grained leucocratic sills, cutting the argillaceous rocks of the Siyeh Formation in the southwestern portion of the Lewis Thrust sheet, that carry abundant pyrite, pyrrhotite, minor chalcopyrite and up to 118 ppm Au.

Exploration on similar Cretaceous to Tertiary alkaline intrusions cutting the Mesoproterozoic, Paleozoic and Mesozoic strata at Howell Creek in the Flathead area of southeastern British Columbia showed grades of up to 1.3 ppm Au, and locally up to 620 ppm Au (Skupinski and Legun, 1989; Brown and Cameron, 1999). An altered trachyte dike within the Paleozoic carbonates in the Crowsnest Pass area returned 367 ppm V, 160 ppm Zn and 81 ppm Pb (Bégin et al., 1995).

Duncan (1970) reported several showings of stratabound chalcocite-bornite (±chalcopyrite) and secondary malachite in quartzite or sandstone intercalated with red or green argillite throughout the Grinnell Formation: 1) 0.17%–0.62% Cu across 1.25–2.0 m intervals extending for several hundred metres along the northwest and northeast flanks of Spionkop Ridge; 2) mineralized intervals, up to 9 m

thick, that were traced for about 90 m on the north flank of Drywood Mountain; 3) up to 5.28% Cu in more than 20 mineralized quartzite beds (0.03–15 cm thick) that were traced along strike for more than 305 m through a 90 m stratigraphic section on the western extension of Whistler Mountain; and 4) 0.36%–0.46% Cu on a spur extending east from Barnaby Ridge towards Grizzly Creek (NTS 82G; Figure 6).

Malachite-stained basic dikes and sills with abundant chalcocite in the chilled margins, intruding the Grinnell strata at the Spionkop showing, assayed up to 3.45% Cu. In addition, a stratigraphically distinct showing about 1.2 km east of the North Kootenay Pass, comprising a malachite-stained, chalcocite-bearing, grey laminated argillite layer 1.8 m thick that was traced for about 60 m and interbedded with red argillite of the Gateway Formation, assayed 0.24%–0.98% Cu (Duncan, 1970).

In 1970, Cominco Ltd. discovered stratabound Pb-Zn±Cu mineralization, comprising laminated streaks, patches and disseminated sphalerite, galena, minor chalcopyrite and traces of pyrite, in dolomitic and clastic strata of the Sheppard Formation in the Carbondale River–North Lost Creek area, near the North Kootenay Pass (Carter and Irvine, 1971). A 3.0–4.6 m thick mineralized succession of grey dolomite and black, thinly laminated siltstone of the Sheppard Formation, about 24 m stratigraphically above the underlying Purcell lava, returned average grades of 0.32% Zn and 0.07% Pb for a 4.2 m core interval from a single 13.1 m deep diamond-drill hole at North Lost Creek. The individual 1.2–1.8 m long core samples assayed 0.02%–0.12% Pb, trace–0.36% Zn and 0.05% Cu, and a surface channel sample gave 0.09% Pb and 1.28% Zn across 0.9 m at this location (Carter and Irvine, 1971).

Halferdahl (1971) reported sparsely disseminated chalcopyrite in about 1.8 m of massive, grey, very fine grained, thickly bedded dolomite near the top of the Sheppard Formation, which assayed up to 0.03% and 0.16% Cu at several different locations, including Yarrow Creek, Sage Creek, Drywood Creek, Castle River, North Kootenay Pass and Carbondale River (NTS 82G; Figure 6). Halferdahl (1971) grouped metallic mineral occurrences of the Clark Range into four main types:

- **Grinnell-type** mineralization is characterized by chalcocite (±bornite±chalcopyrite) as interstitial, laminae, stringers (up to 0.03 by 2.00 cm) or disseminated mineralization in sandstone or quartzite; along contacts of, and fractures in, green argillite pebbles in sandstone; and along bedding planes and fractures in sandstone, often accompanied by secondary malachite. The mineralized beds, typically a few centimetres to less than 2 m thick and traced for up to 0.8 km, occur at different stratigraphic levels in the Grinnell Formation, at the base of the Siyeh Formation and at the top of the Appekunny Formation. At Grizzly Creek, individual mineralized beds are 0.8–5.2 m thick through a 13.1 m stratigraphic interval of the upper Grinnell Formation, whereas more than 25 mineralized sandstone beds (0.03–0.15 m thick) occur within the lower and middle Grinnell Formation on Whistler Mountain. Assays indicate 0.18%–0.62% Cu across 1.3–2.0 m widths in outcrop and up to 1.09% Cu and 7.54 ppm Ag across a 0.5 m interval from a drillhole on Spionkop Ridge; up to 0.7% Cu across 0.5 m at Yarrow Creek; 0.30%–0.95% Cu and up to 3.43 ppm Ag and 1.19% Pb across 1.2–1.5 m at Grizzly Creek; and 0.78%–7% Cu across 0.05–0.15 m at Whistler Mountain.
- **Sill-margin** mineralization is characterized by erratically distributed, very fine grained, disseminated chalcopyrite and chalcocite in the chilled margins of, and sometimes along joints in the centre of, gabbro intrusions cutting strata of the Grinnell Formation and near the top of the Appekunny Formation. The Grinnell mineralization is common in sandstones or quartzites adjacent to mineralized mafic sill margins, suggesting a genetic relationship between these two types of mineralization. A gabbro sill in the lower Grinnell strata assayed 0.22% Cu across 2 m at Yarrow Creek. At Spionkop Ridge, a 2.4–3.0 m thick mafic dike possibly used the east-trending high-angle fault with vertical displacement of at least 100 m, whereas a 2.4–2.7 m thick green diabase sill is split into five segments by the north-trending, possibly high-angle fault and three subsidiary faults. This sill assayed 0.13% Cu across 2.5 m, 0.11% Cu across the lower 1.4 m portion, and 0.82% Cu across the upper 0.9 m

portion. On the northwest flank of Spionkop Ridge, within 18 m north of the east-trending fault, a 0.46 m thick sill returned 0.24% Cu and 13.71 ppm Ag.

- **Siltstone** mineralization comprises disseminated fine-grained chalcocite or chalcopyrite (±bornite±chalcocite) and secondary malachite along bedding planes and joints in argillites or siltstones of the Gateway and possibly other formations above the Purcell lava. The upper Gateway Formation grey siltstone with abundant disseminated chalcopyrite (<0.5 mm in size) at the contact of an alkali syenite intrusion on the north flank of La Coulotte Peak assayed 0.43% Cu, and malachite was noted in a nearby grey silty argillite. Other examples from the Gateway Formation include 1.31% Cu in a 1.2 m thick bed of grey argillite on Lys Ridge, south of West Castle mountain; 0.26% Cu in a 0.6 m thick bed of green-grey argillite on the south end of Barnaby Ridge; 0.70% Cu in green-grey argillite near the south end of Lys Ridge; and 0.98% Cu in an approximately 1.8 m thick layer of the upper Gateway Formation grey argillite, traced for about 60 m down the mountainside at the North Kootenay Pass.
- **Vesicle-filling** chalcopyrite (up to 5 mm blobs) is common in calcite-chlorite (±quartz) amygdules within the top 5–8 cm of the basaltic Purcell lava on the northeast flank of Scarpe Mountain and on the west flank of Lys Ridge, about 1.6 km south of West Castle mountain.

Van Dyck (1971) reported metallic mineralization at several stratigraphic levels in the upper Purcell Supergroup, based on detailed examination of 15 stratigraphic sections in southwestern Alberta:

- Chalcopyrite pods (2 by 4 mm) parallel to bedding, finely disseminated chalcopyrite and bornite, and malachite stains along bedding planes and joint surfaces associated with abundant manganese(?) dendrites occur within buff-weathering dense dolomite, green dolomitic argillite, and siliceous oolitic (pyrite) beds of the Roosville Formation. Very finely disseminated chalcopyrite and pyrite, and malachite staining were also noted in baked green argillite along a mafic sill margin. Assays across mineralized intervals ranging from 0.01 to 0.61 m returned 0.01%–0.11% Cu on Victoria Ridge and Jutland Mountain.
- Sporadically distributed, fine-grained, microdisseminated chalcopyrite and malachite stains occur in 0.03–0.46 m thick, greenish brown-weathering silty dolomite to dolomitic argillite beds of the upper Gateway Formation. Two mineralized horizons assayed 0.01%–0.18% Cu (average 0.1% Cu), with the most abundant mineralization found at Commerce Pass and on Barnaby Ridge.
- Fine-grained (5–50 μm), disseminated synsedimentary chalcocite (±bornite±chalcopyrite) and secondary malachite occur along joint surfaces within at least three buff- to green-weathering, silty to argillaceous dolomite beds (0.6–3.7 m thick) interlayered with barren red and grey siltstone and argillite of the lower Gateway Formation. Assays ranged from 0.01% to 2.3% Cu (average 0.26% Cu) across 0.05–1.5 m mineralized thicknesses, with the highest values measured on Sage Mountain.
- Very fine grained, disseminated galena and sphalerite occur in a 2.4 m section of black laminated siltstone and grey dolomite with 8–10 cm thick beds of intraformational conglomerate of the Sheppard Formation, about 25 m above the underlying Purcell lava in the North Kootenay Pass area. This mineralized horizon assayed 0.07%–0.16% Pb, 0.01%–0.24% Zn and 0.03%–0.04% Cu along the Continental Divide, immediately north of Hollebeke Mountain, and 0.02% Pb, 0.01%–0.02% Zn and 0.01%–0.02% Cu along the North Kootenay trail.
- Sporadic small specks of chalcopyrite occur in vugs and along joint surfaces within silty dolomite or in thin sandy lenses and calcareous nodules of the Sheppard Formation on Pincher Ridge and Victoria Peak, with assays returning up to 0.22% Cu. The former showing comprises a 2.1 m mineralized zone, containing 0.02% Cu, immediately below a mafic sill. Moderate to sparse amounts of disseminated chalcopyrite were also observed in a 0.3 m bed of medium-grained dirty sandstone, about 19 m stratigraphically above the Sheppard–Purcell Lava contact and traced for about 60 m, and

in at least a 0.3 m thickness of grey fine-grained dolomite above or below the mineralized sandstone on the south flank of the ridge between Prairie Bluff and Victoria Peak.

- Finely disseminated chalcocite, bornite stringers (1 mm thick) and cavity fillings, and secondary malachite occur in a 5.1 cm thick quartzite bed, traced for more than 1 km along strike, at the top of a 0.3 m thick unit of interbedded lenticular and irregular quartzite and argillite of the Grinnell Formation, about 15 m stratigraphically above the Appekunny–Grinnell contact, on the northeast spur of Drywood Mountain. Two assays from this mineralized bed averaged 0.24% Cu. In addition, white to brown quartzite beds (0.1–0.3 m thick) with sparse layers of green argillite chips, from the upper Grinnell Formation about 3 m stratigraphically below the Siyeh–Grinnell contact on the southeast spur of Drywood Mountain, contain irregularly dispersed bornite knots (up to 1.3 cm) with malachite haloes. The 0.9 m wide mineralized zone, traced for about 150 m along strike, averaged 0.04% Cu.

Extensive exploration during the 1960s and 1970s by Kintla Explorations Ltd. further characterized some of the previously known showings and discovered numerous new metallic mineral occurrences in southwestern Alberta, including the following:

- Disseminated and fracture-filling galena and a stockwork of galena-bearing veins (up to 1.4 m thick and traced for 244 m) occur in a main mineralized zone measuring approximately 12 m by 305 m within brecciated argillaceous limestones of the lower Siyeh Formation, associated with an extensive northwest-trending fault zone and a galena-bearing gabbro dike, on the south arm of Spionkop Ridge. The massive galena vein assayed 52.20%–57.35% Pb and 80.57–180.0 ppm Ag, with traces of Zn, Mo and Au, across 1.2 m. The adjacent 1.5–3 m of limestone assayed 3.38%–4.96% Pb and 4.11–8.23 ppm Ag (Morton, 1972; Goble, 1972b, 1973a). Goble (1972a) estimated that the main mineralized zone may contain 0.55 million tonnes grading 16.2% Pb and 28.11 ppm Ag, or 0.25 million tonnes grading 59.7% Pb and 113.49 ppm Ag, with traces of Cu, Zn, Mo and Au. Small veins of galena, chalcopyrite and sphalerite occur 30–60 m above this zone in the Siyeh carbonates, and assayed 0.14%–0.62% Pb and 0.07%–0.48% Zn (Goble, 1974c). About 370 m to the southeast along this fault zone, limestones and mudstones of the lower Siyeh Formation with disseminated galena and sphalerite assayed 0.24% Zn, 0.14% Pb and 2.06 ppm Ag (Goble, 1972b, d). About 4.6 km northwest of the main mineralized zone, the same northwest-trending fault is intruded by a mafic dike (2.4 m thick, traced for 1.5 km) at Spionkop Creek; the dike contains galena and sphalerite in amygdules, and is associated with an occurrence of wolframite(?) in the adjacent lower Siyeh Formation carbonates. Mafic dikes and sills cutting the Siyeh Formation carbonates in the Blind Canyon area assayed 0.15%–6.26% Zn, 0.02%–1.30% Cu, 0.04% Pb, trace–29.49 ppm Ag and trace–1.03 ppm Au, whereas a quartz-calcite vein with galena and chalcopyrite returned 4.30% Pb, 1.30% Cu, 17.14 ppm Ag and 343 ppb Au (Goble, 1972c).
- Chalcocite and bornite (±chalcopyrite) occur in the form of veins, masses and disseminated grains, or replace argillite pebbles in quartzite-argillite cycles of the upper Appekunny and lower Grinnell formations, and in mafic intrusions (Drywood Mountain) in the Drywood Creek–Pincher Creek area. Assays from nine different showings returned 0.25%–3.0% Cu and 2.06–10.29 ppm Ag across 0.9–3.4 m thick intervals, with one quartzite bed of the upper Appekunny Formation being continuously mineralized for at least 3.6 km along the strike (Goble, 1973a).
- Disseminated galena and sphalerite/hydrozincite occur in black argillite bands within calcareous siltstone of the Siyeh Formation at the North Kootenay Pass. Assays across a 1.8 m thick mineralized interval returned 2.56% Pb, 1.40% Zn and 79.54 ppm Ag (Goble, 1973a).
- The top 0.3–0.8 m section of the Purcell basaltic lava flows, containing amygdule-filling chalcopyrite, returned 0.95%–1.8% Cu for two different showings at the North Kootenay Pass and the Carbondale River (Goble, 1973a).

- Galena and sphalerite/hydrozincite (±chalcopyrite) occur as stratabound, finely disseminated mineralization, streaks, blebs and coatings on joint planes in a 2.3–7.3 m thick section of interbedded black argillaceous siltstone, grey siltstone, argillaceous dolomite and dolomitic siltstone within the lower 23 m section of the Sheppard Formation. This interval was originally discovered by Cominco Ltd. in the North Kootenay Pass area (Carter and Irvine, 1971) and traced by Kintla Explorations Ltd. through 13 different showings at Carbondale River, South and North Lost creeks, and on Table Mountain, Mount Gladstone and Lys Ridge. Assays returned 0.75%–3.4% Pb, 0.2%–1.43% Zn, trace–1.2% Cu and 94.29–162.86 ppm Ag (Goble, 1973a). Based on five diamond-drill holes, a 7.6–9.1 m thick section of the lower Sheppard Formation strata, containing up to 5% combined galena and sphalerite, 0.25%–0.50% arsenopyrite, and minor chalcopyrite and pyrite, assayed 2.8%–3.5% Zn, 0.5%–1.5% Pb, 0.06%–0.18% Mo and 6.86–154.29 ppm Ag (Goble, 1975). This mineralized section continues for a north-south strike length of 12.1 km between Carbondale River and North Lost Creek in the North Kootenay Pass area. It is estimated to contain 167 million tonnes of 2.61% Pb, 0.80% Zn and 126.86 ppm Ag (Goble, 1973a, b, 1975). About 15.2 m stratigraphically above within the Sheppard Formation, another lithologically similar 1.8 m thick interval gave 1.5% Pb, 1.2% Cu, and 0.3% Zn at North Kootenay Pass (Goble, 1973a).
- Chalcocite and bornite (±chalcopyrite) form blebs, veins and massive and disseminated mineralization, or replace green argillite pebbles in multiple (6–8) quartzite beds (5–30 cm thick) or in zones, up to 6.1 m thick, within quartzites and argillites of the Appekunny, upper Grinnell and lower Siyeh formations on Whistler Mountain, Gravenstafel Ridge, mount Haig and Barnaby Ridge, and at Grizzly Creek. Nine showings returned 0.20%–7.5% Cu and trace–12.69 ppm Ag, with traces of Pb (Goble, 1973a).
- Pyrite and chalcopyrite (±chalcocite±bornite) occur as sporadic veins, disseminated mineralization or replacing argillite pebbles within three siltstone or dirty quartzite beds (0.3–2.1 m thick) of the Gateway Formation on Drywood Mountain (0.3%–0.5% Cu), and within a 0.46 m thick conglomerate of the Middle Cambrian Flathead Formation(?) or a 2.0 m thick siltstone of the Roosville Formation on Victoria Ridge (0.20%–0.68% Cu; Goble, 1973a).
- The upper 0.9–1.5 m portion of a gabbro intrusion at the base of the Grinnell Formation on the southern side of Spionkop Creek assayed 0.25%–1.1% Cu (Goble, 1973a).
- Massive bornite (0.3 cm by 3.8 cm) occurs in a 3.0–4.6 m section of the upper Siyeh Formation black argillite at Spionkop Ridge (Goble, 1973a).
- Samples from a 15 m by 200 m paleochannel(?) within the Waterton Formation on Syncline Mountain assayed 343 ppb Au and 0.10% Cu (Goble, 1973a).
- A 1.2 m thick, chalcocite-bearing siltstone section of the uppermost Sheppard Formation, which assayed 0.3%–0.78% Cu, was traced continuously from Spionkop Ridge to Barnaby Ridge over a strike length of about 55 km. About 30 m stratigraphically lower, a 2.4 m thick, chalcopyrite-bearing siltstone section of the Sheppard Formation assayed 0.33% Cu and was traced at Spionkop and Lys ridges, and on Drywood Mountain (Goble, 1973a).
- A 3.7–9.1 m thick gabbro sill within the upper Grinnell Formation redbed cycles on the north flank of Spionkop Ridge contains disseminated sulphide mineralization that is gradually zoned from a pyrite-chalcopyrite assemblage along the margins through chalcopyrite, chalcopyrite-bornite, bornite and bornite-chalcocite to a central chalcocite zone. Stratigraphically below this intrusion, three or five additional gabbro dikes (1.8–3.7 m thick), exposed over 150–460 m along strike, cut the Grinnell Formation strata. Numerous high-angle reverse faults (270°–350°/70°–90°SW) with displacements of up to 90 m cut some of the gabbro dikes, whereas other dikes use the fault planes. Assays from these intrusions returned 0.02%–5.28% Cu, trace–37.71 ppm Ag (up to 299 ppm Ag from the chalcopyrite-bornite zone in the main sill), 0.15%–0.20% Zn and trace–343 ppb Au (Goble, 1972b, c, d). Kennco

Exploration (Western) Ltd. estimated approximately 1 million tonnes grading 1.83%–3.45% Cu and up to 29.49 ppm Ag for the upper intrusion (Stevenson, 1968). Disseminated chalcopyrite, chalcocite and bornite also occur throughout the chilled margins of a 6–30 m thick gabbro sill near the top of the Appekunny Formation that assayed 0.30%–0.56% Cu and 3.43–9.60 ppm Ag over 0.9–5.5 m (Goble, 1972d).

- Disseminated bornite-covellite-chalcocite (±chalcopyrite) and veinlets of bornite and covellite in argillite pebbles occur throughout several quartzite beds within a 61 m section of the upper Grinnell Formation north of Yarrow Creek. The lowest of these beds, the 'YS' bed (1.5–3.7 m thick), was traced for more than 4.8 km along strike from just north of Yarrow Creek through Blind Canyon to just south of Spionkop Creek. Assays from these beds returned 0.04%–7.20% Cu, trace–68.57 ppm Ag (up to 2036 ppm Ag near the mafic dike at Yarrow Creek) and trace–514 ppb Au (Goble, 1972b, c). The average assays for 1.8–3.0 m intervals of the 'YS' quartzite bed intersected by three diamond-drill holes on Spionkop Ridge, between Blind Canyon and Yarrow Creek, range from 0.99% to 2.35% Cu and from 12.34 to 27.09 ppm Ag (Goble, 1974c). The mineralized 'YS' quartzite bed was estimated to contain a potential 2.2 million tonnes grading 2.0%–2.25% Cu and 5.14–8.57 ppm Ag, or 15–18 million tonnes grading 1.25%–1.75% Cu and 6.86–10.29 ppm Ag (Goble, 1972a, b, d; Goble, 1974c).
- Covellite and bornite veins (0.6 cm by 5.1 cm) and disseminated chalcopyrite and/or bornite-chalcocite occur in chilled margins of multiple 1.8–3.0 m thick mafic sills and dikes cutting the Grinnell Formation north of Yarrow Creek. Some of the sills and dikes occupy the numerous high-angle normal or reverse faults (300°–350°/70°–90°SW), whereas other intrusions are cut by these faults. Some faults cut the lower Grinnell Formation strata but do not penetrate an approximately 30 m thick gabbro sill within the underlying upper Appekunny Formation, indicating some intrusion-induced faulting in the unconsolidated sediments (Goble, 1972d). The gabbro intrusions assayed 0.30%–20.82% Cu, trace–87.77 ppm Ag, trace–1.00% Zn and up to 1.37 ppm Au, with the main mafic sill at Yarrow Creek containing 0.10%–1.25% Cu, trace to 76.11 ppm Ag, 0.26% Zn and trace–686 ppb Au (Goble, 1972b, c). Goble (1972d) estimated a possible combined 0.08 million tonnes grading 1.0% Cu and <3.43 ppm Ag for the gabbro sill and dike within the lower Grinnell strata.
- The upper Appekunny Formation quartzite/sandstone with disseminated pyrite and chalcopyrite returned 0.03%–2.86% Cu, 0.05%–0.10% Zn and trace–2.06 ppm Ag for an 8.5–19.8 m trenched section and drilled intervals at Yarrow Creek (Goble, 1972c).
- A 1.5 m basal section of the Roosville Formation at La Coulotte Ridge, in southeastern British Columbia near the Alberta border, assayed 0.61% Cu and 343 ppb Au. About 0.8 km to the west, the same horizon returned 0.38% Cu, and 0.27% Cu for another 1.5 m section 3 m above, with the copper mineralization being continuous between the two analyzed intervals (Morton, 1971; Goble, 1972c).
- The Cretaceous alkaline intrusive complex, comprising a network of oversaturated monzonite and foid-bearing alkali-feldspar syenite and trachyte dikes (ranging from <2 to 3 m wide) and sills (up to 70 m thick), traced for up to several kilometres, intrudes sedimentary rocks of the Grinnell, Siyeh, Sheppard, Purcell Lava and Gateway formations on the ridge between Commerce Peak and Sunkist Ridge in southeastern British Columbia, near the Continental Divide (Goble et al., 1999). Two samples of alkali syenite with 3%–5% disseminated pyrite-pyrrhotite (±chalcopyrite) from an extensive gossan-like zone on the top 100 m of this ridge at the headwaters of Sunkist Brook assayed 686 ppb Au (Goble, 1972c). The syenite intrusions produced extensive zones of marble and garnetiferous (andradite) skarns within the host Siyeh strata. A 41 m wide silicified alkali syenite breccia dike, extending about 1.2 km east of the main syenite body, assayed 70.63 ppm Au based on samples from the 1935 trench on the ridge between Commerce Peak and Sunkist Mountain (Morton, 1971). About 305 m to the south of this gold occurrence, chalcopyrite (~2%) occurs along the syenite–Purcell Lava contact. A section through the upper Grinnell Formation strata south of the

largest lake on the northwest flank of the ridge contains 47 mineralized quartzite beds (0.05–0.6 m thick), which assayed 0.07%–4.30% Cu with traces of silver. Two quartz veins, 0.6–4.6 m wide and up to 460 m long, related to a large alkali syenite body within the Siyeh Formation strata contain tetrahedrite and azurite near the summit of the ridge above the same lake. These veins assayed 1.30%–1.75% Cu and trace–20.57 ppm Ag (Morton, 1971; Goble, 1972c).

- A 1.2–2.4 m thick and 250 m long massive replacement zone with veinlets, joint coatings and disseminated galena and chalcopyrite is associated with a fault at the base of a gabbro sill within quartzites of the Grinnell Formation at Starvation Creek in adjacent British Columbia. Average assays indicate 9.85% Pb, 0.95% Cu, 505.7 ppm Ag and 514 ppb Au, with a 0.3 m interval returning 610.3 ppm Ag, 3.5% Pb, 1.3% Cu and 686 ppb Au (Morton, 1971; Goble, 1973a).

Morton et al. (1974a, b) studied the mineralogy and sulphur isotopes of the sulphide mineralization within the Mesoproterozoic Purcell Supergroup of the Clark Range in southwestern Alberta and recognized four genetically distinct base- and precious-metal associations:

1) **Cu±Ag** in the form of
   - interstitial and epigenetic bornite and covellite (±digenite±djurleite±idaite±chalcopyrite±galena± tennantite±wittichenite±magnetite) or chalcopyrite (±sphalerite±pyrrhotite±hematite) in arenites and argillites of redbed sequences of the upper Appekunny and Grinnell formations, and in green or black argillites and dolomitic units of the Siyeh Formation (e.g., Yarrow Creek–Spionkop Creek area);
   - amygdule-filling chalcopyrite in the upper part of the Purcell lava flows (e.g., North Kootenay Pass);
   - minor chalcopyrite with pyrite and traces of galena and sphalerite in dolomitic siltstone and siltstone of the lower and middle Sheppard Formation (e.g., North Kootenay Pass–North Lost Creek area);
   - chalcopyrite in calcareous siltstones of the middle Gateway Formation (e.g., Barnaby Ridge and Sage Mountain); and
   - interstitial bornite and covellite in basal arenites of the Roosville Formation (e.g., Commerce Creek–Sage Creek area).
2) **Zn-Pb (±Cu±Ag)** in the form of distorted streaks and blebs (2–5 mm) and disseminated galena and sphalerite (±chalcopyrite±pyrite±secondary hydrozincite) parallel to bedding laminations, and galena in secondary fractures in the lower Siyeh Formation dolomites (e.g., Yarrow Creek–Spionkop Creek area) and in the lower Sheppard Formation blue-grey silty dolomite to black dolomitic siltstone (e.g., Table Mountain–Mount Gladstone area, North Kootenay Pass–North Lost Creek area and just north of Spionkop Creek).
3) **Cu±Ag** in the form of abundant, interstitial chalcopyrite and/or bornite (±chalcocite±covellite± digenite), accompanied by magnetite (±pyrite±arsenopyrite±galena±sphalerite) in gabbro sills cutting the upper Grinnell Formation strata (e.g., Spionkop Creek–Yarrow Creek area).
4) **Zn-Pb (±Cu±Ag)** in the form of disseminated sphalerite, galena, bornite, chalcocite and covellite in mafic sills cutting the lower Siyeh Formation dolomitic strata (e.g., Spionkop Creek–Blind Canyon area), and epigenetic veins of galena with chalcopyrite and tetrahedrite in a mafic sill within the Grinnell Formation (e.g., Starvation Creek in southeastern British Columbia).

Morton et al. (1974b) reported locally significant grades for these metal associations in southwestern Alberta, including

- 0.5%–5.71% Cu and 2.1–20.23 ppm Ag for the sediment-hosted Cu-Ag occurrences, with considerably enriched concentrations in proximity to the mafic sills and/or normal faults;
- up to 7.0% Zn, 4.17% Pb, 0.25% Cu and 6.17 ppm Ag for the stratabound Pb-Zn occurrences;
- up to 5.28% Cu, 0.2% Zn and 299.0 ppm Ag for the mafic sills cutting the upper Grinnell Formation strata; and
- up to 6.26% Zn, 4.3% Pb, 1.3% Cu and 29.49 ppm Ag for the mafic sills cutting dolomitic strata of the lower Siyeh Formation.

Morton et al. (1974a) also grouped the copper sulphide assemblages into two associations characterized by copper content:1) 'copper-poor' assemblage (chalcopyrite±pyrrhotite±hematite±sphalerite); and 2) 'copper-rich' assemblage (bornite–blaubleibender covellite±digenite±djurleite±idalite±wittichenite± magnetite±chalcopyrite±galena±tennantite).

Goble (1976) also reported uranium mineralization in the form of disseminated pitchblende and carnotite within a series of 0.3–1.8 m thick, sandy quartzite beds of the Grinnell Formation, approximately 30.5 m below the overlying Siyeh Formation on the southern face of Spionkop Ridge, about 2.4 km north of Yarrow Creek, which returned an average of 2.13% Cu and 17.82 ppm Ag, and up to 0.24% U_3O_8.

In 1972–1973, Collins and Smith (1977) performed a detailed petrological and geochemical study of cupriferous quartz arenite cycles, containing disseminated copper sulphides, pyrite and tennantite, within the Grinnell Formation on the Whistler Mountain and Grizzly Creek prospects of Cominco Ltd. in southwestern Alberta. The mineralized bodies range from stacked (more than 25 individual units), lenticular horizons several centimetres thick to units 1.5–2.1 m thick, scattered throughout the Grinnell Formation on Whistler Mountain and at Grizzly Creek, respectively. Trench samples of the quartz arenite assayed 0.01%–6.65% Cu and up to 26 ppm Ag and 513 ppb Hg, whereas green argillite returned up to 822 ppm Cu and 12 ppm Ag at Whistler Mountain. At Grizzly Creek, core samples from two diamond-drill holes returned 0.04%–1.18% Cu, 10–25 ppm Ag and up to 220 ppm Pb, 130 ppm Co and 270 ppb Hg for mineralized quartz arenite; up to 1.13% Pb and 400 ppm Cu for weakly mineralized quartz arenite; and up to 510 ppm Cu and 10 ppm Ag for green argillite (Collins and Smith, 1977).

During the late 1970s to early 1980s, Lost Lemon Mines Ltd. performed exploration near Plateau Mountain at the southern boundary of Kananaskis Country and reported up to 0.45 ppm Au and 10.3 ppm Ag from a drillhole in the Dry Creek area (Olson et al., 1994). In addition, 0.76 ppm Au was reported for a sample of calcareous siltstone from a locality northwest of Blairmore (Olson et al., 1994). Although neither of these results could be confirmed, Williamson et al. (1993) did report anomalous Au-As-Sb-Hg contents in sediments from streams draining the Devonian to Permian carbonates of the Livingstone Range in the Dry Creek area. Olson et al. (1994) suggested that these occurrences might indicate epithermal or Carlin-type disseminated Au-Ag mineralization related to the Cretaceous alkaline magmatism in the area. Olson et al. (1994) also quoted unpublished data by W.N. Hamilton indicating anomalous Au, As, Sb, Ag and Hg values in stream sediments from two drainages of a high-angle fault in the David Thompson corridor, just west of the confluence of the North Saskatchewan and Cline rivers.

The GSC and Esso Minerals Canada Ltd. investigated several stratigraphic sections of the Upper Devonian and Mississippian strata in the areas between Jasper and the Smoky River, southwest of Grand Cache, and between Canmore and the Clark Range (Geldsetzer et al., 1987). The geochemical analyses indicated up to

- 3.6 ppm Ag, 0.2% V, 0.12% Zn, 201 ppm Cr, 200 ppm Ni, 74 ppm Cu, 44 ppm Pb and 53 ppm As for the Upper Devonian Palliser Formation carbonates; and

- 4.0 ppm Ag, 0.4% V, 775 ppm Zn, 157 ppm Cr, 155 ppm Ni, 68 ppm Cu, 33 ppm Sb, 23 ppm As and 0.12% Ba for the basal Mississippian Exshaw Formation black shale (Geldsetzer et al., 1987).

In addition, Richards et al. (1994) reported up to 2.19% Zn, 0.48% Ni, 560 ppm Mo, 240 ppm Cu, 128 ppm Y and 47 ppm U for a conglomeratic sandstone layer (1–6 cm thick) at the base of the lower Exshaw Formation planar-laminated, pyritic black shale with calcareous to cherty concretions and yellowish grey marine tuff seams (2.0–5.5 cm thick) at Jura Creek, near Exshaw. This basal layer contains abundant phosphate nodules, abraded bone fragments, fish scales and disseminated vaesite (NiS_2), sphalerite and pyrite, and possibly represents a reworked tuff or submarine lag deposit (Richards et al., 1994).

In 1989, the report of anomalous gold values discovered by Crowsnest Metallics Ltd. in the Crowsnest Pass area revived rumours of an elusive 'Lost Lemon Gold Mine,' which legend says was discovered by two prospectors in 1870 in the Highwood River–Crowsnest Pass area (Stewart, 1990). The reported assays indicated up to 0.21 ppm Au for a melanocratic, pyrite-rich pyroclastic breccia with minor galena and chalcopyrite of the Early Cretaceous Crowsnest Formation at Iron Ridge, west of Coleman along Highway 3, with the pyrite concentrate returning up to 2.55 ppm Au (Peterson et al., 1997).

Encouraged by the initial results, Crowsnest Metallics Ltd. conducted a regional bedrock and stream-sediment geochemical survey in the Crowsnest Pass area later in 1989, which indicated only up to 15 ppb Au (Stewart, 1990). Ventana Metallics Inc. further evaluated the metallic potential of the Crowsnest Formation on the basis of 188 rock and 47 stream-sediment analyses from the Lynx Creek area, which returned up to 40 and 50 ppb Au for rocks and stream sediments, respectively (Williams, 1989). Western Diamex Ltd. confirmed the correlation of the anomalous gold values with the presence of sulphides in the Crowsnest volcanics but did not locate any economic mineralization (Cantin et al., 1995). A 5 kg sample from the original gold-bearing occurrence at Iron Ridge returned only 7 ppb Au, although subsequent analyses produced values of up to 50 ppb Au (Peterson et al., 1997).

In 1992, Willliamson et al. (1993) evaluated the metallogenic potential of the Southern Alberta Rift and reported slightly anomalous values of up to 14 ppb Au, 0.3 ppm Ag, 299 ppm V, 227 ppm Cu, 182 ppm Zn, 99 ppm Pb, 7 ppm Mo, 10 ppm W, 25 ppm As, 21 ppm Bi and 5 ppm Sb for the Crowsnest Formation volcanic rocks. Between 1993 and 1995, Ecstall Mining Corp. carried out a regional stream-sediment geochemical survey over an area of about 7320 km^2 in southwestern Alberta, which indicated anomalous concentrations of gold in those portions of Lost, Carbondale and Racehorse creeks draining outcrops of the Crowsnest Formation (Waskett-Myers and Graf, 1995). Leckie and Craw (1995) also reported anomalous values of 10 ppb Au, 220–249 ppm Cu, 216–222 ppm V, 135–156 ppm Zn, 61–66 ppm Pb and 7–11 ppm As for two of three analyzed samples of the Crowsnest volcanics. In addition, analyses of nine samples of fresh blairmorite, phonolite and trachyte from the Crowsnest Formation in the Crowsnest Pass area by Peterson et al. (1997) returned up to 181 ppm Zn and 131 ppm Cu. Based on these results, they concluded that the Crowsnest volcanics have generally low potential for metallic mineral deposits.

9.2 Types of Mineral Occurrences and Hypotheses of Origin

9.2.1 Copper-Lead-Zinc Sulphides in Mafic Intrusions and Purcell Lavas

Mafic igneous rocks associated with Cu and/or Pb-Zn sulphide mineralization (± elevated concentrations of Ni, PGE, Co, Cr, Ag, Au, Mo, As and Bi) in southwestern Alberta include

- the Mesoproterozoic mafic sills and dikes cutting the Purcell strata in the Clark Range (e.g., Yarrow Creek and on Spionkop Ridge; Morton et al., 1974a, b);
- the Mesoproterozoic Purcell basic lavas in the Clark Range (e.g., North Kootenay Pass; Halferdahl, 1971; Goble, 1973a); and

- the Neoproterozoic(?) Crowfoot diabase dike cutting the Hector Formation clastic strata (Windermere Supergroup) near Bow Lake in Banff National Park (Smith, 1963).

The Mesoproterozoic intrusions and the Purcell lavas represent an upflow of a large volume (>0.05 million km^3) of basaltic magma in an intracontinental-rift environment (Höy, 1989; Lydon, 2007). These intrusions were emplaced at a shallow depth into wet, unconsolidated sediment during intermittent magmatic events between 1.47 and 1.43 Ga, associated with the syndepositional extensional faulting and outpouring of pillowed and amygdaloidal basaltic Purcell lavas up to 150 m thick (Höy, 1989; Lydon, 2007). The high volume of mafic magma emplaced during a period of approximately 25 m.y. (Lydon, 2007), coupled with the geochemical similarity to the modern, within-plate alkali or tholeiitic ocean-island basalts (Höy, 1989; Rukhlov et al., 2010; A. Rukhlov and J. Pawlowicz, Metal potential of the Rocky Mountains fold and thrust belt in southwestern Alberta: geochemical data release, work in progress, 2010), suggest that the Mesoproterozoic magmatism might have been caused by the arrival and lateral spreading of a mantle plume instead of passive-type rifting due to lithospheric tension (Lydon, 2007). Morton et al. (1974a, b) proposed that the buried Southern Alberta Rift (Kanasewich, 1968) represents an 'aulacogen' of an ancient triple junction above the subcontinental mantle plume, similar to the Proterozoic Athapuscow aulacogen of the Great Slave Lake region (Hoffman, 1973).

The Crowfoot diabase dike (Smith, 1963) may represent the Neoproterozoic event associated with rifting, breakup of the Rodinia supercontinent and development of the proto-Pacific passive margin of the North American craton between 730 and 570 Ma (Ross et al., 1989; Hein et al., 1994; Colpron et al., 2002).

Petrographic, mineralogical, fluid-inclusion and sulphur-isotopic evidence suggest that the cyclic circulation of hydrous fluids between wet sediments and the interiors of shallow basic intrusions played an important role in the enrichment of sulphides, both within the Mesoproterozoic intrusions and in their country rocks, in southwestern Alberta (Morton et al., 1974a). The barite-sulphide and sphalerite-chalcopyrite sulphur-isotope thermometers and the fluid-inclusion homogenization temperatures indicated ~400°C for the sulphide mineralization at the contact between the mafic intrusions and the sediments, ~250°C about 1.5 m away from the intrusion and ~100°C about 3 m from the sill (Morton et al., 1974a). The textures of the oxide-sulphide assemblages and the geochemistry of the mafic magmatic rocks in southwestern Alberta suggest at least three mineralization styles:

1) Vesicle-fill sulphides concentrated in the chilled margins of the Mesoproterozoic intrusions and in the upper portions of the Purcell lava flows represent hydrothermal autometamorphic mineralization (Halferdahl, 1971; Morton et al., 1974b).
2) Copper (digenite, chalcocite and covellite) and/or Pb-Zn sulphides concentrated along joints and in quartz-carbonate veins, associated with some of the Mesoproterozoic mafic intrusions and the Neoproterozoic(?) Crowfoot dike, represent epigenetic vein Cu-Pb-Zn (±Ag±Au±Mo) mineralization related to faulting, magmatism and/or hydrothermal activity during either the Proterozoic rifting or the Cordilleran Orogeny (e.g., Morton et al., 1974a; Lydon, 2007).
3) Disseminated pyrrhotite, pyrite, arsenopyrite, chalcopyrite, sphalerite and galena, along with elevated Ni, Co, Cr, Pt and Pd contents (Rukhlov et al., 2010; A. Rukhlov and J. Pawlowicz, Metal potential of the Rocky Mountains fold and thrust belt in southwestern Alberta: geochemical data release, work in progress, 2010), may represent primary magmatic segregations (Morton et al., 1974a).

Assimilation of crustal rocks by mafic magmas is a key mechanism in the genetic models of the Noril'sk Cu-Ni-PGE deposits in Russia (Eckstrand, 1995). Lydon (2007) used examples of the PGE mineralization (up to 3 ppm PGE) associated with the Mesoproterozoic gabbro intrusions within the Belt-Purcell basin (e.g., Dixon, Montana and Yahk area, British Columbia) to illustrate the role of hydrous autometamorphism by interaction of the sills with wet sediments in the origin of these Pd-rich hydrothermal Cu-PGE deposits.

9.2.2 Sedimentary Exhalative Lead-Zinc-Copper-Silver Sulphides

The sedimentary exhalative (SEDEX) Pb-Zn-Cu sulphide mineralization in the Clark Range of southwestern Alberta comprises fine-grained disseminated or conformable streaks and blebs (2–5 mm) of sphalerite (0.15%–0.90% Fe), galena, chalcopyrite and pyrite within well-laminated siltstones, dolomitic siltstones and argillaceous or silty dolomites of the Mesoproterozoic Siyeh and Sheppard formations (e.g., North Kootenay Pass, Table Mountain–Mount Gladstone area and Carbondale River–North Lost Creek area). The individual mineralized beds (ranging from 0.2 m to a few metres thick) extend for more than 10 km along strike (Carter and Irvine, 1971; Goble, 1973a, b, 1975; Morton et al., 1974a, b).

In the Carbondale River–North Lost Creek area near North Kootenay Pass, sphalerite and galena with minor arsenopyrite, chalcopyrite and traces of pyrite are concentrated in a 2.3–7.3 m thick zone of buff-weathering, grey, flaggy to blocky dolomite and the overlying rusty-weathering, black, thinly laminated siltstone of the Sheppard Formation, about 24 m stratigraphically above the Purcell lava (Carter and Irvine, 1971; Goble, 1973a, b, 1975). The contact between the dolomite and siltstone units is gradual. The dolomite is alternately thin and thick bedded, and contains thin discontinuous bands and lenses of dolomitic siltstone, characterized by the highest concentrations of Pb-Zn sulphides, and two to three intraformational conglomerate units, with elongate dolomite pebbles (1–10 mm long) parallel to the bedding, containing more Pb and Cu than Zn. The overlying black siltstone (about 1.8 m), with thin discontinuous quartzitic and sandy layers containing pale sphalerite, is overlain by a 3.0–4.6 m succession of thick-bedded, grey to green, buff-weathering dolomite interbedded with green, flaggy, gritty siltstone that contains scattered chalcopyrite and traces of galena. Sphalerite and galena occur in discontinuous lenses and laminae (<3.8 cm thick) and along conjugate fracture sets with chalcopyrite. Sphalerite forms pale grey and brown spots, patches (up to 3–4 mm in diameter at North Lost Creek), disseminations and rarely white stringers or fracture-fillings. Galena forms streaks intergrown with sphalerite parallel to bedding in silty bands, and cores overgrown by sphalerite. Some galena also occurs in a green dolomite stratigraphically above the black siltstone, and in a basal stromatolitic dolomite overlying the Purcell lava. Minor chalcopyrite occurs in the grey dolomite, the arkosic sandstone at the base of the Sheppard Formation, and through the uppermost 0.3–0.6 m of the underlying Purcell lava. Secondary hydrozincite commonly occurs as a stain on weathered faces of the mineralized grey dolomite and black siltstone (Carter and Irvine, 1971; Goble, 1973a, b, 1975).

In addition, a quartzite bed a few centimetres thick with abundant pyrite spheres (1–2 mm in diameter) at the base of the Siyeh Formation in the South Drywood Creek–Spionkop Ridge area is characterized by anomalous concentrations of Cu, Pb, Mo, Co, Ag, Au, Pd, Pt, Re, As, Bi, Sb, Se, Tl and Te (Morton et al., 1974a; Rukhlov et al., 2010; A. Rukhlov and J. Pawlowicz, Metal potential of the Rocky Mountains fold and thrust belt in southwestern Alberta: geochemical data release, work in progress, 2010).

The SEDEX Pb-Zn-Cu-Ag (±Au±Co±Mo±As±Sb±Bi±Se±Tl±Te) mineralization represents syngenetic accumulation of sulphides on the seafloor or just below the sediment surface around hydrothermal vents controlled by active extensional faults within the rift basins. The hydrothermal fluids range from vent-distal metalliferous brines (generally <250°C), discharged from a compacting sedimentary pile, to high-temperature (>300°C) seawater convection cells driven by the heat of near-surface mafic intrusions (Lydon, 2007).

The Sullivan Pb-Zn-Ag-Au-Cd-Sb-Cu-Bi-Sn past-producer in adjacent southeastern British Columbia is a world-class SEDEX deposit in the central, turbiditic sequence of the Belt-Purcell basin, whereas the Sheep Creek Cu-Co-Pb-Zn deposit in Montana is situated at the margin of the basin (Lydon, 2007). The occurrence of SEDEX-type mineralization within the Sheppard Formation in the Clark Range confirms that metalliferous fluids were discharged during deposition of the late Belt-Purcell rift-cover sequence.

9.2.3 Stratiform, Black Shale–Hosted Zinc-Nickel-Molybdenum Sulphides

Stratiform Zn-Ni-Mo (±V±PGE±Ag±Au±Cd±U±Co±Cu±As±Sb±Se±REE) mineralization occurs in basal black shale, locally interbedded with a thin bentonite horizon, of the Mississippian Exshaw Formation in southwestern Alberta (e.g., Jura Creek; Geldsetzer et al., 1987; Richards et al., 1994). The Exshaw Formation black shale and basal bentonite horizon on the east flank of Mount Gass contain up to 0.36% Zn, 0.20% V, 0.13% Ni, 139 ppm Cu, 112 ppm Mo, 90 ppm Co, 50 ppm Cd, 0.8 ppm Ag, 182 ppb Re, 7 ppb Au, 2.6 ppb Pd, 2.2 ppb Pt, 79 ppm As, 27 ppb Sb, 17 ppm Se and 13 ppm Tl (A. Rukhlov and J. Pawlowicz, Metal potential of the Rocky Mountains fold and thrust belt in southwestern Alberta: geochemical data release, work in progress, 2010).

Black shale near the top of the Triassic Sulphur Mountain Formation in the Athabasca River–Smoky River region contains local horizons of massive pyrite (up to 10 vol. %) and is underlain by phosphate-rich sediments (Gibson, 1965). Abundant pyrite also occurs in black shale of the Jurassic Fernie Group (e.g., Thorne mine on the east flank of Moose Mountain, near the headwaters of Bragg Creek). The Fernie Group black shale northwest of Mount Ptolemy and west of Coleman contains up to 631 ppm Zn, 89 ppm Mo, 10 ppm Cd and 227 ppm As (Williamson et al., 1993).

The syngenetic black-shale polymetallic mineralization represents seafloor exhalative deposits, basin wide but usually less than a few metres thick, of massive to semimassive, rhythmically laminated, clastic or nodular sulphides associated with phosphorites, chert, barite, and bentonite horizons within organic-rich, transgressive shale sequences formed in anoxic basins of a passive continental margin or rifts (e.g., Lefebure and Coveney, 1995; Lott et al., 1999). The best mineralized zones mark the seafloor hydrothermal discharge centres, which are controlled by syn-rift normal faults or reactivated basement faults (Olson et al., 1994).

Examples of black-shale polymetallic mineralization elsewhere include the Nick Ni-Zn deposit within the Middle–Upper Devonian strata of the Mackenzie Platform in the Yukon and the Mo-Ni-Zn-PGE-Au producers, with grades up to 1 ppm Au, 7% Mo, 4% Ni and 2% Zn, within the Lower Cambrian Niutitang and Zunyi formations of the Yangtze Platform in southern China (e.g., Lefebure and Coveney, 1995; Lott et al., 1999).

9.2.4 Kupferschiefer/Redbed–Type Copper-Silver Sulphides

The Kupferschiefer/redbed–type Cu-Ag (±Co±Au±Pb±Mo±U) mineralization in southwestern Alberta comprises stratabound laminae, stringers and finely disseminated bornite, covellite, chalcocite and chalcopyrite (±tennantite±sphalerite±galena±pyrrhotite±pyrite±digenite±djurleite±idaite±wittichenite± magnetite±hematite), and secondary malachite and/or azurite at several stratigraphic levels in the Mesoproterozoic Purcell Supergroup, in

- multiple quartz arenite beds within redbed cycles of the upper Appekunny Formation and throughout the Grinnell Formation (e.g., Whistler Mountain, Grizzly Creek and Spionkop prospects);
- black argillite at the base and near the top of the Siyeh Formation (e.g., Spionkop Ridge and South Drywood Creek);
- two beds of siliceous dolomite to siltstone of the upper Sheppard Formation (e.g., North Kootenay Pass, Spionkop Ridge, Victoria Peak and Drywood Mountain);
- four beds of silty to argillaceous dolomite of the lower Gateway Formation (e.g., Sage Mountain, Grizzly Creek and Drywood Mountain) and a silty dolomite to dolomitic argillite bed of the upper Gateway Formation (e.g., Barnaby Ridge and the northwest end of Sunkist Ridge); and
- dolomite, dolomitic argillite, siltstone and oolitic sandstone of the Roosville Formation (e.g., Victoria Ridge and Jutland Mountain).

The cupriferous quartz arenite cycles form stacks of more than 25 individual thin, lenticular mineralized beds (2.5–15 cm thick) scattered across the Grinnell Formation on Whistler Mountain, and up to 1.5–2.1 m thick individual mineralized zones at Grizzly Creek (Collins and Smith, 1977). The mineralized cycles extend for tens to hundreds of metres along strike, with each cycle consisting of six units (from bottom to top):

1) red argillite containing scattered, well-rounded quartz grains (0.1–0.5 mm) and up to 5% finely disseminated hematite, with mudcracks and salt hoppers
2) greyish green argillite, with gradual transition from the underlying red argillite and upward increase in sand content
3) white to greenish grey, moderately sorted, coarse-grained, crossbedded cupriferous quartzite or sandstone, with some interbedded intraformational conglomerates containing rounded to tabular-rounded green argillite chips or pebbles (0.02–3.0 cm)
4) thin (up to 6 mm) green argillite seam or parting
5) white, medium- to coarse-grained quartzite with ripple-marked upper surface
6) green silty argillite with flat upper surface (Collins and Smith, 1977)

Interstitial chalcocite, bornite, covellite, tennantite, pyrite and traces of chalcopyrite occur as discrete grains (up to 1 mm in diameter) and intergrowths with silica cement mainly in the quartz arenite (unit 3). Very fine grained copper sulphides are often concentrated on the green argillite chips. Secondary copper minerals include azurite and malachite (Duncan, 1970; Halferdahl, 1971; Van Dyck, 1971; Goble, 1973a; Morton et al., 1974a, b; Collins and Smith, 1977).

Several hypotheses have been proposed to explain the origin of the stratabound copper mineralization in the Belt-Purcell basin of southwestern Alberta:

- both sedimentary and epigenetic/hydrothermal origins, similar to the Kupferschiefer deposits in Germany, the White Pine deposit in Michigan and the Dzhezkazgan deposits in Kazakhstan (Duncan, 1970)
- mainly fault-controlled (Grinnell-type copper) and both fault-controlled and possibly sedimentary (siltstone-type copper), with the Sheppard Formation copper occurrences being distinct from the Kupferschiefer-type deposits (Halferdahl, 1971)
- syngenetic, finely disseminated chalcocite (5–50 μm) in the Gateway Formation dolomitic units (Van Dyck, 1971)
- short-range hydrothermal mobilization and redeposition of initially exhalative, syngenetic and diagenetic, stratabound metals within the Belt-Purcell rift basin, with local enrichment of Cu-Ag mineralization in redbed sequences along normal fault zones and contacts with mafic intrusions (Goble, 1973a; Morton et al., 1974a, b)
- copper mineralization controlled by repeated redox cycles during deposition or contemporaneous with cementation of fluvial to lacustrine, cupriferous quartz arenites of the Grinnell Formation deposited by intermittent sheet floods on a floodplain surface in an arid to semi-arid environment (Collins and Smith, 1977); based on the textural relationships of silica cement and sulphides in these quartz arenite units, the highly mobile copper, complexed in solution or floodwater under the prolonged oxidizing conditions during deposition of the argillites, must have precipitated syngenetically in the organically induced reducing environment during the deposition and diagenesis of the quartz arenites (Collins and Smith, 1977).

Recently, Lydon (2007) interpreted the redbed-type Cu-Ag deposits of the Belt-Purcell rift to be the result of migration of warm (~120°C), oxic, saline fluid along bedding or vertical fluid-escape structures during the earliest stages of the rift-cover phase, with the epigenetic sulphides formed in quartzite pore spaces

under reducing conditions before any major compaction of the sediment. The Spar Lake (Troy), Rock Creek and Montanore deposits in northwestern Montana are examples of redbed-type Cu-Ag deposits within sandstones of the Revett Formation (Lydon, 2007), which is a stratigraphic equivalent of the Grinnell Formation of southwestern Alberta.

The stratigraphic positions, lithology and relative grades of the stratabound Cu-Ag sulphide mineralization in the Clark Range of southwestern Alberta correlate remarkably well with the Cu-Ag deposits in the Revett, Spokane, Helena Dolomite and Mount Shields formations of Montana and Idaho, suggesting a large-scale, synsedimentary deposition of metals in the Belt-Purcell basin (Morton et al., 1974a, b). In addition, the stratabound Cu-Ag occurrences within the Purcell strata in southwestern Alberta are associated with sporadic gold (Goble, 1972c; Morton et al., 1974a), similar to the Cu-Ag deposits in the Revett Formation of Montana, which contain about 80 ppb Au (Morton et al., 1974a).

9.2.5 Alkaline Intrusion–Related, Epithermal Gold-Silver-Copper-Lead-Zinc Mineralization

Alkaline intrusion–related epithermal mineralization consists of disseminated pyrite, pyrrhotite and chalcopyrite, along with elevated concentrations of Au-Ag (±Cu±Pb±Zn±Mo±W±As±Bi±Sb±Te±Re), along contacts between Cretaceous alkali-feldspar syenite, trachyte, latite, tephriphonolite and phonolite sills and dikes and strata of the Mesoproterozoic Purcell Supergroup and Middle Cambrian Flathead Formation along the British Columbia border in southwestern Alberta (e.g., La Coulotte Ridge and Jutland Brook; Halferdahl, 1971; Goble, 1974a, b; Morton et al., 1974b; Rukhlov et al., 2010; A. Rukhlov and J. Pawlowicz, Metal potential of the Rocky Mountains fold and thrust belt in southwestern Alberta: geochemical data release, work in progress, 2010). The Cretaceous intrusions are widespread in the adjacent Flathead region of southeastern British Columbia, where they range from stocks and plugs (from 0.1 to >1.2 km in diameter) to small dikes and sills (Skupinski and Legun, 1989; Brown and Cameron, 1999; Goble et al., 1999). Rare Cretaceous alkali trachyte dikes also cut the Paleozoic and Mesozoic strata in the Crowsnest Pass area (e.g., Crowsnest Mountain and Mount Tecumseh; Bégin et al., 1995; Peterson et al., 1997).

The Cretaceous intrusions are coeval and compositionally similar to extrusive rocks of the Early Cretaceous Crowsnest Formation, which contain locally abundant pyrite (±galena±chalcopyrite) accompanied by anomalous concentrations of Au-Ag-Cu-Pb-Zn-V-Mo-W-As-Bi-Sb (Willliamson et al., 1993; Cantin et al., 1995; Leckie and Craw, 1995; Waskett-Myers and Graf, 1995; Peterson et al., 1997). The Crowsnest Formation comprises domes of phonolite, blairmorite and analcime-bearing trachyte, proximal debris flows, agglomerate, crystal and lithic tuff, fallout tephra deposits, and reworked volcanogenic conglomerates and sandstones in the Crowsnest Pass area (e.g., Dawson, 1886; Pearce, 1970; Bégin et al., 1995; Peterson et al., 1997; Goble et al., 1999). Sanidine from the Crowsnest Formation phonolitic flow gave a K-Ar date of 96 Ma (Folinsbee et al., 1957), indistinguishable from the U-Pb date of 98.5 ±5 Ma for an alkali syenite at Trachyte Ridge in southeastern British Columbia. This represents the best age estimate for the Cretaceous magmatic event associated with compressional and transtensional tectonics during the Cretaceous–Tertiary Laramide Orogeny in the Canadian Cordillera (Brown and Cameron, 1999).

Goble et al. (1999) proposed that the Crowsnest Formation volcanic rocks are genetically related to the Cretaceous intrusions of southwestern Alberta and southeastern British Columbia, with Commerce Mountain near the Continental Divide possibly representing a remnant of a volcanic centre during the eruption of the Crowsnest volcanics (Goble et al., 1999). Based on the stratigraphic evidence, the emplacement depth of the Cretaceous intrusions is estimated to be 3–5 km (Brown and Cameron, 1999).

Gold mineralization related to the Cretaceous alkali syenite and trachyte intrusions in the Flathead region of adjacent southeastern British Columbia marks a district-scale metallogenic event (Brown and

Cameron, 1999). Several styles of alkaline intrusion–related, epithermal precious- and base-metal sulphide mineralization have been recognized (Skupinski and Legun, 1989; Brown and Cameron, 1999):

- Sediment-hosted Au-Ag (±W±Mo±V±Pb±Zn±As±Sb) mineralization with Ag/Au ratios of 6–9 is associated with extensive, fine- to medium-grained, disseminated and massive, fracture-controlled pyrite in all the rock types except foid-bearing syenite, carbonatization and argillic alteration of syenite, patchy silicification and high-zinc, high-temperature replacements (mantos) or pods in the adjacent Paleozoic carbonate hostrocks, rare barite-fluorite veins and late hydrothermal or intrusive breccias (e.g., Eastern Outlier at Howell Creek).
- Syenite-hosted, closely spaced (up to 20 vol. %), quartz stockwork and sheeted veins (0.8–15 cm thick) are associated with fine-grained, disseminated and fracture-controlled auriferous pyritization, intense silicification, argillic alteration, abundant to minor fluorite veins and elevated Mo concentrations (e.g., Howell grid E).
- Elevated Au-Pb-Zn is associated with minor pyritization and rare barite veins in the Roosville Formation siltite, the Flathead Formation quartz arenite, and the basal green shale of the Cambrian shale unit intruded by minor syenite and foid syenite dikes, and manto-style irregular zones of sphalerite (±fluorite) and minor malachite in the Elko Formation limestone (e.g., Howe grid A).
- Syenite-hosted quartz-magnetite-pyrite veins (a few centimetres thick) contain Au-Cu-As-Te mineralization, characterized by relatively high gold grades (e.g., 30–620 ppm Au at Trachyte Ridge).

At Howell Creek, the Early Cretaceous alkaline intrusions and sedimentary hostrocks contain up to a few per cent disseminated pyrite, minor chalcopyrite, galena and secondary malachite stains. The mineralization is associated with variable degrees of silicification, albitization (after potassic feldspar), sericitization (after nepheline and feldspar), carbonatization, chloritization, and sodic (natrolite, arfvedsonite after pyroxene), potassic (adularia) and weak argillic (illite, kaolinite and possible smectite) alteration. Fracture-filling fluorite, barite, adularia and calcite are accompanied by quartz stockwork and sheeted veins. Based on drilling, the pyritized and silicified Paleozoic limestone intruded by the syenitic and breccia bodies has an average grade of 1.3 ppm Au over a 59 m interval, whereas pyrite gouge associated with syenite-hosted quartz stockwork and sheeted veins contains up to 219 ppb Au (Skupinski and Legun, 1989; Brown and Cameron, 1999).

The precious- and base-metal mineralization associated with the Cretaceous alkaline magmatic rocks in southwestern Alberta and southeastern British Columbia has many similarities to the syenite intrusion–related epithermal deposits elsewhere (e.g., Brewery Creek in the Yukon, Zortman-Landusky and Golden Sunlight in Montana, Allard stock in Colorado, and Black Hills in South Dakota; Skupinski and Legun, 1989; Brown and Cameron, 1999).

9.2.6 Quartz-Carbonate Vein Copper-Lead-Zinc-Silver-Gold Mineralization

Quartz-carbonate veins and stockworks with sulphides and sulphosalts, characterized by the Pb-Zn-Cu-Ag-Au metal association, occur within

- argillaceous limestones of the Mesoproterozoic Siyeh Formation at Blind Canyon in the Clark Range (Morton, 1972; Goble, 1972a, c, 1973a);
- clastic strata of the Neoproterozoic Miette Group and Lower Cambrian McNaughton Formation (Gog Group) near Twin Lakes in Banff National Park and in the Miette River valley of the Athabasca Pass area, within Jasper National Park (Dawson, 1886, 1901; Shaw and Morton, 1990); and
- the Middle Cambrian carbonates and calcareous shale at the Herbert Lake, Baker Creek, Eldon, Copper Mountain and Castle Mountain/Mount Eisenhower historical prospects and minesites within Banff National Park (Dawson, 1886, 1899; La Casse and Roebuck, 1978; Pană, 2006).

Little information is available on the occurrences located within the national parks. Gold-bearing quartz veins cutting the low-grade metasiliciclastic rocks of the Lower Cambrian McNaughton Formation about 0.5 km east of the British Columbia border in the Athabasca Pass area are possibly related to the Chatter Creek thrust (Shaw and Morton, 1990). These veins may represent 'orogenic' or 'mesothermal' slate belt–type Au-Ag mineralization (Poulsen et al., 2000; Dubé and Gosselin, 2007).

The Paleozoic, carbonate-hosted, quartz-carbonate vein, base- and precious-metal occurrences in the Alberta Rocky Mountains may represent MVT mineralization related to the Laramide syntectonic thrusts and/or postorogenic collapse faults that controlled mineralizing hydrothermal fluid upwelling through the strained carbonate successions (Pană, 2006; Paradis et al., 2007).

The base- and precious-metal sulphide mineralization in quartz-carbonate veins within the Mesoproterozoic Purcell Supergroup strata of the Clark Range area (Morton, 1972; Goble, 1972a, c, 1973a) may represent a metallogenic event associated with syn-rift extensional faulting, mafic magmatism and hydrothermal activity, similar to the world-class Coeur d'Alene (Idaho) and St. Eugene and Vine (southeastern British Columbia) Pb-Zn-Cu-Ag-Au deposits (e.g., Lydon, 2007 and references therein).

9.3 Future Potential

Although numerous metallic mineral occurrences and historical prospects indicate good metal potential for the Alberta Rocky Mountains and Foothills, much of the region is in national or provincial parks and other protected areas where acquisition of metallic mineral rights is not permitted. Moreover, the Government of Alberta implemented the Eastern Slopes Policy in 1977, which defines eight regional land-use zones with different levels of permitted industry activity in the Alberta Rocky Mountains and Foothills (Alberta Department of Energy, 2010). Mineral exploration and development are not permitted or are subject to special conditions within some of the land-use zones. Consequently, there has been limited work on the metallic mineral potential of southwestern Alberta since the late 1970s.

To further evaluate precious- and base-metal potential of the Alberta Rocky Mountain fold-and-thrust belt, AGS examined in the field and carried out bedrock lithogeochemical analysis of several known metallic mineral occurrences associated with sedimentary and igneous rocks in the Clark Range, Crowsnest Pass and Mount Gass areas during 2008 and 2009 (Rukhlov et al., 2010; A. Rukhlov and J. Pawlowicz, Metal potential of the Rocky Mountains fold and thrust belt in southwestern Alberta: geochemical data release, work in progress, 2010). Based on an analysis of the new and published data, several favourable stratigraphic intervals can be outlined in southwestern Alberta.

The Mesoproterozoic Belt-Purcell Supergroup has the highest potential for base- and precious-metal deposits, including (Olson et al., 1994; Lydon, 2007): 1) SEDEX Pb-Zn-Cu-Ag (±Au±Co±Mo), 2) stratabound Kupferschiefer/redbed–type Cu-Ag (±Co±Au±Pb±Mo±U), 3) vein Ag-Pb-Zn (±Au±Cu), and 4) magmatic Cu-PGE (±Ni±Cr±Co±Au±Ag). The basinal strata of the basal Belt-Purcell Supergroup are facies equivalent to the Aldridge Formation turbidites that host the Sullivan Pb-Zn-Ag-Au deposit. The Sheppard Formation represents another prospective interval for the SEDEX deposits within the rift-cover sequence. Quartz arenites of the upper Appekunny and Grinnell formations and argillite of the lower Siyeh Formation have good potential for stratiform Kupferschiefer/redbed–type Cu-Ag deposits. The similar Spar Lake, Rock Creek and Montanore deposits, hosted by the stratigraphically equivalent Revett Formation in Montana, together contain a proven resource of >330 million tonnes of about 0.7% Cu and 50 ppm Ag (Lydon, 2007). Silver (±gold)–rich quartz-carbonate veins with massive galena and sphalerite cut the Siyeh Formation carbonates, and mafic intrusions throughout the Purcell strata may have potential for magmatic Cu-PGE.

Black shale of the Mississippian Exshaw Formation is the most prospective interval for the widespread, stratiform Zn-Ni-Mo (±V±PGE±Ag±Au±Cd±U±Co±Cu±As±Sb±Se±REE) deposits (Richards et al., 1994). The Exshaw black shale at Jura Creek (NTS 82O; Figure 6) and Crowsnest Pass (NTS 82G; Figure 1; J.G. Pawlowicz, pers. comm., 2009) shows the strongest multi-element enrichment, with concentrations up to 2.3 ppm Ag, 15 ppb Au, 41 ppb Pt, 28 ppb Pd, >1.0% Zn, 0.51% Ni, 0.39% V, 463 ppm Mo, 227 ppm Cd, 180 ppm Co, 169 ppm Cu, 143 ppm Li, 137 ppm Y, 60 ppm Pb, 56 ppm U, 43 ppm Th, 441 ppm As, >100 ppm Se, 75 ppm Sb, 1.9 ppm Hg, 1.23 ppm Te, 22 ppm Tl, 17 ppm Cs and 6.3% P_2O_5. The Triassic Sulphur Mountain Formation and Jurassic Fernie Group may represent other favourable intervals for black-shale polymetallic mineralization (Williamson et al., 1993).

The Cretaceous alkaline intrusions and the related Crowsnest volcanics are locally associated with epithermal Au-Ag-Cu-Pb-Zn mineralization (Goble, 1974a, b; Morton et al., 1974b; Leckie and Craw, 1995). However, recent data by AGS (Rukhlov et al., 2010; A. Rukhlov and J. Pawlowicz, Metal potential of the Rocky Mountains fold and thrust belt in southwestern Alberta: geochemical data release, work in progress, 2010) indicate slightly elevated background concentrations of Au, Pt, Pd, Cu and W for the Crowsnest volcanics, confirming the conclusion of Peterson et al. (1997) that these rocks generally have a low metal potential.

10 Lode Gold in the Western Canada Sedimentary Basin of the Alberta Interior Plains

Table 5 summarizes examples of gold-bearing metallic mineral occurrences in the Phanerozoic strata of the Western Canada Sedimentary Basin (WCSB) of the Alberta Interior Plains (Figure 6).

10.1 Historical Perspective

Metallic mineral exploration and, in a few places, mining in the WCSB have occurred intermittently on a small scale in the Interior Plains region of Alberta since the late 1800s (Olson et al., 1994; Eccles, 2000). Southern Alberta has, perhaps, the longest history of geological studies and exploration in the province—more than 140 years.

The Tertiary 'mica traps' or potassic lamprophyres and diorite porphyry, which form small intrusive plugs, dikes and a volcanic vent-intrusive complex (known as the 'Sweetgrass intrusives'; Kjarsgaard, 1994), were first described in the Milk River area of southern Alberta and adjacent Montana in the early 1870s (Dawson, 1884). These peculiar magmatic rocks subsequently received much attention until recently (e.g., Weed and Pirsson, 1895; Kemp and Billingsley, 1921; Williams and Dyer, 1930; Currie, 1976; Burwash and Nelson, 1992; Davis and Kjarsgaard, 1994; Kjarsgaard, 1994, 1997; Buhlmann et al., 2000).

The seven known outcrops in southern Alberta are part of the Eocene Sweet Grass Hills (SGH) intrusive complex (49–54 Ma), comprising five prominent buttes cored by mafic to felsic potassic intrusive rocks piercing the Phanerozoic strata as laccoliths, stocks and numerous sills and dikes in adjacent Montana (Marvin et al., 1980; Lopez, 1995). In addition to significant oil, gas and coal production on both sides of the Canada–United States border, precious- and base-metal mining took place in the Sweet Grass Hills of Montana since the early 1900s. Between 1934 and 1942, the Gold Butte placer-gold mine produced 42.3 kg of gold and 2.7 kg silver from the pediment and alluvial gravels derived from the northwest flank of Middle Butte (Gavin, 1991; Lopez, 1995). In addition, about 1.8 tonnes of ore grading 64.8 ppm Au were produced from a lode gold mine about 0.8 km to the east in 1932 (Lopez, 1995). More recent drilling and trenching revealed several styles of porphyry to epithermal precious- and base-metal mineralization at East, Middle, West and Grassy buttes, with grades up to 157.71 ppm Au and Au/Ag ratios of about 1:1 (Gavin, 1991).

Table 5. Gold occurrences of the Alberta Interior Plains.

Mineralization Type	Metal Association	Maximum Gold Grade	Host Geological Unit	Host Lithology	Geographic Area or Showing/Occurrence Name
Placer and buried placer	Au-Ag-PGE Production up to 100.9 kg/year gold	1030 ppb	Modern alluvial, glacial and preglacial deposits (Cypress Hills, Swan Hills, Hand Hills and Upland formations; Empress Group)	Consolidated and unconsolidated sand and gravel deposits	Major modern rivers and Swan Hills, Grimshaw, Heatherdown, Villeneuve, Entwistle, Whitecourt Mountain, Magrath, Smoky Tower, and Del Bonita occurrences throughout the Interior Plains
Alkaline intrusion–related, epithermal	Au-Ag-Pb-Zn-Cu (±W±Mo±As±Sb±Hg) Past producers in Sweet Grass Hills (adjacent Montana)	65 ppb	Eocene Sweetgrass intrusive-extrusive complex; Late Cretaceous Pakowki, Foremost and Oldman formations	Ultrapotassic alkali minette and benmoreite dikes, plugs, sills, explosive pipes, pyroclastic deposits, and adjacent sandstone, siltstone, shale and coal	Bear Creek, Coulee 29 volcanic-intrusive complex, 49th Parallel dikes (Milk River area, southern Alberta)
Epigenetic sediment-hosted gold (Prairie type of MVT)	Au-Ag-PGE-Cu-Mo (±Pb±Zn±Cd±Sn±Cr±V±As±Sb±Bi±Te±Ga)	837 ppb	Late Devonian Waterways and Early Cretaceous McMurray formations	Carbonates, oil-bearing sandstone, siltstone, shale and coal seams	Firebag River–Fort MacKay area, Birch Mountains (northeastern Alberta)
Polymetallic ooidal ironstone	Fe-Zn-V-Y-REE-Ni-Co-Cr-Mo-Pb-As-Sb-Ba-P (±Au±Ag±PGE±W±U±Th±Bi±Se±Te±Re±Li)	575 ppb	Late Cretaceous Bad Heart Formation	Sideritic ironstone interbedded with mudstone; volcaniclastic beds	Naylor Hills, Clear Hills, Smoky River, Chinchaga River, and Swan Hills areas (northwestern Alberta)
SEDEX and polymetallic black shale	Zn-V-Ba-Y-REE-U-Ni-Cr-Mo-Cu-Co-As-Se-Cd-Sb-Sr-P (±Ag±Au±PGE±Pb±W±Li±Hg±Bi)	138 ppb	Cretaceous Westgate, Loon River, Shaftesbury, Second White Speckled Shale, Kaskapau, and Puskwaskau formations, and Wapiti Group	Interbedded black shale, siliciclastic bone beds, concretionary and bentonite layers with massive and disseminated sulphides, phosphates, barite and volcanogenic debris; sulphide-rich sandstone and siltstone	Zama Lake area, McIvor, Peace, Simonette, Wapiti and Smoky rivers, Birch Mountains (Asphalt and Buckton prospects), Buffalo Head Hills, Caribou Mountains, and Grand Prairie area

Despite the evidence for gold, silver, copper, lead, fluorite and magnetite associated with the SGH intrusive complex and other igneous complexes of the Late Cretaceous to Oligocene Montana alkaline province (Pirsson, 1905; Larsen, 1940; Marvin et al., 1980), the related igneous rocks in southern Alberta had never been evaluated for their metallic mineral potential until Noranda Exploration Co. Ltd. performed extensive exploration in the area in the 1990s (Lau and Dudek, 1991). The prospecting, magnetic and lithogeochemical surveys revealed erratic but highly anomalous gold concentrations (up to 5.70 ppm Au and 0.4 ppm Ag in a pan concentrate and 65 ppb Au in soil samples) associated with hydrothermal brecciation, manganese and barium enrichment, as well as alteration of the Cretaceous calcareous mudstone south of the Milk River in southern Alberta, similar to epithermal systems elsewhere (e.g., Carlin, Vantage and Black Hills deposits; Lau and Dudek, 1991).

Although the results obtained by Noranda Exploration indicated some gold potential in southern Alberta, the subsequent exploration focused on diamond potential of the Sweetgrass intrusives, with metals being largely out of vogue during the early 1990s (Burwash and Nelson, 1992; Williams, 1993; Walker, 1994). This exploration shift towards diamond potential was prompted by the discoveries of diamondiferous kimberlites near Prince Albert in Saskatchewan and at Lac de Gras in the Northwest Territories in the late 1980s to early 1990s, which led to a province-wide staking rush in Alberta (e.g., Dufresne et al., 1996).

Kjarsgaard (1994, 1997) dismissed the classification of the potassic lamprophyres in southern Alberta as lamproites (Williams, 1993) and instead classified these rocks as alkali and peralkaline minettes, similar to the coeval minettes at Highwood and Bearpaw mountains in Montana, with the whole-rock and mineral chemistry being consistent with magma derivation within the diamond stability field. Moreover, Kjarsgaard (1997) compared some of the Sweetgrass minettes with the richly diamondiferous Akluilak ultrapotassic minette dike in Northwest Territories. He emphasized, however, that the inferred Proterozoic tectonothermal and metasomatic overprinting of the underlying Archean Medicine Hat basement block (Davis et al., 1995; Buhlmann et al., 2000) could have destroyed diamonds in the lithospheric mantle beneath it, perhaps explaining the lack of diamonds in both the Sweetgrass minettes of southern Alberta and the Missouri Breaks kimberlites and alnöites to the south in Montana.

In 1993, Consolidated Pine Channel Gold Corp. performed a soil lithogeochemical survey to follow up two separate magnetic 'bull's-eye' anomalies, previously identified by Noranda Exploration Co. Ltd., and analyzed three alkali olivine minette samples taken at different locations along the strike of a dike intermittently exposed over a distance of 1 km at Bear Creek (Williams, 1993). Although the soil samples did not indicate any anomalies except for a few slightly elevated values of up to 11 ppm As, 6 ppm Sb and 0.8 ppm Cd, the dike returned up to 165 ppm Zn, 105 ppm Cu, 86 ppm Pb, 0.9 ppm Ag, 8 ppm Sn, 5 ppm Sb and 1.0 ppm Cd (Williams, 1993). In 1994, Marum Resources Incorporated investigated diamond-indicator minerals and recovered gold grains, along with reporting assays up to 1.20 ppm Au, from a composite sample of the Pakowki Coulee minette plug exposed on the north bank of the Milk River, thus confirming the presence of erratic gold mineralization associated with the Sweetgrass intrusives in southern Alberta (Walker, 1994). However, Kjarsgaard (1994) reported geochemical analyses of 17 minette samples from the Milk River area, with maximum values of 6 ppb Au and 12 ppb Ir, indicating low concentrations of metals in these rocks.

During the late 1960s to early 1980s, several companies evaluated Cretaceous and Tertiary strata in southern Alberta and near Grand Prairie to the north for sediment-hosted uranium deposits, which contain large uranium resources in the United States and are important uranium producers elsewhere in the world (Olson et al., 1994). There has recently been exploration for sandstone-hosted uranium in the Cypress Hills, Milk River and Fort McLeod areas of southern Alberta, where anomalous uranium concentrations at several stratigraphic levels are locally associated with anomalous concentrations of Zn, Pb, Mo, V, Ni, Cr, Th, As and Se (Matveeva and Anderson, 2007).

Sphalerite, galena, chalcopyrite and löllingite in siltstones and sandstones of the Late Cretaceous Wapiti Group were documented in oil and gas wells in the Grande Prairie area, with assays indicating values up to 0.2% Zn and 100 ppm Pb across 3.05 m, 400 ppm Ni across 9.14 m, and 100 ppm U and 400 ppm V across 6.10 m (Olson et al., 1994). Pyritic sandstone of the Wapiti Group in outcrops along the Wapiti, Smoky and Simonette rivers in northwestern Alberta returned up to 0.2% Zn, 200 ppm Pb, 100 ppm Ni and 100 ppm Co (Edmond, 1970). Black shale interbedded with bentonite of the Cretaceous Fort St. John Group returned up to 820 ppm Zn, 310 ppm Cu, 150 ppm Ni and 18 ppm Cd across 3.05 m intervals in five diamond-drill holes by Gulf Minerals Canada Ltd. in the Steen River area of northwestern Alberta (Germundson and Fischer, 1978). In addition, La Casse and Roebuck (1978) mentioned a bornite and azurite occurrence in limy units of the Upper Cretaceous to Tertiary Paskapoo Formation in a coulee along the north bank of Red Deer River, about 9.6 km east of Red Deer (NTS 83A; Figure 1).

Discovery in 1898 of the Pine Point MVT lead-zinc deposits near the south shore of Great Slave Lake in the Northwest Territories and the subsequent development of this world-class mining district between 1936 and 1988 prompted prospecting and reconnaissance geochemical surveys in adjacent northeastern Alberta (e.g., Pană, 2006), which was considered favourable for base metals because of the Paleozoic carbonates exposure (e.g., Dufresne et al., 1994; Olson et al., 1994; Eccles, 2000). Examples of the reported carbonate-hosted base-metal mineral occurrences in outcrops from this region include

- galena in the Middle Devonian Methy Formation dolostone at Whitemud Falls along the Clearwater River;
- up to 0.1% Zn at Vermillion Chutes;
- enargite (±malachite) at three locations along the Clearwater River, west of Whitemud Falls and east of Fort McMurray; and
- unsubstantiated lead-zinc occurrences in Wood Buffalo National Park (e.g., Olson et al., 1994; Pană, 2006).

From the early 1990s to the present, AGS, GSC and industry investigated geology and mineral resources of the WCSB in northern Alberta, involving geophysical, regional lithogeochemical and kimberlite-indicator-mineral (KIM) sampling. These studies resulted in the discovery of kimberlite and ultrabasic fields in the Buffalo Head Hills, Birch Mountains and Mountain Lake areas, and showed the presence of base- and precious-metal mineralization throughout the northern Interior Plains (e.g., Fenton and Pawlowicz, 1993; Fenton et al., 1994; Eccles et al., 1998, 2001a, b; Dufresne et al., 2001; Friske et al., 2003; Adams and Eccles, 2003; McCurdy et al., 2006, 2008; Pană, 2006; Prior et al., 2006; Prior, 2007).

Several of the AGS projects focused on the MVT Pb-Zn potential of the Alberta Plains. Eccles et al. (2001a) performed C and O isotopic analyses and reported pyrite, marcasite, chalcopyrite and galena in the Upper Devonian Winterburn Group carbonates in the Peerless Lake area of northwestern Alberta (NTS 84B; Figure 1).

Attempting to delineate prospective areas for MVT and other sediment-hosted Zn, Pb, Cu, Ni, Ag and Au deposits, Adams and Eccles (2003) investigated Phanerozoic fault and brecciation zones within the WCSB that were coincident with shear zones in the underlying Precambrian basement, structural highs and stratigraphic contrasts. This work was carried out in conjunction with an investigation of formation-water salinity and lithogeochemistry of the basement, as the potential source of metals in northern Alberta.

Pană (2006) summarized MVT Pb-Zn occurrences in the Devonian carbonate-evaporite sequences of the WCSB from a total of 23 wells in the Alberta Plains, based on a previous compilation by Dubord (1987) and studies by Turner and McPhee (1994), Duggan et al. (2001) and Rice and Zerbe (2003). One of the most interesting of these occurrences, coincident with the magnetic trace of the GSLSZ, occurs in the

1280–1290 m depth interval of well 16-34-118-21W5 in northwestern Alberta (Turner and McPhee, 1994). It comprises brecciated Middle Devonian Keg River Formation dolomite containing 35 vol. % sparry dolomite with disseminated pyrite blebs and 15% fine-grained pyrite, sphalerite and minor galena as fracture filling. A sample from 1286.26 m in this drillhole returned 3.76% Zn and 732 ppm Pb (Pană, 2006).

Other Middle to Late Devonian dolostone-hosted pyrite (±sphalerite±galena ±copper sulphides) occurrences associated with fault breccias were documented in wells south of Vermilion Chutes (NTS 84J), in the Pelican Mountain area (NTS 83P) and in the Simonette (NTS 83K), Rainbow (NTS 84L), Tangent (NTS 84D), Wizard Lake (NTS 83H), Bonnie Glen (NTS 83H), Leduc (NTS 83H), Duhamel (NTS 83A), New Norway (NTS 83A) and Malmo (NTS 83A) oilfields (Olson et al., 1994; Pană, 2006, Figures 1 and 21). Reef carbonates of the Leduc Formation yielded up to 9.9% Zn and 15.3% Zn over intervals of 2.29–5.58 m (Olson et al., 1994). Some of these occurrences are associated with the highest concentrations of Zn in Alberta formation waters (Hitchon et al., 1971).

Gold exploration reintensified following reports of anomalous precious-metal concentrations in the Devonian Waterways Formation limestone exposed near Fort MacKay in northern Alberta (Dufresne and Besserer, 2003). In 1993, Focal Resources Ltd. announced assay values up to 68.6 ppm Au, 0.17% Ag, 96.0 ppm Pt, 14.1 ppm Pd, 44.6 ppm Rh, 175 ppm Os, 128 ppm Ru and 360 ppm Ir from outcrop samples, including limestone of the Devonian Waterways Formation, and from 14 drillholes on the company's Bradley property (Dufresne and Besserer, 2003). However, these highly anomalous results were obtained using unconventional analytical methods and could not be reproduced later in a certified laboratory (Dufresne and Besserer, 2003).

Industry and government (AGS and GSC) explored the potential for precious-metal mineralization in the WCSB of northeastern Alberta between 1993 and 2001. Extensive exploration in the Birch Mountains by several companies involved geological mapping, drilling, and lithogeochemical and heavy-mineral-concentrate (HMC) sampling, as summarized in two recent technical reports (e.g., Dufresne and Besserer, 2003; Sabag, 2008).

Using standard analytical methods, Dufresne et al. (1994) reported anomalous concentrations of up to

- 837 ppb Au, 1.1 ppm Ag, 553 ppm Cr, 211 ppm Zn, 97 ppm Pb, 61 ppm Cu, 58 ppm Ni, 951 ppm Sr and 257 ppm B in drillcore samples of oil-impregnated sands, silts, shales and coals of the Lower Cretaceous McMurray Formation; and
- 118 ppm Pb and 32 ppm Sb in a carbonate sample of the Upper Devonian Waterways Formation in the Firebag area.

In addition, a limited till geochemical survey indicated up to 9 ppb Au, 0.7 ppm Ag, 97 ppm Zn and 570 ppm F in the Fort MacKay area (Dufresne et al., 1994).

The sedimentary rocks adjacent to the sub-Cretaceous unconformity in northeastern Alberta showed anomalous concentrations of metals, with values up to

- 140 ppb Au, 21 ppm Ag, 24 ppb Pt and 26 ppb Pd, along with 990 ppm Cr, 150 ppm Ni, 198 ppm As, 24.2 ppm Sb, 28 ppm Bi, 27 ppm Te, 47 ppm Sn, 37 ppm Mo, 31 ppm Ga and 5 ppm Cd for sulphide-bearing sandstone of the Lower Cretaceous McMurray Formation immediately above the sub-Cretaceous unconformity; and
- 3 ppm Ag, 220 ppm Cr, 136 ppm Ni, 52 ppm Sn, 33 ppm Mo, 41 ppm As, 29 ppm Te and 26 ppm Bi for carbonates and calcareous shale of the Upper Devonian Waterways Formation immediately below the sub-Cretaceous unconformity (Dufresne and Besserer, 2003).

Dufresne and Besserer (2003) also reported analyses by standard fire-assay and instrumental neutron activation analysis (INAA) methods in several laboratories that indicated up to 0.26 ppm Au, 7 ppm Ag,

4.94 ppm Pt, 56 ppb Pd, 42 ppb Ir, 30 ppb Os, 18.4 ppb Rh and 17 ppb Ru, along with 140 ppm Cr, 101 ppm V, 41 ppm As and 31 ppm Sn, for the Devonian carbonates across a 3.6 m interval below 72.0 m in drillhole 11-7-96-10W4.

Eccles et al. (2001b) examined and sampled the Upper Devonian Waterways Formation carbonates in the Fort McMurray area to evaluate their MVT base-metal potential. They reported up to 12 ppb Au and 13 ppb Pd, along with 37.4% Fe, 0.43% Ba, 0.13% Zn, 410 ppm As, 342 ppm V and 126 ppm Ni, for a smectite layer and hydrocarbon-rich, faulted and karsted carbonates, containing up to 10 vol. % disseminated and massive sulphides, adjacent to the unconformity between the Upper Devonian Waterways Formation carbonates and the overlying Lower Cretaceous McMurray Formation sandstone and siltstone (Eccles et al., 2001b).

Using scanning electron microscopy (SEM), electron probe microanalysis (EPMA) and X-ray diffraction (XRD), Feng and Abercrombie (1994) first documented 0.5–2 μm scale native Au, Ag, Bi, Cd, Cu, Pb, Sn and Zn, along with their alloys, sulphides, oxides, chlorides, carbonates and other compounds, associated with pyrite, galena, barite, hematite, goethite, ilmenite, rutile, scheelite, $CeCO_3$, $CePO_4$ and secondary quartz in the Precambrian basement granitoids and overlying Phanerozoic rocks of the WCSB from northeastern Alberta (Abercrombie and Feng, 1997). The in situ laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) analyses, averaged over 4–15 individual spots, indicated up to 1.60 ppm Au, 30 ppb Pd, 20 ppb Rh and 10 ppb Pt for the Devonian limestones, and up to 1.08 ppm Au and 20 ppb Pd for the overlying Early Cretaceous sandstones. In addition, the conventional solution ICP-MS analyses returned up to 130 ppb Au for these rocks (Abercrombie and Feng, 1997).

In 1997, Birch Mountain Resources Ltd. re-examined the rock samples investigated by Feng and Abercrombie (1994) and ruled out possible contamination by splitting, thus confirming the presence of the microdisseminated precious- and base-metal mineralization in these samples (De Paoli et al., 1998). Based on the EPMA and SEM work, Ballantyne and Harris (1997) also documented veins (up to 0.1 mm wide) and disseminated (1–200 μm) native Cu, Au, Ag and Pt, Cu-Zn intermetallics, Au-Ag, Au-Cu, Ni-Cu-Zn, Cu-Au-Zn and Au-Ag-Cu-Zn alloys, Sr-sulphate, MoS_2, AgS and ZnS associated with organic material in Devonian carbonates from three diamond-drill holes by Tintina Mines Ltd. in the Fort MacKay area.

Homesteaders initially discovered ooidal ironstone of the Late Cretaceous Bad Heart Formation in the Clear Hills area of northwestern Alberta in 1923 (McDougall, 1954). The iron deposits were extensively explored between the late 1950s and the mid-1970s (Kidd, 1959; Bertram and Mellon, 1975), and were estimated to contain about 1.1 billion tonnes of 34% Fe (Hamilton, 1980).

In the mid-1990s, Marum Resources Inc. evaluated the Clear Hills iron deposits and reported anomalous concentrations of gold (up to 25.03 ppm) associated with the Upper Cretaceous Badheart Formation in the Botha River–Naylor Hills area of northwestern Alberta (Boulay, 1995). These results initiated further precious-metal exploration, including drilling, trenching and sampling of the ironstone deposits (Richardson, 1999; Besserer and Balzer, 2000; Bladek, 2000; Owens, 2001). Richardson (1999) reported up to 268.5 ppm Ru, 223.9 ppm Au, 69.5 ppm Ag, 59.7 ppm Pt, 44.9 ppm Pd and 29.5 ppm Rh in several soil samples. Outcrop and drillcore samples of oolitic ironstone exposed along the banks of the Botha River in the Naylor Hills area returned anomalous concentrations of up to 575 ppb Au and 7 ppm Ag (Besserer and Balzer, 2000). Owens (2001) reported 0.10–3.67 ppm Au, along with 1.4–8.6 ppm Ag, 0.48–7.99 ppm Pt and 0.07–4.83 ppm Pd in trench and outcrop rock samples.

During the last decade, AGS carried out two extensive lithogeochemical studies of the Upper Cretaceous Badheart Formation ironstone. Olson et al. (1999) analyzed 151 archived samples to evaluate the potential of coproduct trace elements within the Clear Hills iron deposits. The analyses showed anomalous concentrations of up to 36 ppb Au, 1 ppm Ag, 6.3 ppb Pt and 5.1 ppb Pd, along with 0.23% Ba, 0.16% V,

0.10% As, 808 ppm Zn, 250 ppm Ni, 210 ppm Co, 180 ppm Cr, 152 ppm Y, 92 ppm Mo, 75 ppm Sb, 59 ppm Pb, 17 ppm Bi, 11 ppm W, 7 ppm Se and 10.54% P_2O_5 (Olson et al., 1999).

More recently, sampling of ooidal ironstone from the Smoky River and Clear Hills regions (NTS 84C–E; Figure 6) confirmed the polymetallic enrichment of the Clear Hills iron deposits, yielding values up to 0.26% V, 0.16% Ba, 0.10% Zn, 766 ppm of total REE, 499 ppm As, 317 ppm Y, 304 ppm Cr, 240 ppm Ni, 213 ppm Ce, 151 ppm Li, 133 ppm Co, 122 ppm Pb, 39 ppm Mo, 32 ppm W, 29 ppm U, 25 ppm Th, 18 ppm Sb, 3.6 ppm Cd, 2.6 ppm Bi, 2.3 ppm Te and 9 ppb Re. However, anomalous Au and/or Ag concentrations were not detected (Kafle, 2009).

Based on another regional geochemical study, Dufresne et al. (2001) concluded that the Bad Heart Formation ooidal ironstone has the highest concentrations of As (up to 360 ppm), Sb, Te and W in northern Alberta, along with the anomalous V, Zn, Co, Cr, Ni and Pb contents. The sulphide-rich zones in the oolitic and volcaniclastic units penecontemporaneous with the Badheart Formation yielded up to 47.2 ppm Au, 325 ppm Ni and 230 ppm Co, along with the anomalous As, Sb, Te, Bi, Pb, Zn, V, Cd and other element concentrations, in the Chinchaga River area (Besserer and Balzer, 2000; Dufresne et al., 2001). In addition, a shale unit of the Westgate Formation returned up to 15 ppb Au, 150 ppm As and 0.37% Ba, along with the elevated Fe, Mn and S contents, in the Peace River area (Dufresne et al., 2001). Metal exploration is still active at the Clear Hills iron deposits (e.g., Stapleton, 2008).

The Upper Cretaceous Colorado Group black shale has been a target of recent geochemical sampling programs and exploration for exhalative base- and precious-metal deposits (e.g., Dufresne et al., 2001; Prior et al., 2006; Sabag, 2008). Ballantyne and Harris (1997) documented native Ag and Au-Ag crystals (>100 μm), and intergrowths with Ag, Cu and Fe sulphides, carbonates and silicates, in heavy-mineral concentrates from drainages and outcrops of the Late Cretaceous Shaftesbury Formation black shale in the McIvor River area of northern Alberta.

Fenton and Pawlowicz (1998) performed a reconnaissance till geochemical survey across northern Alberta that showed a number of local multi-element anomalies, with the highest metal concentrations associated with subcrops of the Upper Cretaceous Shaftesbury Formation in addition to anomalies in the Clear Hills and Naylor Hills areas (NTS 84E; Figure 6).

Dufresne et al. (2001) and Prior et al. (2006) carried out regional geochemical sampling of the Late Cretaceous Loon River, Shaftesbury, Kaskapau, Puskwaskau and Bad Heart formations in northern Alberta. Samples returned up to 12 ppb Au, 3.8 ppm Ag and 11 ppb Ir, along with 61.8% Fe_2O_3, 23.14% P_2O_5, 7.20% Ba, 1.47% As, 0.28% Sr, 0.16% V, 0.10% Zn, 611 ppm Y, 559 ppm Ce, 432 ppm U, 397 ppm Ni, 258 ppm Cu, 240 ppm Mo, 221 ppm Co, 209 ppm Cr, 164 ppm Li, 135 ppm Pb, 47 ppm Se, 32 ppm Sb, 20 ppm Cd, 11 ppm W and 3.8 ppm Hg.

Extensive exploration by industry, involving outcrop sampling and drilling, and regional geochemical sampling by AGS in the Birch Mountains showed highly anomalous concentrations of metals and other elements in interbedded black shale, siliciclastic bone beds and concretionary and bentonite units of the Upper Cretaceous Second White Speckled Shale Formation. Values ranged up to 138 ppb Au, 3.6 ppm Ag, 22 ppb Pt and 14 ppb Pd, along with 16.54% P_2O_5, 3.1% Ba, 0.15% Sr, 0.11% Zn, 0.13% V, 800 ppm Y, 780 ppm Ce, 530 ppm Cr, 510 ppm Ni, 470 ppm As, 250 ppm U, 231 ppm Mo, 181 ppm Cu, 180 ppm Co, >100 ppm Se, 66 ppm Cd, 51 ppm Sb, 17 ppm Bi and 13 ppm W (Dufresne et al., 2001; Sabag, 2008; J. G. Pawlowicz, pers. comm., 2009).

Plouffe et al. (2006) discovered anomalous concentrations of detrital sphalerite with minor galena (>1000 grains in a 20 kg sample) in the coarse sand fraction of glaciogenic sediments about 20 km north of Zama City, which led to staking of the land and recent base-metal exploration in northwestern Alberta. The

dispersed Zn-Pb sulphide grains concentrate in a broad band, subparallel to the northeast-trending GSLSZ, over an area of approximately 1200 km^2 (Plouffe et al., 2008).

Elsewhere in the Alberta Plains region, Sharata Resources Ltd. reported up to 1.0 ppm Ag, 603 ppm Zn, 398 ppm Pb, 154 ppm Cr and 6.3 ppm Cd for the Tertiary Paskapoo Formation sandstone exposed along the Athabasca and McLeod rivers to the east of Hinton (Chin and Olson, 1998). Following up the anomalous placer-gold concentrations, several companies carried out high-resolution aeromagnetic and lithogeochemical surveys, drilling and trenching in the Swan Hills area of central Alberta and reported a discovery of bedrock ironstone containing up to 52.2 wt. % Fe_2O_3 (as total iron), along with anomalous As, Sb and Te concentrations (Dufresne, 2005).

10.2 Types of Mineral Occurrence and Hypotheses of Origin

10.2.1 Ooidal Ironstone Polymetallic Deposits

The ooidal ironstone comprises a 1.5–9 m thick unit with interbeds of sideritic ironstone and mudstone of the Late Cretaceous (Coniacian) Bad Heart Formation within dominantly deep-water marine shale of the Smoky River Group in the Clear Hills and Smoky River regions of northwestern Alberta (Hamilton, 1980). The ooidal ironstone is interpreted to have been deposited in a shallow, clastic, starved-marine environment (e.g., Olson et al., 1999). The proposed hypotheses for the origin of high Fe, Si and P concentrations and stratigraphy of the Bad Heart Formation ooidal ironstone include

- weathered continental source of iron and subsequent diagenesis of original minerals (Donaldson, 1997), and
- magmatic-fumarolic activity or deep-circulating basin fluids producing vast amounts of iron in seawater during deposition of the Bad Heart Formation (e.g., Olson et al., 1994, 1999).

Olson et al. (1994, 1999) and Dufresne et al. (2001) favoured a hydrothermal model for the Clear Hills iron deposits, based on evidence of local volcanism in the Chinchaga River area (NTS 84E; Figure 6) and extensional faulting in the PRA during deposition of the Bad Heart Formation. The locally anomalous paleobiota concentrations support the hydrothermal-venting or sedimentary-exhalative hypothesis. This is similar to those of the modern seafloor hydrothermal-seep environment (Collom, 1997) and by the anomalous concentrations of Zn, V, REE, Y, Ni, Co, Cr, Mo, Pb, As, Sb (±Au±W±U±Th±Cd±Bi±Te±Re±Ba±Hg ±Li; Olson et al., 1999; Dufresne et al., 2001; Kafle, 2009). The northwest-trending brittle basement faults that were active during the Late Cretaceous (Donaldson et al., 1999) might have channelled the metalliferous hydrothermal fluids.

10.2.2 Stratiform Exhalative Sulphide and Black Shale Polymetallic Mineralization

The stratiform sediment-hosted base- and precious-metal mineralization comprises massive and disseminated sulphides and native Au-Ag associated with carbonate veins, phosphates, barite and hydrothermal alteration in carbonaceous black shale interbedded with siliciclastic-rich bone beds and concretionary and bentonite layers of the Upper Cretaceous Westgate, Loon River, Shaftesbury, Second White Speckled Shale, Kaskapau and Puskwaskau formations in northern Alberta (Dufresne et al., 2001; Prior et al., 2006; Sabag, 2008). This syngenetic exhalative mineralization is formed by seafloor hydrothermal discharge and includes both the SEDEX Pb-Zn-Ag-Au and the black shale Ni-Zn-Mo-U-V-Cu-Co-Ag-Au-PGE types in the Peace River (NTS 84C), Buffalo Head Hills (NTS 84F, G), Birch Mountains (NTS 74E, 84H, I) and Caribou Mountains (NTS 84J) areas (Figure 6; Dufresne et al., 2001; Sabag, 2008).

The Shaftesbury Formation shale has higher Ag, Cu, Co, Ni and Cd concentrations in the Buffalo Head Hills and Caribou Mountains than in the Birch Mountains and Peace River area (Figure 6). The Loon River Formation shale with concretionary and bentonite interbeds shows the highest Ag, As, Cu, Ni, V

and Ba concentrations, which are correlated with an increase in the number of bentonitic units in the Buffalo Head Hills and Caribou Mountains, indicating a relationship between volcanic activity and metal concentrations (Dufresne et al., 2001).

Interbedded black shale, siliciclastic bone beds and concretionary and bentonite layers of the Second White Speckled Shale Formation contain up to 20% fine-grained sulphides (mostly FeS), 3%–29% organic carbon and the highest concentrations of metals compared to all other Cretaceous shales in the Birch Mountains area (Dufresne et al., 2001; Sabag, 2008). The polymetallic sulphide mineralization correlates with abundant bentonitic seams, coincident with the positive aeromagnetic anomalies, stratigraphic thickening and fault zones (Sabag, 2008). In addition, the Second White Speckled Shale Formation shows a distinct shale-normalized REE distribution, characterized by negative Ce and positive Eu spikes, and correlation of metals with strong S-Fe-Ba-As-Sb enrichment, indicative of euxinic, low-temperature hydrothermal activity (Dufresne et al., 2001). The presence of magmatic indicator minerals and pyroclastic material, accompanied by the increasing volume of bentonitic horizons, abundant sulphides and Ba enrichment, at the top of the Second White Speckled Shale Formation may indicate a proximal source of volcanogenic debris and exhalative activity in the Birch Mountains area (Sabag, 2008).

Paulen et al. (2007) concluded that the anomalous concentrations of detrital sphalerite grains with minor galena in glaciogenic sediment of the Zama Lake area in northwestern Alberta could not have been transported from the Devonian carbonate–hosted Pine Point MVT Pb-Zn deposits about 330 km to the northeast, but instead must have derived from a proximal Cretaceous bedrock source.

The stratiform sediment-hosted mineralization within the Cretaceous strata of the Alberta Plains is similar to the syngenetic base- and precious-metal occurrences in the deformed WCSB of the Alberta Rocky Mountain fold-and-thrust belt, representing a distinct metallogenic interval associated with syndepositional extensional faulting, magmatism and hydrothermal convection in the foreland basin.

10.2.3 Epigenetic, Sediment-Hosted, Microdisseminated Precious-Metal Mineralization

Epigenetic, sediment-hosted, microdisseminated Au-Ag-Cu-PGE mineralization occurs within the Devonian carbonate and Lower Cretaceous clastic strata near the edge of the WCSB in the Birch Mountains and Fort MacKay area of northeastern Alberta (Feng and Abercrombie, 1994). The Fort MacKay area is underlain by the dissolution edge of the evaporitic Middle Devonian Prairie Evaporite Formation of the Upper Elk Point Group, where hydrochemical transition occurs from the lower relatively oxidized brine regime (Precambrian basement and Elk Point Group) to the upper reduced zone (Beaverhill Lake Group). The dissolution of salt over a 20–30 km wide band parallel to the WCSB margin resulted in deformation and collapse of the overlying strata, producing vertical joints, tensional fractures and minor faults that may act as conduits for the metal-rich brines (Eccles et al., 2001b; Eccles and Pană, 2003).

McDonough and Abercrombie (1995) suggested that structurally controlled convection of mineralized fluid could explain copper mineralization associated with the gossans and calcite-pyrite veins cutting the Precambrian basement and the overlying Middle Devonian strata at Stony Islands and karsted Keg River limestones in the Salt River area. Consistent with this hypothesis, carbonate material from a recent spring in the Fort MacKay area showed up to 0.5 ppm Ag, 54 ppm Pb, 120 ppm Cr and 472 ppm Sr (McDonough and Abercrombie, 1995). Eccles et al. (2001b) pointed out that the distribution of sulphide mineralization correlates with aeromagnetic lineaments and surface-fault expressions, marked by tensional fractures filled with argillaceous residue and by sideritization and silicification of the Upper Devonian Waterways Formation carbonates and along the sub-Cretaceous unconformity in the Athabasca River area, west of Fort McMurray.

Attempting to explain the sediment-hosted precious-metal mineralization in northeastern Alberta, Feng and Abercrombie (1994) proposed a 'Prairie-type' deposit model, in which reduced formational fluids interact with sulphate-rich evaporites and red beds to become oxidized brines. The latter leach gold and other metals from the Precambrian basement and/or redbed units and carry the metals as chloride complexes. The metal-loaded solutions migrating across formations at the solution front of the Prairie Evaporite Formation and/or along fault-breccia zones deposit the metals either at a reducing interface (e.g., organic matter in the overlying carbonates and clastics) or due to mixing with fluids of contrasting Eh, pH or salinity (Abercrombie and Feng, 1997).

Jedwab (1993) reported the occurrence of palladian gold, sperrylite, isoferroplatinum (Pt_3Fe), palladoarsenide (Pd_2As) and other PGEs in silicified dolostones of the Lower Roan in the southwestern Katanga Province of the Democratic Republic of the Congo. Based on the mineralogical and textural evidence, Jedwab (1993) suggested that these PGEs might have a sedimentary origin genetically connected with the evaporitic environment. Harris and Ballantyne (1994) implied that PGEs in Alberta could have derived from a similar type of environment.

Eccles et al. (2001a) suggested that Phanerozoic faults controlled the convection of hydrothermal fluids that produced the epigenetic pyrite-marcasite-chalcopyrite-galena mineralization within carbonates of the Upper Devonian Winterburn Group in the Peerless Lake area of northwestern Alberta. The sub-Cretaceous unconformity and vertical tensional fractures channelled the low-temperature mineralized hydrothermal or formational fluids, which deposited base and precious metals under the locally prevailing reducing conditions (Eccles et al., 2001b).

In general, the epigenetic, sediment-hosted, structure-controlled precious-metal mineralization in northeastern Alberta may represent a variant of the MVT deposits (see Pană [2006] for a comprehensive review of Alberta's MVT occurrences and discussion of the proposed deposit models). Several lines of evidence seem to favour the formation of MVT dolomitization and base-metal mineralization by hydrothermal-fluid convection within the WCSB along the brittle fault zones spatially associated with the Early Proterozoic zones of strain in the crystalline basement, which were reactivated during Cordilleran orogenic tectonism (e.g., Pană, 2006; Paradis et al., 2007).

10.2.4 Alkaline Intrusion-Related, Epithermal Gold-Silver-Copper-Lead-Zinc Mineralization

Epithermal Au-Ag-Pb-Zn-Cu (±W±Mo±As±Hg±Sb) mineralization is associated with the Eocene Sweetgrass intrusive-volcanic complex (50–49 Ma) in southern Alberta (Lau and Dudek, 1991; A. Rukhlov and J. Pawlowicz, Metal potential of the Eocene Sweetgrass intrusive complex in southern Alberta and northern Montana: geochemical data release, work in progress, 2010). The Sweetgrass complex comprises alkali to peralkaline minette and benmoreite plugs (ranging from 25 m by 20 m to 400 m by 200 m), dikes (0.5–3 m thick) and a vent-intrusive complex (450 m by 150 m) exposed at seven localities in the Milk River area of southern Alberta (Burwash and Nelson, 1992; Kjarsgaard, 1994). Ross et al. (1997) interpreted the northwest- and north-northeast-trending linear magnetic anomalies within the WCSB strata of southern Alberta as subvertical dikes, suggesting that the region of the Eocene potassic magmatism might extend northward to the Lethbridge area. Pardasie (2003) confirmed that two northwest-trending (304°) magnetic anomalies are best explained as subparallel, subvertical (63°SW dip) dikes (4–20 m thick) 65–85 m deep below the surface, although the features are perhaps too small to be resolved using a seismic survey.

The Eocene igneous rocks in southern Alberta are part of the coeval Sweet Grass Hills (SGH) intrusive complex (54–50 Ma), composed of mafic to felsic potassic laccoliths, stocks, plugs and numerous sills and dikes piercing the Paleozoic and Mesozoic sedimentary rocks in the cores of five prominent, northwest-trending buttes in adjacent Montana (Lopez, 1995). The SGH intrusive complex, including the Alberta exposures and the Missouri Breaks, Eagle Buttes, Highwood Mountains and Bearpaw Mountains

igneous complexes, mark the Eocene (55–49 Ma) peak of the magmatic activity within the Late Cretaceous–Oligocene (69–27 Ma) Montana alkaline province (Pirsson, 1905; Larsen, 1940; Currie, 1976; Hearn et al., 1978; Marvin et al., 1980; Kjarsgaard, 1997).

On a regional scale, the Montana alkaline province (MAP) and the coeval Challis calcalkaline volcanic field (49–44 Ma) to the southwest in Idaho follow the northeast-trending Eocene dome that coincides with the Great Falls Tectonic Zone (GFTZ; O'Neill and Lopez, 1985). The GFTZ is a repeatedly reactivated zone of crustal weakness interpreted to be a Proterozoic suture separating the Medicine Hat basement block of the Archean Hearn craton to the north from the Archean Wyoming craton to the south (Ross et al., 1991). Recent studies, however, proposed that the Medicine Hat block might be a northern extension of the Wyoming craton and that the GFTZ does not represent a Proterozoic suture zone (e.g., Buhlmann et al., 2000).

Mutschler et al. (1991) suggested that the GFTZ might have acted as a Late Cretaceous–Eocene transtensional zone between the large-scale, northwest-trending, right-lateral transcurrent faults related to the Laramide Orogeny. The resulting upflow of hot asthenospheric mantle beneath the thinned lithosphere and decompression melting would have produced the diversity of igneous rocks seen in the MAP and Challis volcanic field. The large hydrothermal gold deposits associated with these igneous centres (e.g., Zortman and Landusky mining areas in the Little Rocky Mountains) might have been generated by deep-source mantle fluids that were channelled upward with the alkaline magmas along the GFTZ during the late Laramide extension (Mutschler et al., 1991).

Notably, the Sweet Grass Hills of Montana lie isolated from the main part of the MAP, well to the north of the inferred GFTZ and on the northeast flank of the Sweetgrass Arch, a repeatedly uplifted Precambrian structure that was rejuvenated and offset by the northeast-trending Pendroy and Scapegoat-Bannatyne dextral strike-slip faults during the Laramide Orogeny (Lopez, 1995). Emplacement of the SGH magmas could have been controlled by the pre-existing, northwest-trending, basement fracture systems manifested as the geopotential anomalies in the Medicine Hat block and the predominant surface faults in the Sweet Grass Hills of Montana (Lopez, 1995).

Several styles of epithermal Au-Ag-Cu-Pb-Zn mineralization occur in the Sweet Grass Hills of Montana, including

- conformable planar or irregular to nearly spherical replacement zones composed of quartz, fluorite, calcite, gypsum, barite, hematite (specularite), limonite, pyrite and other sulphides in recrystallized, silicified and brecciated limestones of the Mississippian Madison Group adjacent to an augite syenite porphyry showing propylitic to strong argillic alteration and silicification; gold is present in the limestone-solution and marble breccias and in the syenite porphyry (e.g., 1.41–5.07 ppm Au, with Au/Ag ratio of about 1:1, across a 12.5 m interval at Tootsie Creek);
- Au-Te mineralization associated with a quartz-fluorite-pyrite (±calcite-chlorite) stockwork and vein-proximal propylitic and moderate argillic alteration in augite syenite (e.g., 1.03–3.43 ppm Au, with Au/Ag ratio of about 1:1, over a 6.1 m interval southwest of Devils Chimney at Tootsie Creek);
- copper porphyry–like chalcocite-galena vein mineralization with abundant silver and minor gold, controlled by shear and breccia zones in syenite porphyry (e.g., Brown Eyed Queen mine and Gagnon prospect southwest of Mount Royal);
- Limonitized breccia zones with chalcopyrite, pyrite and specularite mineralization in highly altered (possibly argillic and propylitic) trachyte porphyry sills and dikes that cut the Early Cretaceous Kootenai Formation clastic rocks (e.g., on the ridge between Breed Creek and Bear Gulch);
- erratic gold mineralization associated with discontinuous pods of disseminated pyrite, silicification and bleaching along a west-northwest-trending shear zone that cuts hornfelsed Cretaceous Colorado

Group shales intruded and engulfed by numerous dikes, sills and irregular masses of mafic syenite, diorite porphyry and lamprophyres showing weak to moderate propylitic alteration (e.g., 0.34–157.71 ppm Au, with Au/Ag ratio of about 1:1, across a 3 m interval at the Gold Butte mine on the northwest flank of Middle Butte);

- gold mineralization associated with jarosite, goethite, minor pyrite, silicification, brecciation and fractures along the intrusive contact between a felsite 'diatreme' (high-potassic rhyolite breccia) and hornfelsed sandstones, siltstones and shales of the Late Cretaceous Montana Group at Grassy Butte; the Grassy Butte deposit contains a geological resource of 0.36 million tonnes of 1.65 ppm Au, with grades up to 3.09 ppm Au across a drilled interval of 46 m.
- Au, Pb, Ag and very fine grained fluorite mineralization along parallel, northeast-trending and weaker northwest- and north-trending linear bands or shear zones cutting pyritized, propylitized and weakly to strongly argillitized intrusive breccia pipes associated with trachyandesite, trachyte porphyry, phonolite and tephrite laccolithic domes within mudstones and shales of the Late Cretaceous Marias River (Colorado Group) and Telegraph Creek (Montana Group) formations at West Butte (Gavin, 1991; Lopez, 1995; Carlson, 1999).

The Eocene alkali to peralkaline minette intrusions, volcanics and adjacent sandstones, siltstones and shales of the Late Cretaceous Pakowki, Foremost and Oldman formations contain up to 9 ppb Au, 2.8 ppm Ag, 491 ppm Zn, 402 ppm Pb, 181 Cu and 59 ppm Mo, along with elevated As, W, Sn, Sb, Cd, Tl, Se, Te and Re concentrations in the Milk River area of southern Alberta (A. Rukhlov and J. Pawlowicz, Metal potential of the Eocene Sweetgrass intrusive complex in southern Alberta and northern Montana: geochemical data release, work in progress, 2010). The epithermal precious- and base-metal mineralization occurs in

- rusty quartz-carbonate veins cutting the intrusive and volcanic rocks (e.g., Coulee 29 vent-intrusive complex);
- hornfelsed Cretaceous sedimentary rocks adjacent to the intrusives (e.g., 49th Parallel dike); and
- hydrothermally brecciated, Mn- and Ba-rich, calcareous mudstone with abundant calcite-quartz-kaolinite-hematite veinlets and alteration selvages (e.g., Bear Creek; Lau and Dudek, 1991; A. Rukhlov and J. Pawlowicz, Metal potential of the Eocene Sweetgrass intrusive complex in southern Alberta and northern Montana: geochemical data release, work in progress, 2010).

In addition, the Sweetgrass potassic lamprophyres contain up to 0.60% Ba, 0.49% F, 0.22% Sr, 0.12% Cr, 535 ppm Ni, 17 ppb Pd, 12 ppb Ir and 5.9 ppb Pt, reflecting their primary mineral chemistry (i.e., phlogopite, olivine, clinopyroxene, oxides, potassium feldspar and carbonate), and trace amounts of possibly magmatic PGE mineralization (Kjarsgaard, 1994; A. Rukhlov and J. Pawlowicz, Metal potential of the Eocene Sweetgrass intrusive complex in southern Alberta and northern Montana: geochemical data release, work in progress, 2010).

10.3 Future Potential

Available data indicate several types of bedrock metallic mineralization, with trace to significant concentrations of gold and other precious metals in the Alberta Plains region, including syngenetic SEDEX and black shale–hosted polymetallic, alkaline intrusion–related epithermal and the epigenetic sediment-hosted 'Prairie-type' variant of MVT deposits. Highly anomalous and, in some cases, potentially economic concentrations of Au, Ag, PGE and other metals occur within the Cretaceous Colorado Group and equivalent sedimentary rocks of the Peace River, Buffalo Head Hills, Caribou Mountains and Birch Mountains areas of northern Alberta.

Ooidal ironstone deposits of the Late Cretaceous Bad Heart Formation are considered the largest iron resource in Western Canada, with potential coproduct V, Zn, Au and other metals (Boulay, 1995; Olson et

al., 1999; Kafle, 2009). Further exploration for precious and base metals in the Peace River area should concentrate on fault zones as potential conduits for seafloor hydrothermal-discharge centres.

Other prospective units for syngenetic stratiform base- and precious-metal deposits include black shale units of the Westgate, Loon River, Shaftesbury, Second White Speckled Shale, Kaskapau and Puskwaskau formations (Dufresne et al., 2001; Prior et al., 2006; Sabag, 2008).

The Second White Speckled Shale Formation is a favoured exploration target because it contains the highest metal concentrations of any Cretaceous shale in Alberta (Dufresne et al., 2001). There are two potential black-shale polymetallic deposits, about 30 km apart, in the Birch Mountains area of northern Alberta:

- The Buckton zone contains 1.1–1.2 billion tonnes grading 623–776 ppm V, 282–360 ppm Zn, 121–160 ppm Ni, 70–83 ppm Cu, 62–86 ppm Mo, 25–37 ppm U, 19–24 ppm Co and 0.3–0.8 ppm Ag across a 20.5–21.9 m thick section of the Second White Speckled Shale Formation over an area of about 26 km^2.
- The Asphalt zone contains 99–120 million tonnes grading 664–690 ppm V, 282–376 ppm Zn, 122–144 ppm Ni, 89 ppm Cu, 63–73 ppm Mo, 31–47 ppm U, 20 ppm Co and 0.3 ppm Ag across a 7.2–11.6 m thick section of the same strata over an area of approximately 4.5 km^2 (Sabag, 2008).

These polymetallic V-Zn-Ni-Mo (±Cu±Co±Ag±Au±PGE) prospects are similar to black-shale Ni-Zn-Mo occurrences in the Mississippian Exshaw Formation of southwestern Alberta, the Nick deposit in British Columbia and producers in southern China (e.g., Lefebure and Coveney, 1995; Lott et al., 1999). The anomalous concentrations of detrital sphalerite with minor galena and sporadic gold in the glaciogenic sediment over approximately 1200 km^2 in the Zama Lake region of northwestern Alberta (Plouffe et al., 2006, 2008) may indicate a potential for local SEDEX Pb-Zn-Ag-Au sulphide deposits (Paulen et al., 2007).

The Eocene Sweetgrass igneous complex of southern Alberta has potential for alkaline intrusion–related epithermal precious and base metals (Lau and Dudek, 1991; A. Rukhlov and J. Pawlowicz, Metal potential of the Eocene Sweetgrass intrusive complex in southern Alberta and northern Montana: geochemical data release, work in progress, 2010), similar to deposits associated with the main Sweet Grass Hills intrusive complex to the south in Montana and other igneous complexes of the Montana alkaline province (Gavin, 1991; Lopez, 1995; Carlson, 1999).

Favourable conditions for potential epigenetic sediment-hosted Au-Ag-PGE (Prairie-type) and other MVT Pb-Zn (±Ag±Cu) deposits, controlled by Phanerozoic fault and breccia zones coincident with zones of strain in the Precambrian basement, structural highs, unconformities, hydrocarbon reducing interface and highly saline formation brines, may occur in several areas within

- Middle–Late Devonian carbonates (1.7–0.5 km deep) along the Great Slave Lake Shear Zone–Hay River Fault Zone in northwestern Alberta;
- Devonian carbonate and Early Cretaceous clastic strata along brittle faults, salt-dissolution structures and the sub-Cretaceous unconformity near the edge of the WCSB (e.g., Vermillion Chutes, Birch Mountains and along the Clearwater, Athabasca and Firebag rivers) in northeastern Alberta;
- Late Devonian Wabamun Group and Mississippian Banff Formation carbonates in the subsurface along the Peace River Arch in western Alberta; and
- Middle–Late Devonian carbonates (3.8–0.23 km deep) along the Snowbird Tectonic Zone and Rimbley-Meadowbrook and Wimborne-Bashaw reefs in central Alberta (e.g., Eccles et al., 2001b; Adams and Eccles, 2003; Eccles and Pană, 2003; Rice and Zerbe, 2003; Pană, 2006).

Despite locally anomalous precious-metal concentrations, exploration by several companies failed to locate economic Prairie-type gold mineralization within the Phanerozoic strata in northeastern Alberta (e.g., Dufresne and Besserer, 2003).

Finally, Alberta's oil sands reserves in the Lower Cretaceous McMurray Formation have been recognized as a potentially economic source of gold, PGE, rutile, zircon, monazite and other heavy minerals that could be selectively enriched in the tailings from the oil sands bitumen recovery process used by Suncor and Syncrude in the Fort McMurray area (Eccles, 2000; Dufresne et al., 2001). Potential coproducts of the oil sands include Ti, Zr, W, REE, V, Al, Au, PGE and base metals. Olson et al. (1994) reported up to 2.52% V, with significant Ti, Ni, Cu, Ga, Sc, Au and Ag, in fly ash from the oil sands processing by Suncor at Fort McMurray.

Based on the estimated oil sands reserves and geochemistry of the oil sands tailings (grading 6.5–8.1% Ti), the oil sands may constitute a world-class polymetallic deposit containing up to 50 million tonnes of aluminum, 5 million tonnes of titanium, 9922 tonnes of silver and 1417 tonnes of gold (Dufresne et al., 2001). An estimated production of 0.29 million tonnes of titanium concentrate per year from the oil sands

tailings at Fort McMurray would rank as the second largest of its type in Canada and the world's ninth-largest titanium producer (Eccles, 2000). In 2008, Titanium Corporation Inc. continued heavy-mineral studies to optimize the higher grade zircon recovery from the oil sands tailings.

11 Conclusions

Alberta's complex bedrock geology favours several distinct types of metallic mineralization with trace to significant amounts of gold. The documented precious- and base-metal mineral occurrences and geochemical anomalies indicate significant metallogenic potential for 1) the Precambrian shield and Athabasca Basin in the northeast and 2) several metallogenic intervals related to syndepositional rifting, orogenies, recurrent magmatism and hydrothermal activity during Western Canada Sedimentary Basin (WCSB) deposition in the rest of the province. Modern and preglacial placers are the only sources of current gold production, as a byproduct of aggregate operations in Alberta. Other potential deposit types include

- granitoid intrusion– and/or shear-related quartz-carbonate vein Au-Ag-As (±W±Mo±Bi) in the Precambrian shield of northeastern Alberta and mesothermal Au-Ag-Cu-Pb veins in the Rocky Mountains of southwestern Alberta;
- iron-oxide breccia/vein and unconformity-associated Cu-Au-Ag-U-REE (±PGE±Ni±Co) in the Precambrian shield of northeastern Alberta;
- volcanogenic–sedimentary exhalative Zn-Pb-Cu-Ag-Au-Co, including the Broken Hill type, Blackbird type and ooidal ironstone, in the Precambrian shield of northeastern Alberta, within the Mesoproterozoic Purcell rift successions of southwestern Alberta and in the Late Cretaceous basins of the WCSB in northern Alberta;
- stratiform black-shale Ni-Mo-Zn-PGE (±Cu±Ag±Au±V±Cr±Co±U±REE±P) within the Paleozoic and Mesozoic shale basins of the WCSB in southwestern and northern Alberta;
- epithermal Au-Ag (±Cu±Zn±Pb±Mo±W) related to the Cretaceous (Crowsnest-Flathead) and Eocene (Sweetgrass) pulses of alkaline magmatism in southwestern and southern Alberta, respectively;
- magmatic-hydrothermal Cu-PGE (±Au±Ag±Pb±Zn±Ni±Cr±Co±V) associated with the syn-rift Precambrian mafic magmatism in the Rockies, the Cretaceous kimberlite-ultramafic bodies in northern Alberta and the Eocene alkali minettes in southern Alberta;

- Kupferschiefer/redbed–type stratiform Cu-Ag (±Au±Pb±PGE±U) in the Mesoproterozoic Purcell rift successions of southwestern Alberta; and
- epigenetic sediment-hosted Au-Ag-PGE (±Cu±Mo±Pb±Zn±Ni) variety of Mississippi Valley-type deposits within the WCSB, related to fluid convection along reactivated zones of crustal weakness during Cordilleran tectonism.

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