Unravelling the structural control of Mississippi Valley-type deposits and prospects in carbonate sequences of the Western Canada Sedimentary Basin

D. Pană[1]

Pană, D., 2006: Unravelling the structural control of Mississippi Valley-type deposits and prospects in carbonate sequences of the Western Canada Sedimentary Basin; *in* Potential for Carbonate-hosted Lead-zinc Mississippi Valley-type Mineralization in Northern Alberta and Southern Northwest Territories: Geoscience Contributions, Targeted Geoscience Initiative, (ed.) P.K. Hannigan; Geological Survey of Canada, Bulletin 591, p. 255–304.

Abstract: Re-examination of selected MVT outcrops and cores in the Interior Plains and Rocky Mountains of Alberta, corroborated with previous paragenetic, isotopic and structural data, suggests Laramide structural channelling of dolomitizing and mineralizing fluids into strained carbonate rocks. At Pine Point, extensional faults underlying the trends of MVT ore bodies and brittle faults overprinting the Great Slave Lake Shear Zone define a pinnate fault geometry and appear to be kinematically linked. Chemical and isotopic characteristics of MVT parental fluids are consistent with seawater and brine convection within fault-confined vertical aquifers, strong water-basement rock interaction, metal leaching from the basement, and focused release of hydrothermal fluids within linear zones of strained carbonate caprocks. Zones of recurrent strain in the basement and a cap of carbonate strata constitute the critical criteria for MVT exploration target selection in the WCSB.

Résumé : Un nouvel examen de certaines carottes et de certains affleurements de corps minéralisés de type Mississippi-Valley dans les Plaines intérieures et les Rocheuses de l'Alberta, corroboré par des données paragénétiques, isotopiques et structurales antérieures, donne à penser qu'il y a eu canalisation structurale des fluides dolomitisants et minéralisateurs dans des roches carbonatées déformées au cours de la phase laramienne. À Pine Point, des failles de distension sous des corps minéralisés de type Mississippi-Valley et des failles cassantes en surimpression sur la zone de cisaillement du Grand lac des Esclaves, déterminent une géométrie pennée et semblent présenter un lien cinématique. Les caractéristiques chimiques et isotopiques des fluides parentaux des gisements de type Mississippi-Valley sont compatibles avec une convection d'eaux de mer et de saumures dans des aquifères verticaux limités par des failles, avec une forte interaction entre l'eau et le socle, avec un lessivage des métaux du socle et avec la libération concentrée de fluides hydrothermaux dans des zones linéaires de roches couvertures carbonatées déformées. La présence de zones de déformation récurrente dans le socle et l'existence d'une couverture de strates carbonatées sont les critères essentiels pour le choix des cibles d'exploration à la recherche de gisements de type Mississippi-Valley dans le Bassin sédimentaire de l'Ouest du Canada.

[1] Alberta Geological Survey, 4th Floor, Twin Atria Building, 4999 – 98th Avenue, Edmonton, Alberta, T6B 2X3, Dinu.Pana@gov.ab.ca

INTRODUCTION

Mississippi Valley-Type (MVT) deposits typically consist of zinc, lead, and iron sulphides occasionally associated with minor copper and silver, occurring as open-space fillings in carbonate breccia and subordinately as replacement of breccia fragments and wallrock. Usually, MVT districts include clusters of discordant orebodies hosted by highly brecciated dolostone. Popular genetic models for MVT deposits include compaction- and gravity-driven migration of metal-bearing brine through foreland basins and precipitation of the ore in peripheral carbonate platforms. These hydrological genetic models imply an indirect role of tectonism and a relatively minor role of structures in the MVT mineralization. Worldwide, age-dating of MVT deposits in orogenic forelands correlate with the ages of large-scale tectonic events in adjacent orogens, and the most common explanation for the correlation is the hydrological connection through topographically driven fluid-flow from the orogen into the platform carbonate deposits (Leach et al., 2001). The role of faults is considered limited to offsetting paleo-aquifers and setting up conditions for fluid mixing (Bradley and Leach, 2003). The structural control of at least some world-class MVT deposits (e.g. linear arrays of ore-welded breccia zones at Pine Point and Newfoundland Zinc or discordant pods of ore along faults at Polaris) appears to have been downplayed in many reviews (e.g. Sverjensky, 1986; Anderson and Macqueen, 1988; Leach and Sangster, 1993; Sangster, 1995; Leach et al., 2001; Bradley and Leach, 2003). Prompted by recent re-examination of selected outcrops and cores in the Interior Plains and Rocky Mountains of Alberta (Fig. 1), this paper attempts to assess the validity of popular basinal fluid-flow genetic models and the relative importance of stratigraphic versus structural control for MVT deposits in the carbonate sequences of the Western Canada Sedimentary Basin (WCSB). The integration of new and older structural data at deposit and regional scale with existing isotope data suggests that Pb-Zn deposits and occurrences in carbonate successions of the WCSB are structurally controlled both in the orogen and in its foreland. Common debates over the nature of brecciation (dissolution collapse vs. tectonic) or the origin of fluids (brine, meteoric, or hydrothermal), previously considered critical for defining the origin of a particular MVT deposit, appear less relevant when viewed as parts of the complex metallogenetic processes associated with major fault zones.

GEOLOGICAL SETTING

Western Canada Sedimentary Basin stratigraphy records deposition in two successive tectonosedimentary environments: 1) a Late Proterozoic to Middle Jurassic passive continental margin and 2) a Middle Jurassic to Oligocene foreland basin (e.g. Price, 1994; Eaton et al., 1999). Paleogeographic reconstructions of the Paleozoic architecture of the western continental margin of North America show an extensive Middle Cambrian to Upper Jurassic carbonate platform to the east and shale basins to the west (Fig. 2a, b, c). In the area discussed in this paper, these passive margin successions were converted by Mesozoic tectonism into the Rocky Mountains fold-and-thrust belt to the west and into the floor of the Cordilleran foreland basin to the east (Fig. 1). The MVT deposits and prospects of the WCSB are hosted by Cambrian to Devonian carbonate strata, which are well exposed in the Rocky Mountains fold-and-thrust belt, and mostly buried under a wedge of Upper Jurassic to Tertiary clastic strata or Quaternary glacial sediments in the foreland. Summaries of general characteristics (e.g. tonnage, host rocks, alteration, age) and selected analytical data (e.g. isotopes, fluid inclusion homogenization temperatures) from MVT deposits and prospects in the area under consideration are given in Table 1 and Table 2, respectively.

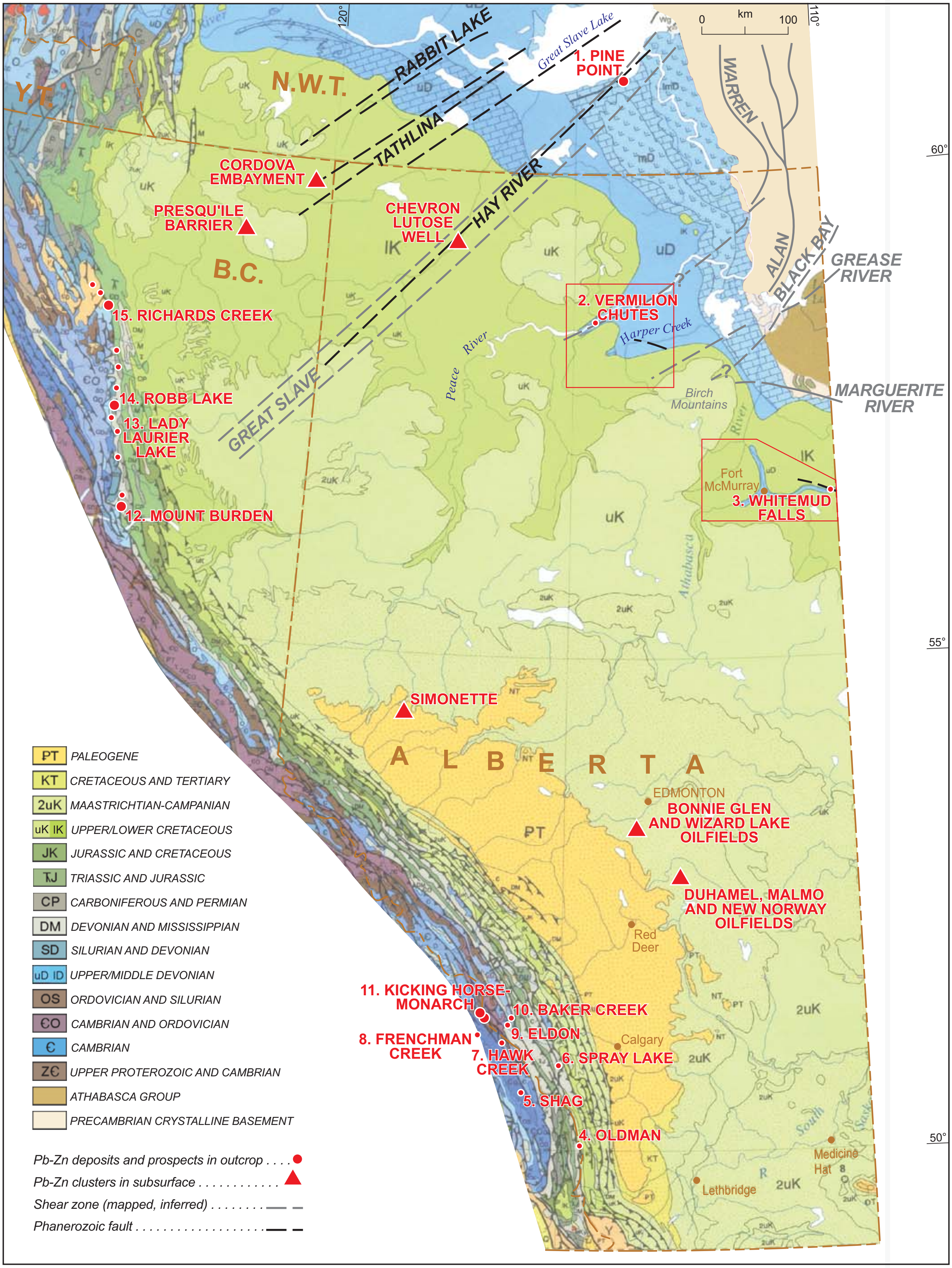
PREVIOUS WORK

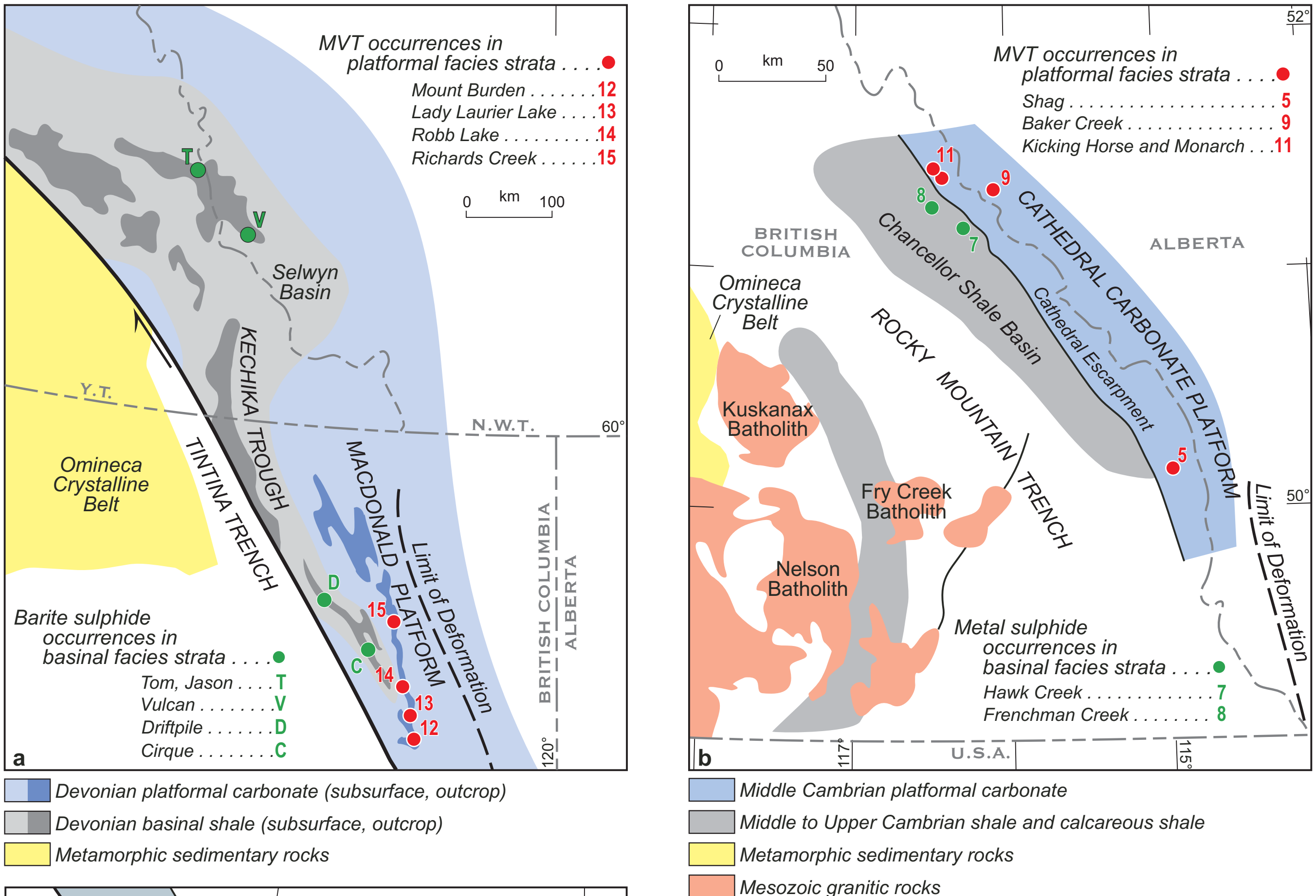
Pine Point, the world-famous lead-zinc mining district in the WCSB, lies near the south shore of Great Slave Lake in the Northwest Territories (Locality 1, Fig. 1). Discovered in 1898, the Pine Point district was the subject of systematic exploration in 1936 after the recognition that deposits occurred along projections of major faults. Exploration rushes took place after the discovery of a large, high-grade deposit by Pyramid Mining Co. in 1966 and the X-25 deposit by Western Mines Ltd. in 1976 (Gibbins, 1988). A series of insightful papers on the geology of Pine Point district were published before mining operations ceased in 1988 (e.g. Campbell 1966, 1967; Skall, 1975; Kyle 1981; Rhodes et al., 1984; Macqueen and Powell, 1983; Krebs and Macqueen, 1984). In the last two decades, as one of the classical examples for MVT deposits, Pine Point district was the focus of many specialized stratigraphic, petrographic,

Figure 1. Location of MVT deposits and occurrences in the carbonate sequences of the Western Canada Sedimentary Basin. Pb-Zn deposits and occurrences from outcrop in the cratonic platform include Pine Point, Vermilion Chutes, and Whitemud Falls. Pb-Zn deposits and prospects in the Rocky Mountain fold-and-thrust belt include Oldman, Shag, Spray Lake, Hawk Creek, Frenchman Creek, Eldon, Baker Creek, Kicking Horse-Monarch, Mount Burden, Lady Laurier Lake, Robb Lake, and Richards Creek. Selected subsurface occurrences are in the Cordova Embayment, Presqu'ile Barrier in northeastern British Columbia, the Chevron Lutose well (16-34-118-21W5), Simonette gas field, Bonnie Glen and Wizard Lake, and Duhamel, Malmo, and New Norway oilfields. *See* Table 2 for a summary of Pb-Zn occurrences in core from the WCSB. Geology *modified from* Wheeler et al. (1996); fault zones in Northwest Territories *from* Okulitch (2006); geophysical trace of Great Slave Shear Zone *from* Eaton and Hope (2003). Boxes around Vermilion Chutes and Fort McMurray indicate areas of fieldwork for this study.

Contents

D. Pană





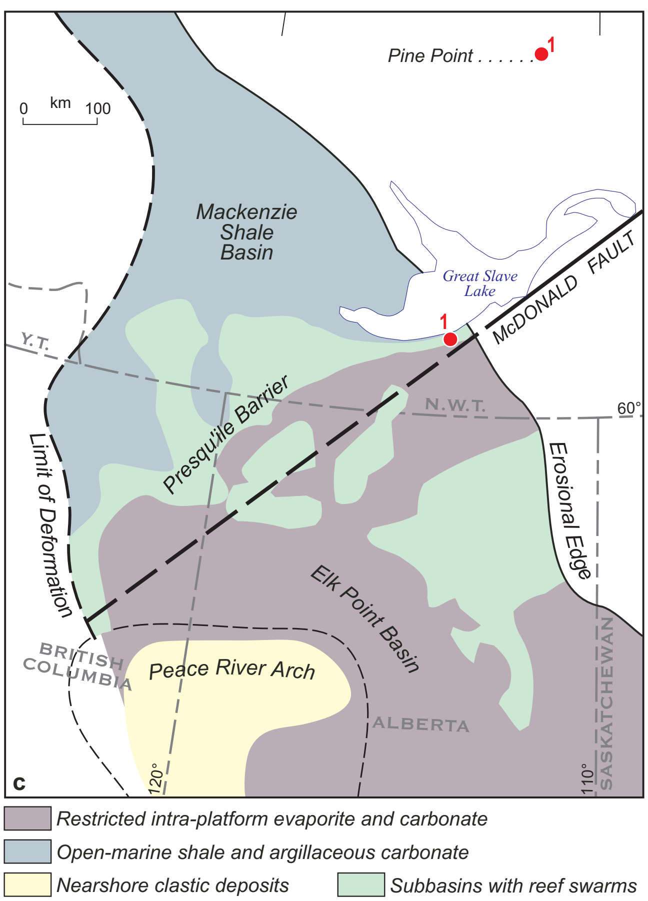


Figure 2. Paleogeographic reconstructions for the host rocks of MVT occurrences and their time equivalents along the western edge of ancestral North America; numbering of MVT occurrences is consistent with numbering in Figure 1. **a.** Northern Rockies, *modified after* MacIntyre (1982); **b.** southern Canadian Rockies, *modified after* Hoy (1982); **c.** Presqu'ile reef barrier in the Middle Devonian WCSB, *modified after* Jackson and Beales (1967) and Qing and Mountjoy (1992).

geochemical, isotopic, paleomagnetic and fluid-flow studies (e.g. Cumming et al., 1990; Arne, 1991; Qing and Mountjoy, 1992; Symons et al., 1993; Qing, 1998a). The Pine Point MVT district inspired the popular topographically driven fluid-flow genetic model (Garven, 1985) and was included in all reviews on MVT deposits (e.g. Anderson and Macqueen, 1988; Sangster, 1995; Leach et al., 2001).

In northern Alberta, hand specimens with lead-zinc mineralization, reportedly from Wood Buffalo National Park, led to early reconnaissance geochemical surveys, but the results were not encouraging (Govett in the late 1950s, *cf.* Godfrey, 1985 and Green, 1971). Gulf Minerals Ltd. (1975) reported a minor zinc anomaly of 0.1% at Vermilion Chutes (Locality 2, Fig. 1). Carrigy (1959) reported a galena occurrence at Whitemud Falls on Clearwater River in dolostone of the Methy Formation (Locality 3, Fig. 1), which he correlated with the Presqu'ile Formation dolomite from Pine Point. Dubord (1987) and Turner and McPhee (1994) listed several Pb-Zn occurrences in wells from northern Alberta and reported a concentration of 3.7% Zn in the Keg River Formation from the Chevron Lutose well (16-34-118-21W5) in northwestern Alberta (Locality L, Fig. 1). Galena occurrences were reported from six wells in a reef buildup of the Swan Hills Formation in the Simonette oilfield (Duggan et al., 2001) (Locality S, Fig. 1). Several sphalerite occurrences have been identified in the Leduc and Nisku formations of the Bonnie Glen and Wizard Lake oilfields (Locality L, Fig. 1) and in the Bashaw reef complex of the Duhamel, Norway, and Malmo fields (Locality D, Fig. 1) including some "ore grade" sections in a Duhamel well between approximately 1500 and 1600 m depth (Haites, 1960, p. 64). Lead isotope data from MVT occurrences in core from northeastern British Columbia and northwestern Alberta have been reported by Nelson et al. (2002) (Localities P, C, and L, Fig. 1). A summary of Pb and/or Zn occurrences in core from carbonate sequences of the WCSB is included in Table 3.

In the southern Rocky Mountains, a number of lead-zinc occurrences and deposits that straddle the Alberta–British Columbia boundary were discovered in the early 1900s (Fig. 1): 4. Oldman River; 5. Shag; 6. Spray Lake; 7. Hawk Creek; 8. Frenchman Creek; 9. Eldon; 10. Baker Creek prospects, and 11. Kicking Horse-Monarch deposits. Except for the Kicking Horse and Monarch mines and Oldman prospect, geological information for the other prospects is incomplete or nonexistent.

In the northern Rocky Mountains, regional exploration programs for sediment hosted lead-zinc deposits were initiated during the late 1960s and led to the discovery of several occurrences hosted by Devonian platformal carbonate (Fig. 1): 12. Mount Burden, 13. Lady Laurier Lake, 14. Robb Lake, and 15. Richards Creek prospects. In the 1970s, development was considered for the Mount Burden, Robb Lake and Richards Creek prospects, but subsequently abandoned. At the same time, the discovery of clastic-hosted lead-zinc deposits in basinal facies rocks of similar age in the Selwyn Basin (Tom, Jason and Vulcan deposits, Fig. 2a) spawned interest in Devonian shale of the Kechika Trough. During the 1970s and 1980s, nine major barite-sulphide occurrences (including the Driftpile and Cirque deposits, Fig. 2a) were found within a 180-km long belt of basin rocks of the Kechika Trough, immediately west of the previously known carbonate-hosted occurrences (MacIntyre, 1982, 1991).

POPULAR BASINAL FLUID-FLOW GENETIC MODELS FOR MVT DEPOSITS

There is a strong belief that the metals in MVT deposits originated in basin shale deposits and were chemically transported by basinal brine to the precipitation site. It is inferred that sulphur was either waiting at the precipitation site (the mixing model) or was transported in the metal-bearing brine, but formed sulphide deposits only at the precipitation site through dilution, pH change and cooling (reduced sulphur model) or through reactions with hydrocarbons (sulphate reduction model) (see review by Sangster, 1995). Two main hydrological models have been proposed to move the ore solutions out of the basin clastic deposits into the platform carbonate: basin compaction-driven dewatering (Sharp, 1978; Cathles and Smith, 1983; Bethke, 1985) and gravity-driven groundwater flow (Garven and Freeze, 1984; Garven 1985; Bethke, 1986). A variation of the compaction model is the tectonic compression model (Macqueen and Thompson, 1978; "tectonic squeegee" of Oliver, 1986; "hot flash" of Machel and Cavell, 1999).

Compaction-driven fluid-flow models

Paleogeographic reconstructions of the Paleozoic architecture of the western continental margin of North America, consisting of an extensive Middle Cambrian to Upper Jurassic carbonate platform to the east and shale basins to the west, have encouraged the application of MVT hydrological models to the WCSB. Compaction-driven flow models assume that mineralizing brine originated as pore fluid in basinal shale and was driven laterally and upwards along aquifers toward the basin margins by compaction and subsidence. For the Pine Point MVT district in the Northwest Territories, Jackson and Beales (1967) proposed that compaction and dewatering of the Mackenzie shale basin to the north of the Presqu'ile reef barrier expelled chloride-metal solutions along the reef aquifer (Fig. 2c). At the near-surface end of this natural plumbing system, the basinal brine would have mixed with locally derived sulphide-bearing fluids from reef and off-reef evaporite deposits, leading to the precipitation of metallic sulphides. Similarly, the belt of MVT occurrences in northern Rocky Mountains was interpreted to have resulted from pre-Laramide migration of formation waters from shale of the Kechika Trough eastward into the early Paleozoic MacDonald carbonate platform of the ancestral North American shelf (Fig. 2a) (Taylor, 1977; Sangster,

Table 1. Principal characteristics of MVT past producers, prospects and occurrences from carbonate sequences of the Western Canada Sedimentary Basin

No. in Fig.1	Locality	Tonnage (t)	Category	Commodity	Grade	Host rocks	Age of host rocks	Structural control	Mineralization type	Alteration	Age of mineralization	Method
Cratonic carbonate platform												
1	Pine Point	64,319,627 11,815,662	Mined/produced Remaining resource (unknown grade)	Zn, Pb	6.95% Zn, 3.00% Pb	Pine Point Fm: dolostone Sulphur Point Fm: dolostone, limestone Muskeg Fm: dolostone, gypsum, anhydrite Watt Mountain Fm: dolostone, limestone Slave Point Fm: dolostone, limestone	Middle Devonian	basement faults kinematically linked to GSSZ/HRFZ	prismatic and tabular breccia bodies, massive ore or coatings on breccia fragments and carbonate crystals, stockworks, veins and irregular seams, disseminations, botryoidal banded sphalerite, stalactitic sphalerite, pencil-like galena	coarse-grained buff to grey vuggy dolomite, white to yellowish white saddle dolomite cement, veins, fractures and vug fillings; late calcite, bitumen	290–248 Ma (Permian) 300 Ma 60 Ma <100 Ma 71 +/- 13 Ma 363 +/- 9 Ma 361 +/- 13 Ma	paleomagnetism [a] two-stage Pb growth curve age [e] three-stage Pb growth curve age [e] apatite fission track [f] paleomagnetism [h] Rb/Sr isochron [g] (sphalerite and leachate) Rb/Sr isochron [g] (sphalerite)
2	Vermilion Chutes	-	-	Zn	0.10%	Mikkwa Fm	Upper Devonian	vertical joints, sinistral shear	-	fine-crystalline dolomite, patchy limonite	-	-
3	Whitemud Falls	-	-	Pb	-	Methy Fm	Middle Devonian	minor vertical fractures, normal shear	-	fine-crystalline dolomite	-	-
Canadian Rockies												
4	Oldman	-	-	Pb, Zn, Ag	-	Upper Palliser Fm: dolomitic limestone	Upper Devonian	shattered and sheared rocks at intersection of shallowly dipping fault and steeply dipping tear faults	galena veins and clusters in dolomite veins, pyrite in shear zones	calcite veining, saddle dolomite crystals up to 4 mm, limonitic veinlets; vugs up to 1 cm with white calcite	syn- to post-Laramide <75 Ma	field relationships [c] field relationships [i]
5	Shag	-	-	Zn, Pb	-	Pika or Eldon Fm: dolostone, dark grey argillaceous limestone	Middle Cambrian	brecciated dolostone	crosscutting veins and shears, disseminations	sparry dolomite, crosscutting calcite veins and shears	-	-
6	Spray Lake	-	-	Pb	-	dolomitic limestone	Upper Devonian	-	-	calcite, residual petroleum	-	-
7	Hawk Creek	26,759	Indicated	Zn, Pb	12.50% Zn	Chancellor Fm: fine-crystalline grey dolomitic limestone, brownish-grey argillites	Middle Cambrian	steeply dipping normal fault	massive fine-grained pods, cleavages, veins, stringers, disseminations	calcite, pyrite	syn- to post-Laramide	field relationships [l]
8	Frenchman Creek	-	-	Cu, Pb, Ag	-	Chancellor Fm: slate, argillaceous dolomitic limestone	Middle Cambrian	zone of shearing	veinlets and stringers in sheared argillites	quartz and calcite veinlets and stringers	-	-
9	Eldon	-	-	Pb, Zn, Cu	-	Chancellor Fm: dolomitic and argillaceous limestone	Middle Cambrian	0°/40° shear zone	vein-type deposit	quartz and siderite veins; sericite	-	-

Note: Superscript indicates the reference
[a] - Beales and Jackson (1982) ; [b] - Godwin et al. (1982); [c] - Holter (1977); [d] - Macqueen and Thompson (1978); [e] - Cumming et al. (1990); [f] - Arne (1991);
[g] - Nakai et al. (1993); [h] - Symons et al. (1993); [i] - Symons et al. (1998); [j] - Smethurst et al. (1999); [k] - Nelson et al. (2002); [l] - this study
Economic characteristics of deposits and prospects in the orogen from British Columbia's Ministry of Energy and Mines MINFILE Mineral Inventory web-page.

Contents

Table 1. (cont.)

No. in Fig.1	Locality	Tonnage (t)	Category	Commodity	Grade	Host rocks	Age of host rocks	Structural control	Mineralization type	Alteration	Age of mineralization	Method
Canadian Rockies												
10	Baker Creek	-	-	Pb	-	Cathedral Fm: mottled limestone, dark grey to black medium-grained dolostone	Middle Cambrian	-	small pockets, veins	coarse grained white vein dolomite and a network of calcite and quartz veining	-	-
11	Kicking Horse/ Monarch	27,213 826,180 822,010	Remaining resource Mined Milled	Zn, Pb, Ag, Cd, Cu	8.00% Zn 5.63% Pb 8.67% Zn 31 g/t Ag 11 g/t Cd	Cathedral Fm and Mount Whyte Fm: dolostone, variably dolomitic limestone	Middle Cambrian	steeply dipping normal faults	stockworks, veinlets, disseminations mostly in breccias; 'gneissic galena'	coarse white to cream dolomite stockworks and veinlets, pyrite, late quartz veins, white fibrous amphibole, talc	post-Laramide collapse Late Cretaceous–Paleocene 370 Ma	field relationships [l] paleomagnetism [i] two-stage Pb growth curve age [b]
12	Mount Burden	-	-	Pb, Zn	-	Stone Fm and Pine Point Fm: fine-grained limestone, micritic to medium-crystalline dolostone	Lower to Middle Devonian	crosscutting patches	scattered blebs in irregular crosscutting patches	white dolomite, quartz, smithsonite, bitumen	-	-
13	Lady Laurier Lake	-	-	Zn, Pb	-	Muncho-McConnell Fm: dolostone	Silurian–Devonian	fracture controlled	-	quartz	syn- to post-Laramide	field relationships [d]
14	Robb Lake	6,449,481	Measured reserves	Zn, Pb	7.11% Pb+Zn	Stone Fm, Dunedin Fm, Muncho-McConnell Fm: dolostone, variably dolomitized limestone	Lower to Middle Devonian; Silurian to Devonian	TGS and Waterfall zones - steeply dipping Laramide fault	crystal aggregates in breccia matrix, rinds on breccia fragments, disseminations	dolomite, quartz, calcite, pyrite, bitumen	syn- to post-Laramide mid-Triassic-early to mid-Cretaceous 370 Ma 47+/-10 Ma 348 Ma	field relationships [l] burial history [d] two-stage Pb growth curve age [b] paleomagnetism [j] Rb-Sr isochron [k]
15	Richards Creek	-	-	Zn, Pb	-	Dunedin Fm, Stone Fm: fine- to medium-crystalline dolostone	Lower to Middle Devonian	fracture controlled	fracture, vein and open space fillings, small massive pods, replacement	pyrite, marcasite, quartz, bitumen	syn- to post-Laramide	field relationships [d]

Note: Superscript indicates the reference
[a] - Beales and Jackson (1982) ; [b] - Godwin et al. (1982); [c] - Holter (1977); [d] - Macqueen and Thompson (1978); [e] - Cumming et al. (1990); [f] - Arne (1991);
[g] - Nakai et al. (1993); [h] - Symons et al. (1993); [i] - Symons et al. (1998); [j] - Smethurst et al. (1999); [k] - Nelson et al. (2002); [l] - this study
Economic characteristics of deposits and prospects in the orogen from British Columbia's Ministry of Energy and Mines MINFILE Mineral Inventory web-page.

Contents

Table 2. Analytical data on sulphides and carbonates from MVT past producers and prospects in carbonate sequences of the Western Canada Sedimentary Basin

No. in Fig. 1	MVT deposit or prospect	$\delta^{18}O$ (‰SMOW)	$\delta^{18}O$ (‰PDB)	$\delta^{13}C$ (‰PDB)	δD_{FI} (‰ SMOW)	$^{87}Sr/^{86}Sr$	$\delta^{34}S$ (‰)	$^{206}Pb/^{204}Pb$	Homog. T (°C)	Min. T (°C) ZnS-FeS	Max. T (°C)	Salinities %equiv. NaCl
1	**Pine Point**											
	fine-crystalline dolomite	-	-6.73 to -7.14 [j]	0.89 to 0.92 [j]	-	0.7082–0.7083 [j]	-	-	-	-	-	-
	medium-crystalline dolomite	-	-5.14 to -9.43 [j]	1.38 to 1.78 [j]	-	0.7081–0.7087 [j]	-	-	-	-	-	-
		-	-3.7 to -9.4 [l]	0.6 to 2.5 [l]	-	0.7081–0.7087 [l]	-	-	-	-	-	-
	coarse-crystalline dolomite (Presqu'ile)	-	-8.52 to -9.86 [j]	-0.34 to 1.28 [j]	-	0.7082–0.7088 [j]	-	-	-	-	-	-
		-	-7.62 to -11.19 [n]	-1.42 to 1.55 [n]	-	0.7082–0.7088 [n]	-	-	-	-	-	-
	Presqu'ile saddle dolomite (gangue)	-	-8.43 to -10.27 [j]	-0.72 to 1.22 [j]	-	0.7081–0.7085 [j]	-	-	90–100 [b]	-	-	-
		-	-7 to -11 [k]	-0.91 to 1.69 [m]	-	0.7081–0.7085 [k]	-	-	92–106 [k]	-	-	-
	late calcite	-	-4.10 to-16.7 [j]	-5.54 to 0.74 [j]	-	0.7085–0.7161 [j]	-	-	-	-	-	high [j]
	sulphides	-	-	-	-	-	12.6 to 24.1; mean 20.1 [c]	-	51–97 [b]	70–200 [a]	-	-
	galena	-	-	-	-	-	12.6 to 22.4; mean 18.4 [c]	18.162–18.187 [f]	-	-	-	-
		-	-	-	-	-	-	18.167–18.187 [s]	-	-	-	-
	pyrite	-	-	-	-	-	16.6 to 23.0; mean 19.7 [c]	-	-	-	-	-
	marcasite	-	-	-	-	-	17.7 to 21.8; mean 19.3 [c]	-	-	-	-	-
	sphalerite	-	-	-	-	-	17.7 to 24.1; mean 21.6 [c]	-	51–97 [b]	-	-	-
		-	-	-	-	-	20.0 to 27.0 [a]	-	-	-	-	-
	fluid inclusions in sphalerite	-	-	-	-	0.7112–0.7522 [o]	-	-	-	-	-	-
	leachates from fluid inclusions in sphalerite	-	-	-	-	0.7086–0.7090 [o]	-	-	-	-	-	-
	fluid inclusions in saddle dolomite	-0.5 to 2 [p]	-	-	-80 to -100 [p]	-	-	-	-	-	-	-
		-1 to+2 [k]	-	-	-	-	-	-	-	-	-	-
		-0.1 to +0.7 [r]	-	-	-	-	-	-	-	-	-	-
	fine-grained dolostone	-	-3 to -1 [k]	-	-	-	-	-	-	-	-	-
	native sulphur and bitumen	-	-	-	-	-	+7.5 to +25.1 [h]	-	-	-	-	-
	native sulphur	-	-	-	-	-	+22.2 to +23.5 [c]	-	-	-	-	-
4	**Oldman**											
	pyrite	-	-	-	-	-	15.85 (weighted mean) [d]	-	-	-	-	-
	sphalerite	-	-	-	-	-	15.64 (weighted mean) [d]	-	-	-	-	-
	galena	-	-	-	-	-	9.89 (weighted mean) [d]	21.778–21.779 [u]	-	-	-	-
	white sparry calcite	18.80 [u]	-11.70 [u]	-2.20 [u]	-	-	-	-	-	-	-	-
	medium- to coarse-grained matrix dolomite	20.86 [u]	-9.70 [u]	0.40 [u]	-	0.71034 [u]	-	-	-	-	-	-
	fine-grained mosaic dolomite	21.37 [u]	-9.21 [u]	0.62 [u]	-	-	-	-	-	-	-	-
	fine-grained matrix dolomite	18.46 [u]	-12.03 [u]	0.43 [u]	-	0.71044 [u]	-	-	-	-	-	-

Note: Superscript indicates the reference
[a] - Evans et al. (1968); [b] - Roedder (1968); [c] - Sasaki and Krouse (1969); [d] - Holter (1977); [e] - Macqueen and Thompson (1978); [f] - Godwin et al. (1982); [g] - Morrow and Cumming (1982); [h] - Macqueen and Powell (1983);
[i] - Sangster and Carriere (1991); [j] - Mountjoy et al. (1992); [k] - Qing and Mountjoy (1992); [l] -Qing (1998a) ; [m] - Qing (1998b); [n] - Qing and Mountjoy (1994); [o] - Nakai et al. (1993); [p] - Nesbitt and Muehlenbachs (1994a);
[q] - Nesbitt and Muehlenbachs (1995a); [r] - Adams et al. (2000); [s] Cumming et al. (1990); [t] - Nelson et al. (2002); [u] - Paradis et al. (2006).

Table 2. (cont.)

No. in Fig. 1	MVT deposit or prospect	δ^{18}O (‰SMOW)	δ^{18}O (‰PDB)	δ^{13}C (‰PDB)	δD_{FI} (‰ SMOW)	^{87}Sr/^{86}Sr	δ^{34}S (‰)	^{206}Pb/^{204}Pb	Homog. T (°C)	Min. T (°C) ZnS-FeS	Max. T (°C)	Salinities %equiv. NaCl
5	**Shag**	-	-	-	-	-	-	-	-	-	-	-
6	**Spray Lake**											
	galena	-	-	-	-	-	0 to 6 [d]	-	-	-	-	-
7	**Hawk Creek**											
	pyrite	-	-	-	-	-	25.6 to 27.9 [a]	-	-	-	-	-
	sphalerite	-	-	-	-	-	24.9 to 25.9 [a]	-	-	70–110 [a]	-	-
	galena	-	-	-	-	-	24.8 [a]	-	-	-	-	-
8	**Frenchman Creek**	-	-	-	-	-	-	-	-	-	-	-
9	**Eldon**											
	sphalerite	-	-	-	-	-	8.1 to 12.2 [a]	-	-	75–110 [a]	-	-
	galena	-	-	-	-	-	8.4 to 11.8 [a]	-	-	-	-	-
	chalcopyrite	-	-	-	-	-	9.2 [a]	-	-	-	-	-
10	**Baker Creek**											
	galena	-	-	-	-	-	9.2 [a]	-	-	-	-	-
11	**Kicking Horse-Monarch**											
	Kicking Horse											
	sphalerite	-	-	-	-	-	20.1 to 31.3 [a]	-	-	70 [a]	-	-
	galena	-	-	-	-	-	25.8 [a]	18.558 [f]	-	-	-	-
	Monarch											
	sphalerite	-	-	-	-	-	19.1 to 23.4 [a]	-	-	80–100 [a]	-	-
	galena	-	-	-	-	-	17.6 to 21.8 [a]	18.557 [f]	-	-	-	-
	epigenetic Cambrian dolomite	10 to 21 [p]	-	-3.0 to +1.0 [p]	-	0.709–0.712 [p]	-	-	120–200 [p]	-	-	20–25 + [p]
	MVT gangue dolomite	11 to 16 [p]	-	-2.8 to +3.7 [p]	-	0.709–0.712 [p]	-	-		-	-	20–25 + [p]
		12 to 15 [q]	-	-1 to 0 [q]	-40 to -80 [q]	-	-	-	100–200 [q]	-	-	-
	Laramide carbonate veins	16 to 22 [q]	-	-3 to +1 [q]	-120 to -155 [q]	-	-	-	90–150 [q]	-	-	0–10 [q]
	Laramide quartz veins	12 to 23 [q]	-	-	-120 to -155 [q]	-	-	-	90–150 [q]	-	-	0–10 [q]
12	**Mount Burden**											
	galena	-	-	-	-	-	-	19.549–19.886 [g]	-	-	-	-
13	**Lady Laurier Lake**	-	-	-	-	-	-	-	-	-	-	-
14	**Robb Lake**											
	saddle dolomite gangue	14.85 to 16.68 [t]	-13.81 to -15.58 [t]	-0.80 to -1.66 [t]	-	0.7118–0.7178 [t]	-	-	-	-	-	-
	sphalerite	-	-	-	-	0.7138–0.7298 [t]	+13.5 to +17.5 [e]	-	87–154 [i]	-	-	16 to >23 [i]
	galena	-	-	-	-	-	+9.6 [e]	19.979–20.190 [g]	-	-	-	-
	sphalerite leachates	-	-	-	-	0.7108–0.7172 [t]	-	-	-	-	-	-
	fine-grained dolomite and limestone	19.61 to 20.48 [t]	-10.12 to -10.97 [t]	0.76 to 1.58 [t]	-	0.7092–0.7097 [t]	-	-	-	-	-	-
	quartz gangue	-	-	-	-	-	-	-	210–260 [e]	-	-	-
	bitumen, illite	-	-	-	-	-	-	-	-	-	175–250 [e]	-
15	**Richards Creek**											
	galena	-	-	-	-	-	-	21.362; 21.430 [g]	-	-	-	-

1973, Sangster et al., 1979; Manns, 1981; Godwin et al., 1982; MacIntyre, 1982, 1991). In the southern Rocky Mountains, MVT occurrences are hosted by platform carbonate on a northwesterly trending shelf adjacent to the Chancellor shale basin developed to the west (Fig. 2b). Associated saddle dolomite and sulphide mineralization at Monarch-Kicking Horse deposits and the Shag occurrences have been interpreted to record Paleozoic eastward migration of brines (Hoy, 1982).

Topographically driven fluid-flow models

The Cretaceous to present-day architecture of the Rocky Mountains and their foreland inspired the topographically driven fluid-flow model of Garven (1985): groundwater recharged in the uplifted orogen sweeps through the adjacent sedimentary basin, driving saline fluids that have evolved deep in the basin into relatively undeformed shallow strata. Elevated temperatures are widespread, caused by the upward and lateral flow of fluids heated in the deep portion of the basin (e.g. Garven 1985, 1989; Bethke and Marshak, 1990; Garven et al., 1993). The availability of fluid is limited only by the plausible recharge rates and aquifer permeabilities and by the longevity of the fluid-flow system. The mineralizing fluids are assumed to have acquired metals and salt, in addition to heat, within the sedimentary strata.

Several versions of the topographically driven fluid-flow model in the WCSB differ essentially in the age of the flow system inferred from indirect arguments rather than unequivocal geochronological data (e.g. Garven, 1985, 1989; Garven et al., 1993; Nesbitt and Muehlenbachs, 1994a). Garven's (1985) original model related fluid circulation to the Cretaceous–Tertiary Laramide Orogen to explain the precipitation of Pine Point ore near the eastern edge of the WCSB. Subsequent work pointed out inconsistencies in the model, and went on to relate fluid circulation, associated mineralization and dolomitization in the WCSB to the Late Devonian–Early Mississippian Antler Orogeny (e.g. Nesbitt and Muehlenbachs, 1994a, 1995a; Root, 2001; Nelson et al., 2002).

SHORTCOMINGS OF BASINAL FLUID-FLOW GENETIC MODELS

Compaction-driven fluid-flow

The principal shortcoming of the compaction-driven fluid-flow model is that pore water volumes in sediment were insufficient to transport the huge mass of metals now present in some MVT deposits (e.g. Garven and Freeze, 1984; Bethke, 1985). Moreover, the rates of continuous outward flow expected in steadily compacting basins would probably be too small to produce the thermal perturbation associated with MVT deposits. To overcome the problem of maintaining high initial fluid temperatures during transport of up to hundreds of kilometres, a process involving overpressuring of aquifers by rapid sedimentation followed by rapid and episodic release of basinal fluids has been proposed (Sharp, 1978; Cathles and Smith, 1983). Numerical modelling for several basins showed that excess fluid pressures and episodic dewatering through compaction are unlikely (Garven and Freeze, 1984; Bethke, 1986).

Topographically driven fluid-flow

The Laramide trap

For the giant Pine Point MVT deposit, Garven (1985) proposed regional-scale fluid-flow involving a topographically high recharging area in the Cordillera, fluid heating and metal extraction from the deep portions of the foreland basin, updip migration and channelling within porous reefs, and precipitation of metal sulphides at the upper end of the aquifer near the basin edge. Fluid inclusion, oxygen, and strontium isotope data from saddle dolomite along the Presqu'ile reef have documented fluid migration along the highly permeable conduit from northeastern British Columbia to the Pine Point district (e.g. Qing and Mountjoy, 1992). The validation of the fluid migration through the Presqu'ile conduit was implicitly viewed as a validation of Garven's (1985) MVT genetic model for Pine Point. In fact, the metal carrier role of the basinal fluid has never passed the status of a postulate and appears to be in conflict with various lines of evidence (e.g. Hitchon, 1993; Adams et al., 2000). For example, when the first comprehensive set of chemical analyses of formation waters in northern Alberta became available, computer modelling proved that under conditions comparable to the deposition of the Pine Point ore, formation waters could not have been the source of metals at Pine Point (Hitchon, 1993). Qing and Mountjoy (1992) have shown that homogenization temperatures of primary fluid inclusions in saddle dolomite along the Presqu'ile barrier decrease updip eastward in conflict with Garven's (1985, 1989) basinal fluid-flow model that postulated similar temperatures along the migration path. Nesbitt and Muehlenbachs (1994b) pointed out that at an average flow rate of 1 to 5 m/a (Garven, 1985), the basinal fluid would migrate through the 400 km length of the Presqu'ile reef conduit in 8×10^4 to 4×10^5a. Over the minimum lifetime for the flow system of approximately 10^6a (Garven, 1985), a considerable volume of surface fluids would have flowed completely through the system and, thus, a low δD signal should be present in gangue dolomites of the deposit. At Pine Point, δD values are relatively high (-80‰ to -100‰ SMOW) compared to those expected for Tertiary meteoric waters (-115‰ to -155‰ SMOW) (Nesbitt and Muehlenbachs, 1994a). The model also predicts that surface fluids should have come close to flushing most of the basinal brines out of the system. However, there is no isotopic evidence for major incursions of Tertiary meteoric water in the Devonian stratigraphy of the WCSB (Nesbitt and Muehlenbachs, 1994b).

These inconsistencies between the postulated Laramide gravity-driven fluid-flow model and geological/geochemical evidence led to speculation of Garven's (1985) hydrological model with respect to the Devonian–Carboniferous architecture of the western margin of North America (e.g. Amthor et al., 1993; Nesbitt and Muehlenbachs, 1994a, 1995a, b; Mountjoy et al., 1999; Root, 2001).

The Antler nemesis

Devonian regional easterly fluid migration from the shale basin into the WCSB carbonate shelf requires a major orogen similar to the Laramide event. Since shale basins record an extensional (Chancellor Basin) and even rift-like setting (Kechika Trough, Selwyn Basin) west of the carbonate platform during the inferred Late Devonian–Mississippian (Fig. 2), providing evidence for mountain-building processes (Antler Orogeny), or at least a topographic high west of the shale basins, they remained a notorious nemesis for advocates of basin-wide Devonian dolomitization and associated mineralization in the the WCSB. Extending the regional picture to the west, the Late Devonian to Early Mississippian architecture of WCSB was variously reinterpreted as a west-facing active compressional continental margin above west-dipping (Root, 2001) or east-dipping (Nelson et al., 2002) subduction zones.

The existence of an Antler Orogen is, however, a contentious issue. Diverse and diachronous Paleozoic tectonism along western North America is routinely assigned to the elusive Antler Orogeny. In the west-central United States, where originally inferred, the Antler Orogeny is poorly understood, with controversial interpretations from the plate tectonic scenario, to its age, and magnitude of deformation. Thrusting is interpreted to have taken place either in a volcanic arc-continent collisional setting or a back-arc non-collisional setting (e.g. Speed et al., 1988; Burchfiel and Royden, 1991). Interpretations of the age of deformation include Late Devonian–earliest Mississippian (Roberts et al., 1958; Giles and Dickinson, 1995) or entirely Mesozoic (Ketner and Smith, 1982), and the inferred deformation could encompass as much as 100 km shortening (Burchfiel and Royden, 1991) or only modest structural transport (Noble and Finney, 1999). Based on the presence of westerly derived Devonian and Mississippian siliciclastic strata, the Antler Orogeny was extended northward into Idaho (Dorobek et al., 1991). Farther north, the existence of the Antler Orogeny in Western Canada has been debated for decades. Scattered evidence for tectonism, metamorphism, and igneous activity of variably constrained Paleozoic age has been interpreted to record extensional, transcurrent, or compressional tectonic settings at the mid-Paleozoic continental margin (e.g. Gabrielse, 1976; Struik, 1981; Eisbacher, 1983; Klepacki and Wheeler, 1985; Gordey et al., 1987; Smith and Gehrels, 1992).

The most "precise view of the nature and timing of mid-Paleozoic deformation… in western Canada" comes from the Middle Devonian stratigraphic record in the Purcell and southern Rocky mountains (Root, 2001, p. 8). The Middle Devonian stratigraphy consists of tidal facies of the Mount Forster Formation and shallow-water carbonate with intercalations of fine-grained clastic material of the overlying Harrogate and Starbird formations. Root (2001) documented angular unconformities, local lateral thickness and facies changes in the Middle Devonian stratigraphy, two syndepositional open folds, and a growth fault. He interpreted the stratigraphic/structural record as a foredeep "wedge-top basin". The derived regional tectonic model for the Antler Orogeny involves westward subduction, an eastward-advancing tectonic wedge hidden under its "wedge-top basin", a "forebulge" represented by the West Alberta Ridge, and the Elk Point "distal foreland basin" (Root, 2001, Fig. 2). The virtual Antler compression and thrust loading of the outer continental margin would have induced all Paleozoic tectonic processes ever inferred in Western Canada. These processes include Late Silurian to Early Devonian development of variously oriented arches, the Late Devonian subsidence rate increase in Western Canada, Upper Silurian to Middle Devonian crustal tilting and subsidence in northern British Columbia, the development of Devonian and Mississippian faults throughout the WCSB and the evolution of the West Alberta Ridge. Root's (2001) interpretation of the Middle Devonian shallow-water facies as a foredeep succession and of the extension-related faults and volcanism as tectono-magmatic processes in a compressional setting is tenuous. The only coarse-clastic deposits are in the lowermost unit and originate in local uplifts that exposed the underlying strata during the deposition of the Mount Forster Formation (Norford, 1981). Root's (2001) suggestion that the uplifts are controlled by deep-seated thrusts is dismissed by the lack of thrusts in the well-exposed underlying Proterozoic section that could be linked to Devonian folds.

Whereas in the Antler Orogen of Nevada Late Devonian–Mississippian time was characterized by thrusting, the stratigraphic record in central British Columbia indicates extensional faulting controlling the deposition of the Earn Group conglomerate (Gordey et al., 1987). To the east, the postulated Antler forebulge – West Alberta Ridge was in fact buried and inactive after Early Frasnian time (Weissenberger and Potma, 2001). In the northern Rockies, immediately west of the exposed carbonate belt, the Kechika Trough and Selwyn Basin are characterized by Lower Cambrian to Mississippian deep-water strata and Late Devonian SEDEX Zn-Pb-Ba deposits along growth faults in a rift-like setting (McClay et al., 1989; Paradis et al., 1998). Nelson et al. (2002) extended the regional picture to the west of the shale basins, to include pericratonic arc-type terranes, and reconstructed a Late Devonian to Early Mississippian west-facing continental arc/back-arc setting above an easterly dipping subduction zone. By invoking possible "local, short-lived collisions such as produced the Antler belt," (Nelson et al., 2002, p. 1029), it is suggested that available geological data in the WCSB could justify a late Paleozoic, topographically driven fluid-flow genetic model. At the same time, Nelson et al. (2002) considered that the back-arc tectonic setting provides support to various other genetic models, including thermal convection of basinal brines (Morrow, 1998) and brine upwelling along basement faults (Godwin et al., 1982; Krebs and Macqueen, 1984; Berger and Davies, 1999). It is unclear how the Pine Point MVT district, which lies hundreds of kilometres in their hinterland, relates to the all-explanatory late Paleozoic back-arc tectonic setting.

Existing evidence for major Paleozoic compression within the Cordilleran Orogen is poor and conjectural. Consequently, tectonic models and reconstructions of the anatomy of a Paleozoic Antler Orogen are highly speculative and inconsistent. The rift-like basin geometry west of the carbonate shelf and the lack of evidence in support of an orogen similar to the Laramide Rockies farther west, makes the extrapolation of Garven's (1985) topographically driven fluid-flow model to the Devonian–Mississippian architecture of the western margin of North America untenable. A rift shoulder cannot provide the topographic drive for regional fluid migration through permeable aquifers across the basin into the opposite shoulder.

Furthermore, the concept of MVT mineralization being part of a regional-scale Devonian continuum, with gradual cooling and continuous chemical and isotopic variation of the deep-basin brine as it interacts with the aquifer during updip migration into the carbonate platform (Nelson et al., 2002), is contradicted by isotope data. Thus, although farther outboard in the configuration of the Devonian continental margin, the gangue sparry dolomite at Robb Lake has lower $\delta^{18}O$ values and fluid inclusion temperatures than the Manetoe dolomite facies and the Pine Point-Sulphur Point reef barrier facies in the Northwest Territories (Morrow et al., 1986, 1990; Qing and Mountjoy, 1992; Nelson et al., 2002). Similarly, whereas lead isotope analyses from carbonate-hosted Cordilleran deposits define mixing lines to highly radiogenic values (Godwin et al., 1982; Morrow and Cumming, 1982; Morrow et al., 1986, 1990), lead isotope data from the Pine Point district form a tight cluster of non-radiogenic values (Cumming et al., 1990). Pine Point lead was unrelated to that of the more westerly deposits (e.g. northern Rockies) and its origin in the Devonian shale basins is precluded.

The application of basinal fluid-flow models to MVT mineralization processes in the WCSB, regardless of the invoked age ("Antler" or "Laramide"), is in conflict with various other lines of evidence. In general, numerical models that coupled groundwater flow, heat transport and solute transport concluded that mineralizing fluids require additional heat over what could be reasonably obtained from burial or advecting basin fluids to explain the fluid inclusion temperatures in the ores (e.g. Deming and Nunn, 1991). In particular, for the Pine Point MVT deposits, fluid inclusions and isotope data modelling revealed that the saddle dolomite gangue precipitated from a locally derived $\delta^{18}O$ enriched fluid and not from the dolomitizing fluid that moved from the deep basin (Adams et al., 2000). Thus, the basinal fluid-flow genetic models for MVT deposits failed numerical and geological testing and had limited predictive value, as "random walk" was the main exploration method derived from them (Sangster, 1995, p. 260). A multidisciplinary study by the British Geological Survey on development of regional exploration criteria for buried carbonate-hosted mineral deposits concluded that "the simulation of parameters and processes, such as basin fertility (mineralizing potential of a basin computed from geochemistry of shales and estimates of temperature) and fluid migration, <u>is based on such simplistic models</u> that it is difficult to believe that…[basinal fluid-flow modelling] could be the basis of a predictive tool" (Sevastopulo, 2000, p. 1171).

In striking contrast, an empirical exploration model designed to test the relation between basement faults and mineralization led to the initial discovery of the entirely concealed giant Pine Point MVT district (Campbell, 1966, 1967). A major fault zone accompanied by a string of sulphide occurrences in the exposed Precambrian Shield was covered along strike to the southwest by carbonate deposits of the WCSB. The assumption that ore-bearing solutions were sourced in the fault zone and hence, deposited orebodies when released into overlying sediments, proved right. Campbell (1967) related the mineralizing fluids to a magmatic source and since no evidence for associated Phanerozoic igneous activity exists, the genetic relation between mineralization and faults was easily rejected (e.g. Jackson and Beales, 1967). The concept of fault-related metallogenesis has resurfaced in different versions (e.g. Roedder, 1968; Macqueen and Thompson, 1978; Krebs and Macqueen, 1984; Berger and Davies, 1999), but it has not been systematically addressed. A comprehensive genetic model for MVT deposits in the WCSB is derived here from the original inspirational empiric model by re-evaluating the relationships between stratigraphy, dolomitization, mineralization, and fractures in light of current knowledge of fault zone processes.

GEOLOGICAL FRAMEWORK OF MVT DEPOSITS AND OCCURRENCES IN THE CANADIAN ROCKIES

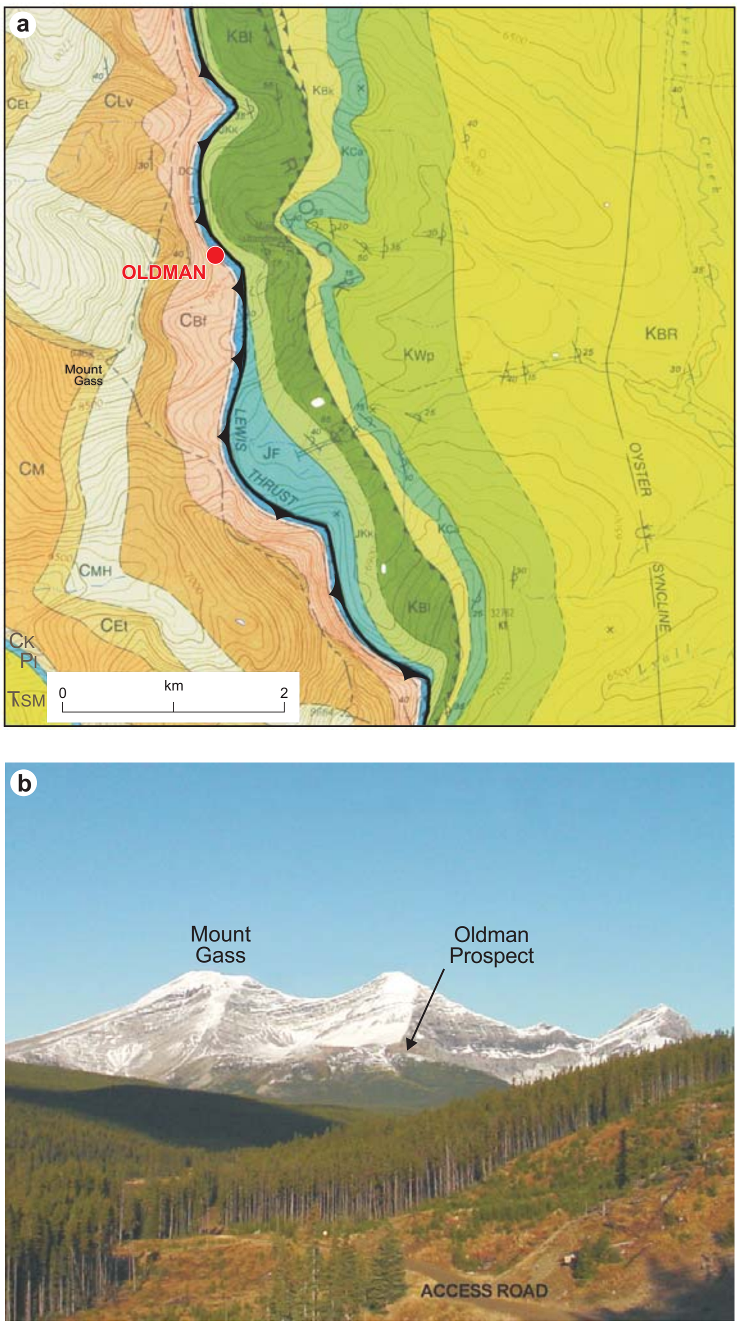
The main ranges of the Rocky Mountains consist largely of Paleozoic carbonate lithologies of the WCSB involved in the Laramide fold-and-thrust belt. Outcrop is extensive and typically continuous, but exploration and development is prohibited over the large areas encompassed by national parks, including Banff and Jasper national parks. Previous exploration and developments for lead-zinc involved the southern Canadian Rockies along the Alberta–British Columbia boundary and the northern Rockies of northeastern British Columbia. Old and limited descriptions of MVT occurrences give valuable hints on the geological controls when integrated with updated local and regional geological maps of the Canadian Rockies.

MVT deposits and prospects in the Southern Canadian Rockies

In the southern Rockies, MVT deposits have been mined in the Field district at Kicking Horse and Monarch, whereas the Oldman, Hawk Creek, Eldon, and Baker Creek prospects have been investigated to different degrees of detail in the past. Geological information on other sulphide showings in the Ottertail River basin, Frenchman Creek, Ice River, Moose Creek, and Shag Creek is rather poor (Fig. 1). Shag Creek prospect, approximately 35 km east of Radium, consists of small, discontinuous sphalerite and galena lenses, thin zones of mineralization, crosscutting calcite veinlets, and shear bands within two layers of brecciated granular dolostone of the Middle Cambrian Pika or Eldon formations (Hoy, 1982). The Frenchman Creek chalcopyrite, galena, and sphalerite occurrence in the Field District (Fig. 2b) is hosted by the sheared Chancellor Formation (Hedley, 1954).

Oldman River

The Oldman River occurrences include the lead-zinc-silver Bearspaw or Oldman prospect near the headwaters of Oldman River on the east flank of Mount Gass (Fig. 3), a lead occurrence on the northeast slope of Beehive Mountain and a copper occurrence at Mount Livingstone (Williamson et al., 1993).



LEWIS THRUST HANGING WALL

TRIASSIC
- TSM SULPHUR MOUNTAIN FORMATION

PERMIAN
- PI ISHBEL GROUP

CARBONIFEROUS
UPPER CARBONIFEROUS
- CK KANANASKIS FORMATION
- CM MISTY FORMATION

LOWER CARBONIFEROUS
- CEt ETHERINGTON FORMATION
- CMh MOUNT HEAD FORMATION
- CLv LIVINGSTONE FORMATION
- CBf BANFF FORMATION

DEVONIAN AND CARBONIFEROUS
UPPER DEVONIAN AND LOWER CARBONIFEROUS
- DCx EXSHAW FORMATION

DEVONIAN
UPPER DEVONIAN
- DPa PALLISER FORMATION

LEWIS THRUST FOOTWALL

CRETACEOUS
- KBR BELLY RIVER FORMATION
- KWp WAPIABI FORMATION
- KCa CARDIUM FROMATION
- KBk BLACKSTONE FORMATION
- KBl BLAIRMORE GROUP

JURASSIC
- JKk KOOTENAY GROUP
- JF FERNIE FORMATION

Figure 3. Location of the Oldman prospect. **a.** Geological framework of the Oldman prospect in the Upper Devonian Palliser Formation above Lewis Thrust. Geology *after* Norris (1993). **b.** Photograph of Mount Gass with the location of Oldman prospect looking west up Oldman River valley (courtesy Bob Sharp).

The two mineralized zones making up the Oldman deposit are found within dolomitic limestone in the upper part of the Devonian Palliser Formation, approximately 60 m above the Lewis Thrust at the intersection of a splay of the thrust, with two tear faults of minor displacement (Fig. 4). This prospect was explored in the 1950s with two short drillholes, three trenches, and two adits. In the northern (lower) adit, the mineralization is found in the walls of a subvertical fracture approximately parallel to the thrust's dip, whereas in the southern (upper) adit, the mineralized zone is parallel to the thrust fault (Table 1; Fig. 5) (Holter, 1977). Rocks are shattered and invaded by a network of white calcite veins and limonitic veinlets parallel to and crosscutting bedding. The limonitic veinlets, more abundant at the lower adit, are about 2 mm thick with 2 cm thick recrystallization halos. A spectacular network of veins consisting of coarse-grained white calcite with some grey saddle dolomite crystal intergrowths (or preexisting crystals) defines a breccia zone with block sizes from 1x 0.5 m to 0.4 x 0.2 m (Fig. 4b). The white veins are commonly 5 cm thick but several are up to 30 cm thick. Galena is the dominant sulphide as veins or clusters in calcite-dolomite veins and with crystal sizes ranging from 0.1 to 1 cm (Fig. 5). δ^{34}S in sulphides decreases in order of precipitation from early pyrite 15.85‰, to 15.64‰ in sphalerite and to 9.9‰ in late galena (Table 2; Holter, 1977). "Thrust faulting has provided pathways in introducing sulphides to the carbonate strata…", which suggests "the age of the Oldman River mineralization to be post-Laramide or contemporaneous with the Orogeny…" (Holter, 1977, p. 104). The subhorizontal development of the layer of hydraulic fracturing above the shallowly dipping fault is consistent with a horizontal $\tau 1$ (maximum principal stress). However, no kinematic indicators have been observed yet and thus, this zone of strain may be related to either thrusting or subsequent normal detachment. The MVT mineralizing fluid discharged exclusively within the Laramide hydrofractured layer during a final phase of stress and fluid release, and sulphides were precipitated along the tear faults. Thus, a pre-orogenic age and, implicitly, the basinal fluid-flow genetic models, are precluded for the Oldman MVT prospect.

Hawk Creek

The Hawk Creek prospect, in Kootenay National Park about 3 km east of the Banff-Windermere highway (Fig. 6), is an 80 m long by 15 m wide pencil-like mineralized zone consisting of sphalerite and small amounts of galena, pyrite, and negligible silver and gold hosted by thin-bedded argillaceous limestone and argillite of the Middle to Upper Cambrian Chancellor Formation (Table 1). "The beds are gently dipping or horizontal and are cut by a pronounced northwest-trending shear zone that dips 45° to 70° degrees to the southwest" (Henderson, 1954, p. 155). Sphalerite replaces dolostone along a shear zone and is banded parallel to the shear planes. This ore texture is similar to the "gneissic galena" described in the fault in the Monarch mine (Ney, 1954, p. 135). Sulphide showings are restricted to dolomitic limestone, dying out in finer grained limestone away from the shear zone. Estimated temperatures of sphalerite precipitation vary from 70 to 110°C and δ^{34}S in sulphides vary from 24.8 to 27.9‰ (Table 2; Evans et al., 1968). A clear genetic relationship between postorogenic shearing of a limestone host, sulphide mineralization and dolomitic alteration can be inferred by integrating an old and rather sketchy description of the prospect (Henderson, 1954) with the regional geology map (Price et al., 1978). The shear zone described by Henderson (1954) appears to correspond to a major northwesterly striking normal fault (Price et al., 1978) (Fig. 6), which is part of a regional set of en échelon normal faults that includes the Stephen-Cathedral Fault in the Field district about 30 km to the northeast.

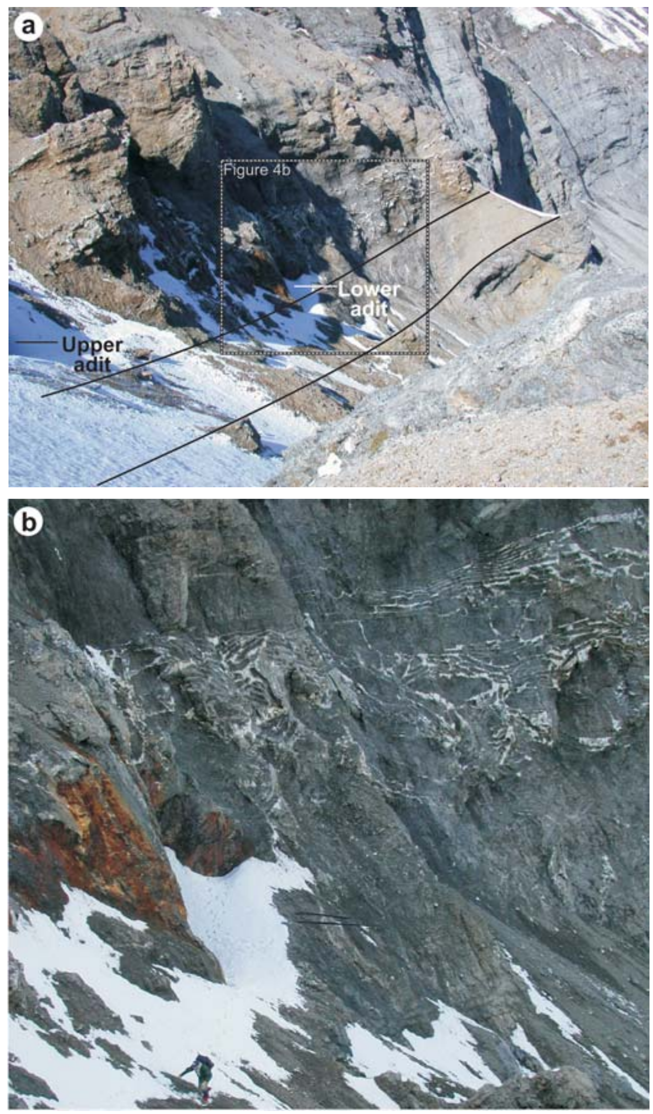


Figure 4. Photographs of the Oldman prospect. **a.** The low-angle west-dipping fault with the location of the two mineralized zones; box-area detailed in Figure 4b. **b.** Intense calcite veining within a roughly concordant strained layer above the low-angle fault in the upper part of the Palliser Formation.

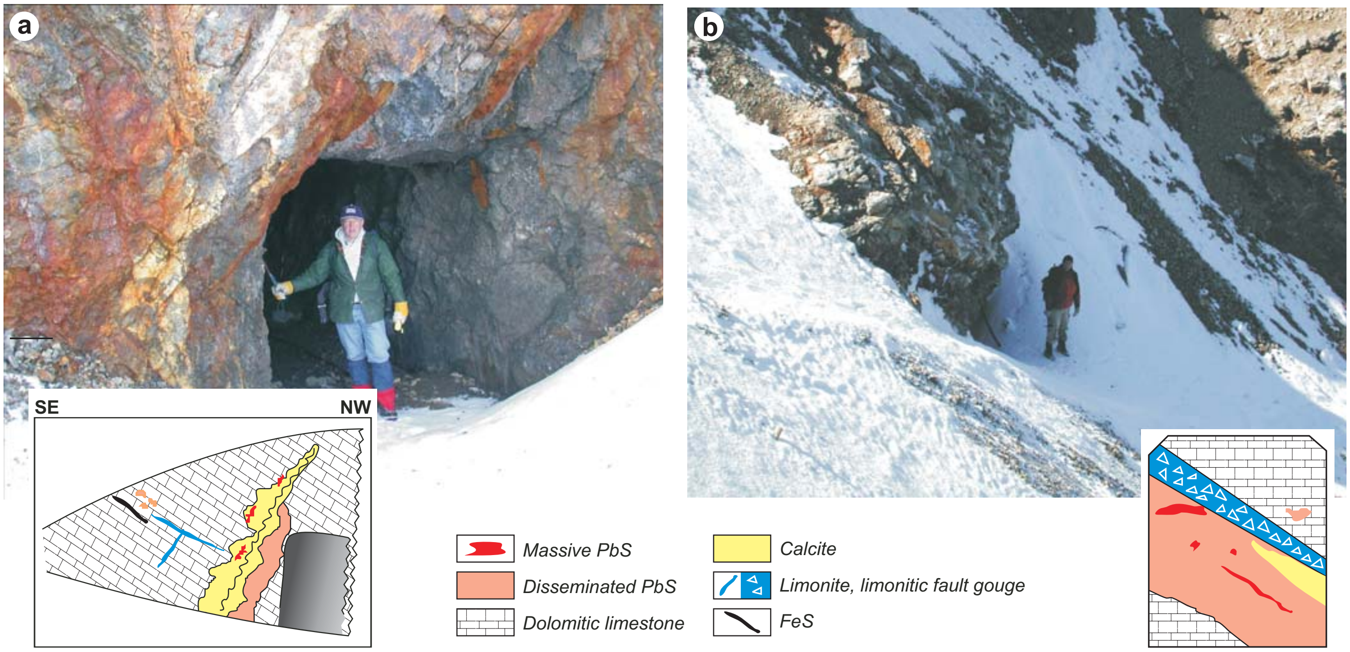


Figure 5. Photographs of the two adits at the Oldman prospect. **a.** The main mineralized zone at the lower (northern) adit: galena vein parallel to calcite-dolomite veins; the main calcite vein dips 70° to the east and includes clusters of galena up to 10 cm in diameter with an average galena content of 10% over the 5 m exposed surface in front of the adit. Inset: diagrammatic view of mineralization at portal of lower adit includes a pyrite-bearing shear zone about 10 m east of the galena vein along the rock face (outside the photo area). The zone is 10–20 cm thick and dips 60° to the northwest. **b.** The entrance in the upper (southern) adit. Inset: cross-section of the face about 2 m south of the tear fault.

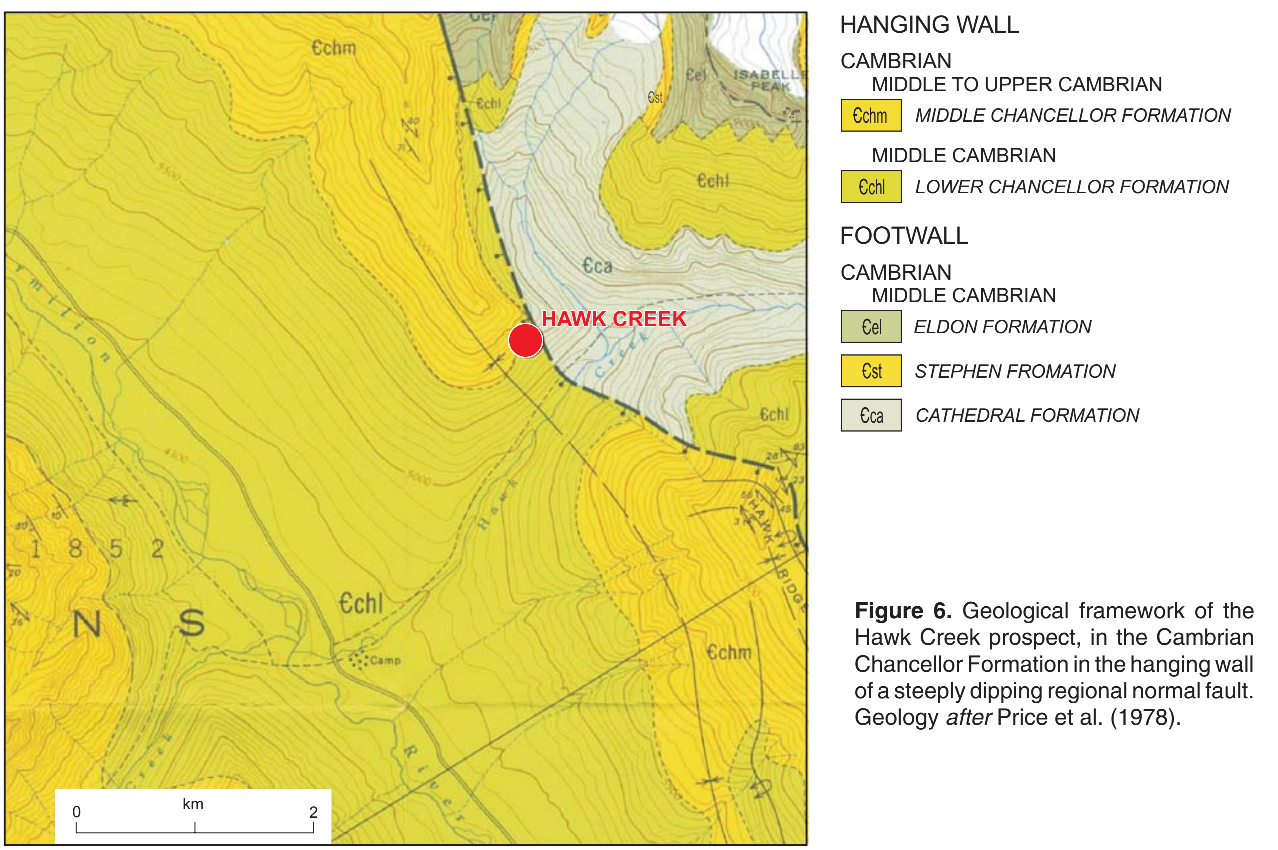


Figure 6. Geological framework of the Hawk Creek prospect, in the Cambrian Chancellor Formation in the hanging wall of a steeply dipping regional normal fault. Geology *after* Price et al. (1978).

Baker Creek

According to Evans et al. (1968), the Baker Creek prospect is situated in Banff National Park, east of Bow River, south of Baker Creek on the west flank of Protection Mountain (Fig. 7). The same prospect had been previously described by Green (1957) as “Eldon mine”. At this prospect, Pb sulphides occur within massive dolomite-mottled micritic limestone and dolostone (Table 1). A spectacular network of calcite and quartz veins is occasionally associated with pockets of galena, minor copper staining and pyrite in a host of dark grey, medium-grained dolomite and some “spotted dolomite” (Green, 1957, p. 2). Evans et al. (1968) identified the black dolomite host as the Middle Cambrian Cathedral Formation invaded by coarse-grained white dolomite, and noticed the resemblance of this lithology with that at the Kicking Horse-Monarch mines. A galena sample yielded a $\delta^{34}S$ value of 9.2‰ (Table 2; Evans et al., 1968).

Eldon prospect

The Eldon prospect as identified by Evans et al. (1968) lies west of Bow River, about 3 km SW of its confluence with Baker Creek (Fig. 7). The host rocks (calcareous and argillaceous rocks of probable Lower or Middle Cambrian) described by Evans et al. (1968) do not correspond to the updated geological map of the region (Price et al., 1980a). The mineralization is related to a southeast-striking shear zone dipping at 40° north (Evans et al., 1968). Estimated temperatures of sphalerite precipitation vary from 75 to 110°C and $\delta^{34}S$ vary from 8.1 to 12.2‰ (Table 2; Evans et al., 1968).

Kicking Horse and Monarch

The Kicking Horse and Monarch deposits exhibit very similar characteristics and occur on the north and south side, respectively, of Kicking Horse River (Fig. 8a). Most galena-sphalerite-pyrite orebodies are hosted by the

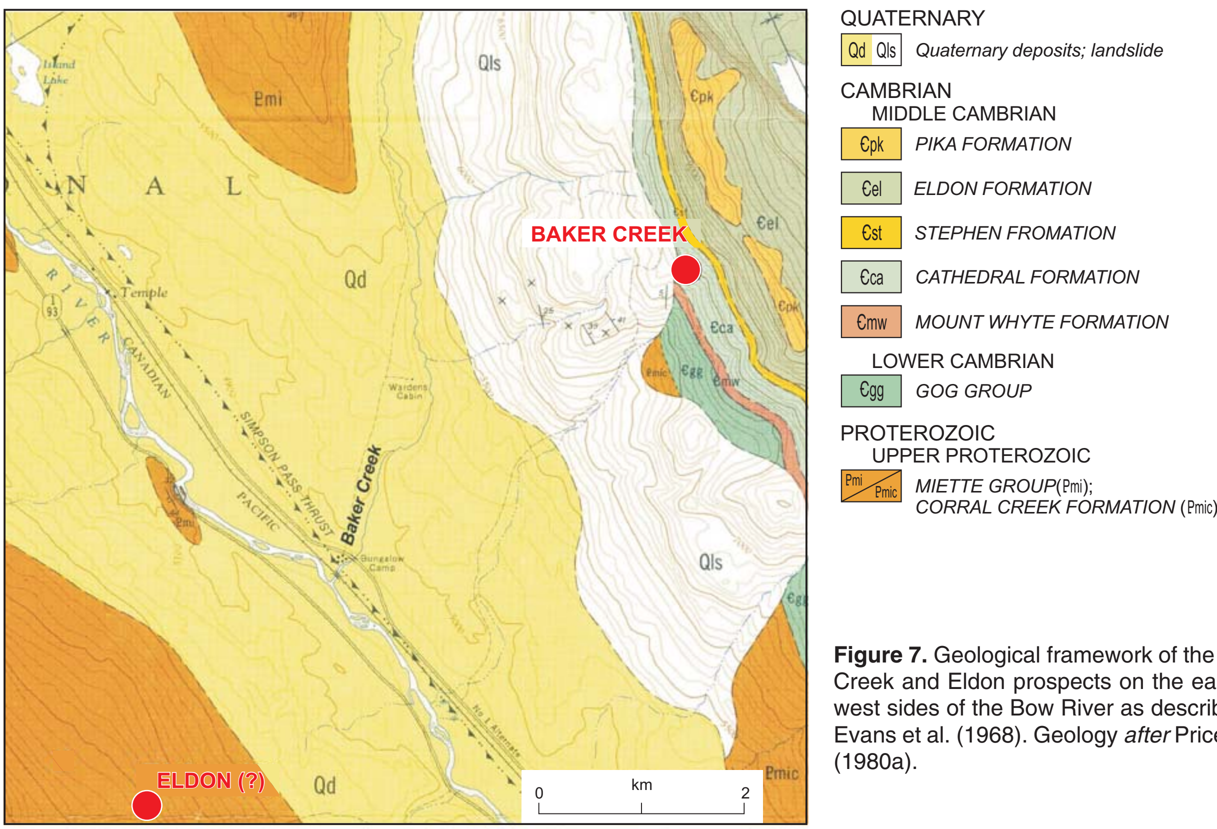
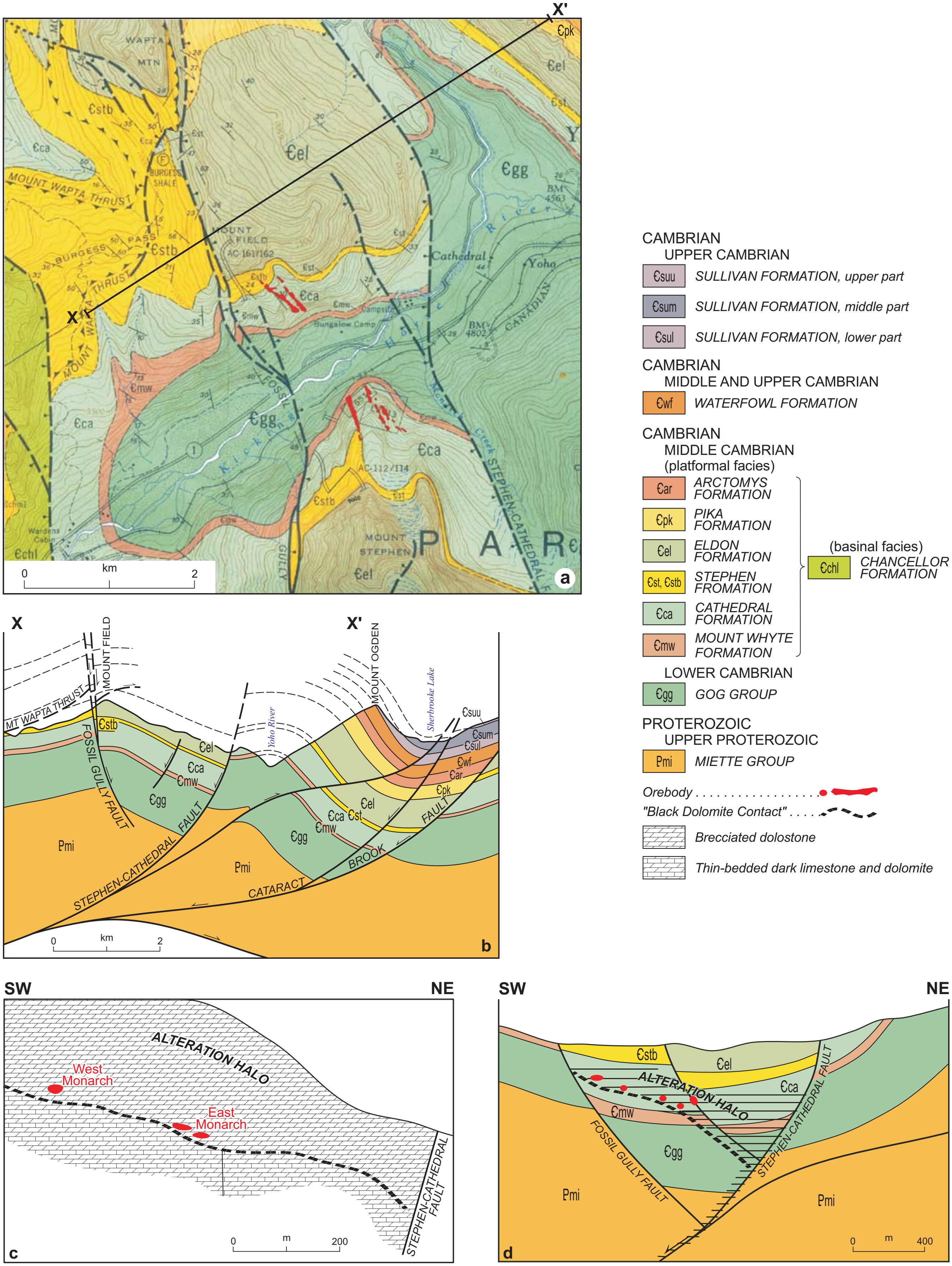


Figure 7. Geological framework of the Baker Creek and Eldon prospects on the east and west sides of the Bow River as described by Evans et al. (1968). Geology *after* Price et al. (1980a).

Figure 8. Geological framework of the Kicking Horse and Monarch deposits on the north and south side of Highway 1, respectively. **a.** Location of the mineralized zones with respect to major structures. **b.** Regional cross-section. **c.** Cross-section through the Monarch Pb-Zn deposit showing the location of orebodies along the “Black Dolomite Contact” (*simplified after* Ney, 1954). **d.** Interpretative cross-section showing the outflow of a metal-charged hydrothermal front leading to replacement reactions and local precipitation of ore in the hanging wall of the normal Stephen-Cathedral fault.


X'
X
a
0 km 2
MOUNT WAPTA THRUST
BURGESS PASS THRUST
MOUNT FIELD
MOUNT STEPHEN
STEPHEN-CATHEDRAL F.
FOSSIL GULLY
Kicking Horse River
Yoho River
CANADIAN
Cathedral Creek
PARK
€pk
€el
€st
€stb
€ca
€egg
€mw
€gg
€chl
b
MT WAPTA THRUST
MOUNT FIELD
MOUNT OGDEN
Yoho River
Sherbrooke Lake
FOSSIL GULLY FAULT
STEPHEN-CATHEDRAL FAULT
CATARACT
BROOK FAULT
Pmi
€suu
€sum
€sul
€wf
€ar
€cst
0 km 2
c
SW
NE
ALTERATION HALO
West Monarch
East Monarch
STEPHEN-CATHEDRAL FAULT
0 m 200
d
SW
NE
ALTERATION HALO
FOSSIL GULLY FAULT
STEPHEN-CATHEDRAL FAULT
0 m 400
CAMBRIAN
UPPER CAMBRIAN
€suu SULLIVAN FORMATION, upper part
€sum SULLIVAN FORMATION, middle part
€sul SULLIVAN FORMATION, lower part
CAMBRIAN
MIDDLE AND UPPER CAMBRIAN
€wf WATERFOWL FORMATION
CAMBRIAN
MIDDLE CAMBRIAN
(platformal facies)
€ar ARCTOMYS FORMATION
€pk PIKA FORMATION
€el ELDON FORMATION
€st, €stb STEPHEN FROMATION
€ca CATHEDRAL FORMATION
€mw MOUNT WHYTE FORMATION
(basinal facies)
€chl CHANCELLOR FORMATION
LOWER CAMBRIAN
€gg GOG GROUP
PROTEROZOIC
UPPER PROTEROZOIC
Pmi MIETTE GROUP
Orebody
"Black Dolomite Contact"
Brecciated dolostone
Thin-bedded dark limestone and dolomite

Middle Cambrian Cathedral Formation in an area bounded by northwesterly trending normal faults (Table 1; Fig. 8a, b, d). To the east, the Stephen-Cathedral fault dips to the west and has a downdip throw of approximately 1 km (Fig. 8b, c, d) (Price et al., 1980b). Splays of the main fracture closer to the orebodies have individual offsets of up to 50 m and carry a "wide zone of dolomite vein-breccia" (Ney, 1954, p. 129). About 1.5 km west of the mines, the Stephen-Field fault (Price et al., 1980b) or Fossil Gully fault (Cook, 1975) dips steeply to the east with a normal vertical displacement of about 300 m. As described on existing geological maps, the structural framework corresponds to a normal flower structure and appears related to a postorogenic collapse tectonic phase (Fig. 8b, d).

Paragenetic relationships and isotope data

Fine-grained, dark brown to black dolomite, which replaced primary limestone during early regional marine alteration, is stratigraphically persistent and fairly well bedded. A second dolomitization phase resulted in white sparry dolomite, which obliterated bedding and fingered out to the west in the hanging wall of the Stephen-Cathedral normal fault. All known orebodies in the Field district as well as minor pyrite and chalcopyrite concentrations are confined to this wedge-shaped alteration halo of late dolomitization. Occurrences of white fibrous amphibole, talc, and graphite in the mineralized zone indicate temperatures of at least 200°C. The sharp interface between light grey, brecciated carbonate rocks affected by the second phase of dolomitization, and the subjacent thin-bedded, black limestone or partly dolomitized limestone, defines the "Black Dolomite Contact", which rises toward the west through strata of the Mount Whyte Formation into the overlying Cathedral Formation (Ney, 1954) (Fig. 8c). The footwalls of all orebodies are either on, or a few metres above the 'Black Dolomite Contact". Irregular vein-like orebodies with sparry dolomite gangue extend into previously more or less dolomitized limestone (Ney, 1954). Hence, the mineralization accompanied a chemical reaction boundary that crosscut stratigraphy (Fig. 8c). $\delta^{18}O$ values of sparry dolomite range from 12 to 15‰ (SMOW), δD_{FI} values of -40 to -80‰(SMOW), $\delta^{13}C$ values of -1 to 0‰ (PDB) and fluid inclusion homogenization temperatures from 100 to 200°C (Table 2; Nesbitt and Muehlenbachs, 1995a). A late population of near-vertical undeformed quartz and carbonate veins, preferentially developed adjacent to faults, yielded $\delta^{18}O$ values of 12 to 23‰ and 16 to 22‰ (SMOW), respectively, δD_{FI} values of -120 to -155‰ (SMOW), $\delta^{13}C$ values of -3 to 1‰ (PDB) and fluid inclusion homogenization temperatures of 90 to 150°C (Table 2; Nesbitt and Muehlenbachs, 1995a). The sparry dolomite of the second dolomitization phase and the late vein carbonate and quartz have complementary and/or overlapping ranges of isotope values and fluid inclusion homogenization temperatures, which suggests an evolving hydrothermal fluid as it cooled and reacted with carbonate along the flow path. As temperatures decreased, $^{87}Sr/^{86}Sr$ values of the mineralizing fluid also decreased, while $\delta^{18}O$ values increased (Nesbitt and Muehlenbachs 1994a). High δD_{FI} values in sparry dolomite compared to low δD_{FI} values in late vein dolomite, and high salinities in sparry dolomite (20–25 wt% NaCl equiv.) compared to low-salinities in veins (0–10 wt% NaCl equiv.) (Nesbitt and Muehlenbachs, 1994a; 1995a) suggest gradual depletion of the deep fluid reservoir and contamination of the hydrothermal plume with meteoric water as it ascended towards surface. Parental fluids of the late quartz and carbonate veins were merely recycled local meteoric waters, infiltrated after the uplift of the Rockies, which acquired heat and small amounts of salt from the carbonate deposits (Nesbitt and Muehlenbachs, 1995a).

Lead isotope values of the MVT ore at Kicking Horse and Monarch mines are distinct from those reported from the Robb Lake prospect and closer to those of Pine Point district (Table 2), thus putting into conflict the idea of a unique Paleozoic regional front of metal-bearing brines advancing eastward from the shale basin into the carbonate platform (Nesbitt and Muehlenbachs, 1994a; Nelson et al., 2002).

Structural versus stratigraphic control

The ore occurs in brecciated dolostone, fissures and fractures toward the base of the wide alteration zone whereas the underlying thin-bedded, black dolomitic limestone is barren (Fig. 8c, d). Sulphide and associated sparry dolomite, quartz, and barite gangue preferentially replace the breccia matrix, but locally the clasts are also replaced (Ney, 1954). Irregular veinlets cut both matrix and fragments and coarse sphalerite and galena commonly rim dark dolomite fragments, with spar dolomite filling the remaining vugs (Hoy, 1982). Paragenetic and textural descriptions indicate that mineralization post-dated or outlasted brecciation. Bands of massive ore on the order of one foot thick occur sporadically. "Sets of closely spaced, steeply dipping fractures, forming zones several tens of feet wide…are associated with the good ore, and appear to have facilitated the replacement process" (Ney, 1954, p. 135). "A conspicuous fault striking north 45° west and dipping 60° northeast forms a large part of the hanging wall …in the East Monarch mine…carries gneissic galena several feet below the main orebody…has the aspect of a possible feeder channel" (Ney, 1954, p. 135).

Existing data suggest that the Stephen-Cathedral normal fault and its splays constituted the pathway for an ascending hydrothermal plume that produced a dolomitic halo in its hanging wall (Fig. 8c, d). Concurrent brecciation, dolomitization, and mineralization indicate active tectonism during ore deposition: while the metal-charged hydrothermal front progressed to the west and upwards across stratigraphy, the metallic load precipitated in tectonic and dissolution breccia as a result of cooling and pH change. The lack of erratic lateral spreading of the mineralization, which would be expected in a regional replacement process, points to a local control of ore precipitation.

Based on structural data from south-central British Columbia where epigenetic dolomite was interpreted to have formed prior to the Early Cretaceous initiation of deformation in the Rockies (Westervelt, 1979), Nesbitt and Muehlenbachs (1994a) interpreted coarse, vuggy, white to cream saddle dolomite and local MVT mineralization resulting from Late Devonian–Mississippian regional fluid-flow. The quartz and/or calcite veining is a late syn- to post-Laramide event. This generalization is controversial (Qing et al., 1995) and in conflict with Ney's (1954) assessment of the paragenetic and structural relationships in the only well-studied MVT deposit of the southern Rockies.

The age of MVT mineralization in the southern Rocky Mountains

The dolostone host rocks, the hydrothermal dolomite and the mineralized zones around the Kicking Horse and Monarch mines acquired their characteristic remanent magnetization coevally during the Cretaceous normal superchron, which ended in Santonian (approx. 84 Ma), and do not retain any older remanent magnetization (Symons et al., 1998). The increase in characteristic remanent magnetization intensity near the MVT orebodies ties the magnetization to the mineralization event. Fold tests showed that the characteristic remanent magnetization postdates the main Laramide deformation event (Symons et al., 1998). This is entirely consistent with the interpretation of a mineralizing hydrothermal plume channelled along the postorogenic collapse faults (Fig. 8d). Thus, the MVT mineralizing and dolomitizing event (associated sulphides and white sparry dolomite as well as late dolomite and quartz veins) is here inferred to have followed shortly after the main Laramide thrusting, most likely in Santonian time. The Oldman prospect is genetically related to faults that are coeval or younger than the ca. 75 Ma old Lewis thrust (Symons et al., 1998).

MVT prospects in northern Rocky Mountains

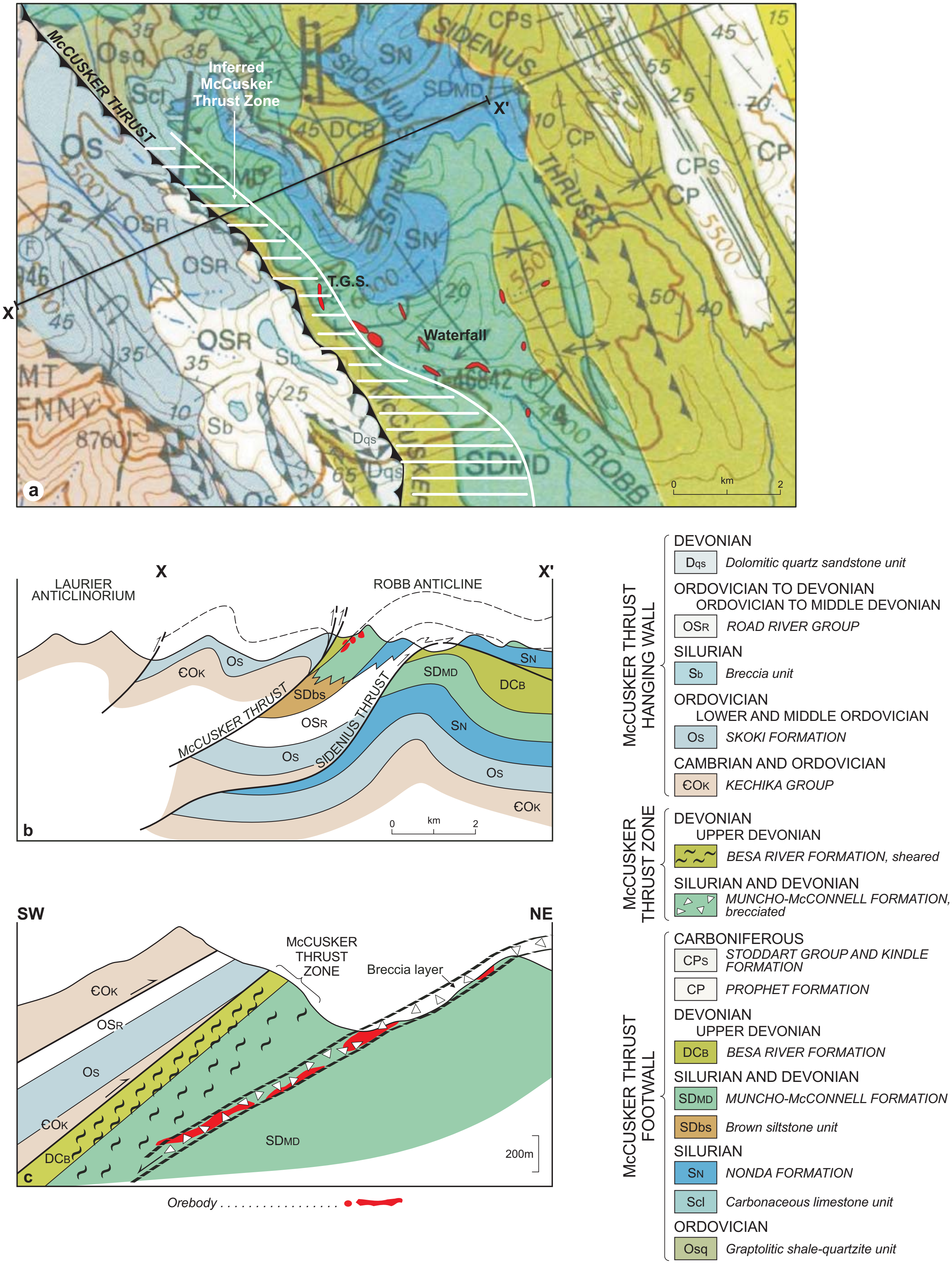
A belt of MVT showings stretches along the eastern margin of the Rockies, north of their intersection with the aeromagnetic trace of the Great Slave Shear Zone (GSSZ) (Fig. 1). Most MVT occurrences are located at various stratigraphic intervals within a Lower and Middle Devonian carbonate sequence more than 600 m thick, at the distal edge of the carbonate platform, now strongly folded and faulted. The mineralization does not appear to be controlled by major carbonate dissolution and unconformities (Macqueen and Thompson, 1978). Richards Creek and Lady Laurier Lake occurrences are fracture controlled, whilst at Robb Lake, only some mineralized zones (e.g. TGS and Waterfall) are clearly discordant to bedding and parallel to steeply dipping Laramide faults (Macqueen and Thompson, 1978; Smethurst et al., 1999) (Table 1; Fig. 9). The mineralization dominantly consists of sphalerite associated with galena ± pyrite or marcasite in a gangue of white sparry dolomite, quartz, calcite, and pyrobitumen, and occurs in a variety of textures.

The Robb Lake district, approximately 10 km northwest of Robb Lake, is by far the best studied of the MVT prospects in the northern Rockies, as it was the most attractive from an economic perspective. Numerous mineralized stratabound and crosscutting breccia bodies with peripheral veins and stockworks are hosted by the platform carbonate of the Silurian to Devonian Muncho-McConnell Formation, with a few occurrences within the overlying Lower to Middle Devonian Stone and Dunedin formations (Macqueen and Thompson, 1978; Nelson et al., 2002) (Fig. 9). Variously dolomitized and mineralized carbonate units are overlain by highly sheared and hydrothermally altered slate and calcareous shale of the Upper Devonian Besa River Formation in the immediate footwall of the McCusker Thrust (Fig. 9) (Thompson, 1986, 1989). The fabric and alteration of these tectonites was later considered indicative for the Cambro-Ordovician Kechika Group in the hangingwall of McCusker thrust (Paradis et al., 1999).

Paragenetic relationships, fluid inclusions and isotope data

Two distinct dolomitization processes affected the carbonate sequence in the Robb Lake area (e.g. Macqueen and Thompson, 1978; Nelson et al., 1999). Widespread, very fine- to fine-grained dolostone and less extensive, medium-grained dolomite are related to early regional diagenetic alteration of limestone in a peritidal environment. Several generations of coarse-grained, white sparry dolomite and zebra dolomite were formed during late polyphase dolomitization processes under subsurface conditions and were confined to the mineralized area (Macqueen and Thompson, 1978). The layering of zebra dolomite is either parallel to bedding or discordant in a herringbone pattern resembling crossbedding (Paradis et al., 1999) indicating that fluid migration was favoured by, but not limited to, primary sedimentary texture. The late dolomitization is associated with brecciation and open-space filling by sphalerite, pyrite, galena and, locally, pyrobitumen. Fragments of zebra dolomite are incorporated into the mineralized breccia.

Paleotemperature estimates on fluid inclusions in quartz, illite, and bitumen and on correlations with conodont alteration indices give a range of 200–230°C consistent with the inferred progressive burial history of the host rocks to a maximum of 5 km during Early Cretaceous time at a geothermal gradient of 35–42°C/km (Macqueen and Thompson, 1978; Sangster et al., 1994). Fluid inclusions have salinities of 16 to 23%NaCl equiv., and the estimated temperature of the mineralizing fluid is in the range of 87 to 154° (Sangster and Carrière, 1991). Obviously, the MVT ore at Robb Lake did not experience the burial history of the host rocks, which constrains the mineralization to post-Early Cretaceous.


McCUSKER THRUST
Inferred McCusker Thrust Zone
SIDENIUS THRUST
ROBB THRUST
T.G.S.
Waterfall
X
X'
a
b
c
km
LAURIER ANTICLINORIUM
ROBB ANTICLINE
SW
NE
McCUSKER THRUST ZONE
Breccia layer
200m
Orebody
McCUSKER THRUST HANGING WALL
DEVONIAN
Dqs Dolomitic quartz sandstone unit
ORDOVICIAN TO DEVONIAN
ORDOVICIAN TO MIDDLE DEVONIAN
OSR ROAD RIVER GROUP
SILURIAN
Sb Breccia unit
ORDOVICIAN
LOWER AND MIDDLE ORDOVICIAN
Os SKOKI FORMATION
CAMBRIAN AND ORDOVICIAN
ЄOK KECHIKA GROUP
McCUSKER THRUST ZONE
DEVONIAN
UPPER DEVONIAN
BESA RIVER FORMATION, sheared
SILURIAN AND DEVONIAN
MUNCHO-McCONNELL FORMATION, brecciated
McCUSKER THRUST FOOTWALL
CARBONIFEROUS
CPs STODDART GROUP AND KINDLE FORMATION
CP PROPHET FORMATION
DEVONIAN
UPPER DEVONIAN
DCB BESA RIVER FORMATION
SILURIAN AND DEVONIAN
SDMD MUNCHO-McCONNELL FORMATION
SDbs Brown siltstone unit
SILURIAN
SN NONDA FORMATION
Scl Carbonaceous limestone unit
ORDOVICIAN
Osq Graptolitic shale-quartzite unit

The pre-mineralized fine-grained limestone and dolostone have $\delta^{18}O$ values ranging from 19.6 to 20.5‰ (SMOW) and $^{87}Sr/^{86}Sr$ ratios of 0.7092 and 0.7097 (Table 2; Nelson et al., 2002). The $^{87}Sr/^{86}Sr$ ratios, higher than those of seawater (0.7078–0.7083; Burke et al., 1982), indicate diagenetic alteration by modified seawater with slightly more radiogenic strontium. The late-stage sparry dolomite gangue shows lower $\delta^{18}O$ values ranging from 14.9 to 16.7‰ (SMOW) and $^{87}Sr/^{86}Sr$ ratios of 0.7118 to 0.7178 (Table 2; Nelson et al., 2002). The $^{87}Sr/^{86}Sr$ ratios of the MVT gangue, much higher than Phanerozoic seawaters (Eocene $^{87}Sr/^{86}Sr$ =0.7077 and Devonian $^{87}Sr/^{86}Sr$ =0.7078–0.7083) and carbonate host, and higher than the shale-derived basinal fluids along the Presqu'ile reef (0.7094–0.7106), indicate strong interaction with the crystalline basement or clastic sedimentary rocks (Machel and Cavell, 1999). $^{87}Sr/^{86}Sr$ ratios of sphalerites (0.7138–0.7298) and their fluid inclusion leachates (0.7108–0.7174) (Table 2; Nelson et al., 2002) are in the range of basement brines (ca. 0.710–0.740) (Frape et al., 1984).

Lead isotope values from Robb Lake and other MVT occurrences in the northern Rockies are much higher and more variable than the shale-hosted Ba-Pb-Zn prospects to the west (Devonian SEDEX) and those of Pine Point district (Table 2).

Relationships between dolomitization and mineralization

Mineralization at Robb Lake takes two forms: mineralized breccia, and veins and vein stockworks (e.g. Paradis et al., 1999). Breccia bodies commonly mineralized with sphalerite, pyrite, and less abundant galena are interconnected within two zones parallel to the structural trend and separated by a 70 m thick barren section (Boronowski and James, 1982 *cf.* Paradis et al., 1999). The sulphides are concentrated in the matrix as individual grains and clusters and as fracture-filling material. Dolomite overgrowth on the matrix fragments and interstitial dolospar and quartz indicate that the breccia was percolated by mineralizing fluids. Alteration and dissolution of carbonate wallrock versus carbonate and ore precipitation appear to have taken place concurrently during and after tectonic brecciation of the Silurian to Devonian dolostone (Fig. 9).

Structural versus stratigraphic control

Recent studies describe several textural types of breccia and unambiguously show that brecciation and mineralization were at least in part contemporaneous, the result of a multi-episodic sequence of events (Nelson et al., 1999, 2002; Paradis et al., 1999). The primary versus secondary nature of the breccia host at Robb Lake has long been a contentious issue (e.g. Sangster, 1973; Macqueen and Thompson, 1978; Manns, 1981). Basinal fluid-flow is often invoked as the main agent responsible for carbonate dissolution, karstification, collapse, and brecciation. Accurate field observations at the "north face" zone of the Robb anticline (Macqueen and Thompson, 1978) constitute a convincing case against the routinely invoked karstification/ mineralization/collapse genetic model for MVT deposits (e.g. Sangster and Lancaster, 1976). There is no spatial relationship between karstification-triggering unconformities and MVT mineralization. Instead, by far the most volumetrically important breccia at Robb Lake is very likely a tectonic breccia described as "rubble breccia" consisting of angular, polymictic, completely displaced fragments up to several metres in size with fragmental matrix ("trash") instead of dolomite cement (Paradis et al., 1999, p. 7).

Existing rock descriptions and their spatial distribution are consistent with strain partitioning and hydrothermal activity near McCusker Thrust (Fig. 9c). The narrow belt of "well-cleaved" rocks with a "slaty, almost phyllitic character", described in the footwall of the McCusker Thrust (Nelson et al., 1999, p. 91) are similar to rocks with distinctive rusty-buff weathering and intense penetrative cleavage described in the immediate footwall of the Herchmer Fault in Deserters Range (Evenchick, 1988). In both cases, this tectonic facies was assigned to the Cambro-Ordovician "Kechika Group". It is conceivable that at Robb Lake this tectonite may represent the main zone of stress release and hydrothermal alteration within the Devonian argillite and shale of Thompson's (1986 and 1989) Besa River Formation that accommodated the Laramide eastward thrusting of the Ordovician to Silurian Road River Group. Contemporaneous stress within the more competent, thickly bedded limestone of Muncho-McConnell Formation may have resulted in bedding-parallel discrete shearing and dolomitization ("the upper unit" of the Muncho-McConnell Formation after Paradis et al., 1999). Farther down and away from the main zone of stress release (i.e., McCusker Thrust), weaker stress may have resulted in the two layers of interconnected

Figure 9. Geological framework of the Robb Lake prospects; *reinterpreted after* Thompson (1986) and Nelson et al. (1999). **a.** Hatched area in the footwall of McCusker thrust is an inferred zone of strain a few hundred metres thick represented by the highly sheared and altered Upper Devonian Besa River strata and by the "upper unit" of the Muncho-McConnell Formation. The upper and lower units consist of identical medium- to thick-bedded dolostone with thin-bedded dolostone interlayers only in the upper unit, interpreted here as result of strain partitioning near a tectonic contact. **b.** Regional cross-section (from Thompson, 1986). **c.** Interpretative cross-section showing a layer of strained and mineralized carbonate associated with a late normal fault (marked as breccia layer).

mineralized breccias identified by Boronowsky and James (1982 *cf.* Nelson et al., 1999). Breccias and the associated stockwork structures are likely formed by hydraulic fracturing (Macqueen and Thompson, 1978). Alternatively, and more likely, the lineaments of strain associated with MVT mineralization may have formed during postorogenic collapse as suggested by the age of mineralization (Smethurst et al., 1999).

Macqueen and Thompson (1978) proposed that metal-bearing fluids might have resulted from compaction and geothermal heating accompanied by dewatering of argillaceous sequences in the Kechika Trough to the west during Laramide tectonism. The reported average zinc values of 36 ppm and 84 ppm for 9 Devonian samples and 13 Mississippian samples, respectively, and lead and copper concentrations generally below the 4-ppm detection limit (Macqueen and Thompson, 1978), cast doubts on the authors' interpretation of the Besa River shale as the probable source of metals. Moreover, the Pb isotopic composition in the MVT prospects of northern Rockies is highly variable and radiogenic and cannot be derived from the non-radiogenic, homogeneous Pb of the shale-hosted Ba-Zn-Pb accumulations to the west (Morrow and Cumming, 1982).

The age of MVT mineralization in Devonian carbonate deposits of northern Rocky Mountains

A two-stage evolution Pb model age of ca. 370 Ma was originally inferred for the 'young carbonate-hosted Pb-Zn deposits" in northern Rockies based on the controversial assumption that Pb in the MVT prospects originates in the adjacent basinal shale (Godwin et al., 1982; Morrow and Cumming, 1982). Additional Pb isotope data from Robb Lake, Mount Burden and Richards Creek defined a series of subparallel linear arrays with unclear age significance (Morrow and Cumming, 1986). Scattered and inconclusive Rb-Sr sphalerite data points from Robb Lake were interpreted by Nelson et al. (2002) to indicate an age similar to the Rb-Sr isochron age of ca. 362 Ma calculated by Nakai et al. (1993) for the Pine Point deposits. Fluid inclusion data points define a steep array and individual ages calculated from pair fluid inclusion and residue range from 39 Ma to 334 Ma. Primary chemical remanent magnetization in sulphide ore and sparry dolomite indicate that the MVT mineralization occurred at 47±10 Ma and postdated the Laramide folding (Smethurst et al., 1999). The Eocene paleomagnetic age corresponds to the waning stages of the Laramide Orogeny and is in agreement with the paleotemperature data, which indicate that the MVT mineralization postdates the uplift of the host rocks from their maximum burial during Early Cretaceous time.

General remarks on MVT deposits and occurrences in the Canadian Rockies

1. No particular stratigraphic interval or depositional environment can be identified to have preferentially localized the MVT mineralization in the Canadian Rockies. Thus, in the southern Rocky Mountains, the MVT occurrences are hosted by platform carbonate strata of the Middle Cambrian Cathedral Formation (Kicking Horse and Monarch deposits), by the uppermost Devonian Palliser Formation (Oldman prospect) and a number of occurrences within the calcareous shale of the basinal Chancellor Formation (e.g. Hawk Creek, Frenchman Creek). In the northern Rocky Mountains, MVT occurrences are at various stratigraphic intervals within a more than 600 m thick Lower to Middle Devonian carbonate sequence, generally at or near the carbonate platform edge. However, the location of the Richards Creek occurrence in the interior of the platform indicates that the original geometry of the basin is not the primary control for MVT mineralizing fluids.
2. The MVT mineralization is epigenetic, invariably and exclusively associated with a late phase of localized, fault-controlled dolomitization, not to the early regional basinal dolomitization, or to the normal diagenetic changes accompanying burial.
3. The MVT mineralization is a syntectonic/post-tectonic process taking place concurrently with brecciation, development of stockwork structures, tensional gashes, cracks, and cleavages; the higher porosity and permeability of the carbonate host rocks are secondary, tectonically initiated, and enhanced by dissolution.
4. The stratabound appearance of MVT deposits is deceiving: strained layers parallel major fractures, which in a fold-and-thrust belt are typically subparallel to stratigraphic units. MVT deposits and sulphide zones are parallel to the structural grain of the Rockies and spatially associated with fractures; these fractures can be either major thrusts (e.g. Lewis and McCusker thrusts), or post-orogenic collapse faults (e.g. Stephen-Cathedral and Hawk Creek normal faults).
5. Very low concentrations of metals in shale adjacent to platformal carbonate deposits that host MVT mineralization (e.g. Kechika Trough adjacent to the Robb Lake MVT district) indicate that this basinal shale is an unlikely source of metals.

Data summarized above preclude the application of Devonian basin-scale fluid-flow genetic models to MVT deposits and occurrences in the Canadian Rockies. Sphalerites have basement Sr isotopic signatures. Deposit specific and variable Pb isotope ratios in galena imply distinct and heterogeneous Pb sources and inefficient mixing of Pb during deposition. It is conceivable that Pb was derived locally by processes involving fluids migrating through recurrent zones of strain concentration in the Cordilleran basement and leaching of Pb lost by U-rich minerals during different tectonic events. Similarly, the distinctive ranges of $\delta^{34}S$ values in sulphide from different MVT deposits and prospects in the Rockies suggest local controls of sulphur isotopes such as temperature, lithology, and the extent of sulphate conversion into HS^-, consistent with the idea of local hydrothermal systems within faults. $\delta^{34}S$ values from MVT occurrences in the Rockies are within the range of sulphur isotope values for HS^- reported from thermal springs along Eocene and post-Eocene extensional faults in southern British Columbia, where circulation of meteoric water through faults is accompanied by dissolution of sulphate minerals from carbonates and bacterial sulphate reduction to HS^- (Grasby, 2002).

The characteristics of MVT deposits and prospects in the Canadian Rockies are consistent with a hydrothermal genetic model involving syn- to post-Laramide upwelling of metal-bearing deep-seated fluids through high-permeability faults and mixing with sulphur-rich meteoric water. Mass flux calculations show that an individual fault-controlled thermal system could produce one million tonnes of Pb-Zn ore in about 1000 years (Grasby, 2002). Consequently, relatively minor fault-related flow systems were needed for MVT "ore zones" of less than 0.85 Mt mined at Monarch-Kicking Horse mines, and of approximately 0.027 Mt and 6.5 Mt estimated at Hawk Creek and at Robb Lake, respectively (Table 1).

MVT DEPOSITS AND OCCURRENCES IN PALEOZOIC CARBONATE OF THE INTERIOR CRATONIC PLATFORM

Pine Point mining district

The Pine Point mining district (Locality 1, Fig.1), situated between the edge of the exposed Precambrian Shield approximately 50 km to the east, and the northern Rockies approximately 500 km to the southwest, consists of 100 lead-zinc deposits (Hannigan pers. comm., 2004) hosted by mid-Givetian carbonate strata of the WCSB (e.g. Norris, 1965; Skall, 1975; Rhodes et al., 1984).

The Givetian stratigraphy used by Cominco Ltd. geologists includes (Rhodes et al, 1984) the Keg River Formation (carbonate platform), the Pine Point and Sulphur Point formations (reef barrier), Muskeg Formation (back-barrier unit deposited to the south), and the Buffalo River and Windy Point formations (fore-barrier units deposited to the north). The Watt Mountain and Slave Point formations are units deposited above the top of the barrier and barrier equivalents.

The reef facies was traced into the subsurface of northeastern British Columbia as the "Presqu'ile barrier" (e.g. Meijer Drees, 1994) and joins the outcropping Silurian–Devonian carbonate front of the northern Rockies (Thompson, 1989). The reef buildup is a 200 m thick linear feature more than 100 km long by at least 10 km wide. It developed during middle Givetian time and restricted Middle Devonian seawater circulation between the open sea to the northwest (Mackenzie Basin), where marine shale and argillaceous carbonate were deposited, and evaporite and carbonate deposits of the Elk Point Basin to the southeast (e.g. Skall, 1975; Qing and Mountjoy, 1992) (Fig. 2c). Marine regression resulted in a partial middle–late Givetian disconformity and karstification of the topographically higher facies of the barrier (Morrow, 1973; Skall, 1975; Kyle, 1981). During the Mesozoic development of the Cordilleran foreland, the Paleozoic stratigraphy formed a northwest-trending homocline with very shallow southwesterly dips averaging 4 m per km (Norris, 1965). Thus, the Presqu'ile reef barrier formed an elongate lens plunging along the basin's dip. The Presqu'ile reef barrier is mineralized at its northeastern end near Pine Point, where it partly overlies the approximately 30 km wide belt of strong linear aeromagnetic anomalies and subtle gravity anomalies known as the Great Slave Shear Zone (GSSZ) (e.g. Hoffman, 1988; Eaton and Hope, 2003).

Minor folds, cleavages, and faults with a normal component of up to 40 m are common in the Middle Devonian stratigraphy in the Pine Point district (e.g. Norris, 1965; Campbell, 1967; Skall, 1975). Closely spaced drilling in the Pine Point mining district documented numerous minor faults and open folds in the Middle Devonian stratigraphy, all trending consistently between N60°E and N65°E (Fig. 10). Based on depositional and diagenetic changes, Skall (1975) inferred two phases of tectonic adjustments: in early middle Givetian time along a South Hinge, and in late middle Givetian along the Main and North hinges (Fig. 10). Basement faults inferred immediately to the east of Pine Point trend approximately N45°E (Norris, 1965) and are part of the geophysical signature of the GSSZ (Fig. 10). To the south and west, the Devonian section is disturbed by faults that seem to parallel the local dip direction of the foreland basin (Morrow et al., 2002; Okulitch, 2006) (Fig. 1).

The GSSZ is a crustal-scale dextral transcurrent fault that extends from the southeastern side of Great Slave Lake to the foothills of the Canadian Cordillera (e.g. Hanmer, 1988; Hanmer et al., 1992; Ross et al., 1994; Geiger and Cook, 2001; Eaton and Hope, 2003) (Fig. 1, 11). In the upper to middle crust, the GSSZ constitutes a steeply southeast dipping zone of anisotropy trending N30°E (Wu et al., 2002) or N35°E (Eaton and Hope, 2003). According to current tectonic models, the GSSZ accommodated Early Proterozoic northeastward convergence, collision, and indentation of the Archean Slave terrane into the Rae terrane (e.g. Hoffman, 1988; Hanmer, 1988). Where exposed east of Great Slave Lake, the GSSZ consists of a 25 km wide corridor of five mylonite belts traced along strike for over 200 km (Hanmer, 1988) (Fig. 11). The sequence of older granulite and amphibolite grade mylonite belts and younger, narrower, greenschist-facies mylonite belts records syntectonic uplift and cooling.

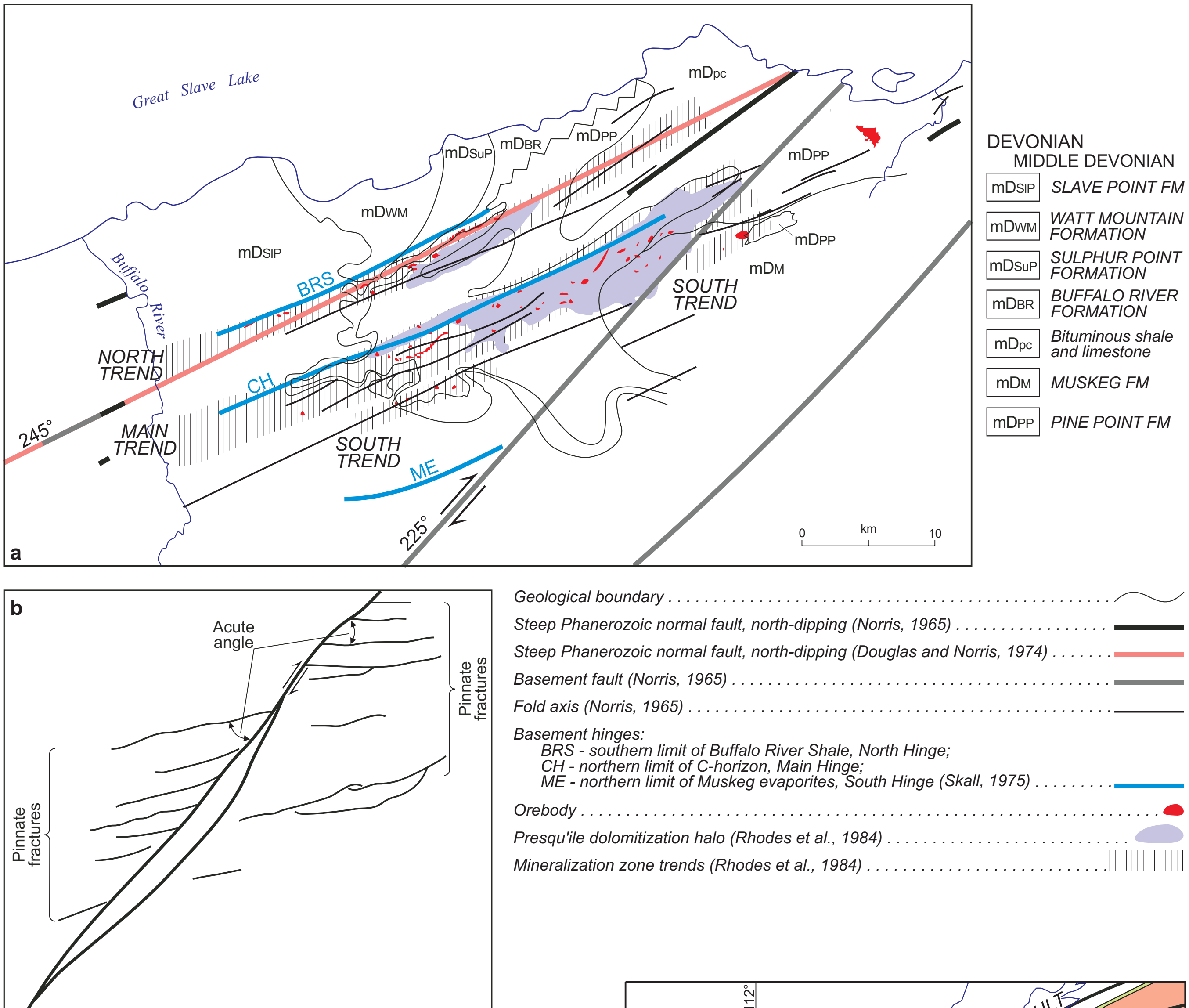


Figure 10. a. Compiled geological map of the Pine Point mining district; geological boundaries, Presqu'ile dolomite halo and the trends of MVT orebodies *from* Rhodes et al. (1984); units *from* Okulitch (2006); structural features *from* Norris (1965); the subsurface southern edge of the Buffalo River shale and northern edge of the "C-horizon" corresponding to the North and Main hinges, respectively. (*From* Skall, 1975). **b**. Schematic representation of a brittle fault with associated pinnate or feather fractures; the acute angles between the fault and the set of pinnate fractures point in the direction of relative motion along the fault. (*From* Twiss and Moores, 1992).

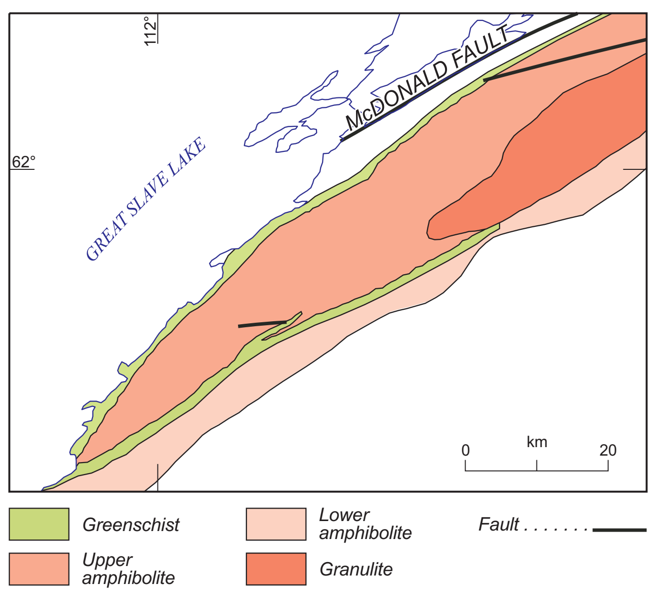


Figure 11. Simplified map of the Great Slave Shear Zone showing the belts of ductile mylonites and brittle faults. (*After* Hanmer, 1988).

By extrapolating along strike the detailed structural and geochronological study of the basement exposed on the southeast side of Great Slave Lake, the tectonic evolution of the Pine Point basement can be inferred to include 1.98–1.92 Ga ductile deformation along the GSSZ that accommodated dextral strike-slip offsets of up to 700 km, and post 1.86 Ga brittle deformation that accommodated some 70–125 km of further dextral strike-slip along the subparallel McDonald fault zone (MDFZ) (Hanmer et al., 1992). A low-grade mylonite recovered from drillhole 15-34-109-4W6 along the GSSZ in Alberta yielded a 1722±11 Ma $^{40}Ar/^{39}Ar$ muscovite age that indicates cooling (possibly syntectonic) above the 350°C isotherm (Plint and Ross, 1993). Thus, currently available isotope data constrain the age of major tectonism along the GSSZ to Early Proterozoic. Precambrian ductile and brittle fault rocks formed during protracted progressive syntectonic exhumation accompanied by inherent relocation and narrowing of the mylonitic belts and thus, may not justify the use of two names (GSSZ and MDFZ, respectively). However, minor reactivations of the transcrustal discontinuity recorded by the Phanerozoic cover of the WCSB, warrant a different name. In this paper, the zone of Phanerozoic strain within the geophysical trace of GSSZ will be referred to as the Hay River Fault Zone (HRFZ) (Fig. 1)

The Presqu'ile reef was viewed as a deeply buried regional conduit system that focused and channelled basinal fluids responsible for extensive dolomitization, secondary migration of hydrocarbons and MVT mineralization (e.g. Garven, 1985; Qing and Mountjoy, 1992; Sangster, 1995). However, the confinement of the Pine Point MVT orebodies to linear arrays near the GSSZ is intriguing and encourages a re-evaluation of their geological controls, in light of detailed mapping of the adjacent basement to the northeast (Hanmer, 1988; Hanmer et al., 1992) and recent regional geophysical studies (Geiger and Cook, 2001; Wu et al., 2002; Eaton and Hope, 2003).

Spatial distribution of the Pine Point orebodies and paragenetic relationships

The Pine Point ore consists of galena, crystalline and colloform sphalerite, pyrite, and marcasite with dolomite and calcite gangue, in complicated paragenetic relationships that suggest several pulses of ore precipitation (Skall, 1975). Krebs and Macqueen (1984) recognized a succession of eight major stages of diagenesis in the Middle Devonian carbonate of the Pine Point district. Widespread, early, fine-grained dolomite interpreted to be of reflux origin and continued migration of bitumen are described as regional processes. In contrast, the precipitation of the medium- to coarse-crystalline, sucrosic, vuggy "Presqu'ile dolomite", pre-ore dissolution, subsequent mineralization, fracturing, remobilization of sulphides, precipitation of coarse-grained (saddle) dolomite, post-ore fracturing and replacement development of late-stage calcite and elemental sulphur overlapped in time and space and are coextensive with the shattered and stockwork-invaded portions of the reef along the Main and Northern hinges at the northwestern periphery of the GSSZ (e.g. Skall, 1975; Krebs and Macqueen, 1984; Sangster, 1995; Eaton and Hope, 2003). Based on their paragenetic, geochemical, and isotopic characteristics, and on spatial distribution and crosscutting relationships, Qing (1991) and Mountjoy et al. (1992) confirmed that early fine-crystalline (their "type 1") and possibly the medium-crystalline ("type 2") dolomite formed penecontemporaneously at or just below the seafloor by Middle Devonian seawater. The coarse-crystalline ("type 3") and saddle dolomite ("type 4") precipitated from the same or similar fluids and are closely associated with MVT ore. There is a trend of slightly increasing $^{87}Sr/^{86}Sr$ ratios (from 0.70822 to 0.7088) and decreasing $\delta^{18}O$ (from 23.3 to 19.7‰ SMOW) with later stages of dolomitization (Mountjoy et al., 1992). Coarse, late-stage calcite occurs mostly in secondary pore spaces, vugs, crusts on saddle dolomite, and fractures. This calcite postdates the precipitation of saddle dolomite and sulphides and shows higher $^{87}Sr/^{86}Sr$ ratios and heavier $\delta^{18}O$, indicating it precipitated from local solutions. Late, semitranslucent calcite encrusts saddle dolomite and yielded the highest $^{87}Sr/^{86}Sr$ ratios (0.71054–0.71613) (Mountjoy et al., 1992).

At Pine Point, coarse dolomitization or Presqu'ile dolomite has affected most of the Sulphur Point Formation in the Presqu'ile Barrier. It extends upward from a near-horizontal plane near the Sulphur Point/Pine Point contact and variably alters Sulphur Point limestone (Fig. 10). Most tabular orebodies are widespread and located at the base of the Presqu'ile dolomite, have restricted vertical extent and are not present along the South Hinge (Rhodes et al., 1984). Common partings along bedding planes and tabular ore-breccia bodies suggest that, at times, the pressure of the mineralizing fluid exceeded the sum of the least principal stress and any tensile strength of the rock to induce subhorizontal hydrofracturing. Locally, chimney-like vertical prismatic orebodies extend upwards from this contact, in breccia bodies commonly developed at the intersection of the basement fault scarps with minor transversal faults inferred from Landsat and Radarsat data (Gibbins, 1988). Massive, higher-grade vertical orebodies penetrate through the reef facies and some even into the Late Givetian Watt Mountain and Slave Point formations. Thus, their formation is constrained to no earlier than Late Devonian in conflict with the karstification hypothesis, which postulates pre-Watt Mountain quasi-contemporaneous karstification, collapse, and mineralization (Kyle, 1981; Rhodes et al., 1984).

The prismatic and tabular orebodies hosted by breccia have strikingly sharp cutoffs, indicating that the mineralization fluids did not penetrate appreciably the adjacent wall rock in spite of its high porosity (Jackson and Beales, 1967; Rhodes et al., 1984). Deeper mineralization, at some hundreds of feet below ground surface produced crystalline sphalerite whilst closer to surface, the presence of colloform crusts and pisolitic sphalerite with low-salinity fluid inclusions similar to late calcite veins indicate local mingling of the ore-bearing brines with surface waters (Campbell, 1967; Roedder, 1968; Krebs and Macqueen, 1984).

"There is a definite relationship between Presqu'ile dolomite development and mineralization since the relative development of coarsely crystalline dolomite coincides with both Main and North Hinge alignment of ore bodies" (Skall, 1975, p. 46). The corresponding fractures acted as channelways for both ascending hydrothermal plume (saddle dolomites, sulphide mineralization, local thermal alteration, and sulphurization of organic matter) and descending meteoric waters (carbonate-evaporite dissolution and extensive internal collapse) (e.g. Campbell, 1967; Macqueen and Powell, 1983; Powell and Macqueen, 1984; Krebs and Macqueen, 1984).

Fault geometry and the inferred Phanerozoic kinematic coherence

The McDonald Fault along the East Arm of Great Slave Lake "although apparently dormant in Paleozoic times may have provided a structural control and a source of some ore bearing solutions in some post-Devonian period" (Campbell, 1966, p. 953). Rhodes et al. (1984) argued against structural control making the following points: 1) the Precambrian faults are sealed by the Late Proterozoic Mackenzie dikes and hence were inactive throughout Phanerozoic time; 2) major faults have not been recognized in the Devonian stratigraphy of Pine Point district; 3) most of the gentle deformation of the stratigraphy postdates the markers used by Skall (1975) to define the Devonian basement hinges; and 4) the aeromagnetic trend of the faults from the East Arm of Great Slave Lake is divergent from the trend of the Pine Point barrier complex. These arguments against structural control can be countered by the following points: a) Isopach and structural maps of various stratigraphic units of the WCSB have documented subtle tectonism along segments of the aeromagnetic trace of the GSSZ. The basement fault inferred by Norris (1965) at Pine Point (Fig. 10a) projects to the northeast into Hanmer et al.'s (1992) McDonald Fault mapped at the northwestern periphery of the GSSZ on the Shield (Fig. 11) where it is accompanied by "post-faulting mineralization similar to Pine Point" (Roedder, 1968, p. 444). To the southwest, Norris's (1965) basement fault projects along the geophysical trace of GSSZ towards a segment of Sikabonyi and Rodgers' (1959) Hay River Fault (Fig. 1). There, a fault breccia in the Devonian Keg River Formation of the Rainbow Lake area intercepted by drillhole 16-34-118-21W5 (location L in Fig. 1) between 1280 and 1290 m depth, includes MVT mineralization with Pb isotope signature identical to the Pine Point lead (Nelson et al., 2002). Geochemical and petrographic evidence suggests that the late saddle dolomite and fracture-lining dolomite in the Givetian Sulphur Point Formation near the Rainbow South Field also located near the HRFZ adjacent to the Alberta–British Columbia boundary were genetically related to Late Cretaceous to Early Tertiary fractures (Lonnee and Al-Aasm, 2000). Thus, "saddle dolomite" precipitated in fractures and breccia zones from a hot fluid that was funnelled upward along faults during the Laramide Orogeny and "fracture-lining dolomite", intimately associated with calcite, quartz, sulphide mineralization, and pyrobitumen, was precipitated from syn- to post-Laramide fluids during thermochemical sulphate reduction (Lonnee and Al-Aasm, 2000). b) There is no need to invoke major displacement for faults to act as conduits for mineralizing fluids. The high porosity formed during the pre-Devonian evolution of the GSSZ through the brittle upper crust and post-Middle Devonian reactivation resulting in metres to tens of metres offsets, below the resolution of the aeromagnetic methods, may have dramatically increased fault permeability. c) The parallelism of the edges of three stratigraphic units with the reef barrier (Skall, 1975) makes a strong case for syndepositional structural control. The fact that the subtle deformation documented in the Pine Point district appears to be post-Devonian (Rhodes et al., 1984) only confirms the correctness of previous geological maps, which show minor folds and normal faults in the Givetian stratigraphy, all trending parallel to the barrier reef (Norris, 1965; Douglas and Norris, 1974). Post-Devonian stresses may have reactivated faults that controlled the reef development and the depositional edges of stratigraphic units. d) The trend of the structures associated with the orebodies is indeed divergent to inferred basement faults along the aeromagnetic trace of GSSZ/MDSZ, but this does not preclude their kinematic link. In fact, the geometric relationships of faults in the Pine Point district suggest kinematic coherence within the area of a 'pinnate' or 'feather' fault. The arrays of minor en échelon normal faults trending to 245° inferred beneath the orebody trends may represent pinnate extensional faults, subsidiaries of the main vertical brittle fault trending to 225° and overprinting the GSSZ (Fig. 10a, b). The acute angle would point in the direction of relative motion of the block containing the minor extensional fractures. More complex kinematic links may include Riedel shears in the upper crust with passive-shear folding of the incompetent Presqu'ile reef above a wide zone of basement transcurrency. Although the geometric relationships are most likely not coincidental, the lack of pertinent kinematic data prevents the elaboration of a well-constrained model. Evidence of local Laramide deformation along the GSSZ geophysical trace presented above and the geometry of the inferred faults at Pine Point suggest that there is a distinct possibility that the GSSZ has accommodated Late Cretaceous–Tertiary stress buildups in the Cordillera. Speculative as it is, the pinnate fault model integrates plausibly the existing data: the extensional faults in the basement, which propagated into the carbonate cover and are marked by orebody trends, may have formed as subsidiary structures during post-Middle Devonian dextral shearing along the HRFZ, which overprinted the GSSZ. Mineralizing fluids percolated upwards along the Main and North hinges and from there laterally into the surrounding strata.

Mineralizing fluids

Fluid inclusion and isotope data provide clear evidence that the mineralizing fluids at Pine Point were not basinal fluids migrating updip along the southwesterly tilted reef barrier (Roedder, 1968; Kyle, 1981; Macqueen and Powell, 1983; Powell and Macqueen, 1984; Krebs and Macqueen, 1984; Hitchon, 1993; Adams et al., 2000). The chemistry of formation waters from the hydrostratigraphic units of northern Alberta indicates that none of them could have directly produced the Pine Point deposit. Hence, "formation waters were not the source of the metals at Pine Point" instead, "the ore fluid was of geothermal origin" with Pb and Zn leached from "normal faults cutting the crystalline basement" (Hitchon, 1993, p. viii).

$\delta^{18}O$ values in saddle dolomite cements increase from 15‰ (SMOW) in northeastern British Columbia to 23‰ (SMOW) in outcrop at Pine Point, indicating that the basinal fluid cooled as it migrated updip eastward along the Presqu'ile barrier (Qing and Mountjoy, 1992). This trend is reflected by homogenization temperatures of primary fluid inclusions in saddle dolomite along the Presqu'ile barrier, which decrease updip eastward from 178°C in northwestern British Columbia to 92°C in the open pits at Pine Point. $\delta^{18}O$ values of the parent dolomitizing fluid, calculated from measured saddle dolomite $\delta^{18}O$ values, homogenization temperatures, and using the dolomite-water fractionation factor (Land, 1985), show a decrease from +2‰ (SMOW) in northeastern British Columbia to -2‰ (SMOW) just west of Pine Point (Adams et al., 2000). These signatures are consistent with the decrease of $\delta^{18}O$ in the parent fluid resulting from isotope exchange at constant water-fluid ratios along the barrier (Adams et al., 2000). However, at Pine Point the parent fluid was at least 3‰ more enriched than calculated values of saddle dolomite at the east end of the barrier (Fig. 12a).

$^{87}Sr/^{86}Sr$ ratios in saddle dolomite decrease eastward updip along the Presqu'ile barrier. Four samples from northeastern British Columbia yielded values from 0.7106 to 0.7094, five samples from NWT yielded values ranging from 0.7092 to 0.7084 and eight samples from the Pine Point open pits gave values from 0.7084 to 0.7081. This variation supports the concept of deep basinal brines with a shale Sr isotope signature migrating through a carbonate aquifer with progressive addition of local nonradiogenic Sr due to water-rock interaction (Mountjoy et al., 1992). However, the strikingly higher and more variable $^{87}Sr/^{86}Sr$ ratios (0.7112–0.7522) in seven sphalerite residue samples from the Pine Point MVT ore (Table 2; Nakai et al., 1993) indicate that the mineralizing fluid contained much more radiogenic Sr than the brine responsible for the late dolomitization of the reef facies (Fig. 12c). $^{87}Sr/^{86}Sr$ data from the Canadian Shield suggest that brines from faults are in equilibrium with the host basement rocks, which indicates strong water-rock interaction resulting in concentrations strongly influenced by the local geology (Frape et al., 1984; McNutt et al., 1990). Sr isotopes in Pine Point sphalerite clearly indicate a strong basement signature (Fig. 12c). Possible isochron regression lines through the sphalerite analyses show initial $^{87}Sr/^{86}Sr$ ratios of 0.7086 to 0.7089 (Nakai et al., 1993), equivalent to the range of saddle dolomite in NWT and only slightly enriched in radiogenic Sr compared to Middle Devonian seawater (0.7078–0.7083; Burke et al., 1982). The linear disposition of the Sr-Sr analysis may represent a mixing line resulting from strong interaction between Devonian seawater and highly radiogenic basement mylonites. However, the lithology within the GSSZ is highly complex, with mylonites derived from magnetite-bearing granite, clinopyroxene tonalite, panels of paragneiss, as well as late granite veins and mafic dykes emplaced into parts of the shear zone, which were rheologically susceptible to brittle failure, or into extensional bends of strike-slip portions of the plastic mylonite belts (Hanmer et al., 1992).

Lead isotopes in Pine Point galena show a remarkable homogeneity, with $^{206}Pb/^{204}Pb$ values in the narrow range of 18.167 to 18.186 indicating either a homogeneous source or thorough mixing of lead during extraction, transport, and precipitation (Cumming et al., 1990). Modelling of U and Pb concentrations and ratios suggested a depleted lower crust source (Cumming et al., 1990), consistent with Pb derivation from the granite-granulite basement underlying the Pine Point district.

The relatively high concentration of the heavy sulphur isotope makes direct derivation of the sulphur from magmatic sources rather unlikely. Similar average values of $\delta^{34}S$ in sulphides (+18.4‰ to +21.6‰; average 20.1‰) and in Devonian Elk Point anhydrites (+19‰ to +20‰) suggest that the sulphur that precipitated metals at Pine Point was derived from seawater sulphate (Sasaki and Krouse, 1969; Dunsmore, 1973). H_2S must have formed via thermochemical sulphate reduction (TSR) elsewhere and migrated to the place of ore deposition (Grasby et al., 2002). Convection of seawater through basement faults reaching depths of 3–5 km allows for temperature increase in the circulating fluids to over 100°C necessary for effective TSR. Fluid temperatures of 87°C at a depth of only 420 m have been reported from a well near Pine Point drilled into the basement along the southwest projection of the GSSZ (Campbell, 1966). It is conceivable that sulphur has entered the convection cells as sulphate in seawater. Minute amounts of H_2S from organic sources (Powell and Macqueen, 1984) may have started the autocatalytic TSR. The continually produced and highly reactive H_2S may have extracted metals from the vulnerable strained silicates, mostly in non-equilibrium textures within the core and damage zone of the basement faults (particular chlorite structures can contain up to 30.5 wt% ZnO, Deer et al., 1992).

The salinity of the saddle dolomite parent fluid decreased as the saline basin brine migrated updip in the Presqu'ile conduit, from 20 wt% NaCl to 10 wt% NaCl (Qing, 1991). Near Pine Point, however, the salinities of fluid inclusions in gangue saddle dolomite and sphalerite are strikingly higher (with values up to 38 wt% NaCl) than that of the barrier fluids (Roedder, 1968; Kyle, 1981) (Fig. 12b). Moreover, both ore

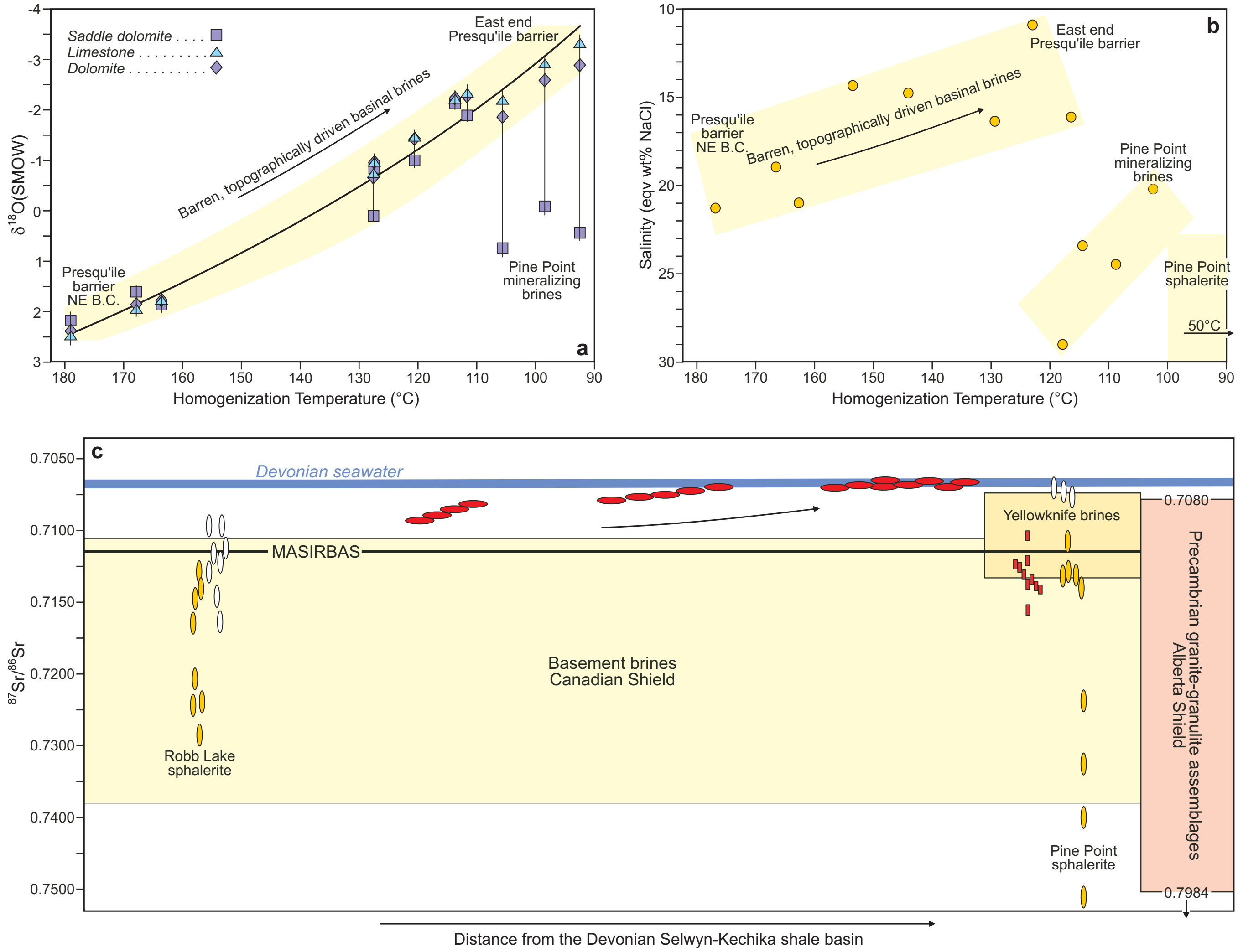


Figure 12. a. Calculated $\delta^{18}O$ values of saddle dolomite parent fluids using Land's (1985) water-rock fractionation factor at constant water/dolostone host and water/limestone host ratios of 1.3 and 1.5, respectively. **b**. Average salinities of saddle dolomite fluid inclusions along the Presqu'ile barrier and at Pine Point, and salinities of sphalerite fluid inclusions at Pine Point. (Data *from* Roedder, 1968; Kyle, 1981; Qing, 1991; Qing and Mountjoy, 1992; and Adams et al., 2000.) **c.** $^{87}Sr/^{86}Sr$ variations with respect to shale basin to the west. Red ovals are $^{87}Sr/^{86}Sr$ ratios in saddle dolomite along the reef barrier; red rectangles are $^{87}Sr/^{86}Sr$ ratios of late-stage calcite confined to the ore zone at Pine Point; yellow and white ovals are $^{87}Sr/^{86}Sr$ ratios in sphalerite residues and leachates, respectively, from the Robb Lake prospect and Pine Point deposits; $^{87}Sr/^{86}Sr$ ratio for Devonian seawater *from* Burke et al. (1982); MASIRBAS is the regional background value of the maximum Sr isotope ratio of basinal shale *from* Machel and Cavell (1999); $^{87}Sr/^{86}Sr$ ratios for brines percolating deep faults in the Canadian Shield *from* Frape et al. (1984) and McNutt et al. (1990); Yellowknife brines *from* McNutt et al. (1990); $^{87}Sr/^{86}Sr$ ratios in the granite-granulite rocks of the Alberta Shield *from* Baadsgaard and Godfrey (1972). $^{87}Sr/^{86}Sr$ ratios in Precambrian rocks scatter widely depending on petrogenetic history (initial Rb/Sr) and age (post-crystalline decay of ^{87}Rb).

and carbonate minerals at Pine Point precipitated from dominantly $CaCl_2$ brines, which contained more S than Cl^-, in contrast with the NaCl basinal brine that migrated along the Presqu'ile conduit and had Cl^- as the principal anion (Haynes and Kesler, 1987). Salinity data are inconsistent with the concept of basinal brines being the mineralizing fluids at Pine Point. Some 75% of the chemical analyses of formation waters in northern Alberta show Pb>Zn, similar to the Canadian Shield brines and very different from other sedimentary basins close to, or containing MVT deposits (Hitchon, 1993).

Na/Br and Cl/Br ratios and $MgSO_4$ concentrations at Pine Point similar to saturated seawater suggest that the parent fluids evolved primarily from highly evaporated, hypersaline seawater, unaltered by dissolution of halite from underlying stratigraphy (Adams et al., 2000). Ca-(Na, Mg)-Cl brines are typical for major faults and shear zones below approximately 650 m depth (Frape et al., 1984). Much of the saline water in fault zones appears to represent mixtures of two end members: local meteoric waters and a distinctive Ca-Cl -rich brine or deep "crustal fluid" of general extent across the Shield (Fig. 13). This crustal fluid could be derived from the mantle

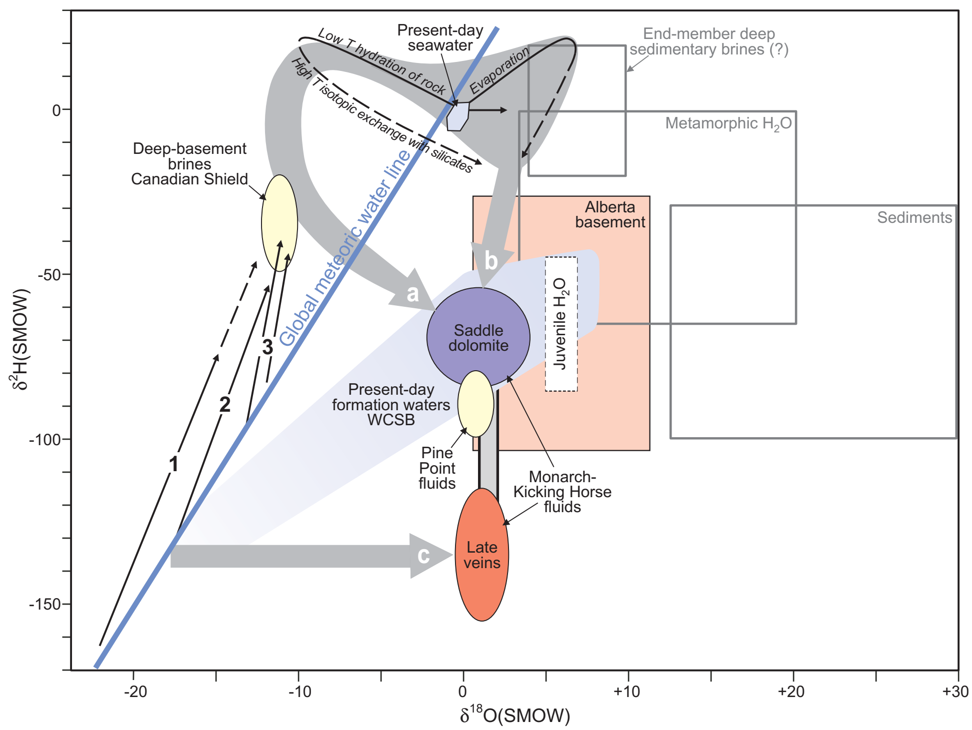


Figure 13. $\delta^{18}O$ and deuterium contents in brines from crystalline rocks of the Canadian Shield and in groundwaters and surface waters compared to fields of mineralizing fluids at Pine Point and Kicking Horse-Monarch mines. The field of present-day formation waters in the WCSB *compiled from* Hitchon and Friedman (1969) and Connolly et al. (1990); basement brines in the Canadian Shield *from* Frape et al. (1984) and the range of $\delta^{18}O$ values for the Alberta basement *from* Burwash et al. (2000). Lines 1, 2, and 3 are calculated regression lines representing mixing between fresh or brackish shallow groundwater or surface water and saline groundwaters or brines for Yellowknife, Thompson and Sudbury mining districts, respectively (Frape et al., 1984). Note $\delta^{18}O$ values lower than 5 ‰ (SMOW) characterize granite-granulite assemblages retrograded (hydrated) to greenschist facies assemblages; other fields for comparison from Sheppard (1986) and Ohmoto (1986). Paths a, b, and c are discussed in text.

and/or the terrestrial hydrosphere (including fossil seawater) but its origin is totally masked by intense water-rock interaction, which modified its original chemical and isotopic composition (Frape et al., 1984). Shallow groundwaters in faults fall on or below the global meteoric water line, with δD and $\delta^{18}O$ values determined by local climatic conditions and evaporation.

δD values ranging between -80 and -100‰ (SMOW) reported from one of the Pine Point orebodies (Nesbitt and Muehlenbachs, 1994a) coupled with existing $\delta^{18}O$ on the mineralizing fluid at Pine Point (Qing and Mountjoy, 1992) plot within the field of Alberta Basin formation waters and partly overlap with the field of the Monarch–Kicking Horse mineralizing fluid (Fig. 13). The low δD values in the Alberta basin were considered to be the result of mixing of original basinal brines with post-Laramide meteoric waters (Hitchon and Friedman, 1969; Connolly et al., 1990). Thus, the Pine Point and Monarch-Kicking Horse dolomitizing/mineralizing fluids appear to be the result of a mixing process between brines and meteoric waters during the Antler (Nesbitt and Muehlenbachs, 1995b) or Laramide (Qing et al., 1995) Orogeny. At Pine Point, where the most complete set of chemical and isotope data exists, the characteristics of the mineralizing fluid deviate significantly from those of the "reference waters", in particular from those of the commonly invoked basinal brine. None of the present-day formation waters from Devonian to Early Cretaceous strata could directly generate the Pine Point ore (Hitchon, 1993). At the same time Na/Br and Cl/Br ratios and $MgSO_4$ concentrations of mineralizing fluids are consistent with saturated seawater chemistry, whereas $CaCl_2$ and Pb>Zn concentrations are similar to the Canadian Shield brines, and Sr and Pb isotope ratios in sulphides indicate a basement source. A complex evolution of the mineralizing fluid can be inferred by integrating chemical and/or isotope data for different segments of a recycling pathway (Fig. 13). Because Phanerozoic deformation along the HRFZ has affected an essentially anhydrous granite-granulite Precambrian basement, fluids involved in chemical extraction of metals from the basement must have been overwhelmingly seawater and basinal brines. Seawater and brine with various isotope compositions infiltrated the strained basement during the continental movements from equatorial latitudes during Devonian time to Late Cretaceous northern latitudes. The influx of fluids and the water-rock interaction was strongest during major tectonic events (Laramide tectonism being the strongest and best documented). Low temperature hydration of basement rocks and isotopic exchange with silicates may have triggered a $\delta^{18}O$ shift towards the field of basement brines, as suggested by similar $CaCl_2$ and Pb>Zn concentrations (path "a", Fig. 13). While preserving various seawater elemental ratios, this fluid has strongly interacted with basement lithologies. Convection within fault-confined vertical hydrological cells led to continuous isotopic exchange with silicates producing a $\delta^{18}O$ shift in fluids towards the field of basement lithologies (path "a", Fig. 13). Basement Sr and Pb isotope signatures in the mineralizing fluid at Pine Point and the decrease in $\delta^{18}O$ in strained granite-granulite Precambrian basement from 5–11‰ to as low as 0.9‰SMOW (Burwash et al., 2000), are all consistent with strong water-rock interaction and favour the idea of metals leaching from the basement (Fig. 13, 14). Variable amounts of seawater and brines intermittently infiltrating the shallow portion of the vertical aquifer during active faulting may not have extensively interacted with the wall rock (path "b", Fig. 13) before being mixed and expelled as hydrothermal fluids together with path "a" fluids. Dolomitization and local mineralization are best explained as multistage events that were related to different stages of tectonic compression in the orogen. The clear involvement of meteoric waters in a subaerial setting, well documented in the Rockies (path "c", Fig. 13), appears to be limited at Pine Point to late dissolution and remobilization of sulphides and carbonates.

Fluid inclusion and organic maturation data have initially suggested that the area of Pine Point Pb-Zn deposits was affected by a local thermal anomaly reaching 100°C, significantly higher than the approximate 60°C of the surrounding rocks (Roedder, 1968; Kyle, 1981; Macqueen and Powell, 1983; Krebs and Macqueen, 1984). In contrast, Arne (1991) and Qing and Mountjoy (1992) argued for a regional temperature increase up to approximately 85–106°C (higher than the 60°C temperatures corresponding to the maximum inferred Cretaceous burial) caused by the influx of hot fluid expelled from the deep basin. Recent synchrotron analysis revealed that sulphur-rich bitumens (up to 40% S), with high-temperature S-S bonding were found only associated with ore, and that bitumens show decreasing H/C and increasing S/C with proximity to orebodies (Grasby et al., 2002). These results indicate that the thermal alteration and incorporation of sulphur in sulphur-rich bitumen is a local effect associated with ore-forming fluids. Thus, sulphur-rich bitumens around MVT ores at Pine Point were recipients of S from hot S-rich fluids and were not significantly involved with sulphate reduction (Grasby et al., 2002).

Homogenization temperatures of 51 to 99°C obtained from fluid inclusions in sphalerites at Pine Point (Roedder, 1968) suggest that the mineralizing fluid is slightly cooler than the parent fluid of the regional saddle dolomite ascending from the basin (Table 2; Qing and Mountjoy, 1992).

Fault architecture

The complex brittle faulting history of the Pine Point basement resulted in a network of upright belts of greenschist mylonites with anastomosing slip surfaces, geochemically altered breccia, cataclasites, and clay-rich gouge up to 100 m wide, that cut at low angle (occasionally high) older ductile mylonites (Hanmer et al., 1992). Vertical belts of greenschist mylonite, breccia-cataclasites, and stockworks within the GSSZ, metres to hundred of metres wide, and metres to tens of kilometres long (Hanmer, 1988), consist of generally fissile and permeable rocks of unknown age. It is conceivable that they accommodated post-Middle Devonian strain and acted as channelways for the MVT mineralizing fluids. The fault "core" and "damage" zones (Fig. 14) are distinct structural and hydrological units that reflect the material properties and deformation conditions and may act as conduits for flow parallel to the fault zone (e.g. Caine et al., 1996; O'Brien et al., 2003). The core zone consists of gouge, cataclasite and mylonites with a wide range of permeabilities (from 10^{-12} to 10^{-22} m^2; Smith et al., 1990). The 'damage zone' typically consists of a network of subsidiary structures that bound the fault core and includes kinematically related fracture sets, small faults, cleavages, veins, and dilational quartz stockworks (Bruhn et al., 1994). Permeability estimates for the damage zone are four to six orders of magnitude greater than the fault core grain-scale permeabilities (Caine et al., 1996). Fluid-flow properties within such vertical aquifers are largely controlled by strain, downdip and along-strike thickness, and structure and composition variations. The fault core zone may act as a short-lived syn-deformational fluid-flow conduit or as a barrier to flow when open pore space is filled by mineral precipitation following deformation (e.g. silicified breccia and clay-rich gouge). These variable fluid-flow properties within subparallel vertical basement faults would explain the linear trends of orebodies at Pine Point above basement fault scarps (Fig. 10).

Inferred hydrological regimes

Vigorous circulation of surficial waters down to mid-crustal levels has been documented for various fossil hydrothermal systems (e.g. Taylor, 1971, 1990). Permeabilities as high as 10^{-12} m^2 are common in fractured basement rocks. Significant in situ permeabilities ($10^{-17} m^2$) have even been reported at more than 9 km depth in fractured granodiorite gneisses (Huenges et al., 1997). The fracturing of granites significantly changes thermal gradients and the flow patterns of the thermal convection regime near fracture zones. A convective pattern of fluid-flow involving inflow of externally derived fluids (essentially seawater) balanced by an upflow of fluid in a fault zone is capable of significant heat transport and large water-rock ratios (e.g. Norton and Knight, 1977).

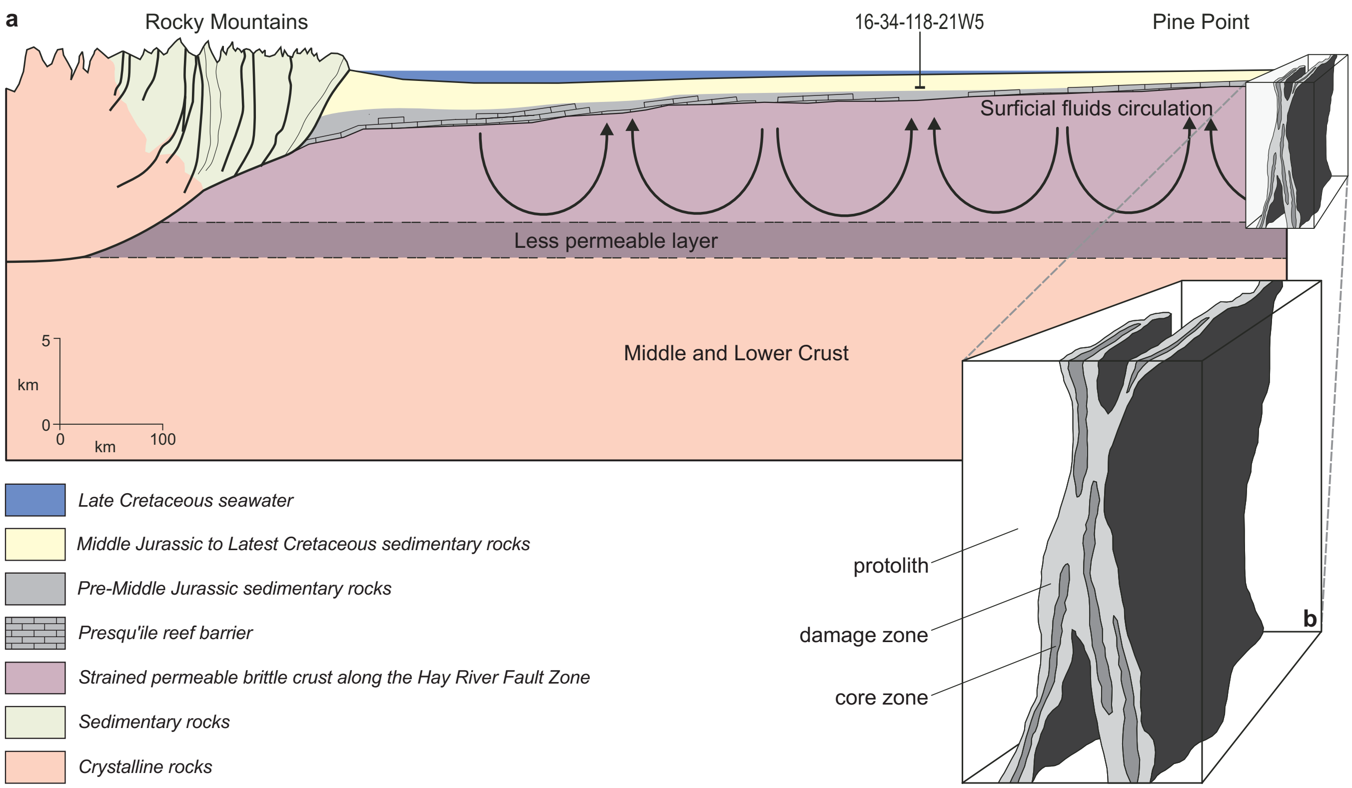


Figure 14. Proposed model for the formation of Pine Point MVT deposits. **a.** Fluid convection in the upper portion of a crustal scale shear zone; *modified after* Etheridge et al. (1983). **b.** Fault zone architecture *after* Caine et al. (1996).

Mass transport numerical models, which include fracture zones in granite, show that thermal convection driven by granite with high concentrations of heat-producing elements can be sufficient to form MVT deposits (Fehn and Liu, 1997). The pattern of flow is much more complex where chemically and/or thermally induced variations in fluid density and/or osmosis also act to drive flow. Changes in porosity and fluid density may induce anomalous fluid pressures and may act as either sources or sinks of fluid. Thus, substantial departures from hydrostatic conditions may have been induced within faults even during tectonic quiescence and isolation from the recharge source by low permeability strata that floored the WCSB. The hydrological regime in each of the basement faults at Pine Point could be simulated by buoyancy-driven convection in a two-dimensional vertical slab. The upper boundary of the slab would be the top of the Presqu'ile reef and the lower boundary an arbitrary, less permeable mid-crustal level (Fig. 14). Disequilibrium phenomena (episodic strain, production and consumption of water by chemical reactions) may have forced the hydrological conditions to adjust to the evolving geological framework represented by the HRFZ and its subsidiary faults. "Geologic forcings", either virtual from porosity and fluid density changes, or actual, such as addition of fluid to the system, induce significant fluid flow in a geological environment (Neuzil, 1995).

A complete mathematical description of spatial and/or temporal variations in the thermodynamic states of a fault zone hydraulic system (e.g. variations in composition of the solid or aqueous phases, variations in temperature or pressure) requires systems of equations at a level of complexity that has not yet been addressed (Ingebritsen and Sanford, 1998). Hydrological aspects that may be considered in developing a tectogenetic model for the Pine Point MVT deposits are discussed here at an intuitive level.

Variation in mineralogy leads to reaction zones or fronts that migrate through space and time. The changes in temperature and pressure cause a concomitant change in chemical equilibrium as the water carrying the solutes moves through P and T gradients. The result is dissolution and precipitation of mineral phases towards a new state of equilibrium.

The widespread occurrence of reticulate networks ("stockworks") in the Pine Point host rocks above fault scarps indicates transient fluid pressures that exceeded the stress required for failure, leading to hydraulic fracturing of the wall rock. When pore pressure exceeds the least principal stress plus any tensile strength of the rock, fluid is relieved by hydraulic fracturing; when the resulting fractures seal, pressures can build up again, eventually leading to another fracturing episode. The pressurization-expulsion cycles would explain multiple pulses of ore precipitation at Pine Point.

Age of the Pine Point mineralization

Various Paleozoic Pb/Pb model ages (386 Ma, 375 Ma, 310 Ma, and 290 Ma) have been calculated by Cumming et al. (1990). The Late Givetian age of the youngest host rocks and the clear evidence for the epigenetic character of the late Presqu'ile dolomite associated with the mineralization preclude the Middle Devonian ages. The Late Carboniferous ages (310 Ma and 290 Ma) were considered by Cumming et al. (1990) more probable, as they were closer to the Permian–Early Triassic paleomagnetic age suggested by Beales and Jackson (1982). Sphalerite Rb-Sr data points from Pine Point define a linear trend whose regression line corresponds to a Late Devonian 361±13 Ma isochron age and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7087±8 (Nakai et al., 1993), which partly overlaps the $^{87}Sr/^{86}Sr$ ranges of Paleozoic, Late Cretaceous and Late Tertiary seawaters (Burke et al., 1982). There is a distinct possibility that the regression line depicts in fact a mixing line between infiltrated seawater-brine and various basement lithologies. More recent paleomagnetic data indicate however, a Late Cretaceous–Paleocene (84–58 Ma) age of mineralization (Symons et al., 1993), which is in good agreement with the ca. 60 Ma three-stage Pb-Pb model age calculated by Cumming et al. (1990). Although not favoured by the original authors, the 60 Ma age may represent the last resetting of the U-Pb system within the GSSZ during the Early Tertiary Laramide tectonism in the Cordillera. Notably, the 1.887 Ga origin used by analogy with the model proposed in the Rockies matches the last resetting of the U-Pb system along the GSSZ (1.92–1.86 Ga; Hanmer et al., 1992). The corresponding depleted source U/Pb ratio of 8.4 is in agreement with the variously retrogressed granulite-granite lower crust underlying the Pine Point MVT district (Cumming et al., 1990; Hanmer et al., 1992).

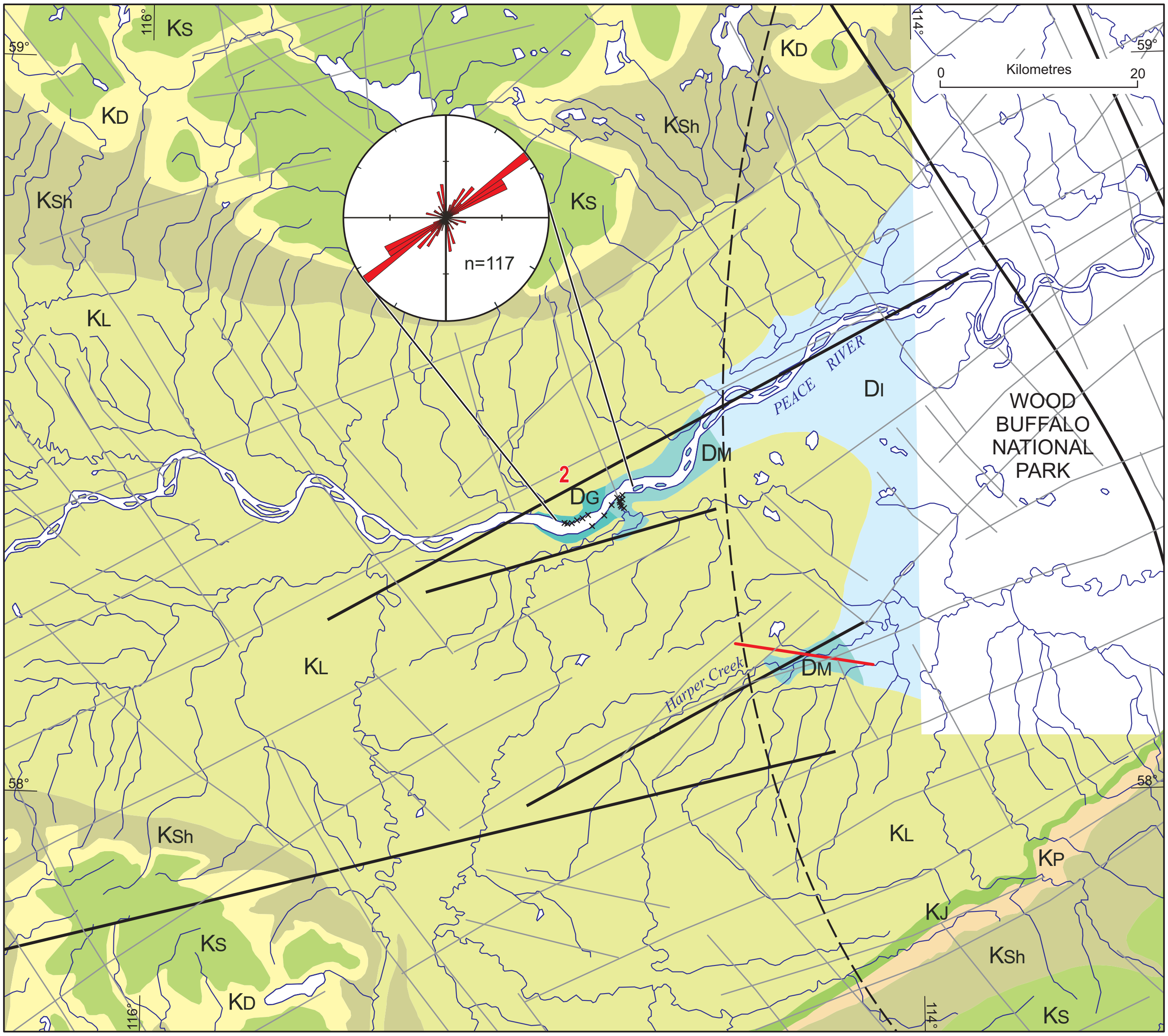
A tectogenetic model for the Pine Point MVT deposits

The Pine Point MVT orebodies are indeed hosted by the highly porous reef facies, but only in the immediate vicinity of the GSSZ. The model proposed here is that the Pine Point MVT mineralization is the result of seawater convection within vertical basement faults kinematically linked to the Laramide HRFZ, which overprinted the GSSZ (Fig. 14). Fluid-flow patterns within vertical confined aquifers were likely controlled by the complex and transient permeability field with in situ porosity and fluid density and chemistry changes, fluctuations in pressure, temperature and mineral precipitation, all triggered by prolonged stress buildups and episodic strain in upper crust fault zones. Minor Laramide tectonic adjustments along the HRFZ and subsidiary faults resulted in a belt of strain concentration in the overlying stratigraphy. The relatively competent and porous reef tended to yield to stress by minor fracturing and brecciation. The facies formed within the tectonically active zone provided excellent facilities for the upflow of chemically active basement brines, dolomitization, and local entrapment of ore-bearing solutions. Thus, concurrent fracturing, brecciation, and solution collapse led to the development of a large pipe-network consisting of vertical and horizontal breccia bodies, and channels clogged with metal sulphides and saddle dolomite gangue.

Outcrop data from northern Alberta

In northeastern Alberta, Devonian carbonate deposits onlap the Precambrian crystalline basement and the non-metamorphosed Early to Middle Proterozoic clastic rocks of the Athabasca Group (Fig. 1). The carbonate bedrock in this region was extensively eroded and now occupies low ground; hence, much of the potential outcrop area is hidden by wetlands and glacial cover. Inliers of Devonian carbonate are found near Fort McMurray along the Athabasca and Clearwater River valleys, in the floor of the oil sands open pit excavations, and in two narrow areas stretching several kilometres each along Peace and Harper rivers. Structural and geochemical data have been collected at ca. 70 stations in Upper Devonian Mikkwa and Grosmont formations in the Vermilion Chutes area and in the Middle Devonian Waterways Formation in the Fort McMurray area (Fig. 1).

On Peace River, approximately 75 km downstream from Fort Vermilion, a 47 m thick section of Upper Devonian carbonate is exposed for 10 km along Vermilion Chutes with Vermilion Falls at its eastern end, some 7 km upstream from the mouth of Mikkwa River (Locality 2, Fig. 1; Fig. 15). This is the only location where a minor Zn anomaly has been reported from a carbonate outcrop in northern Alberta (Gulf Minerals, 1975). The Devonian–Cretaceous unconformity is mapped a few kilometres west of Vermilion Chutes. Beyond the narrow area along the river, the bedrock is covered by Pleistocene and Recent deposits. Corroborating outcrop and subsurface data, Norris (1963) defined three stratigraphic units and assigned the two lower ones to the Mikkwa Formation and the upper one to the Grosmont Formation. The falls cut into the upper mottled unit of the Mikkwa Formation (Fig. 16a) and a wide ledge at the north end of the falls marks the transition to the vuggy reefal hydrocarbon-stained dolomite of the Grosmont Formation (Fig. 16b). A 1½ m thick interval of the lowermost Grosmont Formation is exposed on top of the ledge (Norris, 1963; Buschkuehle, 2003). Structural data have been collected from the Mikkwa Formation along approximately 700 m of outcrop downstream from Vermilion Falls (Fig. 15–17). Bedding planes are subhorizontal with a regional northerly to northwesterly strike. A southwesterly dip of approximately 4° per kilometre was estimated by interpolating data from Vermilion Chutes outcrop and a well at Fort Vermilion (Norris, 1963). Two quasi-orthogonal sets of joints have been recognized. The joint set with azimuths varying between 225° and 250° is definitely predominant, controls the local trend of Peace River and projects northeasterly into the sinistral Warren (Leland Lakes) shear zone mapped on the Alberta Shield (e.g. Godfrey, 1986; Pană et al., in press) (Fig. 1, 15, 17). Intriguingly, vertical joint surfaces of the dominant joint set contain vague but consistent brittle linear features that suggest modest sinistral stretching that lines up with sinistral shear zones in the Shield. A Devonian



CRETACEOUS

- KS *SMOKY GROUP*
- KD *DUNVEGAN FORMATION*
- KSh *SHAFTESBURY FORMATION*
- KP *PELICAN FORMATION*
- KJ *JOLI FOU FORMATION*
- KL *LOON RIVER FORMATION*

DEVONIAN

- DG *GROSMONT FORMATION*
- DM *MIKKWA FORMATION*
- DI *IRETON FORMATION*

Outcrop, examined . . . . ×
Surficial lineament (Misra, 1991) . . . .
Fault (Pana et al., 2001; this report) . . . .
Basement domain boundary (Pilkington et al., 2000) . . . .

NOTES

1. Rose diagram is of joints in Devonian carbonate
2. Bedrock geology from Geological Map of Alberta (Hamilton et al., 1999)

Figure 15. Joint orientation in Devonian carbonate of the Mikkwa Formation along Peace River at Vermilion Chutes; inferred structural lineaments in northern Alberta *from* Pană et al. (2001). Bedrock geology *from* Hamilton et al. (1999). *See* Hamilton et al. (1999) for legend details.

basement fault scarp with approximately the same orientation as the dominant joint set measured in outcrop is suggested by the transition from Devonian basinal shale to platformal dolomite along an east-northeast oriented lineament (Pană et al., 2001). Vermilion Chutes is also situated near the axis of the Devonian Hotchkiss Embayment, an inferred linear zone of subsidence that lines up with the westward projections of shear zones mapped on the Alberta Shield (Pană et al., 2001). North of Vermilion Chutes, a series of east-northeast linear anomalies across southern Caribou Mountains become apparent after directional filtering of aeromagnetic data (Geiger and Cook, 2001) suggesting that a local peculiar fabric overprints the generally northerly trending basement grain depicted by aeromagnetic data in northern Alberta (Fig. 15). There is a distinct possibility that Upper Devonian carbonate in this area may be underlain by a linear zone of recurrent strain in the basement.

Southeast of Vermilion Chutes, along Harper Creek downstream from the mouth of Chamberlain Creek, Devonian carbonate of the Mikkwa Formation forms vertical banks up to 5 m high for at least 3 km (Fig. 15). Flat-lying, slightly dolomitic limestone is overprinted by a minor, high-angle reverse fault trending approximately 100 to 115°. Individual fault planes are locally sealed by coarse secondary calcite, but no significant alteration occurs. A few kilometres upstream, at the confluence of Harper Creek with Lambert Creek, a sulphur-rich spring and a very penetrative set of 50- to 55°-trending joints may indicate another zone of increased strain, roughly perpendicular to the Laramide deformation front (Fig. 15).

Near the town of Fort McMurray, along the Athabasca and Clearwater rivers, outcrops of carbonate rocks are exclusively in the Waterways Formation, the uppermost stratigraphic unit of the west-dipping Devonian carbonate-evaporite succession (Fig. 1, 18). Devonian rocks unconformably overlie the Precambrian crystalline basement. Oil sands of the middle Albian McMurray Formation overlap progressively older Devonian rocks eastward. Outcrops of the Waterways Formation form low scarps up to a kilometre long and usually less than 3 m high, and generally extend less than 3 m back from the scarp face. Bedding is gently flexed (dipping less than 10°) into apparent wide-open folds with amplitudes of 15–30 m and wavelengths of 100 m to 1/2 km. At least some of these apparent folds may be sections through dome structures formed in response to differential subsidence related to salt dissolution and volume changes accompanying hydration of evaporite deposits in the underlying Prairie Formation (Hamilton et al., 1999).

Four joint sets make up two orthogonal systems: System I, with sets striking northwesterly and northeasterly, roughly parallel and normal to the trend of the Rocky Mountains; and System II, with sets striking approximately northerly and westerly (Fig. 18). No single set of either orthogonal system is consistently crosscutting. The four joint sets observed in the Fort McMurray area correspond to joint systems mapped elsewhere on the Alberta plains (Babcock 1973, 1974, 1975), which indicates that these are regional, tectonically induced joints and are not local flexures caused by dissolution. Babcock (1974) noticed that System I is strongly developed close to the Rocky Mountains. The rarity of outcrops with System I dominant in the McMurray area may reflect the decrease in stress strength 600 km away from the Laramide fold-and-thrust belt. System II of the Waterways Formation does not exist in the McMurray sands (Babcock, 1975), which may indicate that the northerly and easterly trending joint sets formed prior to Early Cretaceous. The north-trending joint and fracture direction along the Athabasca River west of Fort McMurray parallels the general grain of the basement as depicted by aeromagnetic data (Lyatsky and Pană, 2003). Joints and minor fractures, particularly the northerly trending set, have a Fe-stained rind within and directly adjacent to the joints (Fig. 19). Occasionally, this rind contains minor amounts (<3%) of pyrite. Rubble within a northerly trending minor fracture along the northern bank of the Athabasca River west of Fort McMurray include nodular fragments of massive pyrite and the wall rock is coated by a limonitic layer up to 4 cm thick (Fig. 19b). Some other fractures are bounded by distinctly bleached rock directly adjacent to the fracture and are often filled with greenish-grey argillaceous residue (Fig. 19b). The ochre to dark brown or black alteration material lines the direct contact of the joints and splays out horizontally at the sub-Cretaceous unconformity (Fig. 19a). The top of the Devonian limestone is totally replaced by a fine-grained to cryptocrystalline, 10 to 15 cm thick limonite-stained layer with less than 5% iron sulphides occurring as fine disseminations and up to 2–5 mm blebs (Fig. 19a). Joints and fractures in limestone are commonly infiltrated by bitumen from the overlying McMurray Formation. The limonite-sulphide rind and relative enrichment in clay minerals within minor vertical fractures indicate rock alteration by a hot, chemically active fluid that percolated the carbonate. Ambiguous field relations are tentatively interpreted to suggest upwelling of basinal brine in a discharge area towards the edge of the basin, followed by infiltration of bitumen from the overlying oil sands. The only visible occurrence of galena reported in outcrop in northern Alberta (Carrigy, 1959) coincides with a 100 m wide fault zone that crosses Clearwater River at Whitemud Falls (Locality 3, Fig. 1, 18). Vertical fracture cleavages and fault planes trend between 110 and 140° (Fig. 20). Another set of minor vertical faults trends northerly, but is less well expressed. The northwest, northeast, and north-northwest joint trends measured in the Devonian Waterways Formation around Fort McMurray roughly correspond to previously inferred faults in the subsurface (Fig. 18).

Examination of Devonian carbonate deposits in outcrops of northern Alberta provide new evidence that joints and fractures acted as pathways for upwelling warm and chemically active fluids. The alteration of the Waterways Formation along the Athabasca River near Fort McMurray is related to barren basinal fluid movement along vertical joints and fractures. The only two occurrences of minor lead (Whitemud Falls) and zinc (Vermilion Chutes) sulphide deposits have

Figure 16. Stratigraphy and structure of Devonian carbonate units on the northern bank of Peace River at Vermilion Chutes. **a.** Carbonate units of the Upper Devonian Mikkwa Formation immediately downstream from Vermilion Chutes; the outcrop face developed along the dominant set of joints trending east-southeast. **b.** Ledge atop resistant Mikkwa limestone and dolomitic limestone overlain by recessive bitumen-bearing vuggy dolostone of the Grosmont Formation. **c.** Orthogonal joint system better expressed in more massive units of the Mikkwa Formation. Orientations given as dip direction/dip.

Figure 17. Linear structural features within the dominant set of vertical joints at Vermilion Chutes. **a.** Plumose structure in Mikkwa Formation at Vermilion Chutes indicating that the joint opened from northeast to southwest. **b.** Consistently oriented minor structures similar to the steps of stretching lineation, suggesting weak sinistral shear.

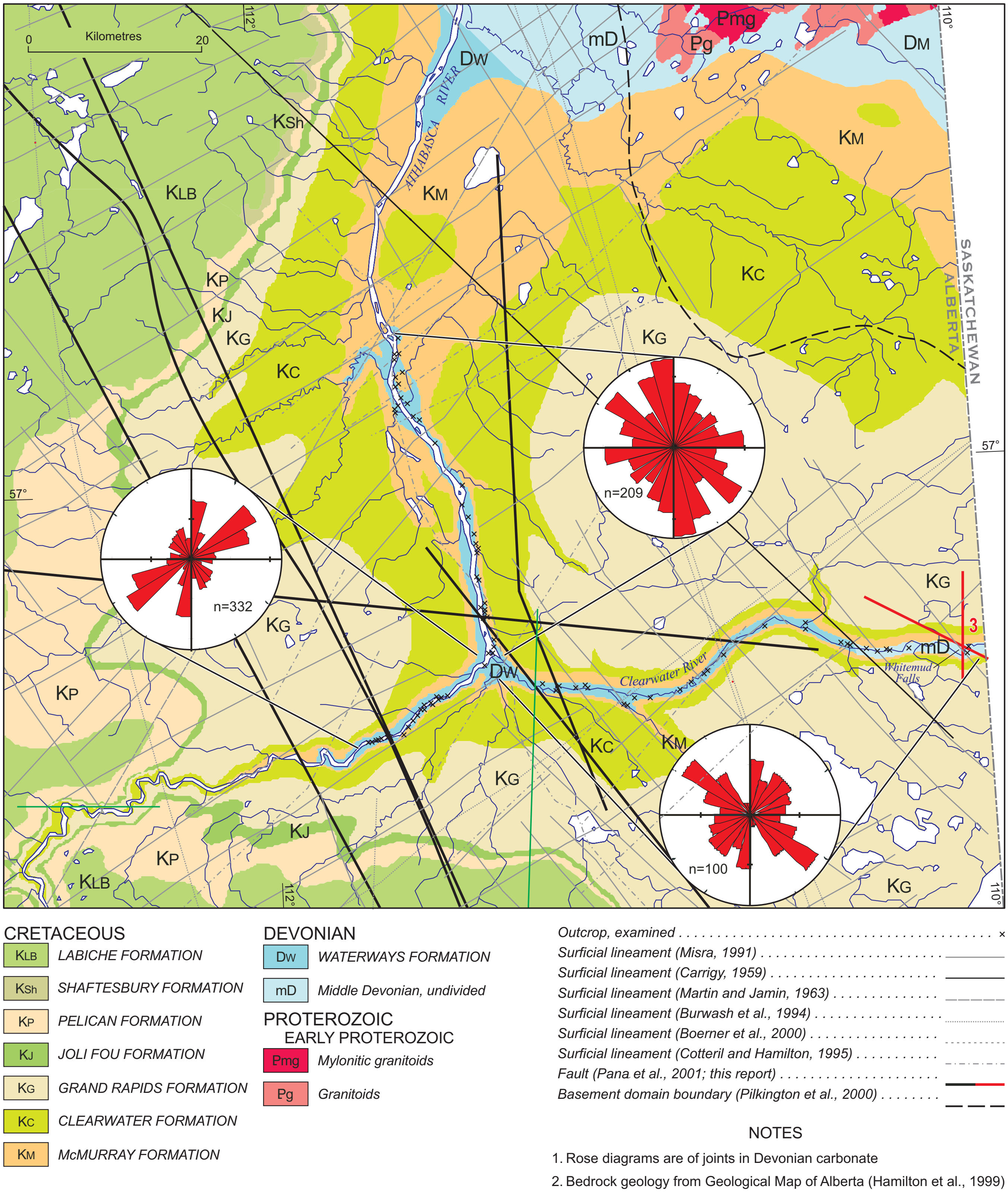


Figure 18. Joint orientation in Devonian carbonate of the Waterways Formation along Athabasca and Clearwater rivers near Fort McMurray. Known and inferred fractures in northeastern Alberta, *from* Pană et al. (2001).

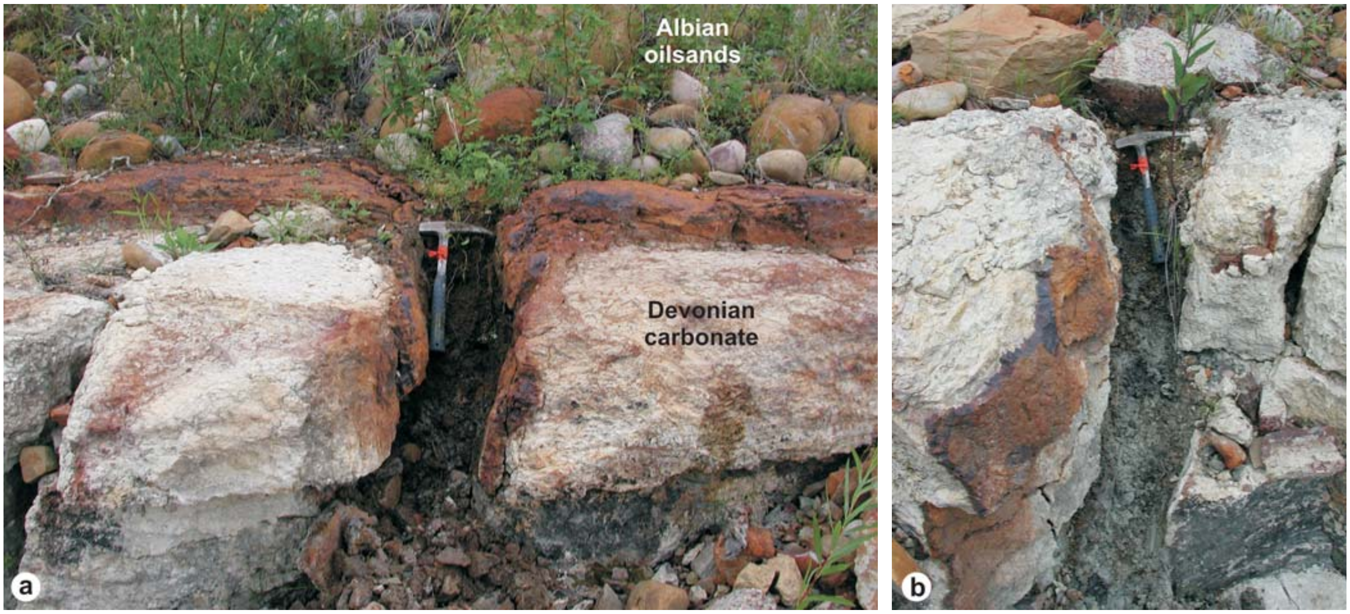


Figure 19. Iron staining in carbonate of the Devonian Waterways Formation on the north side of the Athabasca River, west of Fort McMurray. **a.** Iron staining in the carbonate wallrock of tensional fractures filled with argillaceous residue. **b.** Iron staining in the carbonate wallrock of tensional fractures and along the unconformity between carbonate deposits of the Devonian Waterways Formation and oilsands of the Albian McMurray Formation.

Figure 20. Minor faulting at Whitemud Falls on Clearwater River.

been found in zones of strain in the carbonate successions, which record minor, post-Devonian basement adjustments. Near Fort McMurray, the underlying basement is dominated by the aeromagnetic signature of the Taltson Magmatic Zone, which by analogy with its exposed segment north of Lake Athabasca (McDonough et al., 2000), includes variably retrogressed granulite facies mylonite belts. However, northerly trending shear zones may have been unfavourably oriented and hence not reactivated by the Cordilleran compression.

Pb-Zn occurrences in core from carbonate sequences in the WCSB

The evaluation of the MVT potential in the carbonate successions of the WCSB required examination of core. Dubord (1987) compiled a list of 18 wells from northern Alberta in which Zn and/or Pb had been previously reported. Seven of these wells, along with four other wells, were examined and sampled by Turner and McPhee (1994) who confirmed the occurrence of traces of zinc and/or lead in six of these eleven wells and a significant occurrence in one of the wells originally listed by Dubord (1987). Turner and McPhee (1994) also examined and sampled core from 50 wells in northeastern Alberta and found the highest Zn concentrations (0.16–0.28%) in carbonate core from three, widely separated wells. Core from some of these wells and from about twenty other wells has been examined by Rice and Zerbe (2003). A summary of Pb and/or Zn sulphide occurrences with concentrations in any of these elements higher than 100 ppm in carbonate-evaporite sequences of the WCSB is given in Table 3 and plotted in Figure 21. The only potential ore-grade MVT occurrence was identified in dolomitic breccia of the Keg River Formation above the aeromagnetic trace of the GSSZ from well 16-34-118-21W5 (Table 3, Fig. 13, 21). Up to 15% fine-crystalline pyrite, sphalerite and minor galena are present in fracture fillings in the depth interval of 1280–1290 m. This interval may average 3.7% Zn. Locally, sparry dolomite makes up 35 vol. % of the fracture filling. Minor (10%) pyrite with blebs up to 2 mm occurs mainly in mud-filled, dark-coloured fractures, and minor, disseminated pyrite blebs up to 5 mm are locally associated with spotty, white, sparry dolomite (Fig. 22a). The Pb isotope signature of this sample ($^{206}Pb/^{204}Pb$ = 18.188) is very similar to the basement Pb signature of the Pine Point sulphides (average of $^{206}Pb/^{204}Pb$ = 18.175) (Cumming et al., 1990; Nelson et al., 2002). Interestingly, similar $^{206}Pb/^{204}Pb$ values (18.267 and 18.296) have been reported from Devonian carbonate deposits of the Cordova Embayment along the southwest projection of the Tathlina Fault Zone (localities 29 and 30, Fig. 21) (Table 3) (Nelson et al., 2002).

South of Vermilion Chutes, a pyrite filled fault breccia (Fig. 22b) was encountered in dolostone of the Jean Marie Formation between 252 and 267 m depth (Locality 8, Fig. 21). In the Pelican Mountains, at a depth of 1056.3 m, 10–15% pyrite blebs up to 1.5 cm in size occur in cavities and fractures associated with possible sphalerite and grey, fine-grained and locally vuggy dolomite (Locality 9, Fig. 21). South of Edmonton, in the Leduc and Duhamel oilfields, several occurrences of sphalerite are locally associated with pyrite blebs (Localities 16 to 20, Fig. 21; Table 3). In the Simonette oilfield, Duggan et al. (2001) found Pb and Zn in fault-controlled dolostone with plume geometry within the Middle to Upper Devonian Swan Hills Formation, and reported Pb isotope values from six wells of unspecified location.

General remarks on MVT and sulphide occurrences in the WCSB

MVT deposits and occurrences in the WCSB are spatially related to Early Proterozoic zones of strain in the crystalline basement favourably oriented to intermittently release stress buildups in the adjacent orogen. Devonian tectonic adjustments along these zones of crustal anisotropy may have resulted in the peculiar environment required for reef chain development in the platformal sequences. The MVT mineralization postdated the regional diagenesis-dolomitization and affected only narrow belts of strain concentration within the carbonate rocks. Thus, MVT deposits and occurrences in the WCSB are not simply the products of the normal evolution of a sedimentary basin with carbonate platform sequences (Leach et al., 2001). The far-afield tectonic effects inferred at Pine Point and other MVT occurrences in the foreland are controlled by pre-existing fractures in the basement. Hydrothermal fluids expelled episodically from the basement during major tectonism in the Cordilleran orogen brought about dolomitization and mineralization. The occurrence of highly porous reefs is a favourable geological feature for the development of MVT deposits but not a critical factor, since MVT deposits exist independent of them (e.g. Upper Mississippi Valley, Tri-State).

CONCLUSIONS

Although a powerful means of organizing data in a form that enhances understanding and prediction, genetic models may be inherently biased: they may accentuate the significance of some features at the expense of others, or even operate to exclude perception of data that do not fit the model (Hodgson, 1993). Thus, the controversial application of basinal fluid-flow genetic models apparently led to overlooking the significance of faults in the genesis of MVT deposits and occurrences in carbonate strata of the WCSB. Several lines of evidence indicate that topographically or compaction-driven brine migrating along permeable strata towards the basin edge is not the mineralizing fluid for MVT deposits; it is thus unlikely that basin-scale fluid-flow models are relevant to exploration for MVT deposits in the Canadian Rocky Mountain fold-and-thrust belt and its foreland. At least three general characteristics of the reviewed MVT deposits and occurrences in the carbonates of WCSB can be retained as critical criteria for exploration area selection.

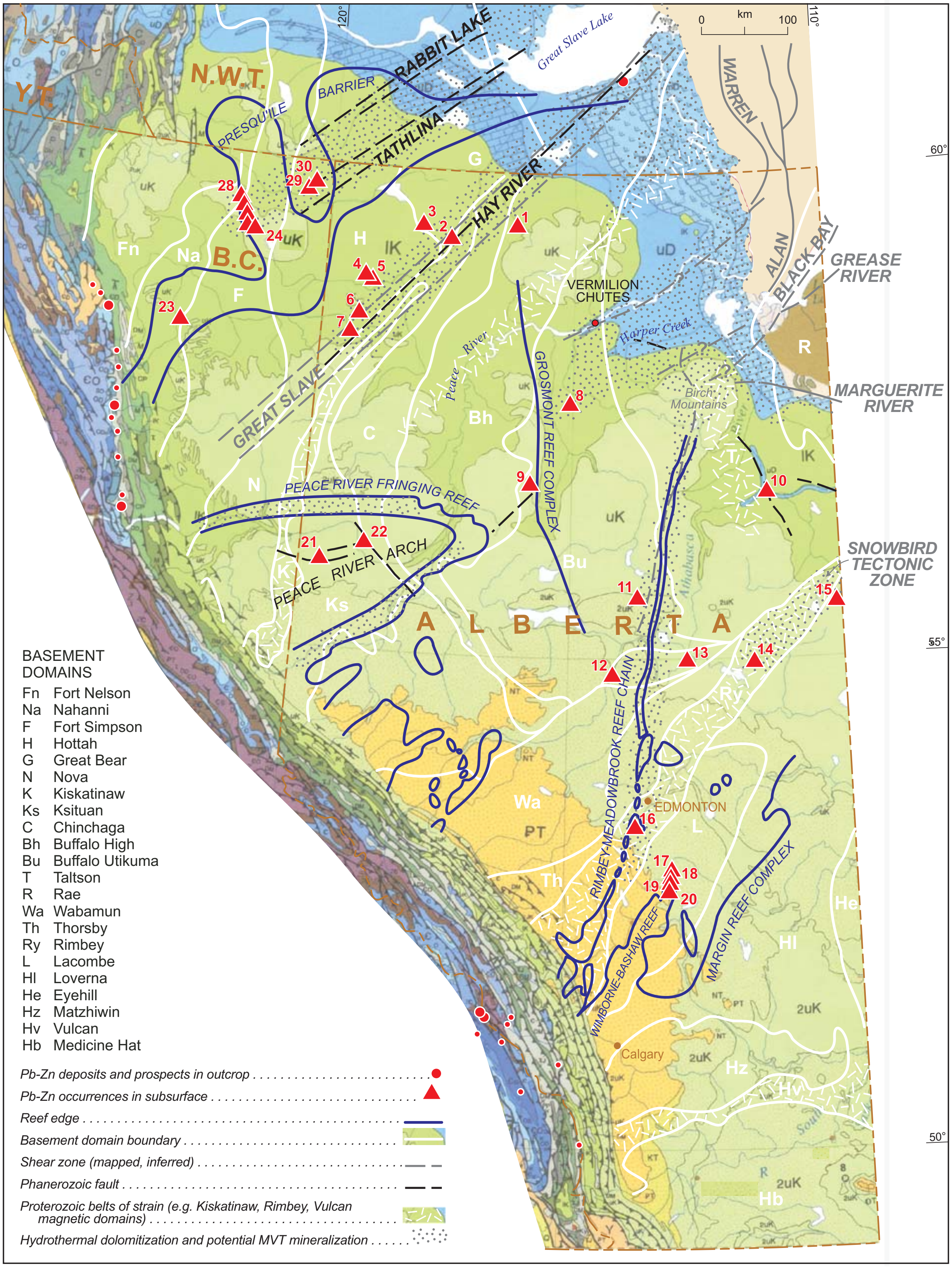


Figure 21. Selected areas of basement strain-related hydrothermal dolomitization and potential MVT mineralization in carbonate sequences of the Western Canada Sedimentary Basin; prospective areas are limited to the shallowest portions of the basin; bedrock geology as in Figure 1; basement domains *from* Pilkington et al. (2000); shear zones on the Alberta Shield *from* Panā et al. (in press); reef edges *from* Switzer et al. (1994) and Nelson et al. (2002); numbers for subsurface occurrences as in Table 3.

Table 3. Subsurface occurrences of sulphides in carbonate successions of the Western Canada Sedimentary Basin

No. in Fig. 21	Well ID	Depth (m)	Sulphide (ppm)	Stratigraphic unit	Age	Source
Northern Alberta						
1	06-34-120-13W5	798.34; 820.94	250 Zn; 222 Pb	Slave Point Fm	M–L Devonian	Turner and McPhee (1994)
2	16-34-118-21W5	1286.26	37633 Zn; 732 Pb	Keg River Fm	Middle Devonian	Dubord (1987); Turner and McPhee (1994)
3	10-22-120-01W6	1234.27; 1237.35	4707 Zn; 5187 Pb	Slave Point Fm	M–L Devonian	Turner and McPhee (1994)
4	09-05-114-08W6	1698.88	1435 Zn	Keg River Fm	Middle Devonian	Dubord (1987); Turner and McPhee (1994)
5	06-33-113-07W6	-	Zn	Keg River Fm	Middle Devonian	Dubord (1987)
6	07-32-109-08W6	-	Zn	Muskeg Fm	Middle Devonian	Dubord (1987)
7	13-20-107-09W6	499.9	151 Zn	Keg River Fm	Middle Devonian	Dubord (1987); Turner and McPhee (1994)
8	04-03-100-07W5	255.73–277.27	Py ± Zn	Jean Marie Fm	Late Devonian	Rice and Zerbe (2003)
9	04-23-089-12W5	1603.26	118 Zn	Muskeg Fm	Middle Devonian	Dubord (1987); Turner and McPhee (1994)
10	08-20-089-09W4	226.47	2816 Zn	Prairie Evaporite Fm	Middle Devonian	Turner and McPhee (1994)
11	06-10-077-25W4	1055.61	1620 Zn	Grosmont Fm	Late Devonian	Turner and McPhee (1994)
12	10-05-068-02W5	-	Pb+Zn	lower Winterburn Gr	Late Devonian	Dubord (1987)
13	05-25-069-20W4	730.78	247 Zn	Leduc Fm	Late Devonian	Turner and McPhee (1994)
14	07-08-071-11W4	588.87	1690 Zn	Beaverhill Lake Gr	M–L Devonian	Dubord (1987); Turner and McPhee (1994)
15	10-22-076-01W4	565.62	125 Zn	Keg River Fm	Middle Devonian	Turner and McPhee (1994)
Central and southern Alberta						
S	-	3798.7–3913.5	Pb	Swan Hills Fm	M–L Devonian	Duggan et al. (2001)
16	11-13-050-27W4	-	Zn	Leduc Fm	Late Devonian	Dubord (1987)
17	14-29-045-21W4	1315.21–1467.92	Zn	Nisku, Ireton, Leduc fms	Late Devonian	Haites (1960); Dubord (1987)
18	13-17-045-21W4	1478.28	Zn	Leduc Fm	Late Devonian	Haites (1960); Dubord (1987)
19	11-29-045-21W4	>1445.06	Zn	Leduc Fm	Late Devonian	Haites (1960); Dubord (1987)
20	044-21W4	-	Zn	Leduc Fm (Malmo, New Norway fields)	Late Devonian	Haites (1960); Dubord (1987)
Peace River Arch						
21	07-30-080-11W6	-	Zn	Wabamun-Banff transition	Late Devonian	Dubord (1987)
22	11-08-083-06W6	-	Zn	Wabamun Gr	Late Devonian	Dubord (1987)
Northeast British Columbia						
23	d-59-K 94J/2	2394.81	Pb	Beaverhill Lake Gp (Presqu'ile Barrier)	M–L Devonian	Nelson et al. (2002)
24	d-57-B 94P/5	2098.24	Pb	Slave Point Fm (Presqu'ile Barrier)	M–L Devonian	Nelson et al. (2002)
25	b-40-A 94P/5	2146.71	Pb	Slave Point Fm (Presqu'ile Barrier)	M–L Devonian	Nelson et al. (2002)
26	b-68-K 94P/5	2096.72	Pb	Slave Point Fm (Presqu'ile Barrier)	M–L Devonian	Nelson et al. (2002)
27	b-99-K 94P/5	2124.76	Zn	Slave Point Fm (Presqu'ile Barrier)	M–L Devonian	Nelson et al. (2002)
28	a-88-F 94P/12	2178	Pb	Slave Point Fm (Presqu'ile Barrier)	M–L Devonian	Nelson et al. (2002)
29	d-37-I 94P/10	1141.00	Pb	Jean Marie Fm	Late Devonian	Nelson et al. (2002)
30	b-68-D 94P/16	1139.00	Pb	Jean Marie Fm	Late Devonian	Nelson et al. (2002)

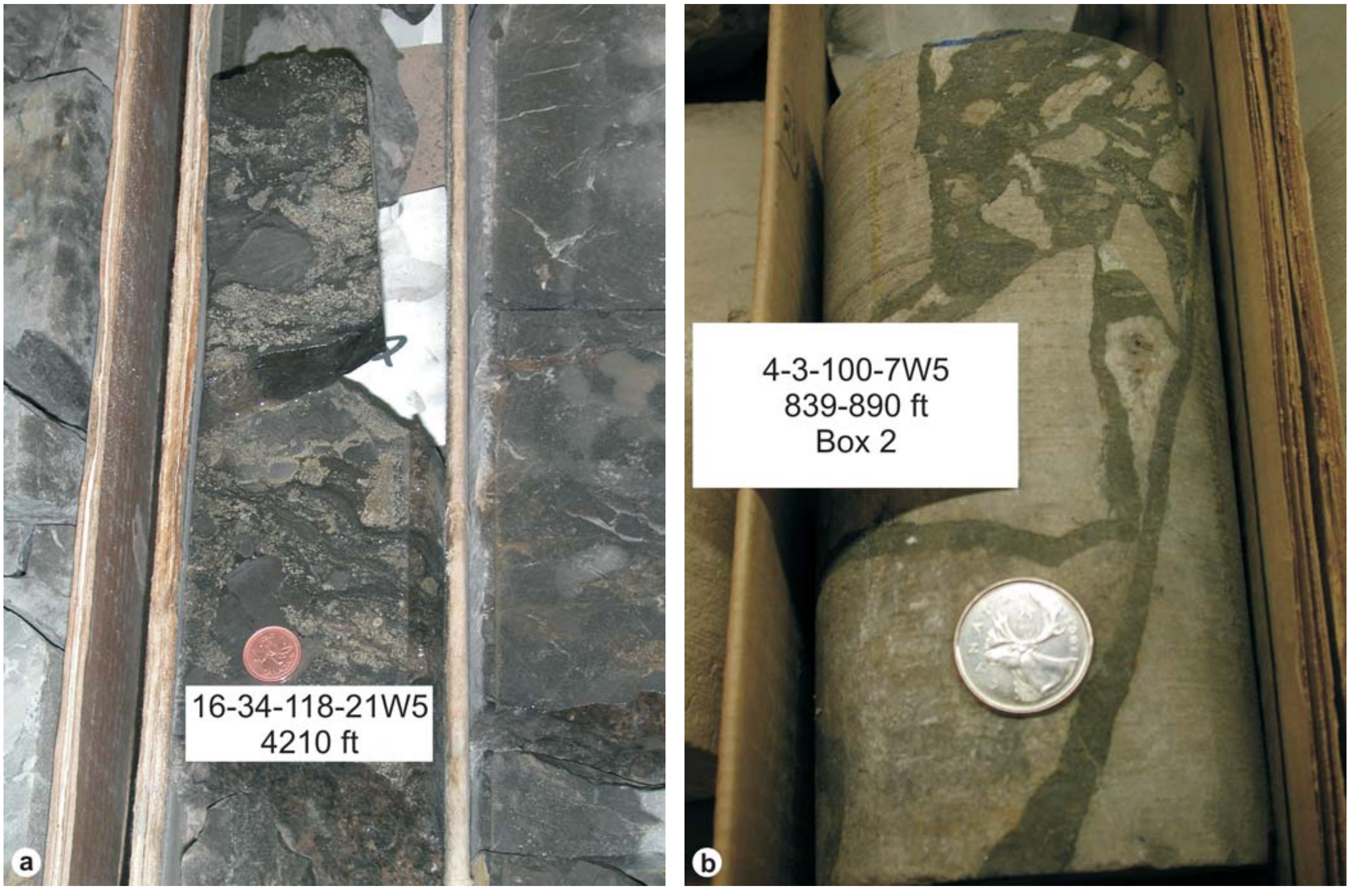


Figure 22. Sulphide-cemented carbonate breccia in core from northern Alberta. **a.** Sphalerite, pyrite and minor galena in brecciated Keg River Formation from drillhole 16-34-118-21W5, above the magnetic trace of the Great Slave Shear Zone. **b.** Pyrite- (and sphalerite?) cemented carbonate breccia from the Jean Marie Formation in the depth interval 252–267 m in drillhole 04-03-100-07W5, north of Birch Mountains.

Within undeformed basinal sequences with flat-lying stratigraphy, as well as in the deformed belt, MVT occurrences are spatially related to 1) deep fractures and fault zones allowing fluid circulation in the basement; 2) haloes of late, coarse dolomite and/or calcite; and 3) local thermal anomalies.

Tectonically induced, secondary porosity of carbonate rocks appears to be the main trap for ore-bearing fluids. Regional-scale dolomitization associated with migration of basinal brine has limited, if any, predictive power in MVT exploration. Only coarse dolomite haloes that can be tied to major faults can be considered a favourable premise for MVT exploration. High salinity of fluid inclusions in saddle or coarse dolomite is another favourable premise for exploration, as only high-salinity fluids carry sufficient metal in solution at the relatively low temperatures of MVT ore fluids. Ore fluids in the basin were most likely seawater and brine that infiltrated faults in the basin floor, and were involved in metal extraction and transport from the basement into overlying carbonate. The likely driving forces are thermal convection, hydraulic pumping and various disequilibrium phenomena within fault-confined vertical aquifers. Multiple pulses of mineralizing fluid were focused along lineaments (from district to orebody scale) where they could react with the strained carbonate caprocks at the site of ore deposition. The involvement of meteoric water was limited to late remobilization processes.

RECOMMENDATIONS

Our recent field observations, corroborated with published information, indicate that all MVT past producers and most lead-zinc occurrences in carbonate sequences of the WCSB are strictly related to fault zone processes (fracturing and possible provision of chemically active thermal waters). Consequently, basement fracture identification may be an effective exploration tool for MVT in the WCSB. In the project area, an ideal exploration target would be the duplication of those geological controls associated with the Pine Point deposits. The principal geological elements in the localization of MVT deposits hinges on the interplay of highly strained and porous Precambrian basement, deposition of a carbonate cap, and subsequent tectonic adjustments responsible for enhanced permeability in the underlying porous basement and for secondary strain and dissolution-related porosity in the carbonate deposits. Regional shear zones mapped on the Canadian Shield extend to the west beneath the Devonian carbonate cover of the WCSB, similar to the GSSZ at Pine Point (Fig. 21). Processing and interpretation of regional aeromagnetic coverage and gravity data can provide information on the broad structural framework of the sub-WCSB basement and thus introduce useful shortcuts in the selection of exploration areas for more detailed studies. Basement domain boundaries (e.g. Ross et al., 1994; Pilkington et al., 2000) may constitute primary targets. Large magnetic and gravity anomalies, interpreted as depicting ancient transpressional shear zones at the contact between basement domains, may have been, similar to the GSSZ, mostly healed and inactive during Phanerozoic time. Steep, straight faults commonly expressed as subtle potential-field lineaments locally follow the older orogenic basement structures (Lyatsky and Pană, 2003) and may have favoured the initiation of hydrological cells within vertical fault aquifers. The identification of facies change lineaments, which may be fault scarps within the WCSB, may constitute a first hint to Phanerozoic tectonism. Following the assumption that reef chains may be indicative of basement instability, a clear account of linear reef buildups in the Paleozoic stratigraphy of the WCSB could also be an important step towards the identification of exploration targets. Selected areas that may have provided the critical conditions for hydrothermal dolomitization and MVT mineralization in the foreland include (Fig. 21):

1. The wide linear zone along the Rabbit Lake and Tathlina fault zones.
2. The linear zone along the geophysical trace of the Great Slave Shear Zone.
3. The Vermilion Chutes area, where gently dipping Upper Devonian carbonate units are slightly sheared along the inferred axis of the Late Devonian Hotchkiss Embayment, a linear zone of enhanced subsidence along the westward projection of the Hudsonian Warren shear zone mapped on the Alberta Shield (Godfrey, 1986). Moreover, Vermilion Chutes is located along a westerly trending lineament of facies change within the lower Leduc Formation, with basinal shale to the north and platformal dolostone to the south (Switzer et al., 1994). Although much of the prospective carbonate area lies within Wood Buffalo National Park, and the bedrock is nearly everywhere concealed by glacial deposits, there is further scope for geochemical and geophysical surveys over parts of this region.
4. The northwestern part of Birch Mountains at the intersection of several major Early Proterozoic shear zones. The dextral Grease River Shear Zone, which projects along the southern side of Lake Athabasca, may continue west to intersect Alan, Black Bay and/or Marguerite River shear zones, and may continue along the northern flank of Birch Mountains.
5. The linear zone along Snowbird Tectonic Zone is an anastomosing, northeast-trending crustal break marked by gravity and magnetic anomalies between the Archean Rae and Hearne provinces. Segments of its aeromagnetic trace across central Alberta, oriented similarly to the Cordilleran stress field as the GSSZ, may have accommodated crustal adjustments during the Laramide compression. Up to 70 m of basement subsidence is recorded by the Lower Cretaceous Upper Mannville Group, south of the Snowbird Tectonic Zone.
6. The northerly trending Rimbey-Meadowbrook reef chain marks a lineament of drastic facies change, with sulphides reported from several wells. The northern segment of this reef chain coincides with a long and narrow (300 km x 10 km) gravity anomaly (Lyatsky and Pană, 2003). Commonly referred to as the "Leduc fault chain", the reef growth may have been controlled by a basement tectonic discontinuity (Haites, 1960; Jones, 1980; Mountjoy, 1980). The Bashaw reef trend in south-central Alberta includes a series of suphide occurrences associated with intense dolomitization and may record basement adjustments and MVT mineralization.
7. The northern and southern flanks of the Peace River Arch concentrated differential movement and have selectively favoured reef growth; subsequent fracturing of the reef during the Late Devonian–Early Carboniferous arch collapse may have created a favourable MVT environment.

The great depths of the carbonate host in most of these speculative areas make MVT development prohibitive and thus, prospective regional exploration targets for MVT deposits are limited to the shallower, northeastern portions of the WCSB. However, regardless of the depth of the carbonate unit, linear zones of strain concentration in the basement act as major conduits for fluids, providing effective sources for hydrothermal dolomite which are considered primary targets for hydrocarbon exploration in the overlying carbonates.

ACKNOWLEDGMENTS

Stimulating discussions in the field with Randy Rice, Maya Buschkuehle, Roy Eccles, Peter Hannigan and Bob Sharp helped clarify existing MVT conceptual models and the ideas presented here, although none are accountable for the conclusions. Dan Magee and Natasha Blunden of the Alberta Geological Survey's GIS and drafting group are thanked for their assistance. This paper benefited greatly from critical reviews by Peter Hannigan, Roger Macqueen, Bob Sharp and Reg Olson.

REFERENCES

Adams, J.J., Rostron, B.J., and Mendoza, C.A.
2000: Evidence for two-fluid mixing at Pine Point, NWT; Journal of Geochemical Exploration, v. 69-70, p. 103–108.

Amthor, J.E., Mountjoy, E.W., and Machel, H.C.
1993: Subsurface dolomites in the upper Devonian Leduc Formation buildups, central part of Rimbey-Meadowbrook reef trend, Alberta, Canada; Bulletin of Canadian Petroleum Geology, v. 41, no. 2, p. 164–185.

Anderson, G.M. and Macqueen, R.W.
1988: Mississippi Valley-type lead-zinc deposits; *in* Ore Deposit Models, (ed.) R.G. Roberts and P.A. Sheahan; Geoscience Canada, Reprint Series 3, p. 79–90.

Arne, D.
1991: Regional thermal history of the Pine Point area, Northwest Territories, Canada, from apatite fission-track analysis; Economic Geology, v. 86, p. 428–435.

Baadsgaard, H. and Godfrey, J.D.
1972: Geochronology of the Canadian Shield in northeastern Alberta II, Charles-Andrew-Colin Lakes Area; Canadian Journal of Earth Sciences, v. 9, p. 863–881.

Babcock, E.A.
1973: Regional jointing in southern Alberta; Canadian Journal of Earth Sciences, v. 10, no. 12, p. 1769–1781.
1974: Jointing in central Alberta; Canadian Journal of Earth Sciences, v. 11, no. 8, p. 1181–1186.
1975: Fracture phenomena in the Waterways and McMurray formations, Athabasca oil sands region, northeastern Alberta; Bulletin of Canadian Petroleum Geology, v. 23, no. 4, p. 810–826.

Beales, F. and Jackson, C.
1982: Multiple genetic and diagenetic models help the unravelling of Mississippi Valley-type ore genesis; *in* 11th International Congress on Sedimentology, Hamilton, Ontario, Canada, (comp.) J.O. Nriagu and R. Troos; Abstracts of Papers, p. 17.

Berger, Z. and Davies, G.
1999: The development of linear hydrothermal dolomite (HTD) reservoir facies along wrench or strike-slip fault systems in the Western Canada Sedimentary Basin; Reservoir, Canadian Society of Petroleum Geologists, v. 26, issue 1, p. 34–38.

Bethke, C.M.
1985: A numerical model of compaction-driven groundwater flow and its application to the paleohydrology of intracratonic sedimentary basins; Journal of Geophysical Research, v. 90, no. B8, p. 6817-6828.
1986: Hydrologic constraints on the genesis of the upper Mississippi Valley mineral district from Illinois Basin brines; Economic Geology, v. 81, p. 233–249.

Bethke, C.M. and Marshak, S.
1990: Brine migrations across North America – The plate tectonics of groundwater; Annual Review of Earth and Planetary Sciences, v. 18, p. 287–315.

Boerner, D.E., Kurtz, R.D., Craven, J.A., Ross, G.M., and Jones, F.W.
2000: A synthesis of electromagnetic studies in the Lithoprobe Alberta basement transect; constraints on Paleoproterozoic indentation tectonics; Canadian Journal of Earth Sciences, v. 37, no. 11, p. 1509–1534.

Bradley, D.C. and Leach, D.L.
2003: Tectonic controls of Mississippi Valley-type lead-zinc mineralization in orogenic forelands; Mineralium Deposita, v. 38, p. 652–667.

British Columbia Ministry of Energy and Mines
MINFILE Mineral Inventory, Mississippi Valley-type deposits database; British Columbia Ministry of Energy and Mines, http://www.em.gov.bc.ca/mining/geolsurv/MinFile.

Bruhn, R.L., Perry, W.T., Yonkee, W.A., and Thompson, T.
1994: Fracturing and hydrothermal alteration in normal fault zones, *in* Faulting, Friction and Earthquake Mechanics, Part 1, (ed.) C.J. Marone and M.L. Blanpied; Pure and Applied Geophysics, v. 142, no. 3-4, p. 609–644.

Burchfiel, B.C. and Royden, L.H.
1991: Antler Orogeny: A Mediterranean-type orogeny; Geology, v. 19, p. 66–69.

Burke, W.H., Denison, R.E., Hetherington, E.A., Koepnick, R.B., Nelson, H.F., and Otto, J.B.
1982: Variation of seawater $^{87}Sr/^{86}Sr$ throughout Phanerozoic time; Geology, v. 10, no. 10, p. 516–519.

Burwash, R.A., McGregor, C.R., and Wilson, J.A.
1994: Precambrian basement beneath the Western Canada Sedimentary Basin; *in* Geological Atlas of the Western Canada Sedimentary Basin, (comp.) G.D. Mossop and I. Shetsen; Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, p. 48–56.

Burwash, R.A., Chacko, T., Muehlenbachs, K., and Bouzidi,Y.
2000: Oxygen isotope systematics of the Precambrian basement of Alberta: Implications for Paleoproterozoic and Phanerozoic tectonics in northwestern Alberta; Canadian Journal of Earth Sciences, v. 37, no. 11, p. 1611–1628.

Buschkuehle, B.E.
2003: Sedimentology and stratigraphy of Middle and Upper Devonian carbonates in northern Alberta: A contribution to the carbonate-hosted Pb-Zn (MVT) Targeted Geoscience Initiative; Geo-Note 2002-14, 14 p.

Caine, J.S., Evans, J.P., and Forster, C.B.
1996: Fault zone architecture and permeability structure; Geology, v. 24, no. 11, p. 1025–1028.

Campbell, N.
1966: The lead-zinc deposits of Pine Point; Canadian Institute of Mining and Metallurgy, Transactions, v. 59, p. 288–295.
1967: Tectonics, reefs and stratiform lead-zinc deposits of the Pine Point area, Canada; *in* Genesis of Stratiform Lead-Zinc-Barite-Fluorite Deposits, (Mississippi Valley Type Deposits), (ed.) J.S. Brown; Economic Geology, Monograph 3, p. 59–70.

Carrigy, M.A.
1959: Geology of the McMurray Formation, Part III, General Geology of the McMurray Area; Research Council of Alberta, Geological Division, Memoir 1, 130 p.

Cathles, L.M. and Smith, A.T.
1983: Thermal constraints on the formation of Mississippi Valley-type lead-zinc deposits and their implications for episodic basin dewatering and deposit genesis; Economic Geology, v. 78, p. 983–1002.

Connolly, C.A., Walter, L.M., Baadsgaard, H., and Longstaffe, F.J.
1990: Origin and evolution of formation waters, Alberta Basin, Western Canada Sedimentary Basin. 2. Isotope systematics and water mixing; Applied Geochemistry, v. 5, p. 397–413.

Cook, D.G.
1975: Structural style influenced by lithofacies, Rocky Mountain Main Ranges, Alberta-British Columbia; Geological Survey of Canada, Bulletin 233, 73 p.

Cotterill, D.K. and Hamilton, W.N.
1995: Geology of Devonian limestones in northeast Alberta, Canada-Alberta MDA Project M92-04-14; Alberta Geological Survey/Alberta Research Council, Open File Report 1995-07, 38 p.

Cumming, G.L., Kyle, J.R., and Sangster, D.F.
1990: Pine Point: a case history of lead isotope homogeneity in a Mississippi Valley-type district; Economic Geology, v. 85, p. 133–144.

Deer, W.A., Howie, R.A., and Zussman, J.
1992: An introduction to the rock-forming minerals, Second edition, Longman, 696 p.

Deming, D. and Nunn, J.A.
1991: Numerical simulations of brine migration by topographically driven recharge; Journal of Geophysical Research, v. 96, no. 82, p. 2485–2499.

Dorobek, S.L., Reid, S.K., and Elrick, M.
1991: Antler foreland stratigraphy of Montana and Idaho: The stratigraphic record of eustatic fluctuations and episodic tectonic events; *in* Paleozoic Paleogeography of the Western United States-II, (ed.) J.D. Cooper and C.H. Stevens; Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, p. 487–508.

Douglas, R.J.W and Norris, A.W.
1974: Geology, Great Slave, District of MacKenzie; Geological Survey of Canada, Map 1370A, scale 1:500,000.

Dubord, M.P.
1987: Carbonate hosted Pb-Zn potential of northeastern Alberta and the applicability of petroleum data for mineral exploration; Alberta Research Council, Open File Report 1987-07, 42 p.

Duggan, J.P., Mountjoy, E.W., and Stasiuk, L.D.
2001: Fault-controlled dolomitization at Swan Hills Simonette oil field (Devonian), deep basin west-central Alberta, Canada; Sedimentology, v. 48, p. 301–323.

Dunsmore, H.E.
1973: Diagenetic processes of lead-zinc emplacement in carbonates; Transactions of the Institute of Mining and Metallurgy, v. 82, Section B, Bulletin no. 804, p. B168–B173.

Eaton, D.W. and Hope, J.
2003: Structure of the crust and upper mantle of the Great Slave Lake shear zone, northwestern Canada, from teleseismic analysis and gravity modelling; Canadian Journal of Earth Sciences, v. 40, p. 1203–1218.

Eaton, D.W., Ross, G.M., and Hope, J.
1999: The rise and fall of a cratonic arch: A regional seismic perspective on the Peace River Arch, Alberta; Bulletin of Canadian Petroleum Geology, v. 47, no. 4, p. 346–361.

Eisbacher, G.H.
1983: Devonian-Mississippian sinistral transcurrent faulting along the cratonic margin of western North America: a hypothesis; Geology, v. 11, p. 7–10.

Etheridge, M.A., Wall, V.J., and Vernon, R.H.
1983: The role of the fluid phase during regional metamorphism and deformation; Journal of Metamorphic Geology, v.1, p. 205–226.

Evans, T.L., Campbell, F.A., and Krouse, H.R.
1968: A reconnaissance study of some western Canadian lead-zinc deposits; Economic Geology, v. 63, p. 349–359.

Evenchick, C.A.
1988: Stratigraphy, metamorphism, structure, and their tectonic implications in the Sifton and Deserters ranges, Cassiar and northern Rocky Mountains, northern British Columbia; Geological Survey of Canada, Bulletin 376, 90 p.

Fehn, U. and Liu, X.
1997: HHP granite fracturing and the genesis of upper Mississippi Valley-type deposits; Geological Society of America Annual Meeting, Abstracts with Programs, v. 29, no. 6, p. 60.

Frape, S.K. Fritz, P., and McNutt, R.H.
1984: Water-rock interaction and chemistry of groundwaters from the Canadian Shield; Geochimica et Cosmochimica Acta, v. 48, p. 1617–1627.

Gabrielse, H.
1976: Environments of Canadian Cordillera depositional basins; *in* Circum-Pacific energy and mineral resources, (ed.) M.T. Halbouty, J.C. Maher and H.M. Lian; American Association of Petroleum Geologists, Memoir 25, p. 492–502.

Garven, G.,
1985: The role of regional fluid-flow in the genesis of the Pine Point deposit, Western Canada Sedimentary Basin; Economic Geology, v. 80, p. 307–324.
1989: A hydrogeologic model for the formation of the giant oil sands deposits of the Western Canada Sedimentary Basin; American Journal of Science, v. 289, p. 105–166.

Garven, G. and Freeze, R.A.
1984: Theoretical analysis of the role of groundwater flow in the genesis of stratabound ore deposits-2. Quantitative results; American Journal of Science, v. 284, p. 1125–1174.

Garven, G., Ge, S., Person, M.A., and Sverjensky, D.A.
1993: Genesis of stratabound ore deposits in the mid-continent basins of North America, 1. The role of regional groundwater flow; American Journal of Science, v. 293, p. 497–568.

Geiger, H.D. and Cook, F.A.
2001: Analyses of crustal structure from bandpass and directionally filtered potential-field data: an example from Western Canada; Canadian Journal of Earth Sciences, v. 38, no. 6, p. 953–961.

Gibbins, W.
1988: Metallic mineral potential of the Western Interior Platform of the Northwest Territories; Geoscience Canada, v. 15, no. 2, p. 117–119.

Giles, K.A. and Dickinson, W.R.
1995: The interplay of eustasy and lithospheric flexure in forming stratigraphic sequences in foreland settings: An example from the Antler foreland, Nevada and Utah; *in* Stratigraphic Evolution of Foreland Basins, (ed.) S.L. Dorobek and G.M. Ross; SEPM (Society for Sedimentary Geology), Special Publication No. 52, p. 187–212.

Godfrey, J.D.
1985: Lead and zinc – commodity profile; Internal report to AENR, Alberta Research Council Internal Report, 22 p.
1986: Geology of the Precambrian Shield in northeastern Alberta, NTS 74M and NTS 74L; Alberta Research Council, Map EM 180.

Godwin, C.I., Sinclair, A.J., and Ryan, B.D.
1982: Lead isotope models for the genesis of carbonate-hosted Zn-Pb, shale-hosted Ba-Zn-Pb, and silver-rich deposits in the northern Canadian Cordillera; Economic Geology, v. 77, p. 82–94.

Gordey, S.P., Abbot, J.G., Templeman-Kluit, D.J., and Gabrielse, H.
1987: "Antler" clastics in the Canadian Cordillera; Geology, v. 15, p. 103–107.

Grasby, S.E.
2002: Modern thermal springs and hydrothermal ore deposits in the southern Canadian Cordillera; Geological Association of Canada-Mineralogical Association of Canada, Joint Annual Meeting, Saskatoon, Abstract Volume, p. 42.

Grasby, S.E., Fowler, M., and Stasiuk, V.
2002: Sulphur compounds in bitumens and pyrobitumens in relation to microstructure and their role in forming the Pine Point Pb-Zn deposit, NWT; Geological Association of Canada-Mineralogical Association of Canada, Joint Annual Meeting, Saskatoon, Abstract Volume, p. 41.

Green, R.
1957: Lead/zinc, notes on lead mines on Protection Mountain, Tp 27 R 15 W5M, 082N/SE Alberta; Alberta Research Council Economic Minerals File PB-IR-03, 3 p.
1971: Geology and mineral resources of northeastern Alberta; unpublished report, Alberta Research Council, 27 p.

Gulf Minerals Ltd.
1975: Vermilion Chutes Property, Gulf Minerals internal file; Alberta Geological Survey/EUB archives.

Haites, T.B.
1960: Transcurrent faults in Western Canada; Journal of Alberta Society of Petroleum Geologists, v. 8, no. 2, p. 33–78.

Hamilton, W.N., Langenberg, W.C., Price, M.C., and Chao, D.K. (compilers)
1999: Geological map of Alberta; Alberta Geological Survey/ Alberta Energy and Utilities Board, Map 236D, scale 1: 1,000,000, CD-ROM.

Hanmer, S.
1988: Great Slave Lake Shear Zone, Canadian Shield: reconstructed vertical profile of a crustal-scale fault zone, Tectonophysics, v. 149, no. 3-4, p. 245–264.

Hanmer, S., Bowring, S., van Breemen, O., and Parrish, R.
1992: Great Slave Lake shear zone, NW Canada: mylonitic record of Early Proterozoic continental convergence, collision and indentation; Journal of Structural Geology, v. 14, no. 7, p. 757–773.

Haynes, F.M. and Kesler, S.E.
1987: Chemical evolution of brines during Mississippi Valley-type mineralization: Evidence from east Tennessee and Pine Point; Economic Geology, v. 82, p. 53–71.

Hedley, M.S.
1954: Mineral deposits in the southern Rocky Mountains of Canada; *in* Guidebook, Fourth Annual Field Conference, Alberta Society of Petroleum Geologists, p. 110–118.

Henderson, G.G.L.
1954: Annual Report from 1953; B.C. Ministry of Mines, p. A155–A156.

Hitchon, B.
1993: Geochemistry of formation waters, northern Alberta, Canada: Their relation to the Pine Point ore deposit; Canada-Alberta MDA Project M92-04-03; Alberta Geological Survey, Open File Report 1993-14, 99 p.

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

Hodgson, C.J.
1993: Uses (and abuses) of ore deposit models in mineral exploration; *in* Ore Deposit Models, Volume II, (ed.) P.A. Sheahan and M.E. Cherry; Geoscience Canada, Reprint Series 6, p. 1–11.

Hoffman, P.F.
1988: United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia; Annual Review of Earth and Planetary Sciences, v. 16. p. 543–603.

Holter, M.E.
1977: The Oldman River lead-zinc occurrence, southwestern Alberta; Bulletin of Canadian Petroleum Geology, v. 25, no. 1, p. 92–109.

Hoy, T.
1982: Stratigraphic and structural setting of stratabound lead-zinc deposits in southeastern B.C.; CIM Bulletin, v. 75, no. 840, p. 114–134.

Huenges, E., Erzinger, J., Kuck, J., Engeser, B., and Kessels, W.
1997: The permeable crust: Geohydraulic properties down to 9101 m depth; Journal of Geophysical Research, v. 102, no. B8, p. 18,255-18,265.

Ingebritsen, S.E. and Sanford, W.E.
1998: Groundwater in Geologic Processes; Cambridge University Press, 341 p.

Jackson, S.A. and Beales, F.W.
1967: An aspect of sedimentary basin evolution: the concentration of Mississippi Valley-type ores during late stages of diagenesis; Bulletin of Canadian Petroleum Geology, v. 15, no. 4, p. 383–433.

Jones, R.M.P.
1980: Basinal isostatic adjustment faults and their petroleum significance; Bulletin of Canadian Petroleum Geology, v. 28, p. 211–251.

Ketner, K.B. and Smith, J.F.
1982: Mid-Paleozoic age of the Roberts thrust unsettled by new data from northern Nevada; Geology, v. 10, p. 298–303.

Klepacki, D.W. and Wheeler, J.O.
1985: Stratigraphic and structural relations of the Milford, Kaslo and Slocan groups, Goat Range, Lardeau and Nelson map areas, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 85-1A, p. 277–286.

Krebs, W. and Macqueen, R.W.
1984: Sequence of diagenetic and mineralization events, Pine Point lead-zinc property, Northwest Territories, Canada; Bulletin of Canadian Petroleum Geology, v. 32, no. 4, p. 434–464.

Kyle, J.R.
1981: Geology of the Pine Point lead-zinc district; *in* Handbook of Stratabound and Stratiform Ore Deposits, (ed.) K.H. Wolf; Part III, v. 9, p. 643–741, Elsevier, New York.

Land, L.S.
1985: The origin of massive dolomite; Journal of Geological Education, v. 33, p. 112–125.

Leach, D.L. and Sangster, D.F.
1993: Mississippi Valley-type lead-zinc deposits; *in* Mineral Deposit Modeling, (ed.) R.V. Kirkham, W.D. Sinclair, R.I. Thorpe and J.M. Duke; Geological Association of Canada, Special Paper 40, p. 289–314.

Leach, D.L., Bradley, D., Lewchuk, M.T., Symons, T.A., Marsily, G., and Brannon, J.
2001: Mississippi Valley-type lead-zinc deposits through geologic time: implications from recent age-dating research; Mineralium Deposita, v. 36, p. 711–740.

Lonnee, J. and Al-Aasm I.S.
2000: Dolomitization and fluid evolution in the Middle Devonian Sulphur Point Formation, Rainbow South Field, Alberta: Petrographic and geochemical evidence; Bulletin of Canadian Petroleum Geology, v. 48, no. 3, p. 262–283.

Lyatsky, H. and Pană, D.
2003: Catalogue of selected gravity and magnetic maps of northern Alberta; Alberta Geological Report/Alberta Energy and Utilities Board, Special Report 56, 42 p.

Machel, H.G. and Cavell, P.A.
1999: Low-flux, tectonically-induced squeegee fluid flow ("hot flash") into the Rocky Mountain foreland basin; Bulletin of Canadian Petroleum Geology, v. 47, no. 4, p. 510–533.

MacIntyre, D.G.
1982: Geologic setting of recently discovered stratiform barite-sulphide deposits in northeast British Columbia; CIM Bulletin, v. 75, no. 840, p. 99–113.
1991: SEDEX-Sedimentary exhalative deposits; *in* Ore Deposits, Tectonics and Metallogeny in the Canadian Cordillera; British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1991-4, p. 25–70.

Macqueen, R.W. and Powell, T.G.
1983: Organic geochemistry of the Pine Point lead-zinc ore field and region, Northwest Territories, Canada; Economic Geology, v. 78, p. 1–25.

Macqueen, R.W. and Thompson, R.I.
1978: Carbonate hosted lead-zinc occurrences in northeastern British Columbia with emphasis on the Robb Lake deposit; Canadian Journal of Earth Sciences, v. 15, no. 11, p. 1737–1762.

Manns, F.T.
1981: Stratigraphic aspects of the Silurian-Devonian sequence hosting zinc and lead mineralization near Robb Lake, northeastern British Columbia; Ph.D. thesis, University of Toronto, Ontario, 252 p.

Martin, R. and Jamin, F.G.S.
1963: Paleogeomorphology of the buried Devonian landscape in northeastern Alberta; *in* Athabasca oil sands, (ed.) M.A. Carrigy; Alberta Research Council, Information Series 45, p. 31–42.

McClay, K.R. Insley, M.W., and Anderton, R.
1989: Inversion of the Kechika trough, northeastern British Columbia, Canada; *in* Inversion Tectonics, (ed.) M.A. Cooper, and G.D. Williams; Geological Society of London, Special Publication No. 44, p. 235–257.

McDonough, M.R., McNicoll, V.J., Schetselaar, E.M., and Grover, T.W.
2000: Geochronological and kinematic constraints on crustal shortening and escape in a two-sided oblique-slip collisional and magmatic orogen, Paleoproterozoic Taltson magmatic zone, northeastern Alberta; Canadian Journal of Earth Sciences, v. 37, no. 11, p. 1549–1573.

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

Meijer Drees, N.C.
1994: Devonian Elk Point Group of the Western Canada Sedimentary Basin, Chapter 10; *in* Geological Atlas of the Western Canada Sedimentary Basin, (comp.) G.D. Mossop and I. Shetsen; Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, p. 129–147.

Misra, K.S., Slaney, V.R., Graham, D. and Harris, J.
1991: Mapping of basement and other tectonic features using Seasat and Thematic Mapper in hydrocarbon producing areas of the western sedimentary basin of Canada; Canadian Journal of Remote Sensing, v. 17, no. 2, p. 137–151.

Morrow, D.W.
1973: The Presqu'ile complex-implications for Middle Devonian paleogeography of northern Alberta and British Columbia; Bulletin of Canadian Petroleum Geology, v. 21, no 4, p. 421–434.
1998: Regional subsurface dolomitization: Models and constraints; Geoscience Canada, v. 25, no. 2, p. 57–70.

Morrow, D.W. and Cumming, G.L.
1982: Interpretation of lead isotope data from zinc-lead mineralization in the northern part of the western Canadian Cordillera; Canadian Journal of Earth Sciences, v. 19, p. 1070–1078.

Morrow, D.W., Cumming, G.L., and Aulstead, K.L.
1990: The gas-bearing Devonian Manetoe facies, Yukon and Northwest Territories; Geological Survey of Canada Bulletin 400, 54 p.

Morrow, D.W., Cumming, G.L., and Koepnick, R.B.
1986: Manetoe facies-A gas-bearing, megacrystalline, Devonian dolomite, Yukon and Northwest Territories, Canada; American Association of Petroleum Geologists Bulletin, v. 70, p. 702–720.

Morrow, D.W., MacLean, B.C., Tzeng, P., and Pană, D.
2002: Subsurface Paleozoic structure and isopach maps and selected seismic lines in southern Northwest Territories and northern Alberta: Implications for mineral and petroleum potential; Geological Survey of Canada, Open File 4366, 22 p.

Mountjoy, E.W.
1980: Some questions about the development of Upper Devonian carbonate buildups (reefs), western Canada; Bulletin of Canadian Petroleum Geology, v. 28, no. 3, p. 315–344.

Mountjoy, E.W., Qing, H., and McNutt, R.H.
1992: Strontium isotopic composition of Devonian dolomites, Western Canada Sedimentary Basin: significance of sources of dolomitizing fluids; Applied Geochemistry, v. 7, p. 59–75.

Mountjoy, E.W., Machel, H.G., Green, D., Duggan, J., and Williams-Jones, A.E.
1999: Devonian matrix dolomites and deep burial carbonate cements: A comparison between the Rimbey-Meadowbrook trend and the deep basin of west-central Alberta; Bulletin of Canadian Petroleum Geology, v. 47, no. 4, p. 487–509.

Nakai, S., Halliday, A.N., Kesler, S.E., Jones, H.D., Kyle, J.R., and Lane, T.E.
1993: Rb-Sr dating of sphalerites from Mississippi Valley-type (MVT) ore deposits; Geochimica et Cosmochimica Acta, v. 57, p. 417–427.

Nelson, J.L., Paradis, S., and Zantvoort, W.
1999: The Robb Lake carbonate-hosted lead-zinc deposit, northeastern British Columbia: A Cordilleran MVT deposit; *in* Geological Field Work, 1998; British Columbia Ministry of Energy and Mines; Paper 1999-1; p. 89–101.

Nelson, J.L., Paradis, S., Christensen, J., and Gabites, J.
2002: Canadian Cordilleran Mississippi Valley-type deposits: a case for Devonian-Mississippian back-arc hydrothermal origin; Economic Geology, v. 97, p. 1013–1036.

Nesbitt, B.E. and Muehlenbachs, K.
1994a: Paleohydrology of the Canadian Rockies and origins of brines, Pb-Zn deposits and dolomitization in the Western Canada Sedimentary Basin; Geology, v. 22, no. 3, p. 243–246.
1994b: Paleohydrology of the Canadian Rockies and origins of brines, Pb-Zn deposits and dolomitization in the Western Canada Sedimentary Basin, Reply; Geology, v. 22, no. 12, p. 1150–1151.
1995a: Importance of paleo-fluid systems in the southern Canadian Rockies in the genesis of mineral deposits in the Rockies and Western Canada Sedimentary Basin; *in* 1995 Alberta Basement Transect Workshop, (ed.) G. Ross; Lithoprobe Report, no. 47, Lithoprobe Secretariat, University of British Columbia, p. 250–253.
1995b: Paleohydrology of the Canadian Rockies and origins of brines, Pb-Zn deposits and dolomitization in the Western Canada Sedimentary Basin, Reply; Geology, v. 23, no. 2, p. 190.

Neuzil, C.E.
1995: Abnormal pressures as hydrodynamic phenomena; American Journal of Science, v. 295, p. 742–786.

Ney, C.S.
1954: Monarch and Kicking Horse Mines, Field, British Columbia; *in* Alberta Society of Petroleum Geologists, Guidebook, Fourth Annual Field Conference, p. 119–136.

Noble, P.J. and Finney, S.C.
1999: Recognition of fine-scale imbricate thrusts in lower Paleozoic orogenic belts – an example from the Roberts Mountains allochthon, Nevada; Geology, v. 27, p. 543–546.

Norford, B.S.
1981: Devonian stratigraphy at the margins of the Rocky Mountain Trench, Columbia River, southeastern British Columbia; Bulletin of Canadian Petroleum Geology, v. 29, no. 4, p. 540–560.

Norris, A.W.
1963: Devonian stratigraphy of northeastern Alberta and northwestern Saskatchewan; Geological Survey of Canada, Memoir 313, 168 p.
1965: Stratigraphy of Middle Devonian and older Paleozoic rocks of the Great Slave Lake region, Northwest Territories; Geological Survey of Canada, Memoir 322, 180 p.

Norris, D.K.
1993: Geology Fording River (East Half), west of Fifth Meridian, British Columbia-Alberta; Geological Survey of Canada, Map 1831A, Scale 1:50 000.

Norton, D. and Knight, J.E.
1977: Transport phenomena in hydrothermal systems: cooling plutons; American Journal of Science, v. 277, p. 937–981.

O'Brien, G.S., Bean, C.J., and McDermott, F.
2003: A numerical study of passive transport through fault zones; Earth and Planetary Science Letters, v. 214, p. 633–643.

Ohmoto, H.
1986: Stable isotope geochemistry of ore deposits, Chapter 14; *in* Stable Isotopes in High Temperature Geological Processes, (ed.) J.W. Valley, H.P. Taylor Jr., and J.R. O'Neil; Mineralogical Society of America, Reviews in Mineralogy, v. 16, p. 491–559.

Okulitch, A.V. (compiler)
2006: Phanerozoic bedrock geology, Slave River, District of Mackenzie, Northwest Territories; Geological Survey of Canada, Map NP-11/12-G, scale 1:1,000,000 (National Earth Science Series, Geological Atlas), Open File 5281.

Oliver, J.
1986: Fluids expelled tectonically from orogenic belts: Their role in hydrocarbon migration and other geologic phenomena; Geology, v. 14, p. 99–102.

Pană, D.I., Waters, J., and Grobe, M.
2001: GIS compilation of structural elements in northern Alberta; Alberta Energy and Utilities Board/Alberta Geological Survey, ESR-Report 2001-1, CD-ROM.

Pană, D.I, Creaser, R.A., Muehlenbachs, K., and Wheatley, K.
in press: Basement geology in the Alberta portion of the Athabasca Basin, with emphasis on the Maybelle River area; *in* Extech IV Athabasca Uranium Multidisciplinary Study: Geoscience Contributions, (ed.) C. Jefferson and G. Delaney; Geological Association of Canada.

Paradis, S., Nelson, J.L., and Irwin, S.E.B.
1998: Age constraints on the Devonian shale-hosted Zn-Pb-Ba deposits, Gataga district, northeastern British Columbia, Canada; Economic Geology, v. 93, no. 2, p. 184–200.

Paradis, S., Nelson, J.L., and Zantvoort, W.
1999: A new look at the Robb Lake carbonate-hosted lead-zinc deposit, northeastern British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 1999-A, p. 61–70.

Paradis, S., Turner, W.A., Wilson, N., and Coniglio, M.
2006: Stable and radiogenic isotopic signatures of mineralized Devonian carbonate rocks of the northern Rocky Mountains and the Western Canada Sedimentary Basin; *in* Potential for Carbonate-hosted Lead-zinc Mississippi Valley-type Mineralization in Northern Alberta and Southern Northwest Territories: Geoscience Contributions, Targeted Geoscience Initiative, (ed.) P.K. Hannigan; Geological Survey of Canada, Bulletin 591.

Pilkington, M., Miles, W.F., Ross, G.M., and Roest, W.R.
2000: Potential-field signatures of buried Precambrian basement in the Western Canada Sedimentary Basin; Canadian Journal of Earth Sciences, v. 37, no. 11, p. 1453–1471.

Plint, H.E. and Ross, G.M.
1993: $^{40}Ar/^{39}Ar$ geochronology of selected crystalline basement samples from the Alberta Basin: the timing of Proterozoic assembly of the subsurface of Western Canada; *in* Radiogenic Age and Isotopic Studies, Report 7; Geological Survey of Canada, Paper 93-2, p. 71–82.

Powell, T.G. and Macqueen, R.W.
1984: Precipitation of sulfide ores and organic matter: Sulfate reactions at Pine Point, Canada; Science, v. 224, p. 63–66.

Price, R.A.
1994: Cordilleran tectonics and the evolution of the Western Canada Sedimentary Basin; *in,* Geological Atlas of the Western Canada Sedimentary Basin, (comp.) G.D. Mossop and I. Shetsen; Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, p. 12–24.

Price, R.A., Cook, D.G., Aitken, J.D., and Mountjoy, E.W.
1980a: Geology, Lake Louise, Alberta-British Columbia; Geological Survey of Canada, Map 1482A, East Half, scale 1:50,000.
1980b: Geology, Lake Louise, Alberta-British Columbia; Geological Survey of Canada, Map 1483A, West Half, scale 1:50,000.

Price, R.A., Mountjoy E.W., and Cook, D.G.
1978: Geology, Mount Goodsir, British Columbia-Alberta; Geological Survey of Canada, Map 1476A, East Half, scale 1:50,000.

Qing, H.
1991: Diagenesis of Middle Devonian Presqu'ile dolomite from Pine Point, NWT and adjacent subsurface; Ph.D. Thesis, McGill University, Montreal, Canada.
1998a: Petrography and geochemistry of early-stage, fine- and medium-crystalline dolomites in the Middle Devonian Presqu'ile Barrier at Pine Point, Canada; Sedimentology, v. 45, p. 433–446.
1998b: Geochemical constraints on the origin and timing of paleofluid flow in the Presqu'ile barrier reef, Western Canada Sedimentary Basin; *in* Dating and Duration of Fluid Flow and Fluid-Rock Interaction, (ed.) J. Parnell; Geological Society, London, Special Publication 144, p. 173–187.

Qing, H. and Mountjoy, E.W.
1992: Large-scale fluid-flow in the Middle Devonian Presqu'ile barrier, Western Canada Sedimentary Basin, Geology, v. 20, p. 903–906.
1994: Formation of coarsely crystalline, hydrothermal dolomite reservoirs in the Presqu'ile Barrier, Western Canada Sedimentary Basin; American Association of Petroleum Geology, Bulletin, v.78, no. 1, p. 55–77.

Qing, H., Mountjoy, E.W., Nesbitt, B.E., and Muehlenbachs, K.
1995: Paleohydrogeology of the Canadian Rockies and origins of brines, Pb-Zn deposits and dolomitization in the Western Canada Sedimentary Basin: Comment and Reply; Geology, v. 23, no. 2, p. 189–190.

Rhodes, D., Lantos, E.A., Lantos, J.A., Webb, R.J., and Owens, D.C.
1984: Pine Point orebodies and their relationship to the stratigraphy, structure, dolomitization and karstification of the Middle Devonian barrier complex; Economic Geology, v. 79, p. 991–1055.

Rice, R.J. and Zerbe, T.
2003: Carbonate-hosted Pb-Zn (MVT) in northeastern Alberta-2002 core program: A contribution to the carbonate-hosted Pb-Zn (MVT) Targeted Geoscience Initiative; Alberta Energy and Utilities Board; EUB/AGS, GeoNote 2003-02, 8 p., CD-ROM.

Roberts, R.J., Hotz, P.E., Gilluly, J., and Ferguson H.G.
1958: Paleozoic rocks of north central Nevada; American Association of Petroleum Geologists, Bulletin, v. 42, p. 2813–2857.

Roedder, E.
1968: Temperature, salinity and origin of the ore-forming fluids at Pine Point, Northwest Territories, Canada, from fluid inclusion studies; Economic Geology, v. 63, p. 439–450.

Root, K.G.
2001: Devonian Antler fold and thrust belt and foreland basin development in the southern Canadian Cordillera: implications for the Western Canada Sedimentary Basin; Bulletin of Canadian Petroleum Geology, v. 49, no. 1, p. 7–36.

Ross, G.M., Broome, J., and Miles, W.
1994: Potential fields and basement structure – Western Canada Sedimentary Basin; *in* Geological Atlas of the Western Canada Sedimentary Basin, (comp.) G.D. Mossop and I. Shetsen; Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, p. 41–47.

Sangster, D.F.
1973: Geology of Canadian lead and zinc deposits; *in* Report of Activities, Part A; Geological Survey of Canada, Paper 73-1A, p. 129–130.
1995: Mississippi Valley-type lead-zinc; *in* Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 253–261.

Sangster, D.F. and Carrière, J.J.
1991: Preliminary studies of fluid inclusions in sphalerite from the Robb Lake Mississippi Valley-type deposit, British Columbia; *in* Current Research, Part E; Geological Survey of Canada, Paper 91-1E, p. 25–32.

Sangster, D.F. and Lancaster, R.D.
1976: Geology of Canadian lead and zinc deposits; *in* Report of Activities, Part A; Geological Survey of Canada, Paper 76-1A, p. 301–10.

Sangster, D.F., Macqueen, R.W., and Thompson, R.I.
1979: Carbonate-hosted lead-zinc occurrences in northeastern British Columbia with emphasis on the Robb Lake deposit: Discussion and Reply; Canadian Journal of Earth Sciences, v. 16, p. 2063–2068.

Sangster, D.F., Nowlan, G.S., and McCracken, A.D.
1994: Thermal comparison of Mississippi Valley-type lead- zinc deposits and their host rocks using fluid inclusion and conodont colour alteration index data; Economic Geology, v. 89, no. 3, p. 493–514.

Sasaki, A. and Krouse, H.R.
1969: Sulfur isotopes and the Pine Point lead-zinc mineralization; Economic Geology, v. 64, p. 718–730.

Sevastopulo, G.
2000: Review on development of regional exploration criteria for buried carbonate-hosted mineral deposits: A multidisciplinary study in northern England; Economic Geology, v. 95, p. 1171.

Sharp, J.M., Jr.
1978: Energy and momentum transport model of the Ouachita Basin and its possible impact on formation of economic mineral deposits; Economic Geology, v. 73, p. 1057–1068.

Sheppard, S.M.F.
1986: Characterization and isotopic variations in natural waters, Chapter 6; *in* Stable Isotopes in High Temperature Geological Processes, (ed.) J.W. Valley, H.P. Taylor Jr. and J.R. O'Neil; Mineralogical Society of America, Reviews in Mineralogy, v. 16, p. 165–183.

Sikabonyi, L.A. and Rodgers, W.J.
1959: Paleozoic tectonics and sedimentation in the northern half of the west Canadian basin; Journal of the Alberta Society of Petroleum Geologists, v. 7, no. 9, p. 193–216.

Skall, H.
1975: The paleoenvironment of the Pine Point lead-zinc district; Economic Geology, v. 70, p. 22–47.

Smethurst, M.T., Symons, D.T.A., Sangster, D.F., and Lewchuk, M.T.
1999: Paleomagnetic age for Zn-Pb mineralization at Robb Lake, northeastern British Columbia; Bulletin of Canadian Petroleum Geology, v. 47, no. 4, p. 548–555.

Smith, L., Forster, C.B., and Evans, J.P.
1990: Interaction of fault zones, fluid-flow and heat transfer at the basin scale, *in* Hydrogeology of Low Permeability Environments, (ed.) S.P. Neuman and I. Neretnicks; International Association of Hydrogeologists, v. 2, p. 41–67.

Smith, M.T. and Gehrels, G.E.
1992: Structural geology of the Lardeau Group near Trout Lake, British Columbia: implications for the structural evolution of the Kootenay Arc; Canadian Journal of Earth Sciences, v. 29, p. 1305–1319.

Speed, R., Elison, M.W., and Heck, F.R.
1988: Phanerozoic tectonic evolution of the Great Basin; *in* Metamorphism and Crustal Evolution of the Western United States (Rubey Volume VII), (ed.) W.G. Ernst; p. 573–605.

Struik, L.C.
1981: A re-examination of the type area of the Devono-Mississippian Cariboo Orogeny, central British Columbia; Canadian Journal of Earth Sciences, v. 18, p. 1767–1775.

Sverjensky, D.A.
1986: Genesis of Mississippi Valley-type lead-zinc deposits; Annual Review of Earth and Planetary Sciences, v. 14, p. 177–199.

Switzer, S.B., Holland, W.G., Christie, D.S., Graf, G.C., Hedinger, A.S., McAuley, R.J., Wierzbicki, R.A., and Packard, J.J.
1994: Devonian Woodbend–Winterburn strata of the Western Canada Sedimentary Basin; *in* Geological Atlas of the Western Canada Sedimentary Basin, (comp.) G.D. Mossop and I. Shetsen; Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, p. 165–202.

Symons, D.T.A., Lewchuk, M.T., and Sangster, D.F.
1998: Laramide orogenic fluid flow into the Western Canada Sedimentary Basin: Evidence from paleomagnetic dating of the Kicking Horse Mississippi Valley-type ore deposit; Economic Geology, v. 93, p. 68–83.

Symons, D.T.A., Pan, H., Sangster, D.F., and Jowett, E.C.
1993: Paleomagnetism of the Pine Point Zn-Pb deposits; Canadian Journal of Earth Sciences, v. 30, p. 1028–1036.

Taylor, A.H.
1977: Carbonate stratigraphy and petrology: Robb Lake zinc-lead property, northeastern British Columbia; M.Sc. thesis, Carleton University, Ottawa, Ontario.

Taylor, H.P., Jr.
1971: Oxygen isotope evidence for large-scale interaction between meteoric groundwaters and Tertiary granodiorite intrusions, Western Cascade Range, Oregon; Journal of Geophysical Research, v. 76, p. 7855–7874.
1990: Oxygen and hydrogen isotope constraints on the deep circulation of surface waters into zones of hydrothermal metamorphism and melting; *in* The Role of Fluids in Crustal Processes, (ed.) J.D. Bredehoeft and D.L. Norton; p. 72–95, Washington, DC, National Academy Press.

Thompson, R.I.
1986: Geology, Halfway River, British Columbia; Geological Survey of Canada, Map 1634A, scale 1:250,000.
1989: Stratigraphy, tectonic evolution and structural analysis of the Halfway River map area (94B), northern Rocky Mountains, British Columbia; Geological Survey of Canada, Memoir 425, 119 p.

Turner, A. and McPhee, D.
1994: Analysis of Paleozoic core data for the evaluation of potential Pb-Zn mineralization in northeastern Alberta, Canada-Alberta Partnership on Mineral Development, Project M93-04-032, Alberta Research Council, Open File Report 1994-18, 51 p.

Twiss, R.J. and Moores, E.M.
1992: Structural Geology; W.H. Freeman and Co., New York, 532 p.

Weissenberger, J.A.W. and Potma, K.
2001: The Devonian of western Canada – aspects of a petroleum system: Introduction; Bulletin of Canadian Petroleum Geology, v. 49, no. 1, p. 1–6.

Westervelt, T.,
1979: Structural superposition in the Lake O'Hara region, Yoho and Kootenay National Parks, British Columbia, Canada; Ph.D. thesis, Laramie, University of Wyoming, 264 p.

Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V., and Roest, W.R.
1996: Geological Map of Canada / Carte géologique du Canada; Geological Survey of Canada Map 1860A, Scale 1: 5,000,000.

Williamson, J., Dufresne, M.B., and Olson, R.A.
1993: The Southern Alberta rift in southwest Alberta - Program to identify targets for metallic mineral exploration; Alberta Research Council Open File Report 1993-13A, prepared by R.A. Olson Consulting Ltd., as Canada-Alberta MDA Project M92-04-002, 68 p.

Wu, X., Ferguson, I.J., and Jones, A.G.
2002: Magnetotelluric response and geo-electric structure of the Great Slave Lake shear zone; Earth and Planetary Science Letters, v. 196, p. 35–50.