Introduction

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Abstract: This volume reports on a Targeted Geoscience Initiative project investigating the potential for Mississippi Valley-type mineralization in northern Alberta and the Great Slave Plain of southern Northwest Territories.

The primary project objective was to delineate and describe the origin, distribution, and potential for carbonate-hosted lead-zinc deposits in the region and develop an understanding of the relationships of fluid flow and ore deposition to a regional framework of stratigraphy, structure, and diagenesis.

Papers in this volume report on regional and local structural characteristics and control on ore mineralization, investigate dolomite-type distribution, microthermometry and isotope and geochemical properties of dolostone, discuss isotopic variations in mineralized samples throughout the area, and examine the thermal history and hydrodynamics of the area. Good potential exists for Mississippi Valley-type mineralization in the Targeted Geoscience Initiative project area.

Résumé : Le présent volume est un compte rendu d'un projet de l'Initiative géoscientifique ciblée portant sur la présence éventuelle de minéralisation de type Mississippi-Valley dans le nord de l'Alberta et dans la plaine du Grand lac des Esclaves dans le sud des Territoires du Nord-Ouest.

L'objectif principal du projet était de délimiter et de décrire l'origine, la répartition et la présence éventuelle dans la région de gisements de plomb-zinc encaissés dans des roches carbonatées et d'établir les relations entre l'écoulement des fluides et la mise en place du minerai, d'une part, et le contexte stratigraphique, structural et diagénétique régional, d'autre part.

Les articles inclus dans ce volume portent sur les caractéristiques structurales de la minéralisation et le contrôle structural exercé sur celle-ci à l'échelle régionale et locale, la répartition des types de dolomite, la microthermométrie et les propriétés isotopiques et géochimiques de la dolomie, les variations des isotopes dans des échantillons minéralisés provenant de partout dans la région, et l'histoire thermique et les conditions hydrodynamiques de la région. Il existe un bon potentiel pour une minéralisation de type Mississippi-Valley dans la région visée par le projet de l'Initiative géoscientifique ciblée.

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INTRODUCTION

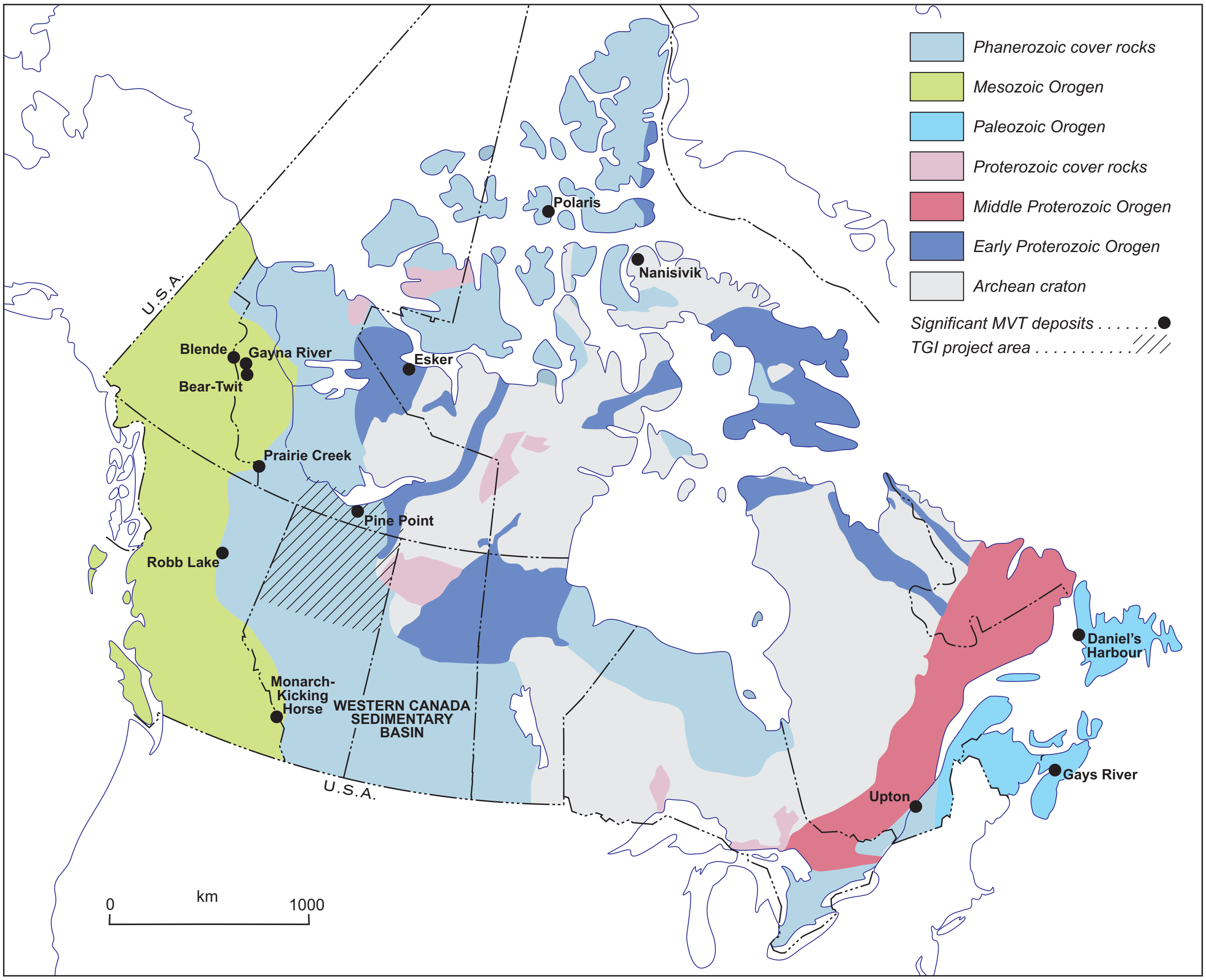
Mississippi Valley-type (MVT) lead-zinc deposits are so-named because of their initial recognition as a unique class of deposit after the discovery and study of a group of lead-zinc orebodies hosted in carbonate rocks in the drainage basin of the Mississippi River in central United States. The deposit-types also occur in Canada, Europe, Australia, China, Peru, Morocco, and South Africa, although major districts are found only in the United States, Canada, Poland, and Australia. Notable Canadian examples include Pine Point, Polaris, Nanisivik, Daniel's Harbour, Prairie Creek, Monarch-Kicking Horse, Gays River, Upton, Robb Lake, Gayna River, Blende, Bear-Twit, and Esker (Fig. 1).

MVT deposits account for about 35 per cent of the world's lead and zinc resource. They are generally small; most are less than two million tonnes (total reserves) and zinc-dominant. Grades seldom exceed 10 per cent combined lead and zinc (Leach and Sangster, 1993). In Canada, most MVT mineral production (except for Monarch-Kicking Horse) occurred between 1964 and 2002. During this time, about 30 per cent of Canada's annual lead and zinc production was derived from MVT deposits (Sangster, 1996). At the end of 2002, all MVT mineral production in Canada ceased with the closure of all mines. Tonnages and grades of produced resources as well as estimated remaining resources for the 13 MVT districts in Canada are presented in Figures 1 and 2. Geological resource estimates range from 850 000 to 83 million tonnes (produced and remaining resources). The total established resource in the Pine Point district indicates it encompasses the largest deposit in Canada. Grades in Canadian MVT deposits range from 3 to near 23 per cent combined lead and zinc (Fig. 1, 2), and they are all zinc-rich relative to lead. The Polaris and Prairie Creek deposits are anomalously large and rich in combined lead and zinc (17.1 and 22.6%, respectively).

Mississippi Valley-type lead-zinc deposits are epigenetic stratabound carbonate-hosted ores composed predominantly of sphalerite, galena, and iron-sulphides, specifically pyrite and/or marcasite. These deposits occur principally in dolostone, rarely in limestone and sandstone, as open-space fillings in collapse breccias or less commonly as replacements in high-grade zones. Mississippi Valley-type ores originate from basinal brines at temperatures of 75–200°C and are typically deposited in carbonate platform settings in relatively undeformed epicratonic sedimentary basins or in foreland thrust belts (Leach and Sangster, 1993). Rarely, the deposits are found in continental rift basins; these particular ore accumulations constitute a variant of MVT deposits in that they are fracture-controlled and contain abundant fluorite and barite (Leach and Sangster, 1993). The deposits or orebodies occur in clusters and these areas of concentrated occurrence form MVT districts. The districts can contain up to 300 orebodies and cover hundreds or thousands of square kilometres. Characteristically, deposits within districts exhibit remarkable similarities in mineral assemblage, isotopic composition, texture and ore-control (Leach and Sangster, 1993). Host rocks for MVT deposits range in age from Proterozoic to Cretaceous, but most known deposits occur within Cambro-Ordovician to Triassic strata (Leach and Sangster, 1993).

Noteworthy features of MVT deposits are as follows (Anderson and Macqueen, 1982; Leach and Sangster, 1993; Sangster, 1996):

1) they commonly occur at shallow depths on flanks of basins or on arches between basins;
2) they are not associated with igneous activity;
3) they are stratabound on a regional scale, but discordant on the deposit-scale as a result of breccia systems crossing formation boundaries;
4) the deposits form districts that are localized by faults, breccias, shale edges, basement highs and facies tracts, which all may permit upward migration of ore fluids;
5) deposits are commonly localized by unconformities within platform sequences;
6) ore deposition temperatures are relatively low (75–200°C), but are typically higher than temperatures attributable to local basement-controlled thermal gradients;
7) deposits are mineralogically simple: the dominant minerals are sphalerite, galena, pyrite, marcasite, dolomite, calcite and sometimes quartz;
8) the associated alteration processes generally include dolomitization, brecciation, and host rock dissolution, and sometimes silicification and crystallization of feldspar and clay minerals;
9) there is always evidence of host rock dissolution expressed by slumping, collapse, brecciation, and tilted bedding;
10) the ore fluids are dense basinal saline brines typically containing 10–30 weight per cent salts as determined from fluid inclusions in the constituent minerals, and predominantly contain sodium and calcium chlorides;
11) isotopic compositions of lead and sulphur indicate crustal sources for metals and reduced sulphur;
12) the sulphide mineral textures are extremely varied, ranging from coarse-crystalline to fine-grained, massive to disseminated, or laminated aggregates of colloform sphalerite intergrown with galena;
13) there is commonly a strong regional fault control system with respect to localization and emplacement of deposits;
14) the hydrological system may be controlled by an overlying regional seal such as shale above the host carbonate;



CANADIAN MVT DEPOSITS

DEPOSIT	PRODUCTION AND REMAINING RESOURCE (t)	GRADE Zn (%)	GRADE Pb (%)
Pine Point (incl. GSR)	83 395 479	6.9	3.1
Polaris	26 000 000	13.5	3.6
Nanisivik	18 696 383	8.9	0.7
Gays River (incl. Jubilee)	6 691 531	5.2	2.3
Daniel's Harbour	6 531 730	8.0	
Monarch-Kicking Horse	853 393	8.6	5.6
Robb Lake	7 100 000	4.7	1.5
Prairie Creek	11 900 000	12.5	10.1
Bear-Twit	8 163 720	5.4	2.6
Blende (incl. Goz Creek)	27 257 748	4.0	2.0
Gayna River	50 000 000	4.7	0.3
Upton	1 309 530	2.0	0.6
Esker	1 000 000	7.1	

Figure 1. Location of significant Canadian MVT deposits with tonnages and grade. *Adapted from* Sangster (1996). TGI project area is depicted.

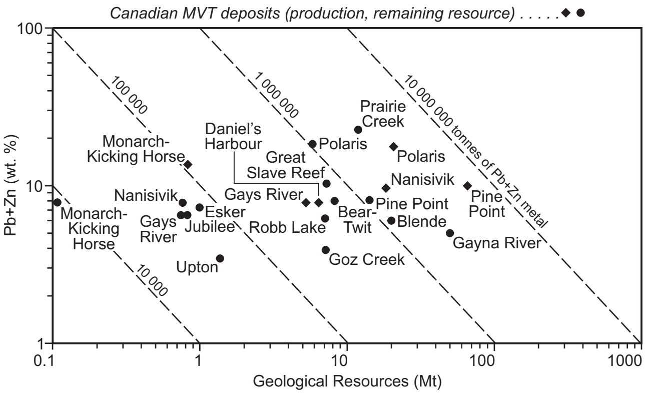


Figure 2. Tonnage-grade plot of significant Canadian MVT deposits. Produced resource and estimated remaining reserves are shown.

15) organic material in the form of kerogen or bitumen in the host rocks and petroleum in fluid inclusions are common in many MVT districts; and,

16) open space, developed by a number of processes, seems to be a prime prerequisite for the development of an ore deposit.

In 2000, an innovative scientific initiative was announced by the federal government to provide integrated geoscience knowledge of areas of elevated mineral potential in order to stimulate private sector mineral exploration. This Targeted Geoscience Initiative (TGI) program was delivered in partnership with provincial and territorial geological surveys. Industry and universities were important participants as well. One such project under the umbrella of the TGI program was a study evaluating the potential for MVT mineralization in northern Alberta and southern Northwest Territories (NWT). The project area boundaries were 56.5 to 62° latitude and 110 to 120° longitude (see Fig. 1 for location of project area). The primary objective of this project, led by the Geological Survey of Canada (Natural Resources Canada) in joint partnership with the Alberta Geological Survey and the C.S. Lord Northern Geoscience Centre, was to delineate and describe the origin, distribution and potential for carbonate-hosted lead-zinc deposits and showings in the region and to develop an understanding of the relationships of fluid flow and ore deposition to a regional framework of stratigraphy, structure, and diagenesis. By characterizing the geochemistry of significant occurrences and relating the mineralization to regional stratigraphy and structure, a better understanding of the petrogenesis of MVT occurrences can be attained. The integrated geological investigation undertaken in this project examined the relationship of stratabound MVT mineralization to the regional stratigraphic framework and evaluated the structural features critical for fluid migration and ore deposition.

The area of study encompasses the world-class Pine Point mine site, the largest MVT deposit in Canada, and the surrounding Pine Point MVT district near the south shore of Great Slave Lake (Fig. 3). There are some 93 defined orebodies within the Pine Point property; fifty of these orebodies have been mined. The Pine Point district also includes seven drill-defined orebodies located within the Great Slave Reef property due west of the Pine Point property (Fig. 3).

Limited mineral exploration for MVT deposits has taken place outside the two principal mining properties. Therefore, a need to pursue a detailed geological survey of the region was deemed essential to gain a better understanding of the regional mineralizing system. An initial phase in this project examined the distribution of lead-zinc deposits and showings in the project area. This lead and zinc deposit, showing and anomaly data, specifically compiled to display relevant information commonly used to describe and characterize MVT deposits, is presented as a Geographic Information System map-based spatial database (Hannigan, 2005a). Once these anomalies and showings were affiliated with regional stratigraphic units and structures, specific strategic areas were identified where sample collection and analysis were then executed. A compilation of all analytical results with respect to both their geographic and stratal location is presented in another Geographic Information System map-based spatial database (Hannigan, 2005b). Samples of interest were examined initially by means of petrography in order to determine mineral phases and, if possible, paragenetic sequences involved in ore formation and deposition were established. Based on these results, laboratory analyses were performed to determine the geochemical signature of each sample.

GENETIC MODELS FOR MVT DEPOSITS

The characteristics of Mississippi Valley-type deposits support the sedimentary-diagenetic origin model of Jackson and Beales (1967), who used the Pine Point deposit as their principal example. Their model is based on the theory that basinal-derived fluids or brines acquire heat, metals and other solutes during their migration and deposit sulphides in the host carbonate rocks when conditions are favourable for precipitation. Fluid drive was generated by sediment compaction and movement of the fluids was gained by porosity variations (Jackson and Beales, 1967). This movement of warm brine from well-compacted sediments into strata of higher porosity is very similar to the process of migration of petroleum from its source beds along permeable conduits or strata to various trap configurations. Jackson and Beales' (1967) model speculated that fluids acquire their metals through brine leaching, and transport them as chloride or organic complexes, precipitation occurring when hydrogen sulphide is encountered. Nearby evaporite deposits (Muskeg Formation at Pine Point) filter hydrogen sulphide into the migration route and biogenic or thermogenic sulphate reduction then takes place at the site of mineral precipitation, possibly in the presence of petroleum. Fluid inclusions residing in sphalerite, carbonates, and

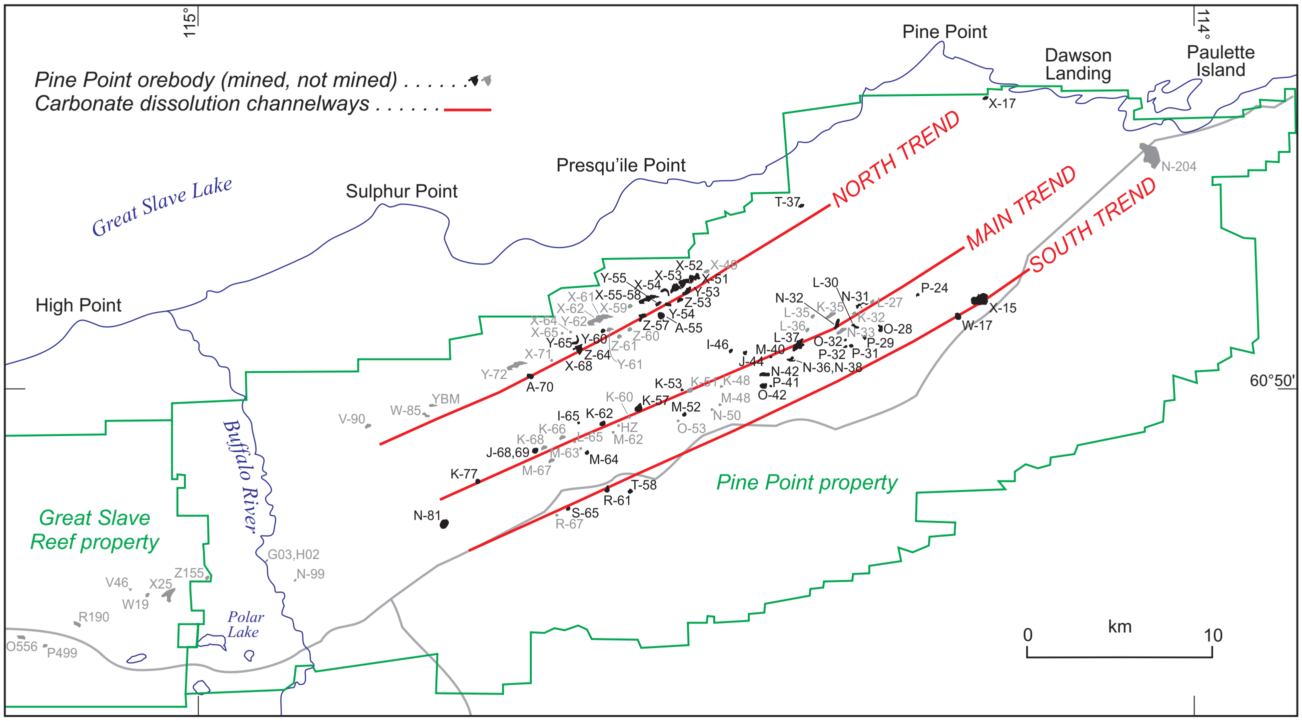


Figure 3. Pine Point mining camp with orebody locations in the Pine Point and Great Slave Reef properties. *Adapted from* Turner (2006). Major mineralized trends are indicated.

fluorite in MVT deposits are remarkably similar from deposit to deposit and are equivalent to brines found in petroleum wells. They generally have densities greater than one, exhibit salinities usually greater than 15 weight per cent salts, contain concentrated solutions of Na and Ca chlorides, and carry organic matter in the form of methane or oil-like droplets (Anderson and Macqueen, 1982).

Cathles and Smith (1983) and Bethke (1985) demonstrated that the steady-state compaction of basinal sediments invoked in Jackson and Beales' (1967) basinal compaction model does not adequately provide sufficient rates of discharge to produce the heat necessary for the elevated temperatures recorded in fluid inclusions of the host rocks in the ore districts. One possible mechanism for overcoming this concern is a process that releases fluids by episodic means in overpressured zones of compacting sediments (Cathles and Smith, 1983). Their proposed model does require, however, rapid sedimentation and swift transport of fluids from the basin through the aquifers, thereby producing thermal anomalies in the ore districts.

Another mechanism of formation fluid-flow that may be applicable to regional MVT mineralization in certain basins is the conceptual, topographically driven fluid-flow model proposed by Garven and Freeze (1984). Their model proposes that groundwater, recharged in the uplifted orogen on the flank of the basin, migrates through shale units into the underlying carbonate unit by cross-formational fluid flow (Fig. 4). As the fluid continues to migrate updip through the deep portion of the basin along the carbonate aquifer, it acquires heat and dissolved components. The fluids or brines are eventually discharged by means of an immense hydrothermal system on the basin's cratonic flank. Metals that are leached from source units in the shale spread throughout the basin, but are concentrated at the discharge end where conditions may be favourable for precipitation of ore. Garven (1985) proposed that fluid flow migrated along the Presqu'ile barrier in a northeast direction from the recharge area in the Cordillera on the western margin of the basin, through an aquifer updip into the shallow discharge area near the outcrop or shallow subcropping margin of the carbonate aquifer on the northeast side of the basin (Fig. 4). This model indicates that fluid circulation was initiated as a result of the Cretaceous–Tertiary Laramide Orogen and mineralization took place during or in the immediate aftermath of that tectonic episode. Later work by Nesbitt and Muehlenbachs (1994, 1995), Root (2001) and Nelson et al. (2002) speculated that mineralization and dolomitization in the WCSB were likely associated with the Late Devonian–Early Mississippian Antler Orogeny.

The correlation of regional brine migration with tectonic compressional deformation in the topographically driven fluid-flow model does not adequately manifest itself with respect to MVT mineralization in extensional basins such as Nanisivik. Olson (1984) proposed an alternative fluid flow system where ore fluids migrated by means of combined thermal and density convection cells ultimately driven by heat flow.

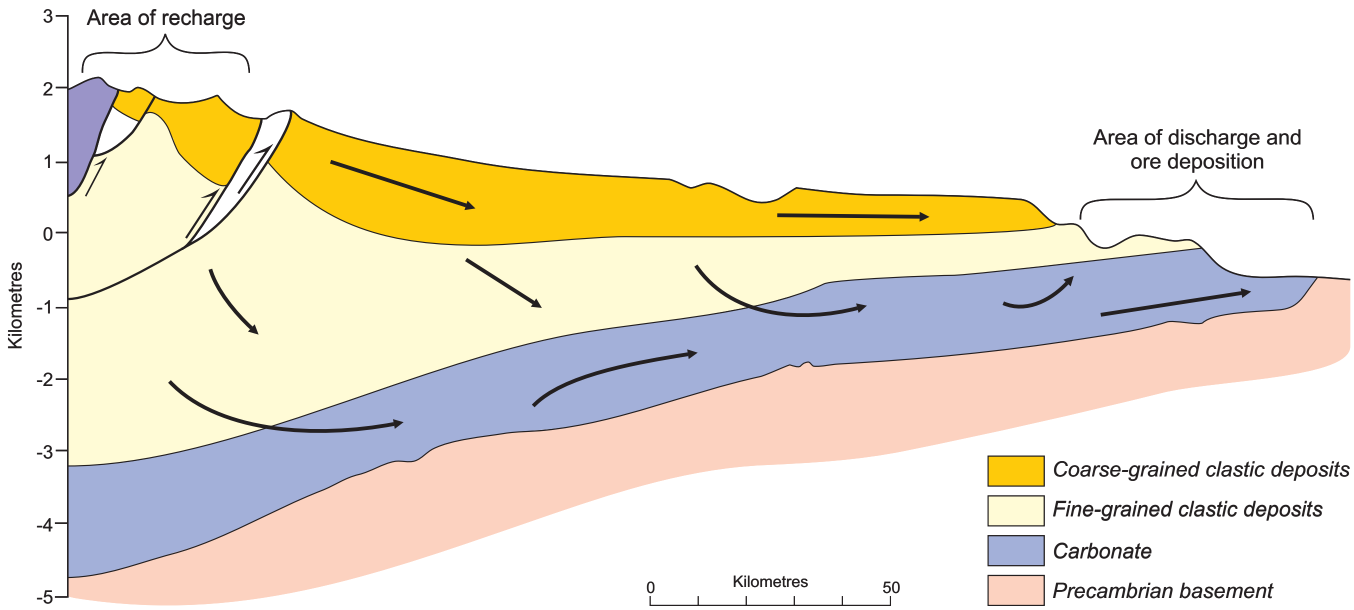


Figure 4. Topographically induced fluid-flow model by Garven and Freeze (1984).

The fluid-flow models cited above provide an appropriate mechanism for the delivery of metal-bearing fluids to the site of deposition, but there remains a need to define the chemical processes required to localize the deposition of sulphides. Possible models are the reduced sulphur model, the sulphate reduction model, and various fluid mixing models (Leach and Sangster, 1993).

The reduced sulphur model assumes that metals and reduced sulphur are transported together in the same fluid. Ore deposition is achieved by means of cooling, dilution of the brine by meteoric waters or less saline groundwater, or by changes in pH (Anderson and Macqueen, 1982; Leach and Sangster, 1993). Sverjensky (1984) indicated pH values of 4.5 or lower are required in order for reduced sulphur and metals to be transported in the same fluid. These acidic conditions are incompatible if the fluid is transported through a carbonate aquifer as proposed in the topographic recharge fluid-flow model cited above. Anderson and Macqueen (1982) indicate that metal solubilities are too low in solutions containing reduced sulphur for metal transport to occur. Evidence consistent with the reduced sulphur model is the presence, in some instances, of uniform colour-banding in sphalerites on a district-wide scale (McLimans et al., 1980). This feature indicates that local sources of sulphur external to the fluid are likely not present since individual sources would not produce such a consistent feature (McLimans et al., 1980). Similarly, the uniform sulphur isotope composition of ore sometimes observed in MVT districts is consistent with a single metal/sulphur-bearing fluid (Leach and Sangster, 1993). The consistent sulphur isotope compositions, however, may also indicate the presence of well-homogenized mineralizing fluids.

The sulphate reduction model is based on the premise that the reduced sulphur concentration increases at the deposition site as a result of sulphate reduction processes (Leach and Sangster, 1993). One mechanism proposed for this model involves bringing both metal and sulphate to the precipitation site, where methane or other organic matter are also present. The organic matter reduces the sulphate to precipitate the sulphides. The spatial association of evaporite deposits and bitumen in some MVT deposits (such as Pine Point; Powell and Macqueen, 1984) indicates that biogenic or thermogenic sulphate reduction are feasible mechanisms (Machel, 1989).

Mixing models imply that sulphide is supplied at the site of deposition where the metal-rich brine is mixed with a H_2S-rich fluid (Anderson and Macqueen, 1982; Leach and Sangster, 1993). The mixing of fluids will produce high degrees of supersaturation, large chemical and/or concentration gradients and relatively rapid rates of precipitation of sulphides. These chemical processes result in precipitation of fine-grained, dendritic, and colloform ores, all of which are found at Pine Point. Fluid mixing can also yield large crystals if the chemical gradients are small and mixing is very slow, as for example, by means of diffusion of H_2S through the wall-rock (Leach and Sangster, 1993).

EXPLORATION FOR MVT DEPOSITS

The diagnostic and permissive geological features and models for mineralization discussed above provide a set of general exploration concepts for application in discovering new MVT deposits in the Western Canada Sedimentary Basin (WCSB). Strata of exploration interest are carbonate successions developed on the flanks of large and deep sedimentary basins. Unconformities and paleokarsts are important features to look for in these favourable strata. Arching or flexing of the underlying basement produce highs on the basement surface. These highs may define zones of increased fluid movement or heat flow. Basement faults may provide escape routes for metal-bearing fluids and conduits for increased heat flow. Another favourable indicator of MVT mineral potential is the presence of dolostone sequences associated with evaporitic strata and organic matter. Areas of discharge of regional brines migrating from foreland highs to platform-carbonate lows are potential strategic locations. Carbonate fronts dividing basinal shale and platform carbonate strata are promising areas. Other associated diagnostic or permissive features representative of potential MVT mineralization are highly permeable zones such as reefs or abundant open-fractures or faults, white sparry dolomite associated with vuggy dolostone, and collapse breccias. All these favourable indicators are present at Pine Point and these features should be considered in future exploration strategies beyond the Pine Point district in Western Canada.

HISTORY OF EXPLORATION FOR LEAD AND ZINC IN THE TGI PROJECT AREA

Great Slave Plain, NWT

Surface showings of lead and zinc mineralization near Pine Point on the southern shore of Great Slave Lake were first brought to the attention of Klondike-bound prospectors by local Indians in 1898. Bell (1902) visited the showings in 1899 and reported the mineralization as occurring in Devonian limestone adjacent to numerous sinkholes. Several assays from this showing did not reveal anomalous silver content and the lack of precious metals in this very remote area precluded significant industrial work taking place for the next few decades. In the early part of the twentieth century, various field parties of the Geological Survey of Canada visited the lead-zinc exposures (Camsell, 1915; Cameron, 1917, 1918). Cameron (1917) identified the mineralized host rock as coarse-crystalline vuggy dolomite with cavities occupied by curved rhombohedral dolomite crystals ('saddle dolomite'). He also found similar coarse-crystalline vuggy dolomite at Windy Point on the southwest shore of Great Slave Lake and correlated these rocks with host rocks at Pine Point (see Turner, 2006, his Fig. 2 and 6 for location of Windy Point). Scattered crystals of galena in a crosscutting calcite vein and active tar springs with bitumen were noted at Windy Point.

Initial concerted exploration at Pine Point began in 1929 when the Consolidated Mining and Smelting Company merged with the Atlas Exploration Company. Test-pitting, drilling, and exploratory shaft-sinking commenced on the mining claims encompassing the lead-zinc showings (Bell, 1929). At this time, five orebodies of good grades containing fine-grained cubical galena intergrown with botryoidal sphalerite were discovered, and two mineralized trends were identified. The lead-zinc ore was drill-indicated to be near 500 000 tons (0.45 million tonnes). Numerous similarities between the Pine Point occurrence and MVT deposits in the Tri-State region of the Mississippi Valley were observed at this time (Bell, 1929).

In 1947, Consolidated Mining and Smelting Company (Cominco Ltd.) staked a large concession in the Pine Point area surrounding all known mineralization. The concession was acquired in order to test new geological concepts with respect to the localization of orebodies; i.e. significant lead and zinc occurrences have a specific stratabound control similar to classic Mississippi Valley-type deposits and a structural control as speculated by the projection of major Precambrian faults from the cratonic Shield southwestward beneath the property. Between 1948 and 1963, extensive exploration work was undertaken by Cominco within the concession. This work delineated 8.8 million tons (8.0 million tonnes) of ore averaging 2.6 per cent lead and 5.9 per cent zinc in several orebodies. The induced polarization geophysical exploration method was tested at Pine Point in 1963 and successfully led to the discovery of numerous additional orebodies, adding greatly to proved mineral reserves in the area (Lajoie and Klein, 1979). Production at Pine Point began in 1964 and continued until 1988. Ninety-three orebodies have been identified on the property (Fig. 3). Total production over the life of the mine has been 70 880 230 tons (64 million tonnes) of ore grading 3.0 per cent lead and 7.0 per cent zinc (Rhodes et al., 1984; Brophy, 1987; Ellis and Hearn, 1990; Ellis, 1995). Fifty orebodies were mined; all except two by open-pit methods. Estimated resource remaining in the Pine Point area may be 12.0 million tons at 6.3 per cent zinc and 2.7 per cent lead at a 2 per cent Pb+Zn cutoff grade (calculated by author from World Minerals Geoscience Database).

During mining and production at Pine Point, additional exploration took place on adjacent and nearby properties. New orebodies were discovered on the Pyramid claims (X-15 and W-17 in 1965; Thorpe, 1966); Buffalo River Exploration property (A-55 in 1966; Thorpe, 1972); Coronet claims (R-61 and S-65 in 1966; Thorpe, 1972) and the Yellowknife Base Metals property (YBM orebody in 1966; Thorpe, 1972). Pine Point Mines Ltd., a subsidiary of Cominco formed to finance Pine Point mine production, purchased these properties and added them to their reserve and production inventory (Gibbins et al., 1977).

Lead and zinc exploration also took place westward along the Presqu'ile barrier outside of the Pine Point property. Immediately to the west of the Pine Point property on a group of claims owned by Western Mines (Westmin), the Great Slave Reef (GSR) project was undertaken (Fig. 3). Although the area had been previously staked in 1965 as a result of the start-up of production at Pine Point, little work was done on the property because favourable stratigraphic units were too deep for effective conventional induced-polarization geophysical exploration. Western Mines acquired the property in 1975 and commenced an extensive drilling program. The drill program was based on the premise that the 'Main Hinge Zone', along which many of the ore deposits at Pine Point are located, extends westward into the GSR property (Fig. 3). Drilling completed between 1975 and 1981 outlined seven additional lead-zinc orebodies on the GSR property (Fig. 3). Estimated resource potential of the seven orebodies on the property is 8 000 000 tons (7.25 million tonnes) at a grade of 10.3 per cent combined lead and zinc (2% Pb+Zn cut-off) (Beales et al., 2002). No production of these orebodies has taken place to date, principally because of their greater depths and extensive groundwater discharge in this area.

Presqu'ile-type dolomite also outcrops on the northwest shore of Great Slave Lake at Windy Point and northward along the eastern shore of Prairie Lake (Norris, 1965); consequently, much lead-zinc mineral exploration has taken place in this area. Williams (1977) described the reef-like mass at Windy Point as identical lithologically to the ore-bearing reef complex at Pine Point, and correlation between the two has been proposed. In 1955, more than two thousand mining claims were staked in this area by Windy Point Mining Company (McGlynn, 1971). These claims were geochemically prospected, mapped, and drilled in 1956. Lead-zinc mineralization found in these holes proved to be uneconomic and no zones of significant size were found. Between 1965 and 1980, geophysical work and diamond-drilling continued in areas of interest throughout the Windy Point property, but only minor amounts of mineralization were encountered. There does not seem to be substantial evidence of major faulting in the region although several minor faults with small displacements cutting the Paleozoic dolostone have been observed (Gibbins, 1984). Most sulphides occur in coarse-replacement dolomite (Presqu'ile) in the reefal complex. Galena and sphalerite occur as isolated crystals, sparse irregular patches, or veinlets in brecciated fine-grained dolomite (Gibbins, 1984). The mineralization is commonly associated with oil staining and coarse vuggy dolospar.

North of Windy Point, another property called Qito was explored by Cominco Ltd. (*see* Turner, 2006, his Fig. 2 and 6 for location). Zinc and lead soil anomalies were obtained and tested by means of geophysical surveys and drilling between 1976 and 1980. Trace to minor amounts of galena, and sphalerite clots and disseminations were found within karsted dolomite in these drillholes.

Adjacent to the southern shore of Great Slave Lake, the continuation of the favourable diagenetic Presqu'ile dolomite facies was confirmed by extensive and wide-spaced drilling on the Hay West property owned and operated by Cominco Ltd. (*see* Turner, 2006, his Fig. 2 and 5 for property and drillhole locations). This property bounds the Great Slave Reef project area on its western boundary and straddles the Hay River. The property was staked in 1978 and worked until 1981. Forty-two drillholes totalling about 19 500 m were completed in the region. Outcrop on the property is very sparse, mostly confined to the Hay River Escarpment and Hay River gorge. Therefore, much of the geological information obtained in the area was acquired by drilling, down-hole geophysical logging, and seismic geophysical surveys. The Hay West property straddles the westward continuation of the Presqu'ile barrier complex. Recrystallization of Sulphur Point and upper Pine Point carbonate strata to coarse-crystalline dolomite was confirmed in these holes and appears to follow northeasterly trends subparallel to the Great Slave Shear Zone (Gibbins, 1984). The reconnaissance diamond-drilling program was successful in defining the approximate boundaries of the Muskeg evaporite facies, Presqu'ile barrier reef complex and the boundary of the carbonate front toward the western edge of the property (Gibbins, 1984). Several holes encountered hydrogen sulphide gas, and a blowout of crude oil, methane and hydrogen sulfide occurred in one of these holes. Three holes encountered thick sequences of collapse breccia and minor quantities of lead and zinc. Seismic surveys were successful in identifying collapse structures on certain horizons of interest. One of these seismically identified collapsed structures was confirmed by drilling (Gibbins, 1984).

Another mineral property (Tathlina) was acquired by Gulf Minerals Canada in 1978 directly west of the Hay West property (*see* Turner, 2006, his Fig. 5 for property location). An abandoned oil well on this property (NWT Desmarais Lake No. 1 C-19) was reported to have encountered minor lead and zinc mineralization. The drilling undertaken on this property confirmed the presence of Presqu'ile dolomite and lead-zinc mineralization. Electromagnetic geophysical work, drilling, and down-hole geophysical logging outlined an embayment on the carbonate-shale facies front (Gibbins, 1984). These claims occur on the northern flank of the Tathlina Uplift and south of the northeasterly trending Tathlina Fault. In this area, the entire Pine Point Group grades laterally to the west into shale of the Horn River Formation. Macqueen and Ghent (1975) discovered significant lead and zinc in shale samples from the Horn River Formation and the bituminous member of the Pine Point Group. They speculated that these shales might be a source of lead-zinc mineralization in the region. Visible mineralization was encountered in three of the 11 drillholes completed by Gulf Minerals. Rock geochemical spot anomalies were encountered in separate drillhole but these were not related to any visible sulphides (Gibbins, 1984).

Northern Alberta

Exploration for lead and zinc in northern Alberta was much less intensive and very sporadic chiefly because Wood Buffalo National Park occupies a large proportion of the area of prime MVT exploration potential (i.e. areas where Middle Devonian carbonate strata are at or near surface, making mining economic). However, one must consider northern Alberta as prospective for MVT carbonate-hosted deposits because rocks of similar stratigraphy and lithology to strata containing substantial MVT mineralization at Pine Point as well as Robb Lake in the Cordillera of northeastern British Columbia, are present in the area. In the late 1950s, accounts of hand specimens with lead and zinc mineralization were reported in Wood Buffalo National Park (Godfrey, 1985) but no follow-up work was done and the locations of these reported mineralized samples are not published. Carrigy (1959) reported a single occurrence of galena filling a small, calcite-rimmed cavity associated with Methy dolomite (Keg River-equivalent) at Whitemud Falls on Clearwater River east of Fort McMurray near the Alberta–Saskatchewan boundary.

Devonian carbonate rocks hosting lead and zinc mineralization in the subsurface of northern Alberta have been encountered in several hydrocarbon test wells. Dubord (1987) and Turner and McPhee (1994) listed and studied several of these wells and confirmed lead and zinc mineralization in a few locations. At least 11 wells within the project area in Alberta have visible sphalerite and/or galena mineralization in Devonian carbonate rocks (Hannigan, 2005a). Several additional wells in the TGI project area have significant anomalous lead and zinc geochemical values in carbonate in the subsurface (Hannigan, 2005a). Numerous hydrocarbon test wells to the south of the project area have visible lead and zinc mineralization in carbonate strata (Hannigan, 2005 a; *see* Panǎ, 2006, his Fig. 21 and Table 3 for listing of subsurface occurrences in all of Alberta). There are also a few subsurface occurrences of lead and zinc in the Peace River area of Alberta that classify as stratiform clastic sediment-hosted type deposits, as they occur in clastic strata ranging from Mississippian to Cretaceous in age.

The most significant Pb-Zn carbonate-hosted occurrence in Alberta is found in the Chevron Lutose well (16-34-118-21W5) in faulted and dolomitized Keg River Formation at the 1265.4 to 1304.9 m depth interval (*see* Panǎ, 2006, his Fig. 21 for well location). Interestingly, this well is located directly above the subsurface extension of the Great Slave Shear Zone that is also proximal to the Pine Point deposit in southern NWT. Aeromagnetic mapping confirms the extension of this prominent basement structure into northwestern Alberta (Morrow et al., 2006). The reported concentration of metal in this interval was 3.1 per cent Zn and 0.05 per cent Pb over 20.7 m (Turner and McPhee, 1994). The mineralized section contains about 3 to 5 per cent of honey-coloured disseminated sphalerite. The sphalerite also occurs in fracture-fills of the brecciated host. The breccia contains 10 to 20 per cent disseminated pyrite and sphalerite. No galena was detected visually. The richest interval in the core returned a value of more than 10 per cent Zn, which exceeded the detection limit of the Inductively Coupled Mass Spectrometer instrument. This interval was not re-analyzed, however, by the fire assay method.

Although limited mineral exploration by industry in northern Alberta indicates lead and/or zinc mineralization is widely scattered and uneconomic, there are numerous significant favourable features in the carbonate strata. Subsurface core studies of Keg River carbonate strata in the Rainbow oil and gas field in northwestern Alberta proximal to the Great Slave Shear Zone show that dolomitization, brecciation, and the presence of cements containing fluorite, chalcopyrite, sphalerite, and/or galena are indicative of hydrothermal activity in the immediate region (Aulstead and Spencer, 1985; Aulstead et al., 1988; Muir and Dravis, 1991, 1992). Fluid inclusion data and the occurrence of saddle dolomite indicate thermal anomalies with respect to the host rocks are present at Rainbow field. Hydrothermal activity is surmised at Rainbow because of the association of higher-temperature saddle dolomite with epigenetic lead and zinc mineralization, hydrocarbons, and sulphate-rich carbonate proximal to major basement faults. Packard et al. (1990) and Duggan et al. (2001) also discussed these same hydrothermal characteristics in Wabamun carbonate strata in the Peace River Arch area and in the Swan Hills Formation in the Simonette oilfield, respectively. In northeastern Alberta, adjacent and south of Wood Buffalo National Park, favourable geological MVT features are present. Dubord (1987) interpreted several faults and a large area of interstratal karst near the margin of the cratonic platform adjacent to the Canadian Shield. Park and Jones (1987) reported dolomitization and brecciation in Devonian carbonate in northern Wood Buffalo National Park. Several basement structures have been interpreted from aeromagnetic surveys near Fort McMurray in northeastern Alberta, which may provide necessary conduits for the introduction of metal-bearing fluids (Garland and Bower, 1959). Hitchon (1993) discovered significant concentrations of Zn and Pb in modern saline formation waters emanating from the Middle Devonian Keg River Formation in northern Alberta suggesting a possible ore-source in the area that has not been discovered. However, Hitchon (1993) did not believe these modern metal-rich formation waters were similar to fluids responsible for lead and zinc mineralization at Pine Point because of the major difference in the lead-zinc ratio (orebodies at Pine Point have Pb:Zn ratios ranging from 1:1.7 to 1:2.6 whereas Devonian formation waters in the Keg River Formation in northern Alberta range from 5.5:1 to 0.6:1; Hitchon, 1993). The age of the Pine Point deposits derived from Pb isotope and Rb-Sr dating, specifically 290 Ma from Pb isotopes (Cumming et al., 1990) and 361±13 Ma from the Rb-Sr dating technique (Nakai et al., 1993), indicates that metal-bearing fluids responsible for Pine Point ore deposition are much older and likely different than modern formation waters.

Numerous lead-zinc occurrences have also been discovered in carbonate outcrops on the western flank of the WCSB in the Cordillera. Such occurrences include Monarch-Kicking Horse in Yoho National Park in British Columbia, Hawk Creek in Kootenay National Park in B.C., Oldman in southwestern Alberta, Eldon, Baker Creek and Spray River in Banff National Park, Robb Lake in northeastern British Columbia, and Prairie Creek in southwestern NWT (Fig. 1;

see Pană, 2006, and Rice and Lonnee, 2006 for detailed descriptions with references for many of these Cordilleran lead and zinc occurrences).

GEOLOGY OF PROJECT AREA

Previous work at Pine Point

Numerous geological studies and papers have been completed on the Pine Point deposit discussing its characteristics as well as proposing hypotheses for its formation and timing of mineralization. Campbell (1957, 1966, 1967) studied the stratigraphy and structure and suggested that major Precambrian faults in the vicinity of Pine Point provided the loci for the development of the barrier reef, the shattering and recrystallization of the reef, and the deposition of metals in orebodies. He also pointed out that mineralization occurs predominantly at certain stratigraphic horizons within the coarsely recrystallized dolomite barrier reef. Beales and Jackson (1966) and Jackson and Beales (1967) developed their compaction-driven fluid-flow model as a result of studying the Pine Point deposit. Their model, discussed above under mineralization models, has been supported by more recent studies. Macqueen and Ghent (1975) found anomalous lead and zinc in Devonian shale (Horn River Formation) in the Mackenzie shale basin to the north of the Presqu'ile barrier complex. These metalliferous strata directly overlie the Lonely Bay Formation, a Middle Devonian carbonate succession that may have acted as the permeable conduit through which metal-rich fluids were transported into the barrier. Medford et al. (1983) completed strontium isotopic analyses on dolomite, and fluid inclusion microthermometry and analyses in dolomite and sulphides at Pine Point, and determined that $^{87}Sr/^{86}Sr$ ratios in gangue minerals were elevated compared to Devonian seawater. These results imply that the metal-bearing fluids were derived from sedimentary rocks characterized by higher Rb/Sr ratios, such as shale. Smith et al. (1983) studied geophysical borehole logs across a widespread area of the Mackenzie Basin in order to evaluate the shale compaction history of the basin. Evidence from sonic logs indicates that a late-stage shale compaction dewatering episode directed pore fluids downward through the limestone conduit, expelling the metal-bearing solutions into the permeable reef complex. They also observed a pattern of shale compaction suggestive of channelled fluid flow along linear conduits toward the mineralized strata, thereby rejecting the hypothesis of a broad front of fluid movement. The documented temperatures of mineral precipitation (60 to 175°C, Roedder, 1976) can be justified by the burial position of the source strata at the time of mineralization (Smith et al., 1983).

Roedder (1968) studied fluid inclusions in sphalerite and carbonate minerals at Pine Point. He found that freezing temperatures of primary inclusions in Pine Point ore are indicative of ore forming from very saline brines. The homogenization temperatures of these fluid inclusions indicate filling-temperatures ranging from 50 to 100°C. Roedder (1968) concluded that the inclusion evidence suggests upward flow of hot metal-bearing brines, possibly derived from deep Precambrian faults, mixing with relatively fresh cold water that subsequently precipitated the ore.

Sulphur isotopes of sulphides, sulphates, elemental sulphur and bitumen were measured at Pine Point by Sasaki and Krouse (1969). Their work suggested that the most plausible source for Pine Point sulphur is Middle Devonian seawater sulphate, most likely derived from connate brines from the contiguous evaporite basin. According to Sasaki and Krouse (1969), the reduction of sulphate to sulphide was attained by biological means by sulphate-reducing bacteria, even though isotope fractionation was very small in the area.

Fritz (1969) and Fritz and Jackson (1972) examined oxygen and carbon isotopes as well as geochemical characteristics of carbonate deposits at Pine Point and determined that at least three distinct dolomite generations are present, which were subsequently invaded by solutions depositing lead and zinc minerals and calcite. Their analytical results were used to help resolve the paragenesis of the ore deposits associated with these dolostone units.

Kesler et al. (1972) attempted to determine the flow direction of mineralizing fluids at Pine Point by examining the morphology of crystals and crystal aggregates. They concluded that solution movement during sulphide precipitation was parallel to the Presqu'ile barrier reef trend and controlled in part by the joint system in the area. Local concentrations of the sulphate-reducing agent in the reef trend brought about rapid precipitation of sulphides in isolated pockets. This process may have produced the botryoidal sphalerite and skeletal galena observed in many orebodies at Pine Point.

Kyle (1981, 1983) provided detailed accounts of the lead-zinc mineralization and their associated host rocks at Pine Point. In these papers, controls for lead and zinc mineralization are proposed on the basis of orebody locations in the barrier, ore textures, and zoning of orebodies. Kyle (1981) discussed the concept of multiple phases of metal enrichment by the exhalative supply of metals to the seafloor along hinge zones.

A definitive paper on Pine Point was authored by Rhodes et al. (1984) who discussed the orebodies and how they relate to the stratigraphy, structure, dolomitization, and karstification within the barrier complex. They speculated that the barrier was initially formed either by subtle tectonic movements or by eustasy, deformation of the barrier was generated either by differential sediment compaction or warping of the underlying evaporite deposits, coarse dolomitization and karstification were related to the mixing of fresh and saline waters, and metals were introduced by chloride-rich brines derived from the basin to the west and subsequently precipitated in paleokarst structures after encountering reduced sulphur.

Krebs and Macqueen (1984) developed a paragenetic sequence of diagenetic and mineralization events for the Pine

Point deposit. They recognized eight major stages of diagenesis, and speculated on the origin of the three dolomite types. The first stage involved the development of fine-grained dolomite likely formed by evaporative reflux. Coarse-grained dolomite (Presqu'ile) then formed by the subsurface mixing of meteoric and seawater as well as hot ascending solutions. Hydrothermal or saddle dolomite and sulphide mineralization were formed by means of hot, ascending hydrothermal fluids. They speculated that sulphide mineralization took place as a result of hot, metal-bearing solutions arising from depth along the hinge lines, migrating through fractured and brecciated collapse zones within the carbonate rocks, and mixing with a local source of hydrogen sulphide. These diagenetic stages prove useful in defining the relative timing of sulphide mineralization with respect to the carbonate diagenetic phases.

The application of organic geochemistry with respect to sulphide ores at Pine Point was discussed by Macqueen and Powell (1983), Powell and Macqueen (1984), Macqueen (1986) and Fowler et al. (1993). In these studies, the concept of a thermal sulphate reduction reaction process was proposed as a possible mechanism to precipitate ores. This model provides an important means for generating the large volumes of sulphide necessary for the formation of the numerous orebodies in the area. The determination of maturation patterns of organic matter in the region indicates that burial depths of the organic-bearing strata are quite significant and forces one to consider that extraneous heat sources or thermal anomalies are associated with some of the dolomitization events as well as mineralization at Pine Point. It was also advocated in these papers that organic matter may contain adsorbed metals or act as agents for transport of metals in organic complexes.

Haynes and Kesler (1987) discussed the major element chemical compositions of fluid inclusions in sphalerite and dolomite at Pine Point. The single metal/sulphur-bearing fluid model is rejected in this study because of these chemical composition results. Specifically, they argued that the detection of significant sulphur in ore-stage fluid inclusions implies mixing of separate sulphur-rich and metal-bearing fluids at Pine Point.

The timing of mineralization in MVT deposits is particularly difficult to determine as a result of several factors, including the occurrence of these deposits in stable tectonic areas precluding the use of geological field observations of post-ore events in order to determine relative timing of mineralization, the lack of magnetic minerals in the strata making paleomagnetic methods untenable, and the lack of igneous material or feldspars in the immediate region from which one can apply the classic argon-dating method. Despite these restrictions, numerous papers have been written discussing the dating of the mineralization episode at Pine Point. The paleomagnetic method of dating MVT stratabound ore deposits was attempted at Pine Point (Beales et al., 1974). In this paper, it was concluded that the intensities of magnetization were too low after demagnetization to lead to any specific conclusions with respect to the age of mineralization. Another attempt using the paleomagnetic technique was described in a paper by Symons et al. (1993), who speculated that the observed remanent magnetism provided a cluster with respect to a unique pole position. This pole position indicated that ores at Pine Point are Late Cretaceous to Eocene in age, suggesting that metal-rich brines were possibly forced into the Presqu'ile barrier during the Laramide Orogeny. Cumming et al. (1990) studied lead isotopes in the district and determined that there is a remarkable lead isotope homogeneity throughout the area. This homogeneity allows one to utilize the single-stage lead-evolution model procedure, thereby giving a mineralization age of 290 Ma. This Late Pennsylvanian age is younger than the host rocks but much older than the Laramide tectonic event. In this same paper, it was also revealed that Pine Point leads are much less radiogenic than those reported in Devonian carbonate deposits in the Cordillera to the west. This difference in lead isotope signature likely indicates unique paleogeographic positions, indicating separate and distinct mineralization events. Apatite fission-track analysis in the Pine Point district was attempted by Arne (1991) in order to determine the regional thermal history. The analysis of annealed fission-tracks in apatites revealed that a heating episode occurred subsequent to the deposition of Devonian rocks. The heating event, which is attributed to deep burial, reached its maximum during Cretaceous time before a cooling episode took place when Devonian strata were uplifted and eroded. The maximum attained paleotemperatures fall in the same range of estimated temperatures of ore formation, suggesting that these deposits formed during deep burial in Cretaceous time. This interpretation indicates that convective transport of heat is not necessary as heat is generated solely by deep burial. Rb-Sr dating of sphalerites seems to be a promising technique for the direct dating of ore minerals in MVT deposits. Sphalerites in the Pine Point district define a Rb-Sr age of 361±13 Ma indicating that mineralization occurred shortly after deposition of the Middle Devonian host carbonate (Nakai et al., 1993). This model is not consistent with the tectonic-driven fluid flow model of Garven (1985) that ascribes mineralization resulting from effects generated by Laramide Cordilleran deformation.

Qing and Mountjoy produced a series of papers (1992, 1994a, b) discussing the characteristics of various carbonate phases found throughout the Presqu'ile barrier complex and the relation of their petrographic, paragenetic, isotopic, and microthermometric attributes to diagenesis, migration of hydrocarbons and local MVT mineralization. The diagenetic and geochemical trends identified in these publications suggest that hotter and more radiogenic basinal fluids moved eastward updip along the barrier complex and mixed with cooler ambient waters. Adams et al. (2000) noted a dramatic shift in the nature of ore-forming fluids at Pine Point as manifested by ^{18}O enrichment, the significant increase in salinity, and the dramatic chemical shift from NaCl to $CaCl_2$ composition of the parent hydrothermal brine. They speculated that this abrupt shift in brine character is caused by the

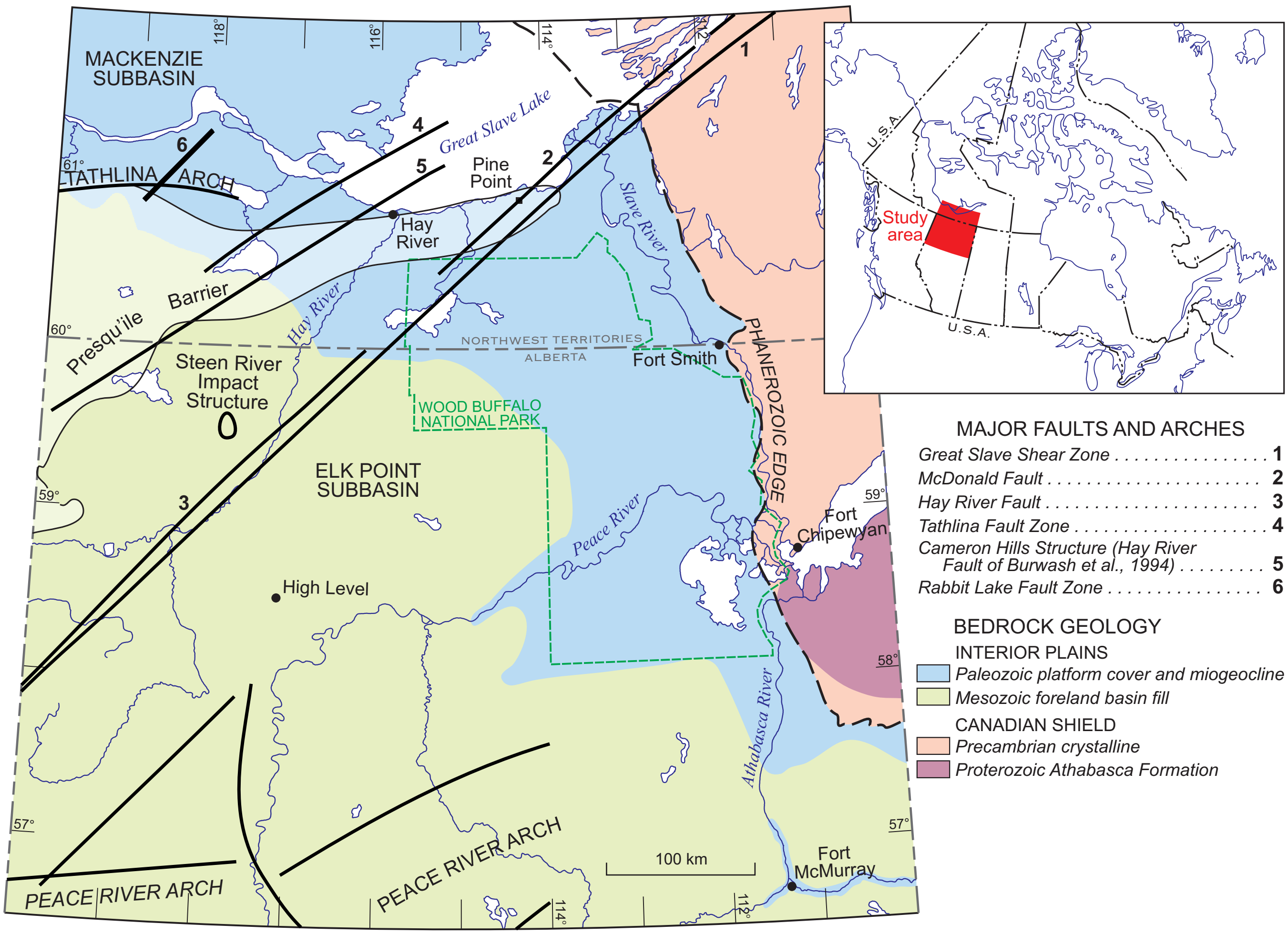


Figure 5. Bedrock geology and regional tectonics of TGI project area. *Modified from* Morrow et al. (2006) and Pană (2006). Spatial distribution of Presqu'ile barrier and Elk Point and Mackenzie subbasins are depicted.

introduction of a second, more saline and cooler brine to the barrier complex at Pine Point. The warm NaCl-rich brine migrating along the paleoaquifer mixed with a cooler supersaline $CaCl_2$ brine, possibly derived from basal clastic deposits or redbeds underlying the barrier.

Geological setting

Characteristic Mississippi Valley-type deposit features such as karst development, dolomitization, and the genetic association with evaporite and hydrocarbon deposits are all present in the Pine Point district. The host rocks at Pine Point are Middle Devonian reef complex and platformal carbonate. Mineralization is epigenetic and occurs as open-space cavity-fills and local replacements within carbonate strata. Within the Givetian carbonate succession, a narrow linear buildup of carbonate up to 200 m thick formed the Presqu'ile barrier (Fig. 5; Kyle, 1981; Rhodes et al., 1984). The barrier separates two depositional subbasins: the Mackenzie to the north where shale and argillaceous limestone were deposited, and the Elk Point to the south where evaporite and lesser carbonate were laid down. The barrier complex exhibits a gentle regional dip to the west and is traceable westward in the subsurface into northeastern British Columbia. Skall (1975) demonstrated that subtle tectonic adjustments along three hinge lines trending N65°E were responsible for the development of a number of paleoenvironmental facies (Fig. 3; marked as North, Main and South trends). These hinge lines seem to be approximate projections of the underlying Precambrian McDonald–Great Slave fault system, although Skall (1975) pointed out that the trend of the hinges and the fault system are not exactly parallel. The hinges also correspond to lines of weakness where preferential karstification, coarse-grained dolomitization and mineralization were concentrated (Fig. 3).

Precambrian basement

The northeast portion of the project area is occupied by Proterozoic cover rocks and orogens of the Canadian Shield

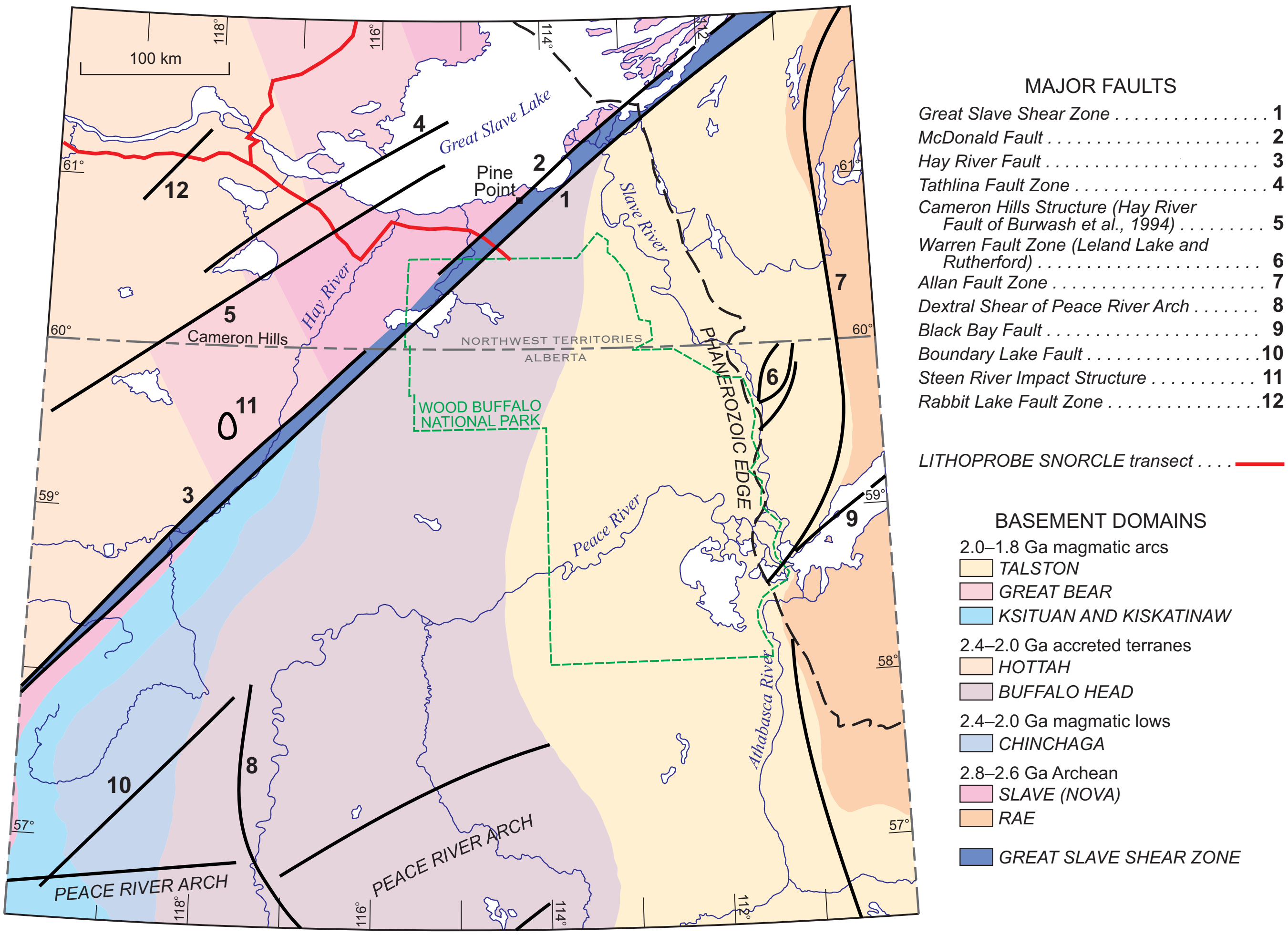


Figure. 6. Exposed and subsurface basement domains and major structural features in project area (*from* Morrow et al. (2006) and Ross et al. (1991)). Basement terranes based on geophysical properties and radiometric ages from Villeneuve et al. (1993). LITHOPROBE SNORCLE transect lines from Wu et al. (2002).

craton. The Canadian Shield in this region consists of intensely deformed metamorphic and intrusive rocks of Archean and Proterozoic age overlain in part by weakly deformed neo-Proterozoic (Helikian) sedimentary rocks in the Athabasca Basin. Various discrete Archean crustal blocks are separated by Proterozoic rocks of orogenic origin. This tectonic collage of Precambrian rock is differentiated on the basis of geological, geochrononological, geochemical, and geophysical means into a series of discrete basement domains (Hoffman, 1989; Ross et al., 1994; Morrow et al., 2006). The collage is exposed in outcrop in the northeastern part of the project area and extends beneath the Phanerozoic sedimentary wedge of the Western Canada Sedimentary Basin where it constitutes the basement beneath these sediments (Fig. 5, 6). Major basement domains beneath the sedimentary wedge in the project area include the Archean Slave and Rae provinces and Proterozoic accreted terranes (Hottah, Buffalo Head), magnetic lows (Chinchaga) and magmatic arcs (Talston, Great Bear, and Ksituan) (Fig. 6) (Ross et al., 1991, 1994; Villeneuve et al., 1993; Morrow et al., 2006). The assembled Proterozoic domains welded the various Archean crustal blocks. Early Proterozoic collisional tectonics caused major discontinuities to form in the basement such as the Great Slave Shear Zone (GSSZ) (Fig. 6). Potential-field geophysical signatures can trace many of these major discontinuities beneath the basinal sediments. Various discontinuities, faults, and lineaments in the basement as well as in the overlying sedimentary wedge, possibly indicating structures of fundamental importance for fluid origin and migration, both important aspects for petroleum and mineral exploration, are compiled in Panǎ et al. (2001) within the project area and are discussed elsewhere in this volume (Panǎ, 2006). Some of the major faults and discontinuities identified in the project area in addition to the GSSZ are McDonald Fault, Hay River Fault, Tathlina Fault Zone, Rabbit Lake Fault Zone, Warren Fault Zone, Allan Fault Zone, Black Bay Fault, and

Boundary Lake Fault (Fig. 6). Precambrian basement in the Pine Point district consists of granite, granite gneisses, and quartzite of the Archean Slave Province (Norris, 1965).

A LITHOPROBE transect was completed in the project area and much information with respect to influences of Precambrian basement rocks on overlying Phanerozoic rocks and underlying mantle were collected and interpreted. The SNORCLE (Slave–Northern Cordillera Lithosphere Evolution) transect lies in the northern part of the project area in southern Northwest Territories (Fig. 6) (e.g. Lewis et al., 2002; Wu et al., 2002). The transect acquired hundreds of kilometres of multichannel seismic reflection profiles that allowed a much clearer understanding of the continental assembly of Precambrian basement in Western Canada and its effect on the evolution of the overlying Western Canada Sedimentary Basin (WCSB).

Western Canada Sedimentary Basin

The Targeted Geoscience Initiative project area in northern Alberta and southern Northwest Territories is situated in the Interior Plains of the WCSB (Fig. 1). The WCSB consists of a northeasterly tapering wedge of Phanerozoic supracrustal rocks overlapping the westward extension of the Precambrian craton (Porter et al., 1982; Price, 1994). The sedimentary wedge thickens to the southwest from zero thickness at its eastern craton boundary to near 6 km just east of the deformed belt of the Cordillera (Porter et al., 1982; Wright et al., 1994). Two major, westward-thickening sedimentary successions of approximate equal volume constitute the fill of the WCSB and are derived from two completely different tectonic settings. The older and deeper succession consists of Upper Proterozoic to mid-Jurassic dominantly marine sediments. These easterly derived rocks were deposited on a stable, passive continental margin and the adjacent craton by oceanward progradation (Fig. 5; Podruski et al., 1988). These episodic transgressive and regressive miogeoclinal deposits predominantly consist of platformal carbonate, shale, and evaporitic sediments. The cratonic platform succession was buried by a second major wedge of shallow-marine and nonmarine clastic sediments of Late Jurassic to Tertiary age (Fig. 5). These sediments are westerly derived and were deposited by cratonward progradation of clastic detritus from an evolving Cordilleran orogen coinciding with accretion of foreign terranes onto the western continental margin of North America (Porter et al., 1982). The collisional accretion of terranes to the active convergent continental margin produced an overriding mass of thrust sheets inducing the formation of the foreland basin to the east (Price, 1994). These rising thrust sheets provided both the detritus and the tectonic load to tilt the cratonic platform sediments southwestward toward the continental margin (Podruski et al., 1988). Both sedimentary successions have been affected by the development of various cratonic arches.

Sedimentary host rocks for Mississippi Valley-type mineralization in northern Alberta and southern Northwest Territories are carbonate successions within the older cratonic platform sediment wedge. Although much of the Phanerozoic WCSB is underlain by carbonate deposits of Cambro-Ordovician, Devonian, or Carboniferous age, Devonian carbonate rocks are the most significant with respect to exploration for MVT mineral deposits in the project area. Devonian carbonate deposits occur proximal to surface in the northern and eastern portions of the project area, establishing this succession as most feasible for effective exploration and development. In these same areas, uplift and erosion has effectively removed pre- and post-Devonian carbonate strata. A compilation of known carbonate-hosted lead-zinc occurrences throughout the whole project area (823 occurrences; Hannigan, 2005a) indicated all occurrences are hosted in Middle and Upper Devonian carbonate. Pine Point lead-zinc deposits are hosted in Middle Devonian strata. For these reasons, much of the work completed in this project and presented in this volume involve prospective Devonian strata, specifically the relationships of MVT mineralization with the stratigraphic and structural history and framework of the Devonian System. Unfortunately, with respect to mineral exploration, a large portion of the exposed or near-surface Devonian rock in the project area is encompassed by Wood Buffalo National Park (Fig. 5).

Bedrock and subsurface geology in the project area have been mapped and discussed by numerous authors, including Law (1955), Greiner (1956), Douglas (1959, 1974), Belyea and McLaren (1962), Belyea and Norris (1962), Norris (1963, 1965), Richmond (1965), Hriskevich (1966), Craig et al. (1967), Belyea (1971), Douglas and Norris (1974), Corrigan (1975), Williams (1977; 1981a, b, c; 1982), Cutler (1983), Meijer Drees (1993), Cotterill and Hamilton (1995), and Okulitch (2006a, b, c).

Cratonic platform

A major episode of tectonic uplift and extensive erosion that effectively removed almost all lower Paleozoic strata preceded Middle Devonian deposition in northern Alberta and southern NWT. There are very minor outcrops of Upper Silurian and Lower Devonian strata adjacent to the Precambrian Shield. The La Loche Formation contains conglomeratic arkosic and dolomitic sandstone (Okulitch, 2006a, c). Gentle folding of the pre-Devonian surface produced a series of basins and arches that profoundly affected subsequent Devonian sedimentation. Two major positive features affecting sedimentation in northern Alberta and southern NWT are the Tathlina and Peace River arches (Fig. 5). Both of these arches are cored by Precambrian granitic rock. These intracratonic arches restricted marine encroachments onto the craton from the west (Reinson et al., 1993). An elongate northwest-trending basin developed that was open to the north and northwest but restricted to the south and southeast. Initial Devonian sedimentation during Emsian and Eifelian time occurred in a restricted-marine environment. Rocks of the Lower Elk Point Group (Basal Red Beds, Mirage Point, Ernestina Lake, Cold Lake, Contact Rapids and Chinchaga formations) consist of interbedded redbeds, evaporites, shallow-marine clastic deposits, and minor carbonate (Fig. 7, 8). At Pine Point, the igneous-metamorphic Precambrian assemblage is unconformably overlain by 100 to 350 m of clastic and evaporitic rocks of pre-Eifelian age (Basal Red Beds, Cold Lake Formation, and Lower Chinchaga Member; Fig. 7). The Eifelian Upper Chinchaga Member consisting of evaporite deposits and lesser dolostone and limestone unconformably overlie the older succession (Fig. 7).

Subsequent to initial restricted Devonian deposition, an open-marine carbonate-depositing sea transgressed the platform (Reinson et al., 1993; Kent, 1994). Basinwide deposition of normal marine carbonates took place in a ramp-to-platform setting and formed the Lower Keg River Member ('Keg River Platform' in Fig. 7, 8). The Lower Keg River Member constitutes the initial unit in a Devonian first-order cycle corresponding with the Upper Elk Point Group lithostratigraphic megasequence (Early Givetian; Facies A from Skall (1975) in Fig. 9; Moore, 1989; Reinson et al., 1993). At Pine Point, Lower Keg River strata underlie back-barrier, fore-barrier and barrier strata. The succession maintains a constant thickness near 65 m in the Pine Point district (Rhodes et al., 1984). This homogeneous unit consists of dense to sucrosic dolostone with carbonaceous to argillaceous wisps. There are up to three locally defined, pyritic, calcareous shale beds occurring about 3 to 6 m below the top of the unit. These E-shale markers vary from a few centimetres to a metre thick and have proved to be excellent marker beds in the Pine Point property (Fig. 9). Partly equivalent platform carbonate in the northwestern part of the study area are found in dolostone and fossiliferous limestone of the Lonely Bay Formation, which is in mappable continuity with Lower Keg River carbonate as well as the underlying Upper Chinchaga evaporite deposits (Fig. 7; Meijer Drees, 1993).

Continued subsidence and marine transgression led to the development of an extensive mid-Givetian upper Keg River barrier-reef complex on the southern flank of the Tathlina Arch. The complex, called the Presqu'ile barrier, extends across the basin from the Pine Point mine site near its eastern margin to northeastern British Columbia at the Cordilleran deformation front (Fig. 5). Southeast of the barrier, abundant isolate reefs, reef mounds and banks of the Upper Keg River Member were laid down on Lower Keg River platform deposits. North and west of the barrier, Horn Plateau isolate reefs grew on the Lonely Bay carbonate platform (Fig. 7; Meijer Drees, 1993). The Presqu'ile barrier effectively restricted the sea to the south and normal marine sedimentation ceased. In this region, the regressive phase of the Upper Elk Point cycle is represented by the development of a carbonate-evaporite shelf and evaporite basin called the Elk Point subbasin (Fig. 5). The evaporitic succession defined as the Muskeg Formation in northern Alberta and southern NWT and the Prairie Formation in north-central Alberta contains halite, anhydrite and evaporitic dolostone (Fig. 7, 8). Normal marine sedimentation did continue, however, north of the barrier in the Mackenzie subbasin, where fore reef deep-water 'bituminous shale and limestone beds' (Meijer Drees, 1993) or Horn River Formation (Fig. 7) were deposited. The barrier at Pine Point consists of two superimposed buildups: the lower or Upper Keg River buildup (lower Pine Point Group in Skall, 1975; Pine Point Formation in Rhodes et al., 1984) and the succeeding Sulphur Point Formation (upper Pine Point Group in Skall, 1975; Fig. 7, 9). The lower buildup constitutes approximately two-thirds of the barrier and is a flat, lensoid accumulation of dominantly carbonate sand and mud. As the barrier grew, the various facies in the lower buildup prograded northward. The superimposed Sulphur Point buildup is a tabular carbonate accumulation containing local bioherms with related bioclastic limestone and carbonate sand (Rhodes et al., 1984). Near the end of the Upper Elk Point cycle, a marine incursion into northwestern Alberta and southern Northwest Territories resulted in deposition of shelf carbonate of the Sulphur Point Formation south and east of the barrier as well as atop the barrier itself.

At Pine Point during Middle Devonian time, the North, Main and South hinge lines delineated blocks of carbonate sediment that underwent dissimilar subsidence leading to abrupt transitions in lithofacies as well as rapid changes in thickness. The resultant stratigraphic units, representing unique depositional environments at Pine Point, required a subdivision into various depositional facies (Skall 1975; Rhodes et al., 1984). Such facies include the *Tentaculites* (F) and Buffalo River Shale (G) in the basin to the north of the reef complex; the off-reef (B), shallow fore-reef (C), and clean arenite (E) in the fore reef; the organic barrier (D) in the reef complex itself; and the gastropod (H), *Amphipora* (I) and south flank back-reef (J) to the south of the barrier (Fig. 9).

The Upper Keg River Member (lower Pine Point Group) lies conformably on the marine platform (Fig. 7). The formation is composed of a diverse assemblage of lithofacies that has been extensively dolomitized. The maximum thickness of the assemblage is 175 m at the axis of the reef complex and thins to the north and south forming a lens-like accumulation (Rhodes et al., 1984). A basal member, 12 to 18 m thick, (Facies B of Skall, 1975) directly overlying the Lower Keg River Member is a moderately argillaceous fossiliferous unit that has been strongly leached. Spongy or vuggy porosity, which remains after leaching of the fossils, occurs beneath the entire barrier and also extends well to the south under the Muskeg Formation. This unit, called the B-spongy member (Rhodes et al., 1984), contains the N-204 orebody that occurs in the northeastern corner of the Pine Point property (Fig. 3, 9). Above the B-spongy member, a variety of interfingering carbonate lithofacies form a broad carbonate bank. The interfingering, north-prograding lithofacies occurring in the barrier reef-complex from south to north are 1) a fine, dense to sucrosic, very fossiliferous dolostone with fair to good porosity (organic barrier facies, D; D-1 in Skall, 1975); 2) a sucrosic to sandy, clean bioclastic grainstone-dolomite of a massive uniform appearance (clean arenite facies, E); 3) a fine grainstone to mudstone to wackestone that is progressively more bituminous and argillaceous to the north (off-reef facies, B in Skall 1975; B-E and B-marine;

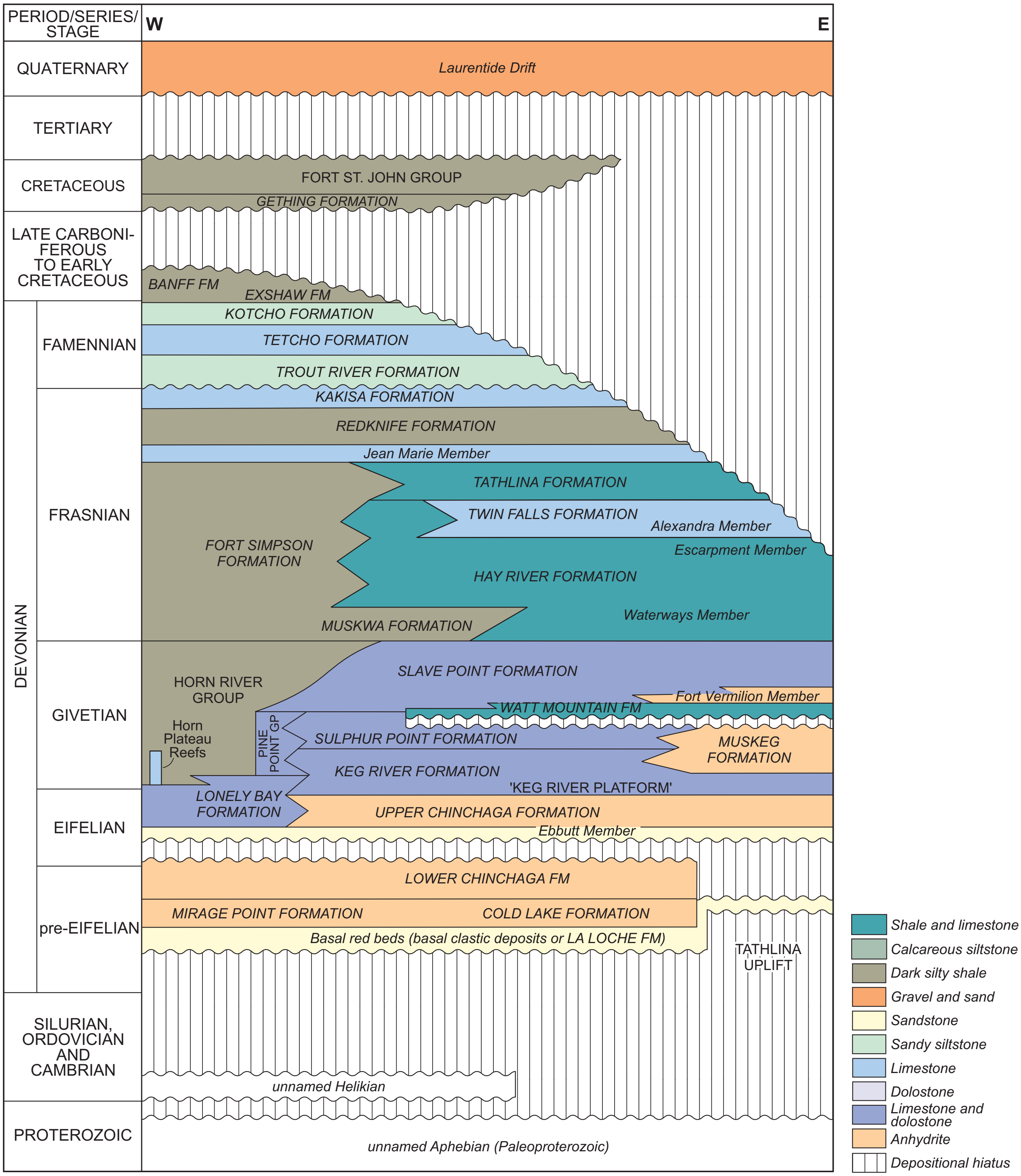


Figure 7. Stratigraphic chart illustrating nomenclature and schematic relationships in the Pine Point district in southern Northwest Territories. *Adapted from* Morrow et al. (2006).

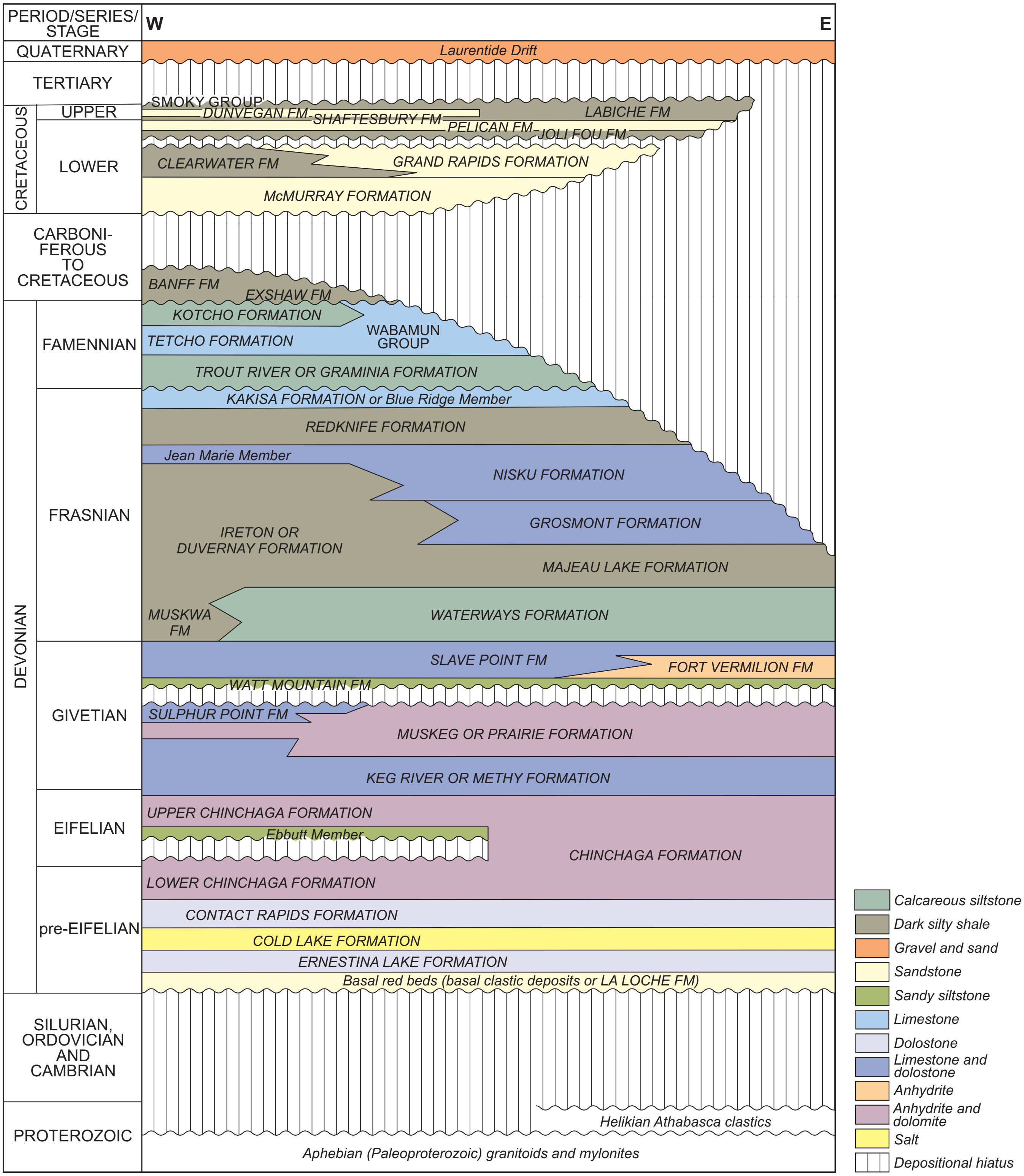


Figure 8. Stratigraphic chart illustrating nomenclature and schematic relationships along an east-west transect across northern Alberta. *Adapted from* Morrow et al. (2006).

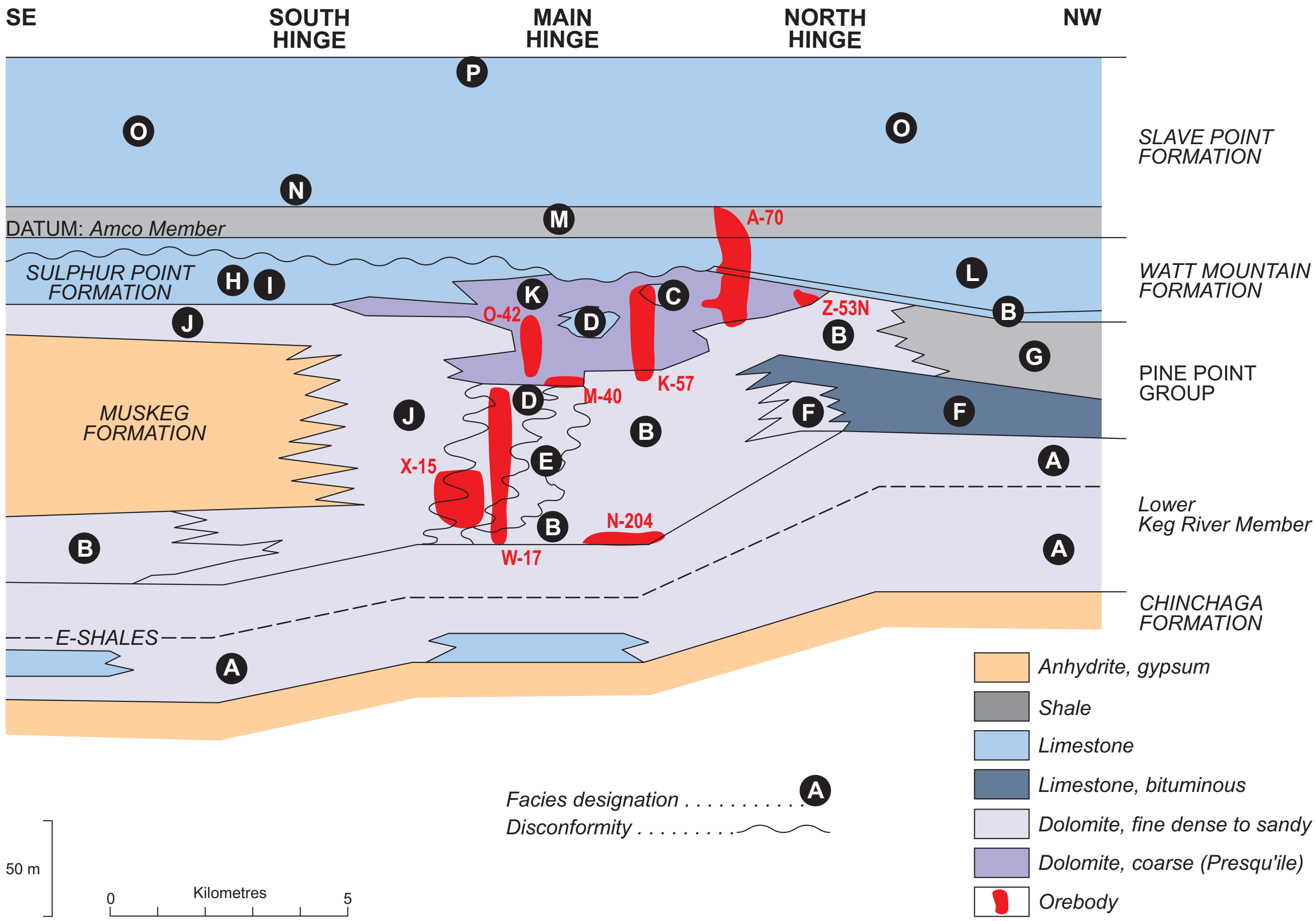


Figure 9. Schematic diagram of Middle Devonian stratigraphic relationships in the Presqu'ile barrier and their relation with selected orebodies at Pine Point. *Adapted from* Skall (1975).

Rhodes et al., 1984); and 4) a black, very bituminous limestone hosting *Tentaculites* representing the basinal environment (*Tentaculites* facies, F) (Fig. 9). Facies F continues well north of the barrier where it is integrated into the Horn River Formation (Fig. 7).

Rhodes et al. (1984) emphasized in his discussion on barrier lithofacies that the barrier is not an organic reef because only about 10 per cent of the strata is organic floatstone and no boundstone or framestone are present. The lower carbonate buildup consists of carbonate sand bounded by carbonate mud to the north. According to Rhodes et al. (1984), it is more appropriate to describe the barrier as an organic bank or sediment pile. Even though there are substantial north-south and vertical variations of lithofacies in the carbonate bank there is, however, a consistency of facies along the strike of the barrier. The schematic diagram of the barrier shown in Figure 9 is drawn with great vertical exaggeration. The slope of the barrier and the angle of progradation in real space are near horizontal (about one or two degrees). The near-flat geometry indicates that the height of the barrier was never great and the lithofacies successions were deposited in water depths ranging from zero to 30 m. These depths are ideal for the evolution of contrasting depositional environments that are expressed by their diverse lithofacies (Rhodes et al., 1984).

The Sulphur Point Formation (facies C, D-2, D-3, H, and I) conformably succeeds the Upper Keg River Member on the barrier whereas to the south it transitionally overlies the Muskeg Formation (Facies J; Fig. 9). Thicknesses of the Sulphur Point Formation range considerably, from 65 m in the barrier complex to 30 m on the south side of the barrier and 9 metres far to the south in Wood Buffalo National Park. The formation thins to the north of the barrier and abruptly terminates. There is a distinct colour contrast between the Sulphur Point and the underlying Upper Keg River Member. The Sulphur Point unit is cream to white with little or no impurities whereas the underlying facies is darker as a result of varying levels of organic matter. Similar to Upper Keg River Member, the Sulphur Point Formation exhibits lateral and vertical facies variations at Pine Point. In the organic barrier, two subfacies defined by Skall (1975; D-2 and D-3) occur in the Sulphur Point Formation. Restricted to the south-central part of the barrier at the contact between Sulphur Point Formation and Upper Keg River Member, the D-3 facies is a fine, dense, fragmental dolomite with poor to fair vuggy porosity, and is situated beneath facies K (Presqu'ile dolomite). Secondary veining and brecciation are common in this unit. Rhodes et al. (1984) speculated that the restricted presence of D-3 facies implies an intervening period of nondeposition and partial subaerial exposure. Following this subaerial exposure episode, patch reefs of stromatoporoidal boundstone and rudstone developed on the paleotopographic high (facies D-2 of Skall, 1975). On the backreef side of the high, bioclastic debris was shed from the barrier complex producing the bioclastic limestone of the gastropod facies (facies H; Fig. 9). At the same time farther south, deposition of lagoonal, subtidal, and supratidal laminated algal and pelletoidal grainstone and mudstone occurred (Skall's 1975 facies I; Fig. 9). North of the patch reefs, a micritic to sandy limestone was deposited in the proximal or shallow fore-reef facies (Skall's 1975 facies C). The limestone unit also developed in the upper part of the barrier complex and was preserved as limestone remnants in the Presqu'ile facies (Fig. 9).

South of the barrier complex, Muskeg Formation dolostone (Skall's 1975 facies J) and evaporite deposits are present. The Muskeg Formation is equivalent to the Upper Keg River Member and the basal Sulphur Point Formation (Fig. 9). There are prominent Muskeg back-reef beds extending north to the Main hinge of the barrier intercalated with basal Sulphur Point beds indicating a short and abrupt regression. These beds are called C-horizons and form useful marker beds (not shown in Fig. 9). The evaporite and carbonate of the Muskeg Formation in the Elk Point basin are 350 to 400 m thick. This succession is thicker than the time-equivalent strata in the barrier because of greater subsidence and rapid sedimentation rates in the basin. At Pine Point, fine-grained dolostone predominates (facies J). Thickness of the Muskeg J-facies ranges from 18 to 170 m. This facies was deposited in a back-barrier restricted environment. As D- and E-facies of the Upper Keg River Member prograded northward, the J-facies prograded in the same direction (Fig. 9). The South hinge coincides with the northern extension of the evaporite deposits of the Muskeg Formation.

In the Mackenzie subbasin north of the barrier, marine, fissile, calcareous shale with disseminated iron sulphides was deposited. It is partly equivalent to the upper part of the carbonate barrier complex. This formation, called Buffalo River (facies G; Skall, 1975; Fig. 9) thickens northward to a maximum thickness of 60 m. The North hinge coincides with the southern limit of Buffalo River Formation deposition. Buffalo River shale was laid down commencing during Upper Keg River deposition and continued beyond the Sulphur Point depositional interval (Rhodes et al., 1984).

The Presqu'ile dolomite was originally interpreted as a reefal development and consequently assigned formational status (e.g. Norris, 1965; Campbell, 1966). Skall (1975) recognized that the Presqu'ile facies (facies K; Fig. 9) is not a dolomitized reef core, but a spectacular later-stage diagenetic dolomitization event that affected a broad array of primary carbonate lithofacies. The Presqu'ile dolostone is now interpreted as a coarse-crystalline vuggy dolomite facies not defined by environmental conditions or timing of deposition of the original carbonate lithologies. The coarse texture of this dolomite destroyed much of the original carbonate fabric making environmental interpretation difficult. The vugs are filled or lined with late-stage, white coarse-crystalline dolomite and lesser calcite, sulphides, altered bitumen and native sulphur (Krebs and Macqueen, 1984). Rhodes et al. (1984) estimated that 60 to 70 per cent of the Sulphur Point Formation on the Pine Point property has been altered by coarse-crystalline dolomitization. Generally, Presqu'ile dolomitization extends upward from the Upper Keg River-Sulphur Point contact to the top of the Sulphur Point Formation (Fig. 9). Occasional remnants of Sulphur Point limestone are preserved in the barrier complex (Facies D, Fig. 9). A variable limestone unit caps the barrier complex. Presqu'ile dolomite is occasionally found in facies B of the underlying Upper Keg River Member. Occasionally, it extends upward across the sub-Watt Mountain disconformity into the overlying Slave Point Formation. The main aerial distribution of the Presqu'ile dolomite follows the North and Main hinges (Fig. 9). It is thickest along the Main hinge, where it varies from 60 to 70 m. Many of the Pine Point orebodies occur in karsted carbonate deposits that are altered to Presqu'ile dolostone (e.g. M-40, O-42, and K-57, part of A-70 in Fig. 9), but deposits are not restricted to this diagenetic facies (e.g. X-15, W-17, and N-204; Fig. 9).

Upper Elk Point deposition was terminated by a significant base-level drop delineated by a major unconformity upon which coastal marine and continental shale, sandstone and limestone of the Watt Mountain Formation were deposited (Fig. 7–9; Meijer Drees, 1993; Reinson et al., 1993). Skall (1975) described a regression occurring near the middle–upper Givetian boundary resulting in the formation of a partial disconformity and subaerial karst development that affected the topographically higher parts of the barrier. Skall (1975) speculated that the main part of the barrier was exposed up to 30 m above sea level. To the north of the barrier, however, marine sedimentation continued unabated as evidenced by the termination of the disconformity and transformation of the stratigraphic surface into a conformity between the underlying B-facies and overlying Watt Mountain Formation (Fig. 9). The conformable relationship is confirmed by thicker accumulations of Watt Mountain carbonate north of the barrier. Kyle (1981) interpreted extensive karstic development on the barrier, displayed in the development of abundant collapse breccias filled with detritus, resulting from subaerial sinkholes formed by percolation of vadose waters. Karstification is considered to be an important ground-preparation process in the host rock for subsequent MVT sulphide mineralization (Leach and Sangster, 1993). Green waxy shale commonly scattered in the uppermost part of the barrier complex below the disconformity was interpreted by Skall (1975) as a residual deposit that developed on the subaerial exposure surface.

Following emergence of the barrier at the beginning of Late Givetian time, Watt Mountain micritic limestone with occasional waxy shale or clay layers was deposited on the disconformity above and south of the barrier complex (facies L; Skall, 1975). This formation averages less than 10 m in thickness where it disconformably overlies the barrier complex, but increases to near 33 m north of the barrier. The Watt Mountain Formation was deposited in tidal flat, lacustrine and lesser lagoonal and restricted environments. The formation has historically been assigned to the Upper Elk Point Group. Meijer Drees (1988) and Williams (1984) interpreted a major unconformity below the Watt Mountain Formation indicating that a significant erosional event preceded Watt Mountain transgression. They suggested that this formation, therefore, be reassigned to the next first-order cycle called the Beaverhill Lake Group. Subsequent cycle sedimentation continued with deposition of peritidal anhydrite and carbonate of the Fort Vermilion Member in northern Alberta and southeastern Northwest Territories. The Fort Vermilion Member is partly laterally equivalent and also overlain by open-marine platform carbonate deposits of the Slave Point Formation (Fig. 7, 8).

Conformably overlying the Watt Mountain Formation at Pine Point is the layered Slave Point Formation. Skall (1975) subdivided the Slave Point Formation into four facies: the M (Amco member), N (Fort Vermilion equivalent), O, and P facies (Fig. 9). The basal member, called the Amco 'shale' consists of a 3 m thick, very argillaceous limestone between two slightly argillaceous micrite layers. Skall (1975) defined the Amco member as a shale and it proved to be a useful stratigraphic time-marker. The M-facies (Amco member) was deposited in an open-marine environment as a result of subsidence at the end of Watt Mountain deposition. Overlying the Amco member is facies-N, a micritic limestone locally altered to dolomite. It ranges in thickness from 10 to 18 m and has blotchy bedding, fenestral structures and is laminated. It developed in a tidal flat environment. Facies-O, a shallow platform sequence, consists of sandy micrite to micritic sand with abundant large intraclasts. Thicknesses range from 25 to 50 m. The uppermost lithofacies in the Slave Point Formation is the 6 to 12 m thick P-facies. This highly fossiliferous unit consists of lime mudstone, pelletoidal grainstone and skeletal grainstone. Generally, the Slave Point Formation in the Pine Point area maintains a uniform and layered character.

The regressive phase of the Beaverhill Lake cycle is marked by basinal shale and argillaceous limestone of the Waterways Formation capping and onlapping Slave Point bank successions. These rocks are deposited extensively over much of the southern and eastern parts of the study area (Fig. 8). Subsequent to deposition of Slave Point platform carbonate in southern Northwest Territories, initial deposition of the Hay River Formation containing shale and argillaceous limestone (Waterways member) took place (Fig. 7).

There is a conformable cyclical transition between the Beaverhill Lake megasequence and the overlying Woodbend Group corresponding to renewed marine transgression in the basin. In northern Alberta, shelf limestone of the Waterways Formation is overlain by deep-water organic-rich limestone and shale of the Majeau Lake Formation (Fig. 8; Switzer et al., 1994). Infilling of the basin continued with deposition of Duvernay and Ireton shales and lesser carbonates. In northern Alberta, a shelf-platform reef complex developed over the prograding Majeau Lake shale. This reef complex, called Grosmont (Fig. 8), consists of limestone, dolomitic limestone and shaly limestone of the Mikkwa Formation overlain by vuggy, petroliferous dolomite of the Grosmont Formation (Okulitch, 2006b). In southern NWT, a westward prograding siliciclastic wedge consisting of shale, argillaceous limestone and siltstone of the Hay River Formation is partly laterally equivalent to Fort Simpson deep-water shale (Fig. 7; Morrow and Rhodes, 2001). The Twin Falls Formation, a westwardly prograding carbonate platform, overlies Hay River siliciclastic deposits (Morrow and Rhodes, 2001).

Even though overall inundation of the craton continued after Woodbend Group deposition, Winterburn Group rocks were laid down under general shallowing conditions. Widespread shelf carbonate sediments of the Nisku Formation were deposited in east-central and north-central Alberta above the Grosmont complex (Fig. 8). To the west, insufficient filling of the basin prevented the development of shelf complexes, resulting in deposition of Nisku-equivalent shale. In southern NWT, another west-prograding siliciclastic wedge (Tathlina Formation) was deposited on the Twin Falls carbonate platform (Fig. 7; Morrow and Rhodes, 2001). In northwestern Alberta, northeastern British Columbia, and southern NWT, sufficiently rapid sediment fill in the basin during subsidence induced favourable conditions for the development of biostromal shelf carbonate of the Jean Marie Member of the Redknife Formation (Reinson et al., 1993). Next, a major regression marked by deposition of terrigenous clastic deposits of the Redknife Formation (exclusive of Jean Marie Member) occurred. A subsequent marine incursion resulted in deposition of shallow-marine shelf carbonate of the Blue Ridge or Kakisa limestone. Another major regression occurring at the close of Winterburn sedimentation is marked by deposition of a northwestward-thickening wedge of Trout River or Graminia siliciclastic strata (Fig. 7, 8; Reinson et al., 1993).

The transgression signifying initial deposition of the Wabamun first-order cycle is marked by prograding ramp carbonate and shale of the Tetcho and Kotcho formations. The Tetcho carbonate ramp covered northwestern Alberta and southwestern NWT (Fig. 7, 8). The carbonate was deposited during uniform basin-wide subsidence. This succession represents final Devonian deposition in the basin.

The broad, shallow-water ramps that developed throughout the basin during Late Devonian time persisted through the Early Carboniferous. The former Peace River Arch began to downwarp at this time forming a broad depocentre called the Peace River Embayment containing deep-water, open-marine deposits (Barclay et al., 1997). In the study area, Carboniferous strata are preserved in the western subsurface

(Okulitch, 2006b, c). The most extensive preserved depositional unit consists of two shallowing-upward cycles separated by a minor disconformity. The lower cycle consists of black, organic-rich deep-water marine shale overlain by regressive nearshore sandstone (Exshaw and lower Banff formations; Barclay et al., 1997). The upper cycle contains deep-water shale and muddy carbonate overlain by shelf grainstone, which, in turn is overlain by tidal muddy carbonate and clastic deposits (upper Banff Formation) (Fig. 7, 8). A major Late Carboniferous to Early Cretaceous unconformity overlying the Banff Formation occurs over much of the study area, except in the Peace River Arch area where the stratigraphic succession ranging from Carboniferous Viséan Shunda platform carbonate to argillaceous and partly dolomitic Triassic Charlie Lake Formation, is present in the subsurface (not shown on Fig. 8).

Foreland basin

The foreland basin succession in the study area is represented by prograding, northeastward- tapering, westerly derived clastic wedges supplied by the evolving Cordilleran Orogen. The initial sediments of the foreland basin succession form the Fernie-Kootenay tectonostratigraphic assemblage (not shown in Fig. 8) (Podruski et al., 1988). This assemblage is present only in the subsurface at the southwest corner of the project area in the vicinity of the Peace River Arch. Two shallowing-upward and coarsening-upward clastic cycles in the Fernie Group and overlying Nikanassin Formation are present.

The main tectono-stratigraphic assemblage, or clastic wedge, lying above the major Late Carboniferous to Early Cretaceous unconformity is the widespread Mannville assemblage consisting of coarse-clastic continental and fine-clastic shallow-marine deposits. Mannville deposition occurred during a major inundation of the Boreal Sea from the north (Podruski et al., 1988). The assemblage contains both transgressive and regressive phases. Initial deposits above the unconformity, such as the McMurray Formation in northeastern Alberta (Fig. 8) and Gething Formation in the Deep Basin in northwestern Alberta and northeastern British Columbia, are continental coarse-clastic sediments occupying major valley systems. Later, a marine incursion from the north formed estuarine and shallow-marine deposits (shale and siltstone) also in the McMurray and Gething formations (Fig. 7) (Podruski et al., 1988). Maximum transgression produced shallow-marine sand and shale in the Deep Basin (Bluesky Formation) and paralic to shallow marine sand and shale in northeastern Alberta (Wabiskaw Formation). The regressive phase, or Upper Mannville, in northeastern Alberta consists of open-marine shale of the Clearwater Formation and overlying thick sandstone of the Grand Rapids Formation (Fig. 8).

The next overlying tectonostratigraphic assemblage is the Colorado Group, consisting of widespread marine shale with thin, shallow-marine coarse-clastic interbeds (Podruski et al., 1988). The rising sea of the Late Albian transgression deposited the Joli Fou shale. The Joli Fou was then overlain by a brackish estuarine sandstone, siltstone, and shale succession (Pelican Formation). Marine shale succeed the Pelican Formation (Shaftesbury Formation) (Fig. 8). There is also an extensive deltaic and shoreline complex that was shed from the west into the Cretaceous Interior seaway at this time. These coarse-clastic deposits constitute the Dunvegan Formation. Marine sedimentation continued with shale of the La Biche Formation and Smoky Group capping the stratal column in northern Alberta (Fig. 8).

In southern NWT, shallow-marine shale of the Lower Mannville Gething Formation is overlain by the Fort St. John Group (Fig. 7). In the Fort St. John Group, the Loon River Formation containing dark marine shale, siltstone, and minor sandstone is overlain by dark marine shale and siltstone of the Shaftesbury Formation (Okulitch, 2006b, c).

Structure and epeirogenic tectonism

Initial intensive exploration drilling strategy undertaken by Cominco at Pine Point was based on the hypothesis that major Precambrian faults along the East Arm of Great Slave Lake (McDonald-Great Slave Shear Zone; Fig. 5, 6) constitute an important structural control for the distribution of orebodies in that they provided conduits for the introduction of heat and metal-bearing solutions into the Devonian carbonate succession subsequent to its deposition (Campbell, 1966, 1967). This early exploration strategy, accomplished by drilling widely spaced fences along projected trends of Precambrian faults (Norris, 1965), resulted in the discovery of many orebodies and expanded the ore reserves dramatically. Campbell (1967) also recognized that facies development and tectonic movements are related.

In Skall's (1975) discussion on the development of paleoenvironmental facies, it was stated that epeirogenic tectonic adjustments along three parallel hinge lines following the strike of the barrier profoundly impacted lithofacies distribution at Pine Point. These subtle tectonic movements presumably occurred during mid-Givetian time in the cratonic platform sedimentary succession. The hinge lines reflect linear trends where orebodies are concentrated (Fig. 3). The lines parallel interpreted Middle Devonian faults and fractures (Douglas and Norris, 1974) but are divergent from the trend of the major Precambrian McDonald fault system east and south of the property (i.e. N65°E for the hinge lines; N45°E for the McDonald-GSSZ fault system). Rhodes et al. (1984) argued against profound structural control for the distribution of orebodies at Pine Point because of this observed divergence of structural trends. They also observed that Middle Proterozoic dike swarms crossing the McDonald fault in the East Arm of Great Slave Lake to the northeast of Pine Point are not dislocated and the Lower Keg River and Chinchaga stratigraphic units underlying the barrier complex at Pine Point form uniform blankets of sediment without any sign of vertical displacement. These observations imply that little or no reactivation occurred in the McDonald-GSSZ fault system since Proterozoic time, and this lack of movement likely indicates that the system is effectively sealed, preventing the movement of heat or metal-rich fluids upward along the faults into the Phanerozoic carbonate cover. However, one can argue that the subparallelism of the hinge lines with facies fronts, pinchouts, and depositional limits indicates a certain degree of syndepositional structural control (Skall, 1975; Pană, 2006). Also, the divergent trends do not exclude a kinematic link where the parallel, en échelon normal faults trending N65°E are subsidiary extensional splays of the main vertical brittle fault (Pană, 2006).

Faulting and fracturing are also present in the Middle Devonian carbonate succession and are concentrated along the hinge zones but not restricted to them (Skall, 1975). These hinge zones remained as lines of weakness where post-Devonian reactivation may have occurred. Movement on various post-Amco faults also affected the mid-Givetian structures. Skall (1975) pointed out that contemporaneous faulting and fracturing can also be caused by compaction or volume shrinkage as a result of diagenesis. Rhodes et al. (1984) identified from structural contour maps subtle undulations postdating Amco deposition trending both north-south and east-west. They speculated that these undulations were caused by differential compaction or loading and warping of underlying lower Elk Point evaporite successions. In some ore zones, high-angle faults with displacements of 2 to 10 m are present. These young structures displace all the strata (Rhodes et al., 1984).

Similar northeast and east-northeast linear trends recognized by aeromagnetic contours, structural contours, isopach maps, facies changes, and coarse-grained dolomite belts in bordering areas to the west of Pine Point such as Tathlina Lake and Rabbit Lake have been mapped (Morrow et al., 2006; Janicki, 2006a). This pattern of linear structures likely represents a series of horsts and grabens occurring at the west end of Great Slave Lake (Gibbins, 1988).

Dolomitization

At Pine Point, dolomites are differentiated into three main types: fine-crystalline, coarse-crystalline (Presqu'ile) and coarse-crystalline white dolospar (saddle dolomite) (Skall, 1975; Kyle, 1981; Krebs and Macqueen, 1984; Rhodes et al., 1984). Qing (1991) introduced a fourth type (medium-crystalline) that was described in subsequent papers discussing the Presqu'ile barrier (Qing and Mountjoy, 1992; 1994a; Qing, 1998a, b). Results of geochemical analysis of medium-crystalline dolomite proved to be similar to that of fine-crystalline dolomite (Qing, 1998a), so the threefold division is adopted in this paper.

Much of the Keg River Formation and J-facies of the Muskeg Formation (lower carbonate succession in the Presqu'ile barrier) has been recrystallized to a fine-crystalline dolomite (<30 microns crystal-size) on a property-wide basis (Krebs and Macqueen, 1984). Sedimentary structures and fossils are recognizable, although fossils have been leached forming moldic porosity. The dolostone consists of a very uniform mosaic of fine-grained dolomite crystals. This early-stage dolomitization event associated with development of the South hinge and the resulting deposition of Muskeg evaporite and carbonate units in the restricted shelf to the south of the barrier is speculated to have been formed by the reflux mechanism (Adams and Rhodes, 1960; Skall, 1975; Krebs and Macqueen, 1984). The reflux model is consistent with widespread distribution of the dolomite that formed during Middle Givetian time. Refluxing Mg-brines derived from Muskeg evaporite pans not only dolomitized the adjacent back-reef limestone, but also limestone in the barrier and the fore-reef. Kyle (1981) objected to the reflux model because of hydrological considerations, and proposed a mechanism involving evaporative pumping of seawater through carbonate sediments and subsequent mixing in the subsurface with meteoric water occurring at the time of cessation of South Hinge tectonic adjustments ('Dorag' dolomitization model; Badiozamani, 1973) as a more appropriate model.

As discussed above, much of the coarse-crystalline Presqu'ile dolomite affects a large part of the Sulphur Point Formation and locally the B-facies of the Upper Keg River Member, but rarely above the disconformity into overlying Watt Mountain and Slave Point formations (Krebs and Macqueen, 1984). Crystal sizes range from 30 to 200 microns in size. In contrast to the fine-crystalline dolomite, the original fabrics of the precursor carbonate are destroyed or occur as relicts (Krebs and Macqueen, 1984). The vuggy habit is characteristic of this dolomite and vugs range in size from several millimetres to a few centimetres and locally up to metre-sized cavities. The vugs are filled or partly lined with white dolomite, calcite, sulphides, bitumen and/or native sulphur and these vug-fills are clearly post-Presqu'ile dolomite accumulations. Isolated remnants of limestone are preserved in coarse-crystalline Presqu'ile dolomite in the upper barrier complex of the Sulphur Point Formation, contrasting sharply with the underlying carbonate succession, where fine-crystalline dolomitization is pervasive. The contacts between coarse-crystalline dolomite and limestone remnants are sharp, irregular, and transect bedding (Kyle, 1981). The main areal distribution of Presqu'ile dolomite on the Pine Point property follows the North and Main hinges, where they also reach their maximum thickness. Fritz and Jackson (1972) and Kyle (1981) concluded that subsurface mixing of fresh and marine water ('Dorag' dolomitization) was the mechanism that formed this coarse-crystalline dolomite facies. Krebs and Macqueen (1984) argued against this model because the distribution of the dolomite should, therefore, be restricted below the Watt Mountain disconformity. However, as stated above, coarse dolomitization crosses the disconformity in parts. Warm ascending solutions likely played at least a subsidiary role in the dolomitization process. Krebs and Macqueen (1984) suggested that the Presqu'ile dolomite and its associated, white, void-filling dolomite, or saddle dolomite, was formed by various, superimposed complex processes or stages including subsurface mixing of fresh and marine waters and hot ascending hydrothermal solutions. Repeated invasion of these dolomitizing waters produced the large aureoles of Presqu'ile dolomite along the porous hinge lines.

The third dolomite type present at Pine Point is the white 'vein' dolosparite or saddle dolomite occurring in association with infilled solution cavities and sulphides. This dolomite type also includes white spots or crystals of dolomite developed in a speckled pattern in the Presqu'ile dolomite. The dolomite is widespread, coarse-crystalline and has curved crystal faces and cleavage. Under cross-polarized light, it exhibits sweeping extinction and contains abundant inclusions. The saddle dolomite has complex age relationships, ranging from pre-ore, syn-ore to post-ore (Krebs and Macqueen, 1984). Regardless of the age relationships of the dolomite, the fluid-inclusion filling temperatures (90 to 100°C) of the dolomite suggest a 'hydrothermal' origin. The maximum depth of burial of the barrier complex at the time of mineralization was about 1500 m. If a geothermal gradient of 30°C/km is assumed in this area, then the resulting burial temperature should have been about 60°C. Thus the fluid-inclusion filling temperatures of the saddle dolomite are too high to have been formed by burial alone. Hot ascending solutions, possibly derived from deeply buried Precambrian faults, heated the groundwater in these open fractures and voids and precipitated the dolomite cements (Krebs and Macqueen, 1984).

Karstification and brecciation

At Pine Point, karst refers to both surface and subsurface solution features and pore space. Rhodes et al. (1984) cited karstification of the barrier as the major control for ore deposition at Pine Point. They pointed out that the trend and geometry of these paleokarst bodies are similar to the orebodies and are therefore strongly related. The mineralization is pervasive in interconnected paleokarst networks. The networks are mainly developed in the porous barrier complex along the North and Main hinge zones and are related directly to distinct lithofacies. At Pine Point, karstification not only occurs along these distinct trends but is also embodied in four distinct karstic orebodies: tabular, prismatic, abnormal prismatic, and B-spongy type (Rhodes et al., 1984). These orebody types are illustrated in Figure 10. Tabular karst is the most common and widespread solution network in the Pine Point district. This karstic network occurs along a crude stratabound horizon that coincides with the base of the Presqu'ile dolomite near the Sulphur Point-Upper Keg River contact (Fig. 10). The tabular ore deposits are elongate, flat-lying bodies associated with an interconnected network of karst channels along this horizon. These karst channels can attain thicknesses of up to 12 m and widths of up to 240 m.

Most production to date at Pine Point has been derived from normal prismatic orebodies, which are chimney-like, vertically elongate entities associated with major cavity dissolution and prismatic openings that extend upward from the tabular horizon (Fig. 10; Rhodes et al., 1984). These local zones of enhanced dissolution likely coincide with areas of greater structural weakness where more intense jointing and fracturing increased porosity and permeability. The dissolution caused sagging and collapse of the overlying strata, sometimes affecting up to 100 m of stratigraphy. These collapse structures seem to be related to structurally elevated areas (ridges or domes). The collapse process allowed the resedimentation of the openings by clastic carbonate units ranging from well-laminated internal sediments to breccias incorporating surrounding and overlying material at and above the tabular karst horizon (Rhodes et al., 1984). The breccias show fine fragmentation at the base of the cavity structures and grade upward into coarser and fewer distorted fragments. The finer grained internal sediments and overlying breccias contain the prismatic ore.

There is a type of karstic structure of similar geometry to normal prismatic bodies that does not root in the tabular ore horizon. These 'abnormal' prismatic orebodies are separate karstic features from the dominant paleokarst network hosting tabular and normal prismatic deposits in that they are formed by the collapse of tabular or prismatic bodies into underlying strata as a result of continuing dissolution, and are thought to represent modern karst or sinkholes (Rhodes et al., 1984; Fig. 10). Erosion has removed the original host strata. Some of these modern unconsolidated structures are mineralized (e.g. X-15 and W-17 orebodies; Fig. 9).

The B-spongy mineralization habit has been discovered to date in only one orebody at Pine Point. The N-204 orebody is situated near the northeastern corner of the property (Fig. 3, 9) where the B-spongy horizon is near surface (Fig. 10). The

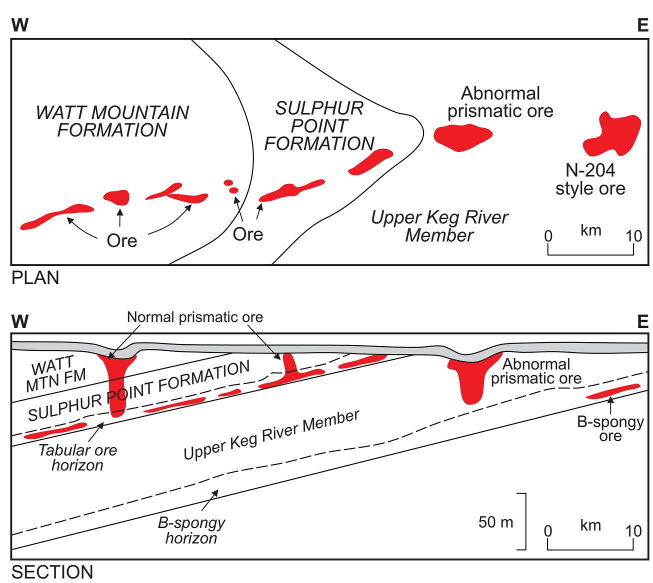


Figure 10. Schematic plan and vertical section of orebody types and their relation to the regional stratigraphy. *Adapted from* Rhodes et al. (1984).

B-spongy member contains fine-grained dolomite containing fossil moldic porosity. At the eastern part of the Pine Point property, this open porosity is accompanied by fine crackle brecciation (Rhodes et al., 1984). Mineralization is disseminated in the moldic and breccia porosity. The dissolution or karstic process in this horizon produced substantial vuggy, fracture, and intergranular porosity.

Mineralization

Mineralization at Pine Point consists of sphalerite, galena, marcasite, and pyrite with associated native sulphur and bitumen and occasional pyrrhotite, celestite, barite, gypsum, anhydrite, and fluorite. Gangue minerals are dolomite and calcite. Common sulphide textures in the district are disseminations, banded encrustations, crystalline galena and sphalerite, and colloform sphalerite. These sulphide concentrations commonly have sharp contacts with barren host rocks. Dimensions of the 100 known orebodies in the Pine Point district vary from 60 to 2000 m in length, 15 to 1000 m in width and 0.5 to 100 m thick. Rhodes et al. (1984) indicated that mineralization is pervasive in the paleokarst networks and strongly controlled by individual stratal horizons, although some orebodies are strongly discordant. Mineralization occurs as replacement of karst-filling internal sediments and breccia, open-space filling, and peripheral disseminations in vuggy porosity. The highest-grade mineralization seems to be restricted to karstic structures hosting the greatest amount of internal sediment fill. The most typical host lithology for ore-grade mineralization is the coarse-grained, vuggy Presqu'ile dolomite. The orebodies occupy the most permeable portion of the highly porous Presqu'ile barrier complex. They vary in size from 90 000 tonnes to as much as 13 600 000 tonnes (Kyle, 1981). The metal contents of the produced orebodies vary from 3.3 to 14.1 per cent zinc and 1.0 to 8.8 per cent lead. The combined lead-zinc content ranges from 4.4 to 21.1 per cent. The orebody producing the greatest amount of lead and zinc was the X-15 body where 349 485 tonnes of lead and 1 083 404 tonnes of zinc were extracted (Rhodes, pers. comm., 2001) (Fig. 3).

Prismatic orebodies tend to have coarser crystalline galena occurring peripherally to the main ore zone. They also are more lead-rich than their tabular counterparts. The tabular orebodies are generally zinc-rich. Some of the prismatic bodies are zoned with a lead-rich core, passing outward into a zinc-rich zone and enveloped by an iron-rich aureole (Kyle, 1981). The areal distribution of iron-sulphides is wider than galena and sphalerite. There are relatively small, barren sulphide bodies on the Pine Point property consisting mostly of iron sulphides with minor lead and zinc. Tabular orebodies that do not have associated prismatic oreshoots seem to have a more regular grade.

Overview of studies completed for the TGI project

After the identification of appropriate characteristics regarding MVT mineralization at Pine Point and their relation to the regional stratigraphic and structural framework, numerous field-related geological studies were performed to identify areas of enhanced mineral potential. Figure 11 illustrates the areal coverage of the various geoscientific papers presented in this volume. Although most papers discuss various aspects of MVT potential within the bounds of the project area (Fig. 11), some papers have expanded their discussions into other areas of the WCSB.

As discussed previously, the concept of structural control for MVT deposits has been the subject of considerable debate. In this volume, Pană's study of various known MVT deposits and occurrences in the WCSB, both in the Interior Platform and Cordillera (Pană, 2006; Fig. 11) argues for the direct relationship of MVT deposits and occurrences in the WCSB with fault-zone processes. By re-examining outcrops and cores containing MVT mineralization or closely associated hydrothermal dolomite and validating these observations with paragenetic, isotopic, and structural data, Pană (2006) concludes that MVT mineralization is likely related to convectional movement of fluids within zones of recurrent strain in the host rocks as well as in the underlying Precambrian basement. If Pană's hypothesis proves to be correct, the identification of structural trends in the project area would be an extremely useful exploration tool.

This structural theme is pursued further in this volume in two additional papers (Morrow et al., 2006; MacLean, 2006; Fig. 11). Morrow et al., (2006) performed subsurface mapping of significant stratigraphic formation tops derived from oil and gas wells penetrating Devonian strata in the project area. In their paper, a series of subsurface structure and isopach maps were constructed and many of the abrupt inflections of the contours on these maps seem to coincide with previously identified faults and fault zones from the literature. Significantly, new features were identified from the subsurface mapping work and they were compared with subvertical faults identified from aeromagnetic and seismic data in the area. These features may have provided access for circulating MVT mineralizing solutions. MacLean (2006) interpreted a series of seismic lines in the southern Northwest Territories that confirmed the long-standing opinion regarding a regionally extensive orthogonal pattern of structural lineaments in the area, which in turn, seems to have greatly influenced Middle Devonian facies development and the orientation of the carbonate bank edge. The author also observed the close association of hydrothermal dolomite with some of the structural features in this region.

The close association of certain types of dolomite to MVT mineralization at Pine Point led to a series of papers dealing with dolomite types, their characteristics and distribution, and geochemical and isotopic properties. Janicki (2006a) mapped the areal extent and thickness, by visual examination of core and well cuttings, of white sparry dolomite in the Great Slave Plain of NWT, a close associate of MVT mineralization at Pine Point (Fig. 11). Coniglio et al. (2006; Fig. 11) provides a detailed study of the petrography, geochemistry and fluid inclusion microthermometry of various dolomite types in the Middle Devonian succession of the southern NWT. Their work challenges the current paleohydrological model for dolomitization of the Presqu'ile barrier. A microthermometric study of fluids associated with mineralization in the Pine Point camp was completed by Turner (2006; Fig. 11). In that study, constraints were placed on the trapping temperatures and salinities of fluids associated with both ore and gangue minerals in the area. Gleeson and Gromek (2006; Fig. 11) used bulk fluid inclusion chemical analyses in dolomite and sphalerite to determine the origins of hydrothermal sulphide- and dolomite-mineralizing fluids in the project area. Rice and Lonnee (2006; Fig. 11) investigated the diagenetic and isotope geochemistry of Devonian carbonate in northeastern Alberta and discussed the relationship of their observations with the potential for significant MVT mineralization in this area of Alberta.

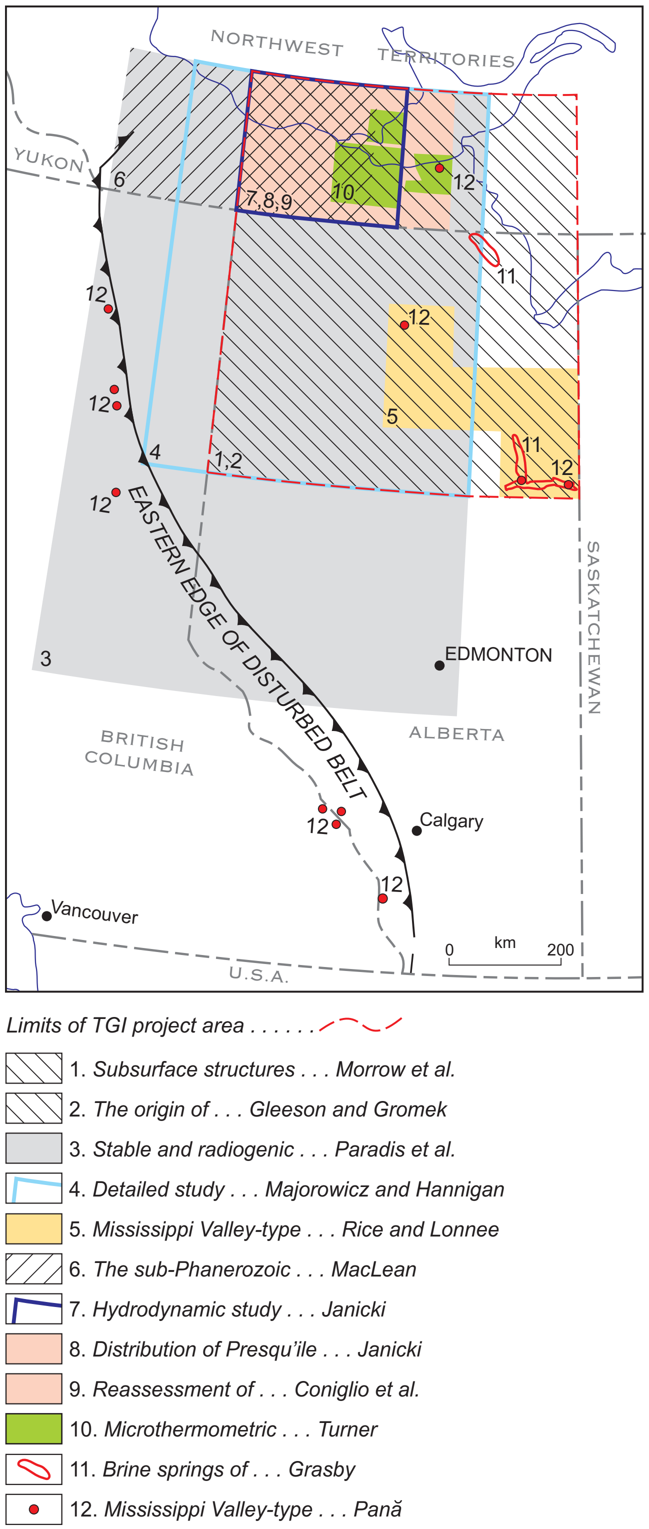


Figure 11. Study areas of papers in this volume.

Stable and radiogenic isotopic signatures of mineralized carbonate deposits were established in the project area and comparisons were made between these occurrences in the Interior Platform and northern Rocky Mountains in the paper by Paradis et al. (2006; Fig. 11). This paper confirms a link between MVT carbonate-hosted Pb-Zn mineralization and hydrothermal dolomite in the northern Canadian Rocky Mountains and the Interior Platform of the WCSB.

Other papers in this volume include a hydrodynamic study of Middle Devonian formations in southern NWT (Janicki, 2006b; Fig. 11) giving current conditions for formation fluid movement and composition that may provide clues for paleofluid movement, and a study investigating the chemistry and geochemistry of brines from modern springs in northern Alberta (Grasby, 2006; Fig. 11). The regional temperature regime in the project area was investigated by Majorowicz and Hannigan, (2006; Fig. 11) and it shows anomalous heat-flow conditions in the northern part of the project that may explain the enhanced homogenization temperatures of saddle dolomite in the same area.

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