# CARBONATE HOSTED PB-ZN POTENTIAL OF NORTHEASTERN ALBERTA AND THE APPLICABILITY OF PETROLEUM DATA FOR MINERAL EXPLORATION

by

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## Table of Contents

## Figure Captions



## Tables

## INTRODUCTION

The mineral potential of northeastern Alberta is poorly known due to the minimal amount of exploration in the region. This report addresses two primary aspects of evaluation of the mineral potential in this region. The first deals with a general procedure for the evaluation of the area. The second concerns the applicability of well data from petroleum exploration to mineral exploration and commodity evaluation.

For the evaluation of a commodity in general, using carbonate hosted lead-zinc (Mississippi Valley-Type or MVT) as a type example, the approach used here examines the following:

1. the economic potential of the commodity;
2. the geological characteristics of the mineralization;
3. Canadian examples of similar types of deposits;
4. mineralization theories;
5. potential stratigraphic hosts in northeastern Alberta;
6. prospecting approaches including the evaluation of borehole geophysics;
7. the applicability of petroleum exploration data;
8. applications of this approach to other commodities; and,
9. significance and suitability of groundwater modeling to the overall evaluation procedure.

The information gathered through petroleum exploration, specifically geophysical logs, cores and cuttings, may prove to be an integral part of a data base enabling an evaluation of the mineral potential. These data are available through both the ERCB (public domain) and service companies such as CANSTRAT. Some of the types of available data and the applications of these data to mineral evaluation are discussed.

## ECONOMIC POTENTIAL OF THE COMMODITY

Before the process of evaluation is initiated the following must be determined - What is the future of this commodity in light of projected demand, prices, existing reserves, and logistic problems with exploration and development? In other words, "is the commodity worthy of examination"?

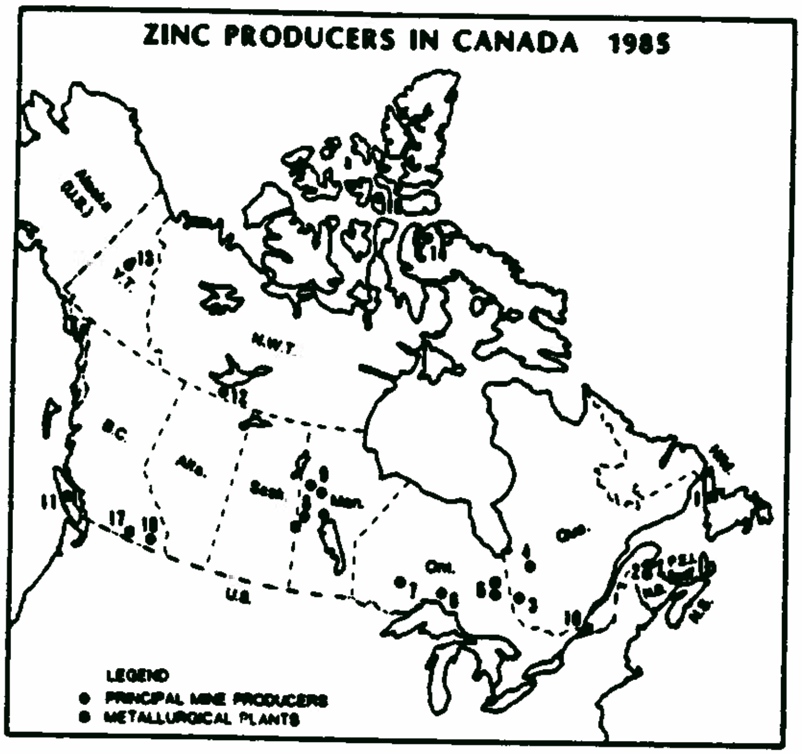
### Pb-Zn

Lead-zinc is found in volcanogenic, sediment-hosted exhalative, carbonate-hosted and vein deposits in Canada (Sangster, 1983). In 1973, 77% and 60% of Canada's lead and zinc, respectively, came from volcanogenic deposits, whereas 15.5% Zn and 20.5% Pb was obtained from carbonate-hosted deposits (Sangster & Lancaster, 1976). The remainder is presumably derived from vein and sediment-hosted exhalative deposits. Sangster (1986) summarized the classification, distribution and grade tonnage of Canada's lead-zinc deposits. As of 1985 there were 15 principal zinc producing mines and four processing metallurgical plants in Canada (Gauvin, 1986) (Fig. 1). For the same period there were 12 lead producers and 2 facilities with lead processing capabilities (Bigauskas, 1986) (Fig. 2). The current soft market prices for lead and zinc have led to the subsequent shutdown of some of the mines listed in figures 1 and 2 - the most notable being Pine Point. The discussion that follows covers Pb and Zn from all primary sources.

### Lead

Bigauskas (1986, p. 34.6) suggested that "for both the short term and the long term the price of lead is expected to remain low by historical standards." There are 9 400 000 tonnes proven reserves of deposits not yet in production in Canada (Bigauskas, 1986, p. 34.10). This is equal to 35 years of domestic supply at current production rates <u>excluding</u> proven reserves in existing mines.

figure 1




**Principal Producers**
(numbers refer to numbers on map above)

1. Newfoundland Zinc Mines Limited
2. Brunswick Mining and Smelting Corporation Limited
3. Corporation Falconbridge Copper Lake Dufault Division
   Noranda Inc. and Les Mines Gallen Limitée (Gallen Mine)
4. Noranda Inc. Matagami Division
5. Kidd Creek Mines Ltd.
6. Noranda Inc. (Geco Division)
7. Mattabi Mines Limited
   Noranda Inc. (Lyon Lake)
8. Hudson Bay Mining and Smelting Co., Limited (Chisel Lake, Osborne Lake, Stall Lake, Ghost Lake, Anderson Lake, Westarm, Flin Flon, White Lake, Centennial, Trout Lake, Spruce Point)
9. Sherritt Gordon Mines Limited (Fox Lake mine and Ruttan mine)
10. Cominco Ltd. (Sullivan mine)
    Teck Corporation (Beaverdell mine)
    Dickenson Mines Limited (Silmonac mine)
11. Westmin Resources Limited
12. Pine Point Mines Limited
13. United Keno Hill Mines Limited
14. Nanisivik Mines Ltd.
15. Cominco Ltd. (Polaris mine)

**Metallurgical Plants**

5. Kidd Creek Mines Ltd., Timmins
8. Hudson Bay Mining and Smelting Co., Limited, Flin Flon
16. Canadian Electrolytic Zinc Limited, Valleyfield
17. Cominco Ltd., Trail

Figure 1. Principal Zinc Mines and Smelter Facilities in Canada (From Gauvin, 1986)

figure 2


Princial mine producers
(numbers refer to locations on map above)

1. Brunswick Mining and Smelting Corporation Limited
2. Kidd Creek Mines Ltd.
3. Noranda Inc. (Geco Division)
4. Mattabi Mines Limited
   Noranda Inc. (Lyon Lake, "F" Group)
5. Hudson Bay Mining and Smelting Co., Limited
6. Cominco Ltd. (Sullivan mine)
   Teck Corporation (Beaverdell mine)
7. Dickenson Mines Limited (Silmonac mine)
8. Westmin Resources Limited (Lynx and Myra, H.W.)
9. United Keno Hill Mines Limited (Elsa)
10. Pine Point Mines Limited
11. Nanisivik Mines Ltd.
12. Cominco Ltd. (Polaris mine)

Metallurgical Plants

A. Brunswick Mining and Smelting Corporation Limited, Smelting Division, Belledune

B. Cominco Ltd., Trail

Figure 2. Principal Lead Mines and Smelter Facilities in Canada (From Bigauskas, 1986)

## Zinc

The long term outlook for zinc prices is slightly better than the outlook for lead. It is estimated that the industry will require at least five years (dated from 1985) to work off the overcapacity in zinc production (Gauvin, 1986, p. 66.4). However, there are 20 492 700 tonnes of undeveloped proven zinc reserves in Canada (Gauvin, 1986, p. 66.8). This is equal to 17 years of production at current rates excluding proven reserves in existing mines.

## Exploration and Development Logistics

The occurrence of proven, undeveloped deposits elsewhere, the large reserves at producing mines such as Pine Point, the high costs of exploration, and the depressed markets suggests that the exploration for Pb-Zn in northern Alberta at the present time may not be economically feasible for most mineral companies. Notwithstanding this negative future outlook, carbonate hosted Pb-Zn is used as the type example for commodity evaluation in this report. The geological setting of northeastern Alberta is not favorable for the occurrence of volcanogenic or vein Pb-Zn deposits. However, owing to the abundance of Paleozoic carbonates in northeastern Alberta, the potential for carbonate-hosted deposits warrants further examination.

# GEOLOGICAL CHARACTERISTICS

It is important to understand the style of mineralization, or geologic occurrence, of a commodity if a proper exploration program or evaluation procedure is to be undertaken. Aspects that should be considered include the geological setting, (including structural and stratigraphic controls), types of mineral and gangue development, and conditions of mineralization as indicated by available geochemical data.

## Pb-Zn Example

Sangster (1976, p.303) suggested that "small sphalerite occurrences can be regarded as a normal feature of carbonates". Anderson and Macqueen (1982, p.109) reinforced this concept by commenting that "It is important to remember that MVT ore deposits are simply unusually large representatives of a ubiquitous phenomenon: occurrences of sphalerite and galena are commonplace in the carbonate succession". In other words, lead-zinc showings are to be expected in carbonate rocks and are not necessarily indicative of an economic deposit. This suggests that caution must be taken not to interpret every showing of galena and sphalerite as being significant.

Characteristics of MVT's

The characteristics of MVT's have been discussed by many authors, most notably by Ohle (1958; 1980), Anderson & Macqueen (1982) and Wolf (1981; 1976). These characteristics include:

1. the ores are stratiform and epigenetic (Beales & Onasick, 1970);
2. the deposits are commonly found at or near the edges of basins or on arches between basins (Anderson & Macqueen, 1982);
3. the majority of deposits exist in carbonates (Anderson, 1978) with a bias towards dolostones (Anderson & Macqueen, 1982);
4. igneous rocks are not associated and are ruled out as potential ore solution sources (Jackson & Beales, 1967);
5. the ores are simple in mineralogy and consist of galena and sphalerite with varying amounts of fluorite and barite. Precious metal contents are low but may include Co, Ni, Ag, Cu, Cd, In, Ge, and Ga (Jackson & Beales, 1967; Ohle, 1958; Anderson & Macqueen, 1982). Conversely, Heyl et al.(1974) commented that the mineralogy and associated trace element distribution of MVT ores was subtly complex;
6. in most cases deposits are found in passive structural regions (Ohle, 1958), or within foreland fold and thrust belts and in unmetamorphosed host rocks (Anderson & Macqueen, 1982).
7. some deposits are controlled by paleokarst development and/or

unconformities and mineralization is a function of porosity (Anderson, 1978; Callahan, 1977);

8. Some deposits occur near or at carbonate fronts (Anderson, 1978);
9. the temperature of ore forming fluids range from 80 - 200 C and salinities are from 5 to 10 times that of normal seawater (Roedder, 1968);

The most significant unknown about MVT deposits is the timing of mineralization. Different approaches have been attempted by many authors including paleomagnetism, K-Ar, and Pb-Pb isotopes (See Sangster, 1983, p. 14 for summary and bibliography). Various attempts have been made at estimating the time constraints of mineralization but none have been successful to the point where the information is useful.

## CANADIAN EXAMPLES

For a specific commodity, the distribution and occurrence of Canadian deposits warrant examination for the express purpose of identifying any common geological characteristics between the proven mineralized areas and the area being evaluated.

### Alberta region

To date no significant occurrences of Pb-Zn mineralization have been recorded from northeastern Alberta. A.W. Norris, who has extensive field and subsurface experience in northeastern Alberta, has never encountered any Pb-Zn mineralization in the region (pers. comm., 1987). However, in the early 1960's, there were unsubstantiated reports of prospectors finding lead-zinc mineralization within Wood Buffalo National Park (Godfrey, 1985). In addition, Carrigy (1959, p. 22) reported a galena showing in the Fort McMurray area.

Evans *et al*.(1968) summarized the surface occurrences and some of the subsurface occurrences of Pb-Zn in western Canada. The most notable deposits in Alberta are in the Kicking Horse Pass region and include the Hawk Creek, Eldon, Baker Creek, Kicking Horse and Monarch. These deposits are all hosted in dolostones of the middle Cambrian Cathedral Formation. Subsurface occurrences of Pb and Zn mineralization, summarized from various authors, are shown in Figure 3 and indicated in Table 1. These occurrences are limited to middle and upper Devonian host rocks.

Other Canadian Examples

Numerous regions of MVT mineralization have been documented including northeastern British Columbia (Macqueen, 1976; Macqueen & Thompson, 1978), the Cornwallis Pb-Zn District (Kerr, 1977) and the Nanasivik area (Olson, 1984; McNaughton & Smith, 1986). Gibbins (1983) and Sangster & Lancaster (1976) described various Pb-Zn occurrences in northern Canada. There are also small showings in southwestern Ontario and deposits in the Atlantic region (Anderson & Macqueen, 1982).

The Pine Point district is one of Canada's best known examples of Mississippi Valley Type mineralization and warrants further examination because of its close proximity to northern Alberta and its geological setting in the Alberta Basin (Fig. 4). The property is 65 km (E-W) by 24 km (N-S) and contains 87 individual deposits. Reserves as of 1983 were 25.7 million tons of 2.7% Pb and 6.3% Zn (Rhodes et al., 1984). At the time of writing this article, Cominco had ceased mining operations at Pine Point due to low base metal prices.

Figure 3

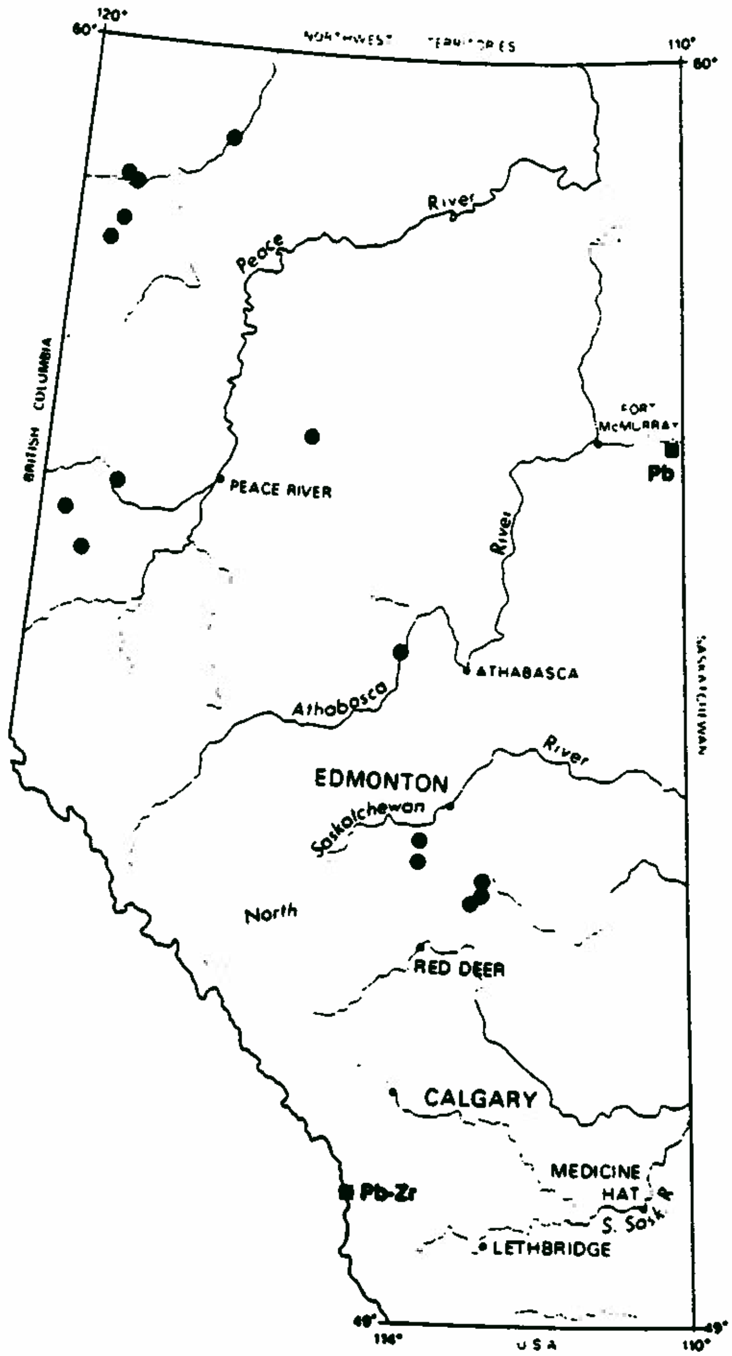



Figure 3. Occurrences of Lead-Zinc in Alberta. Subsurface occurrences indicated by circles, surface showings by squares. Sphalerite unless otherwise noted. (Data from Hitchon, 1977, and others)

Figure 4

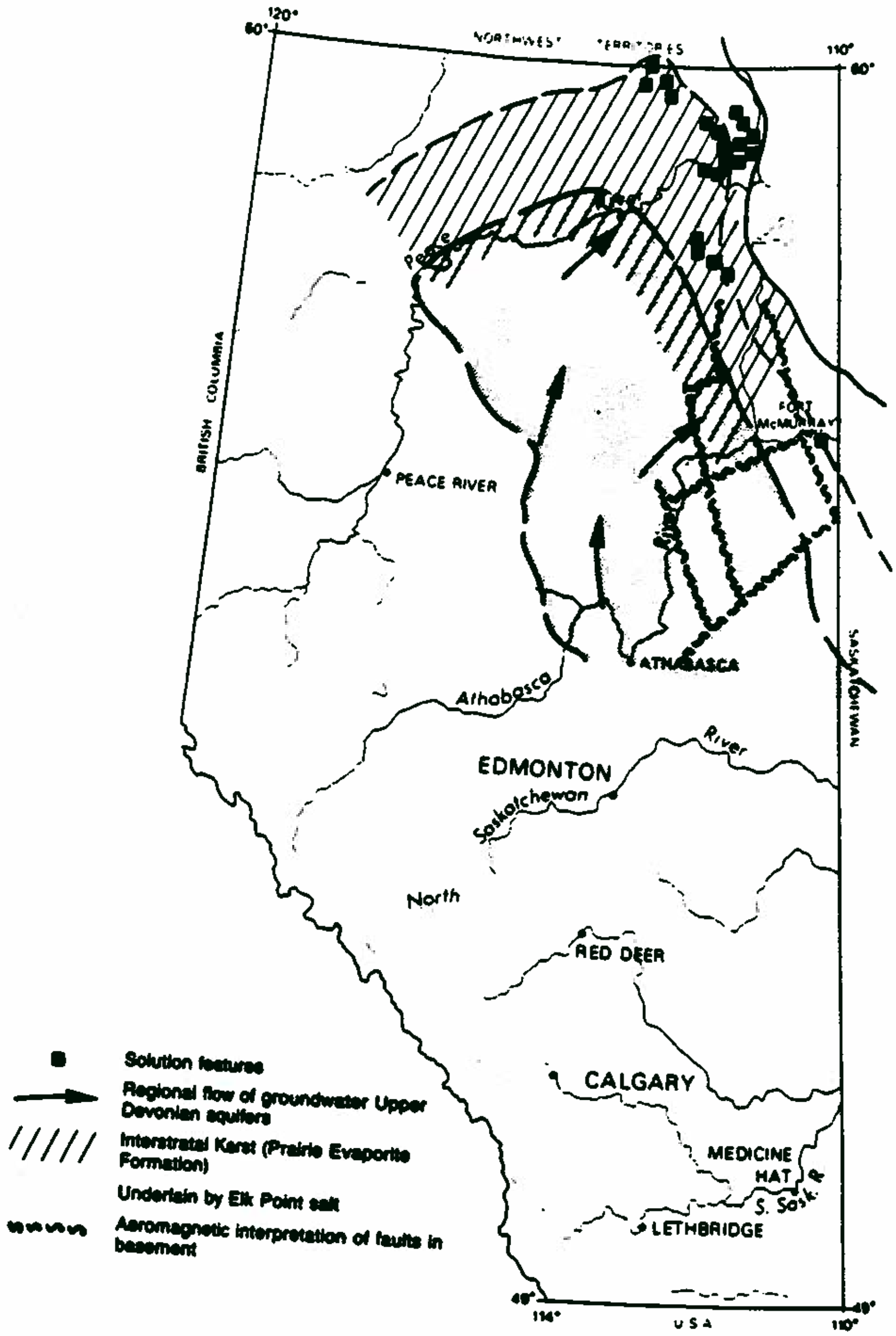



Figure 4. Limit of salt solution and direction of regional flow systems in upper Devonian aquifers in the northeastern Alberta Basin (After Ford and Quinlan, 1973).

Table 1

| WELL NAME | LOCATION | Pb/Zn CONTENT | HOST |
|---|---|---|---|
| Chevron Lutose | 16-34-118-21 W5 | Zn | Keg River |
| B.A. Saddle River | 11-23-76-9 W6 | Zn | Belly R./Spray R. Ctct |
| B.A. Zama Lake | 9-5-114-8 W6 | Zn | Keg River |
| B.A. Zama Lake A | 6-33-113-7 W6 | Zn | Keg River |
| Home KCL Chisholm | 10-5-68-2 W5 | Pb+Zn | lower Winterburn Group |
| IOE Rainbow | 13-20-107-9 W6 | Zn | Keg River |
| Calstan et al Loon River | 4-23-89-12 W5 | Zn | Muskeg |
| BP Ethyl Whitburn 7-3 | 7-30-80-11 W6 | Zn | Wabamun-Banff Transition |
| PCL Dome Oak | 11-8-83-6 W6 | Zn | Wabamun |
| | | | |
| Socony-Duhamel #29-11 | 11-29-45-21 W4 | Zn | Top D3 |
| Socony-Duhamel #29-14 | 14-29-45-21 W4 | Zn | Top D2, Ireton, D3 |
| Socony-Flint | 13-17-45-21 W4 | Zn | Top D3 |
| Banff Aquitaine | 7-32-109-8 W6 | Zn | Muskeg |
| Sun-Orr #1 New Norway | 44-21 W4 | Zn | ?? |
| Texaco Wizard Lake | ? | Zn | ?? |
| Imperial Golden Spike #11 | ? | Zn | ?? |
| Imperial Leduc 253 | 11-13-50-27 W4 | Zn | ?? |
| Imperial Golden Spike #8 | ? | Zn | ?? |

Table 1. List of mineralized wells in Alberta. Incomplete data is a result of dated and incomplete information source.

The district is located on the south shore of Great Slave Lake. The Pb-Zn mineralization is hosted by the middle Devonian reef complex, and the platformal carbonates of the Pine Point Barrier Complex (Krebs & Macqueen, 1984) [1]. The ores are epigenetic and occur predominantly as cavity fillings and replacements (Rhodes et al.,1984).

The major control on ore body distribution is thought to be a function of the east-northeast trending hingelines oriented parallel to the barrier itself. These hingelines are indicated by porosity and permeability trends and are closely, but not exactly, aligned with the Macdonald Fault system, which occurs in the Precambrian basement and projects under the Paleozoic cover in the Pine Point region (Krebs & Macqueen, 1984; Kyle, 1981).

Many aspects of Pine Point have been considered in the literature including: stratigraphy, structure, dolomitization and karstification (Rhodes et al., 1984); diagenesis and mineralization (Krebs and Macqueen, 1984); paleoenvironmental interpretation (Skall, 1975); overall geological synthesis (Kyle, 1981); fluid inclusion studies (Roedder, 1968); mineralization (Jackson and Beales, 1966); mineralization theory with respect to basin dewatering (Beales and Jackson, 1967), and; hydrogeological modeling of mineralizing systems (Garven, 1985). An extensive reference list is found in Krebs & Macqueen (1984).

## MINERALIZATION THEORIES

Mineralization models can, in some cases, point to exploration strategies. The main pitfall to using any kind of model for this approach is the assumption that the model is indeed valid. There

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1 This "reef" complex is not an ecologic or organic reef - it is more properly described as a carbonate bank, see Rhodes et al.,(1984, p. 1002)

has been a tendency in the past to generalize the features of MVT's, especially with respect to the origin of the deposits. Pine Point has served well as the Canadian type example and most Canadian authors have developed mineralization models with a bias towards the district.

## Pb-Zn Examples

Models of mineralization for MVT's are variations on one of two themes, the "mixing" and the "non-mixing" types. The non-mixing model involves the transport of both metals and reduced sulphur, in the same mineralizing fluid, to the site of deposition. The mixing model involves the transport of the metals to a site that has a source of reduced sulphur (See Anderson & Macqueen, 1982, p. 114 for summary). This source of sulphur may be another fluid (hence the mixing aspect) or may be derived through the reduction of sulphate by organic matter or methane.

Most authors (Anderson, 1978; Anderson and Macqueen, 1982; Cathles and Smith, 1983; and others) are proponents of the basinal dewatering theory of Jackson and Beales (1967). Sangster (1983, p. 8), however, suggested that the "basin evolution model could not apply to all MVT districts and it appeared not to be the unifying model that it had first appeared to be". He uses this point to argue that as a class of deposit, MVT's should be grouped to reflect their diversity. Sangster also pointed out the salient differences of the various MVT deposits and, based on metal ratios and local geological features, proposed three subtypes: 1) Pb>>Zn - Cratonal, 2) Pb=Zn - Basinal, 3) Zn>>Pb - Platformal. Based on the metal ratios of subsurface occurrences of Pb-Zn in Alberta (Table 1) and the assumption that the ratios are representative, any expected mineralization in northeastern Alberta would be of the basinal to platformal subtype. Sangster (1983) suggested that the basin evolution model of Jackson & Beales (1966) may apply to basinal sub-types but not to the other sub-types. He did not propose a specific mineralization model for the Zn>>Pb sub-type.

Sverjensky (1983) explained that the differences in metal ratios between different deposits may be due to water-rock interaction of the ore fluid en route to the site of ore deposition. There is a correlation between the Zn/Pb ratio of an ore deposit and the lithology of the aquifer encountered by mineralizing fluids. The full case is too detailed to present here, but in short, carbonate aquifers are conducive to relatively long stages of sphalerite deposition whereas sandstone aquifers are more likely to result in galena rich deposits. The following three models point to the differences in current opinion on mineralization.

Anderson and Macqueen (1982, p. 110) described the basinal dewatering theory as follows:"basin-derived fluids which acquire heat, metals and other solutes during their travels, deposit sulphides in the carbonates they encounter as they emerge from deeper parts of the basin. Fluids driven by sediment compaction derive their metals through brine leaching, carry them as chloride or organic complexes, and precipitate them as H2S is encountered." Supportive geochemical evidence for this theory are the striking chemical similarities between basinal brines and fluid inclusions contained in ores and gangue (Anderson and Macqueen, 1982).

In a modeling study of the Illinois Basin and associated MVT mineralization, Bethke (1986) listed three variations of the basinal brine theory:

a) fluid movement due to sediment compaction (Jackson & Beales, 1967).
b) episodic dewatering through excess pore pressure release (Cathles & Smith, 1983).
c) gravity driven ground water flow due to topographic differences (Garven, 1985).

His modeling indicated that sediment compaction during basin subsidence and episodic dewatering were unlikely to have resulted in mineralization in the Upper Mississippi Valley District. This suggests that, in some cases, mineralizing fluids are gravity driven (Bethke, 1986). If this is indeed the case, an argument can be made for mineralizing fluid flow, developed during the Laramide Orogeny, forming the Pine Point Deposit. He also suggested that "exploration targets should be located in likely discharge areas of past or present regional ground-water flow regimes" and that "structural or stratigraphic features which cause groundwaters to converge or ascend help localize deposits". This localization of flow was also emphasized by Cathles & Smith (1983) and Hitchon (1977). Holcombe (1985) suggested that high grade mineralization may correlate with high flow velocities and that the common setting of orebodies at basin margins and paleohighs may be a consequence of the paleoflow regime.

For the Pine Point Deposit, Krebs & Macqueen (1984, p. 462) suggested that "base metals were derived from the deeper crust, as was heat generation along the deep-seated, reactivated Precambrian McDonald fault system. Above the impermeable Precambrian basement, the hot, mineralized solutions escaped into the highly fractured and brecciated collapse zones within the Pine Point Barrier, where they combined with hydrogen sulphide and/or methane. Hydrogen sulphide was generated locally within the barrier... or.. could have migrated to the barrier from deeper portions of the basin to the southwest". The "highly fractured and brecciated collapse zones" are a result of karst development in the Pine Point Barrier but may also be due, in part, to solution associated with the mineralizing fluids (See Anderson & Macqueen, 1982, p. 114, for discussion).

Sverjensky (1981) suggested a model for the formation of the Viburnum Trend, Missouri, that involved the transport of both reduced sulphur and base metals in the same solution to the site of deposition. This model was based on textural data and sulphur and lead isotope data. Dunsmore & Shearman (1977) supported a one-fluid model in which both metals and sulphate were transported in an oil-brine emulsion. Reduction of the sulphate occurred at the site of ore deposition. The brines, metals and sulphate were suggested to have been derived from one stratigraphic assemblage of carbonate and anhydrite rocks

Cathles & Smith (1983, p. 994), in a discussion advocating the episodic dewatering of a basin resulting in MVT style mineralization, suggested five basin characteristics favourable for Pb-Zn deposit formation:

1) the basin should contain abundant units with low permeability such that geopressured zones are possible;
2) hydrodynamic conditions such that fluid flow is downward into a basal aquifer;
3) the basin must have a stable margin and the metal content of a number of fluid pulses must be deposited in the same near surface locality;
4) a thin but highly permeable basal aquifer enabling hot fluids to enter the near surface environment without significant cooling;
5) structures that focus dewatering fluids to allow smaller fluid pulses to be more effective and channel outflow to a few major escape localities.

Hitchon (1977, p. 19) and Hitchon et al.(1969) noted that in the western Canada Sedimentary Basin the Upper Devonian and Carboniferous succession in the medium depth portion of the Alberta Basin is a low fluid-potential drain. This sequence channels flow from most of the Alberta Basin towards the Fort McMurray area. Downdip from the western limit of solution of Elk Point group salt (Fig. 4), saline waters are moving updip from the deeper parts of the basin in the Upper Elk Point group and Beaverhill Lake Formation. These saline waters are in turn diluted by freshwater from Cretaceous rocks near the subcrop regions of the various Devonian strata (Hitchon et al., 1969, p. 1399).

There are no conclusive arguments for or against any of the presented models. The mixing models are supported mainly by the geological settings of most MVT deposits, fluid inclusion data and geochemical data. The non-mixing models are supported by textural data and the occurrence of district wide mineralization event stratigraphy. This discussion will approach the evaluation of the Pb-Zn potential with the assumption that the basinal dewatering theory, for the most part, is sound and applicable to northeastern Alberta.

## POTENTIAL STRATIGRAPHIC HOSTS IN NORTHEASTERN ALBERTA

The Devonian stratigraphy of northeastern Alberta has been summarized by Norris (1973) and a regional synthesis of the depositional history of the Devonian in western Canada was presented by Basset & Stout (1967) and Porter et al.(1982). A geological map of northeastern Alberta is shown in Figure 5. The Devonian stratigraphy of northeastern Alberta is shown in Figure 6. The terms Nyarling and Methy Formation are used by officers of the Geological Survey of Canada but there are questions as to the validity of the nomenclature (Hadley, 1987).

Northeastern Alberta is characterized by a shallowly west dipping sequence of siliciclastics, carbonates and a minor amount of evaporites that unconformably overlies the Precambrian basement. This sequence consists of Devonian rocks that are unconformably overlain by Cretaceous siliciclastics.

The stratigraphic nomenclature in the region is currently in a state of flux. The Devonian interval is comprised of, from the base upwards, the Elk Point Group, Beaverhill Lake Group, Woodbend Group, the Winterburn and the Wabamun Formations (ERCB, 1984).

Unconformities occur at the upper surfaces of: a) the Slave Point Formation; b) the Upper Elk Point subgroup (local); c) the uppermost Devonian strata (Fig. 6) (Norris, 1973); and, d) the

Figure 5

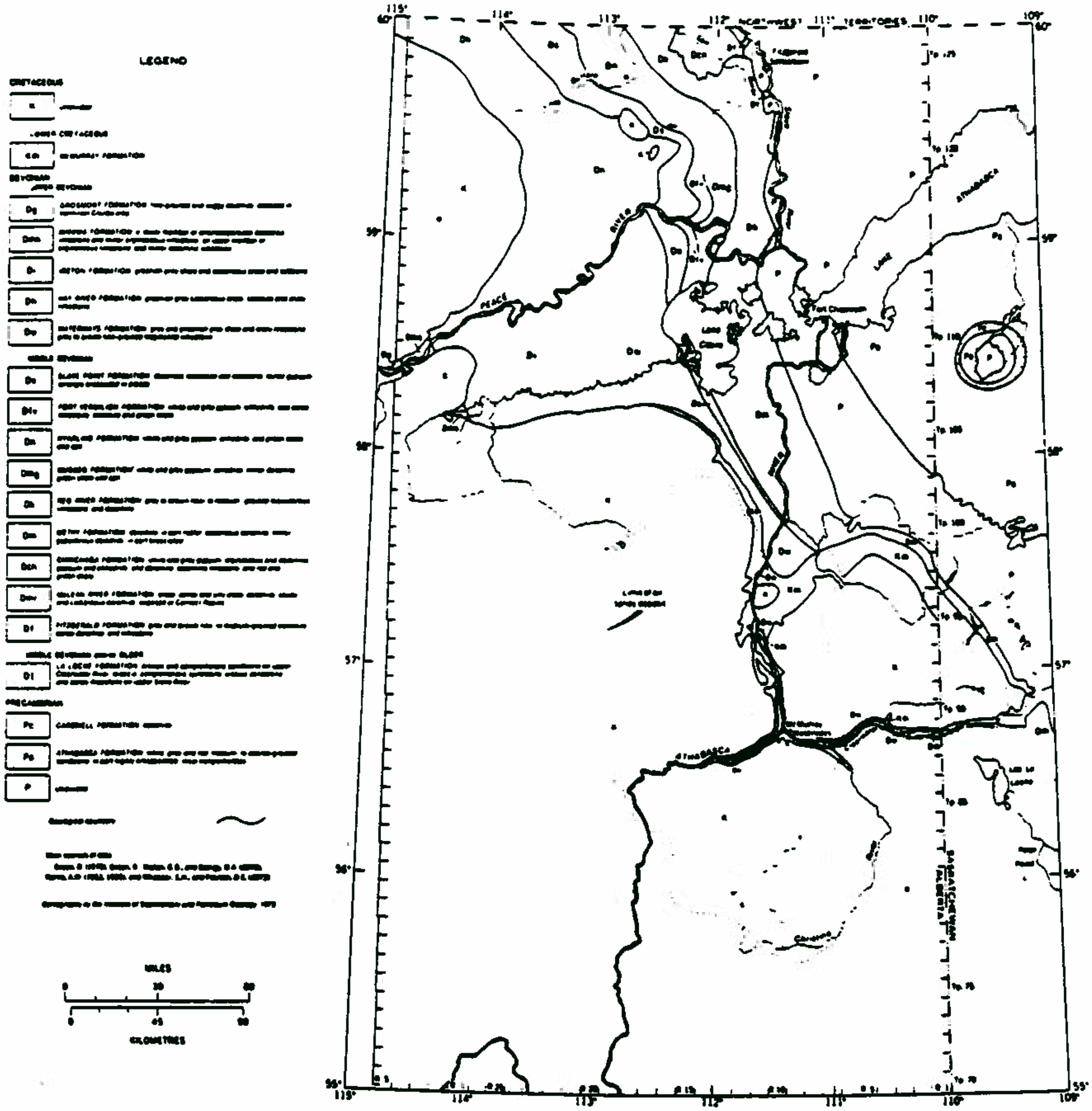

Figure 5. Geological map of northeastern Alberta (From Norris, 1973)

figure 6

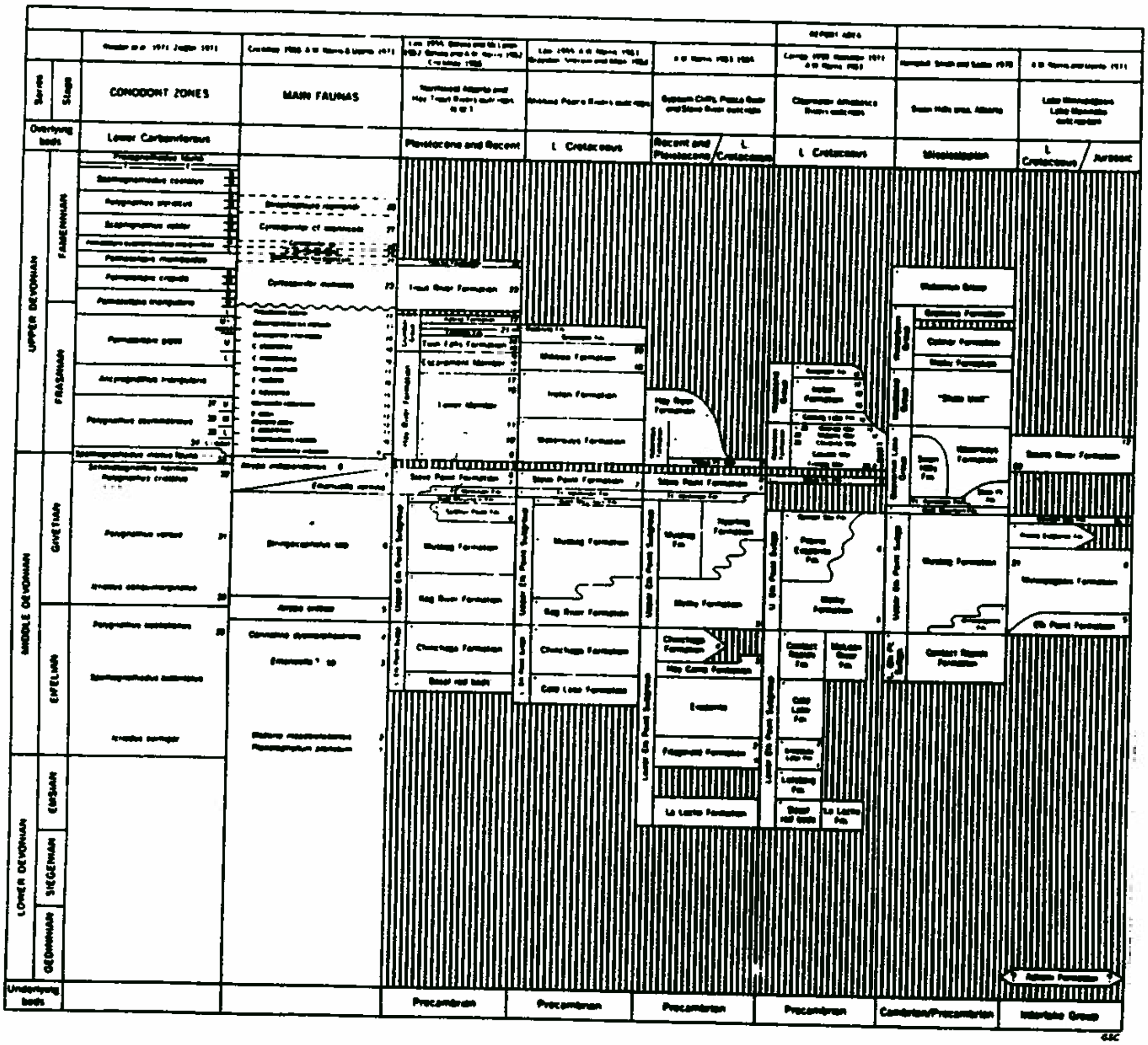


Figure 6. Devonian Stratigraphy of northeastern Alberta (From Norris, 1973).

Fort Vermilion Formation in the Wood Buffalo Park area (Park and Jones, 1985).

Park and Jones (1985) described the features resulting from repeated exposure of Devonian strata in the Peace Point region. These features included brecciation and karsting but there was no mention of any Pb-Zn mineralization.

Engineering logistics and economic constraints negate the consideration of strata deeper than aproximately 600 metres. To be considered, the potential host rock should have: 1) well developed localized porosity derived from karst or solution processes; 2) excellent fluid conduits leading to and from the host rock area.

In any event, stratigraphic horizons that have the greatest potential for mineralization include those with well developed karst features and those that have been dolomitized (see section on Characteristics of MVT's, point 3.). In light of the mineralization theory proposed for Pine Point by Krebs and Macqueen (1984), the strata that are above major Precambrian structural zones should also be considered to have good potential.

With these constraints in mind, the areas that have the most potential, based on the stratigraphic succession and basement structures, are shown in Figure 7.

## PROSPECTING APPROACHES INCLUDING BOREHOLE GEOPHYSICS

Any type of exploration program must be cost-effective and effective with respect to the scale and type of deposit being sought. For any commodity, the various types of available exploration methods should be evaluated to determine which type or types of methods are indeed effective.

figure 7

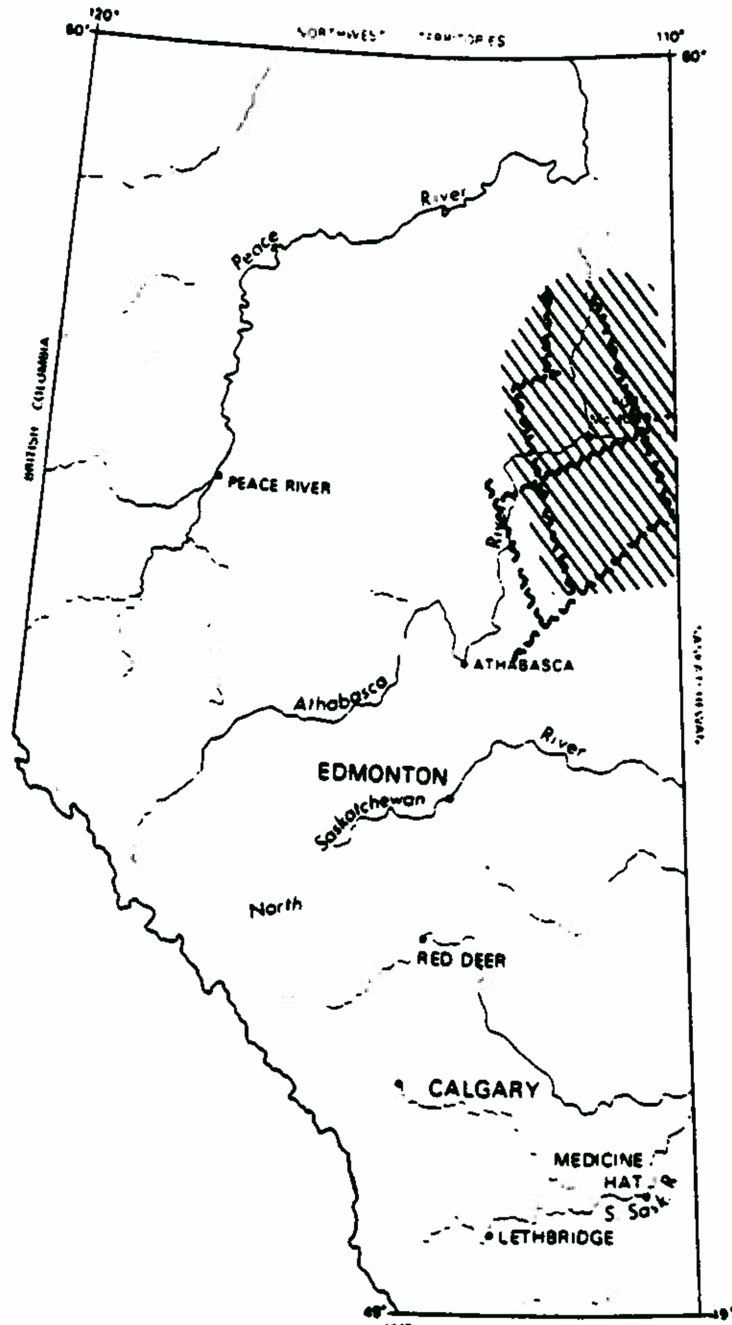


Figure 7. Basement Faults and areas of potential based on stratigraphy and fault location (fault locations based on aeromagnetic interpretations by Garland & Bower, 1959).

Prospecting Methods

Geophysical methods (i.e. self-potential, applied potential, induced polarization, magnetic and seismic) of exploration and prospecting for MVT style mineralization are, for the most part, ineffective. However, "the near-surface relatively high-grade deposits at Pine Point, N.W.T. Canada and in Ireland were detectable by geophysical methods" (Callahan and McMurry, 1967, p. 352). It should be noted that the Pine Point deposit was found by prospectors en route to Alaska during the gold rush in 1898 (Kyle, 1981; Lajoie & Klein, 1979).

Methods that have been used for the exploration of MVT deposits include IP, EM, gravity and geochemistry ("zinc-zap") for the Pine Point, Nanasivik, Cornwallis, and Mackenzie Mountains area, respectively (Gibbins, 1983). All the aforementioned mines were developed using geophysics after surface showings had initially been discovered by prospectors. These are cases where geophysics was used to develop a known deposit and not where geophysics played a part in discovering a deposit. For example, the exploration program at Pine Point has used geophysics to outline new orebodies. Lajoie & Klein (1979) determined that the induced polarization (IP) method was far superior to the electromagnetic (EM) and the self-potential methods at the Pine Point Mine. They also found that gravity surveys responded to sinkholes and large orebodies. The drawback to any electromagnetic geophysical method is the variable conductivity of the ores (Lajoie & Klein, 1979). This in part may explain the lack of response of the ores to resistivity geophysical logs as seen below.

Callahan (1977) stressed the importance of the relationship between MVT mineralized areas and the character and distribution of paleophysiographic features (i.e. facies changes, solution collapse features, sedimentary draping, etc.). This relationship can be used to prospect on the premise that these features may be identifiable using airborne geophysics. In other words, airborne geophysical methods do not have the capability to directly identify MVT type Pb-Zn targets but, in some cases, may be used to geophysically map surfaces or horizons that are deemed to have good potential. Both Barringer Research Ltd. and Geoterrex Ltd. have expressed interest in this approach.

Geochemical exploration techniques will not be addressed here, apart from the fact that both stream silt and water sampling have been shown to be relatively successful methods for Pb-Zn exploration.

Smith et al. (1983) documented fluid migration from compacted shales in the Mackenzie Basin to the northeast of Pine Point. Their technique, using sonic logs to identify dewatered intervals in shales, delineated conduits through which mineralizing fluids were suggested to have flowed. These dewatered intervals are identified by a slight increase in transit time of the log on a depth verses shale transit time plot. This increase in transit time represents relatively undercompacted shales. Where these undercompacted intervals overlie compacted intervals and permeable strata, it is assumed that downward dewatering has occurred. Assuming that the Alberta Basin is the source for any mineralizing fluids, this approach could be used, in a regional sense, to define potential areas of mineralization.

Two recent studies may have implications for MVT mineralization exploration. For the Pine Point deposit, Powell & Macqueen (1984) determined that the organic matter in proximity to mineralization had been altered by heat and reaction with sulphur. These altered bitumens are characterized by certain isotopic signatures. Assuming that the organic matter is indeed significant in the mineralization process, it would follow that organic geochemical trends and patterns in barren rocks may indicate mineralizing fluid paths or point to mineralized regions. A study by Gregg & Hagni (1987) involved the examination of irregular cathodoluminescent banding in late dolomite cements to indicate the presence of mineralizing brines. They suggested that metal cations in mineralizing brines had a interuptive effect on dolomite crystal growth, which in turn resulted in the development of complex crystal faces. A regional study of the subsurface dolomites in northeastern Alberta might point to fluid paths. Both approaches are academic in nature and speculative, but would be interesting projects for university style research.

Anderson & Macqueen (1982, p. 115) and Anderson (1978, p. 18) summarized the characteristics of MVT's relevant to the exploration of the same. These included unconformities and karsting in basin margin settings, basement control in the form of arching, flexing or faulting, dolomitized units, and the presence of organic matter and evaporites.

In summary, the exploration for MVT style mineralization is difficult using geophysical methods. Prospecting and geochemistry are the most efficient ways to outline potential areas of mineralization. Geophysics may, however, play an important role in developing near surface, relatively high-grade orebodies, similar to those at Pine Point, after a deposit has been identified by other means.

Borehole Geophysics Applications to Exploration

The practical application of borehole logs for mineral exploration has presumably not been evaluated specifically for carbonate hosted Pb-Zn deposits as evidenced by the lack of any published information on the subject. This may be a result of the following:

1) the obviousness of significant amounts of sphalerite and galena in oil well drill cuttings eliminating the need for examination of geophysical log response;
2) the lack of data on the response of different geophysical logs to Pb-Zn mineralized zones; and,
3) the effectiveness of other exploration techniques (i.e.

geochemistry or ground geophysics) with respect to borehole geophysics.

However, borehole geophysics (designed specifically for mineral exploration and evaluation, and not from petroleum exploration) have successfully been used for the evaluation of magnetite (Evans, 1970; Baltosser and Lawrence, 1970), gypsum and anhydrite (Threadgold, 1970). Anderson (1973) suggested that potash and coal may also be quantitatively evaluated using borehole geophysical data from petroleum holes. If the gap between the petroleum exploration geophysics and the geophysics designed specifically for mineral evaluation can be bridged, a large established data base would be available for mineral potential evaluation.

The types of borehole logs run in a geological sequence are largely dependant on the host lithology. Typically, in a carbonate sequence, the following logs can be expected: gamma-ray, laterolog, and two or more porosity logs (sonic, density and neutron, in that order) (Telford et al.,1976, p. 773). The gamma-ray log determines the natural radiation emitted by Th, K, and U, and usually is used to identify shale content. The laterolog is a focussed resistivity tool that measures, for the most part, the resistivity of the formational fluids to electric current. The sonic log measures the travel time of a compressional acoustic wave through the rock and is a function of lithology, interconnected pore space and pore fluid. The density log indicates the density of the host rock and pore fluids. The neutron log measures the hydrogen content of the rock and pore fluids and is used to estimate porosity.

The indentification of sphalerite and galena on most of the logs described is not possible in that the minerals do not have physical properties with characteristic log responses. For instance, the radioactive element content of sphalerite and galena is negligible, therefore the gamma log could not detect the minerals. The density log, however, might identify both sphalerite (3.85 gms/cc) and galena (6.17 gms/cc) under the proper set of geological circumstances. Pb-Zn ores with resistivities ranging from 1.3 to 1700 ohmmetres have been described by Telford et al.(1976, p. 453). These may be identifiable on resistivity logs, assuming that the mineralization is distinct enough and abundant enough as to not have any characteristic log signatures overwhelmed by the host rock. It should be noted that there have not been any quantitative or qualitative studies on this approach to mineral identification through petroleum exploration borehole geophysics and that these comments on the suitability of various logs are purely speculative. Another problem that arises is the type and quality of the available data. For example, holes that were drilled before the advent of certain technologies (i.e. density logs) would not be amenable to this evaluation approach.

To evaluate the feasability of this approach, nine petroleum exploration holes known to have intersected mineralized horizons were obtained from CANSTRAT. Two of these holes had been logged with density and resistivity tools over thin mineralized intervals that contained up to 3% sphalerite (Fig. 8). The density logs do not show any characteristic signature over the mineralized intervals. This may be a result of the low concentration of sphalerite with respect to the host rock, the physical limitations of the resolution of the tool, or the inappropriateness of the method. The pertinent resistivity logs (Fig. 8), like the density logs, do not show any characteristic response.

The conclusion reached here, based on a highly cursory, qualitative examination of geophysical logs, is that this procedure for Pb-Zn exploration and evaluation is not viable. In the event that the economic outlook for Pb-Zn improves, an in depth study of geophysical log response involving test sites under simulated field conditions and varying concentrations of minerals may be warranted. This approach may be more appropriate, at

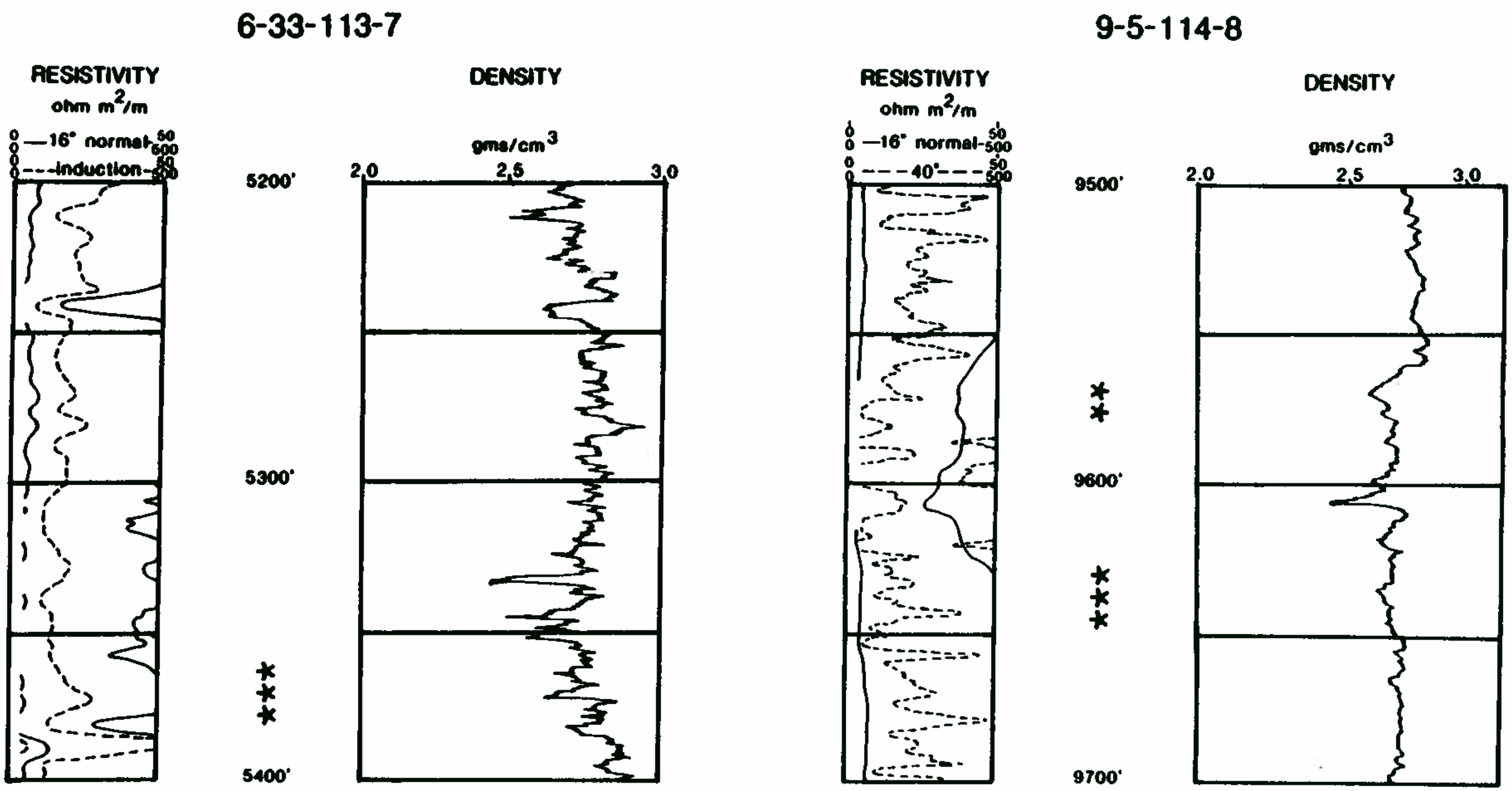


Figure 8. Density and electric log response to lead-zinc mineralization. Mineralized intervals are indicated by asterisks and contain up to 3% combined sphalerite and galena.

present, for other minerals such as potash and gypsum, which show characteristic geophysical log responses.

## APPLICABILITY OF PETROLEUM EXPLORATION DATA

A large amount of data from petroleum exploration is available through the ERCB. These data are stored on computer and, for the most part, can be manipulated to obtain various styles and types of output. For instance, in cases where specific stratigraphic horizons are targeted for evaluation a listing of cored intervals within that horizon is easily obtainable. Isopach maps are also easily generated using this data base. A complete listing is impractical here but the main information pertinent to any exploration program includes: 1) well location; 2) formational picks; 3) geophysical logs, and; 4) cored intervals.

The distribution of petroleum exploration drillholes in northeastern Alberta, superimposed on a structure map of the depth to the Precambrian basement, is shown in figure 9. The number of drillholes in areas of thin cover is limited and this may be a limitation to this data base.

The use of borehole geophysics, as demonstrated above, is of limited applicability to the exploration and evaluation of certain commodities. The physical limits of the tools themselves limit the capability of the log to indicate a commodity. The likelihood of identifying any type of low tonnage-high grade commodity from geophysical logs would be small except in the case of radioactive materials. This approach has the best chances of success in the search for high tonnage deposits with characteristic geophysical responses.

The detailed examination of core and drill cuttings would be a more effective way of identifying mineralized horizons. With the time involved in examination of cuttings and core, this method would only be reasonable in the case of high tonnage deposits or low tonnage mineralization that is limited to an easily identifiable geological feature. However, this method would involve extensive man-hours and financial commitment to ensure a complete survey. This commitment is not likely to be forthcoming from small exploration companies but, in rare situations, may be acceptable to larger companies. Therefore, for the most part, for commodities that do not have an excellent long term outlook and are not high tonnage, the use of a petroleum well data base for mineral evaluation and exploration does not appear to be cost effective.

## SUITABILITY AND SIGNIFICANCE OF GROUNDWATER MODELING

Groundwater modeling of regional systems as possible transport agents for mineralizing fluids is in its relative infancy. Mathematical models have been suggested specifically for the Illinois Basin (Bethke, 1986), Pine Point (Garven, 1985), the Ouachita Basin (Sharp, 1978), and for sedimentary ore deposits in general by Holcombe (1985). Concept papers on basin dewatering relevant to modeling include those by Sawkins (1984), Cathles and Smith (1983), Mazzullo (1986), and those noted previously in the Models of Mineralization section.

The main drawback to any type of modeling for exploration purposes is that models are descriptive and not predictive. The papers listed above document models that describe generalized regional flow systems that <u>may</u> have formed known deposits. A known flow system may indicate regional areas of potential mineralization but will not indicate specific targets. Garven (1985, p. 322) stated "hydrogeologic modeling ... could be used to refine exploration models on a regional scale, but attempts to extend the method into predictive simulation of ore formation at a local scale would probably encounter both theoretical and data limitations that may be difficult to surmount in the forseeable future".

figure 9

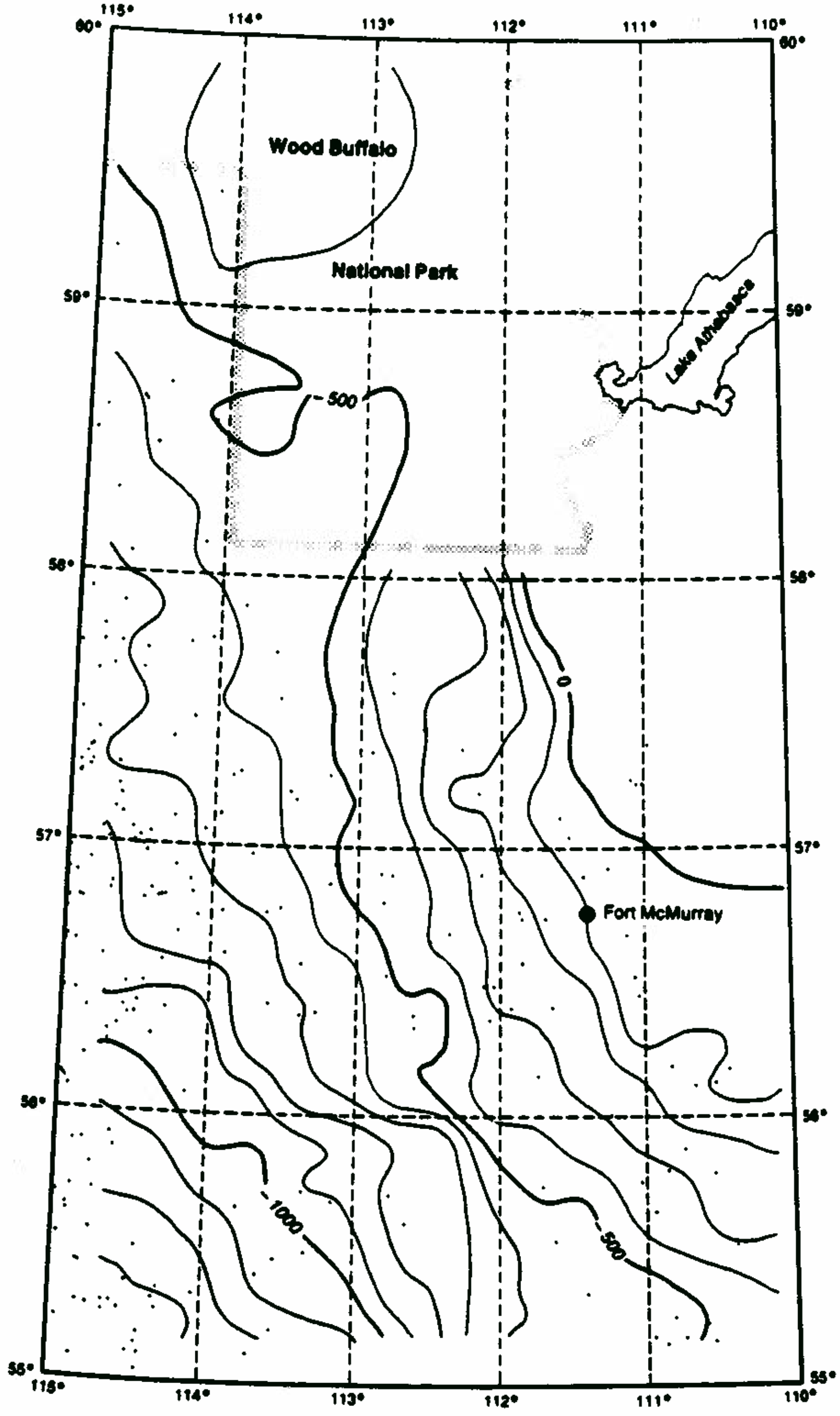


Figure 9. Drill hole distribution and depth to Precambrian basement in northeastern Alberta. Data obtained from ERCB computer files.

## DISCUSSION

The timing of basin dewatering and certain aspects of mineral deposition are the most significant "unknown factors" in the evaluation of the mineral potential of northeastern Alberta. These aspects can be addressed in a simplistic manner by examining:

1) the source of metals

Hitchon (1979, p. 113) noted the presence of large amounts of leachable trace metals in Devonian shales from western Canada. Analyses of oil field brines from Mississippi by Carpenter et al. (1974) and northern Alberta by Billings et al.(1969) support the assumption that high metal contents in brines are not uncommon. Therefore, it is valid to assume that metals in solution are indeed available for deposition from migrating basinal fluids.

2) fluid flow is gravity driven

This point has been discussed previously. By making the link between the timing of hydrocarbon migration and the timing of movement of mineralizing fluids a time bracket may be inferred for the Alberta Basin. Masters (1984) suggested that oil generation from Cretaceous source rocks began at the end of the Cretaceous. Watts (1987) suggested that geochemical data indicated that the migration of hydrocarbons into the Nisku reefs occurred during Upper (sic) Cretaceous time and also commented that the main phase of dolomitization of the reefs began during the Mississippian and continued until the sediments were buried to the oil window level in the Cretaceous. Based on the basin modeling and the Cretaceous ages suggested for the timing of significant fluid transport within the Alberta Basin, it is assumed here that any gravity driven system that had the potential to deposit Pb-Zn most likely occurred during the late Cretaceous as a result of the Laramide Orogeny.

Another problem is that basin modeling dictates that fluid flow is along a basal aquifer, enabling the fluid to acquire heat and maintain the temperatures as indicated by fluid inclusions. If mineralization is in part controlled by basement faulting, as suggested by Krebs & Macqueen (1984) and others, the heat may be aquired from basement fluids rising up along the structures. In these cases, a basal aquifer is not necessarily required.

3) a host rock is available for mineral deposition

The potential host rocks, based on lithologic character and the degree of porosity development have already been discussed. However, another significant aspect of the host rock is the availability of the pore space for mineralization. For example, if there was a significant amount of hydrocarbon in the pore space and the hydrocarbon was relatively immobile due to hydrodynamic conditions, the pore space would not be available for Pb-Zn deposition. Rouchet (1984), Masters (1984) and Hoffman & Strausz (1986) have indicated that the upper part of the Paleozoic unconformity and basal Cretaceous sands acted as the regional fluid migration path for oils found in the Ft. McMurray area and in the "carbonate trend". The unconformity surface is presently saturated with hydrocarbons. This part of the succession has well developed porosity and permeability due to karsting and, if available for mineralization, would make an excellent host rock. But, it is possible that the pore space was already occupied before mineralizing fluids were available.

4) that fluid flow is focused

Masters (1984, p. 23) indicated that the major path of the Cretaceous oils was not along restricted channels but "more like a huge wave or flood across vast areas". Assuming that hydrocarbon transport and mineralizing fluid movement are part of a continuum, this is in contrast to the focused flow that has been suggested as a requisite for mineralization. This may be a moot point if mineralization was not related to the basin dewatering system developed during the Laramide Orogeny. Again, the lack of understanding of the timing of mineralization leads to problems.

## CONCLUSIONS and SUMMARY

1) The economic outlook of Pb-Zn for the next 20 years is poor and, as a result, active exploration for this commodity in the near future is unlikely. The exception may be in the case of larger companies with sufficient cash flow to obtain and maintain claimed land.

2) MVT ores are typically stratiform and epigenetic, occur in dolostones, are sometimes controlled by paleokarst development and are commonly found near the edges of basins. The lack of understanding of the timing of mineralization is the largest obstacle to a better understanding of MVT mineralization.

3) No significant lead-zinc mineralization has been reported from northeastern Alberta. Surface showings exist in the Cambrian dolostones in the Kicking Horse Pass region. Subsurface lead-zinc has been reported in middle and upper Devonian rocks of central and northwestern Alberta, respectively.

4) Most MVT mineralization models invoke basin dewatering as the requisite mechanism. Two types of models, mixing and non-mixing, are differentiated on the basis of the source and type (transported or in situ) of reduced sulphur.

5) Potential host rocks in Alberta, based on pore space development, include the Slave Point Formation, locally the top of the Upper Elk Point subgroup, and the Paleozoic unconformity surface. If basement faults are assumed to influence mineralization, specific areas can be delineated that have 'good' potential.

6) For the most part, geophysical methods are ineffective for the exploration of MVT mineralization. Airborne geophysics may identify horizons with good potential but cannot directly indicate Pb-Zn mineralization. IP, EM and gravity methods have been used

successfully at established mines to outline new orebodies but their use for exploration at a reconnaissance scale is not recommended. Prospecting and geochemical techniques are the most effective ways of outlining potential areas of mineralization.

7) The applicability of petroleum exploration data as a data source for mineral exploration is limited. The use of borehole geophysics for Pb-Zn exploration appears, at the present level of understanding of the response of downhole petroleum geophysical tools to mineralization, to be ineffective. However, the use of the same data base for other commodities, such as gypsum and potash, may be appropriate. ERCB computerized data files are useful for subsurface mapping, identifying the types of geophysical logs available for a specific well, logged intervals and available core.

8) Groundwater modeling as an exploration tool is limited in that the method, at best, can only describe regional flow systems that in turn can indicate regional targets. Attempts to refine the procedure to a local scale would be hampered by both theoretical and data limitations.

REFERENCES

Anderson, W. (1973): Potential uses for borehole logs in mineral exploration; Candaian Mining and Metallurgical Bulletin, v. 67, no. 743, pp. 164-168.

Anderson, G.M. (1975): Precipitation of Mississippi Valley-type ores; Economic Geology, v. 70, pp. 937-942.

Anderson, G.M. (1978): Basinal brines and Mississippi Valley-type ore deposits; Episodes, no. 2, pp. 15-19.

Anderson, G.M. (1983): Some geochemical aspects of sulphide precipitation in carbonate rocks in International Conference on Mississippi Valley Type Lead-Zinc Deposits, Kisvarsanyi, G., Grant, S.K., Pratt, W.P. and J.W. Koenig (eds.); Proceedings Volume, University of Missouri-Rolla, Rolla, Missouri, pp. 61-76.

Anderson, G.M. and R.W. Macqueen (1982): Ore deposit models - 6. Mississippi Valley-type lead-zinc deposits; Geoscience Canada, v. 9, pp. 108-117.

Baltosser, R.W. and H.W. Lawrence (1970): Application of well logging techniques in mineral mining; Geophysics, v. 35, no. 1, pp. 143-152.

Barnes, H.L. (1983): Ore-depositing reactions in Mississippi Valley-type deposits: in International Conference on Mississippi Valley Type Lead-Zinc Deposits, Kisvarsanyi, G., Grant, S.K., Pratt, W.P. and J.W. Koenig (eds.); Proceedings Volume, University of Missouri-Rolla, Rolla, Missouri, pp. 77-85.

Basset, H.G. and J.G. Stout (1967): Devonian of western Canada: in International Symposium on the Devonian System, v. 1, D.H. Oswald (ed.); Alberta Society of Petroleum Geologists, Calgary, pp. 717-752.

Beales, F.W. (1975): Precipitation mechanisms for Mississippi Valley-type deposits; Economic Geology, v. 70, pp. 943-948.

Beales, F.W. and S.A. Jackson (1966): Precipitation of lead-zinc ores in carbonate reservoirs as illustrated by Pine Point ore field, Canada; Transactions of the Institute of Mining and Metallurgy, Sec. B75, pp. B278-B285.

Beales, F.W. and E.P. Onasick (1970): The stratigraphic habitat of Mississippi Valley-type orebodies; Transactions of the Institute of Mining and Metallurgy, Sec. B, v. 79, pp. B145-B154.

Bebout, D.G. and W.R. Maiklem (1973): Ancient anhydrite facies and environments of the middle Devonian Elk Point Basin, Alberta;

Bulletin of Canadian Petroleum Geologists, v. 21, no. 3, pp. 287-343.

Bethke, C.M. (1986): Hydrologic constraints on the genesis of the Upper Mississippi Valley Mineral District from Illinois basin brines; Economic Geology, v. 81, no. 2, pp. 233-249.

Bigauskas, J. (1986): Lead: in Canadian Minerals Yearbook 1985 Review and Outlook, G. Cathcart (ed.), Energy, Mines and Resources Canada, Mineral Report 34, p. 34.1-34.12.

Billings, G.K., Kesler, S.E., and S.A. Jackson (1969): Relation of zinc-rich formation waters, northern Albeta, to the Pine Point Ore Deposit; Economic Geology, v. 64, pp. 385-391.

Brown, J.S. (1970): Mississippi Valley type lead-zinc ores; Mineralium Deposita, v. 5, pp. 103-119.

Callahan, W.H. (1977): Some thoughts regarding premises and procedures for prospecting for base metal ores in carbonate rocks in the North American Cordillera; Economic Geology, v. 72, pp. 71-81.

Callahan, W.H. and H.V. McMurry (1967): Geophysical exploration of Mississippi Valley-Appalachian type strata-bound zinc-lead deposits; Geological Survey of Canada, Economic Geology Report no. 26, pp. 350-360.

Carpenter, A.B., Trout, M.L. and E.E. Pickett (1974): Preliminary report on the origin and evolution of lead and zinc-rich oil field brines in central Mississippi; Economic Geology, v.69, pp.1191-1206.

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

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

Coles, R.L., Haines, J.V. and W. Hannaford (1976): Large scale magnetic anomalies over western Canada and the Arctic: A discussion; Canadian Journal of Earth Sciences, v. 13, pp. 790-802.

Davis, J.H. (1977): Genesis of southeast Missouri lead deposits; Economic Geology, v. 72, pp. 443-450.

du Rouchet, J. (1985): The origin and migration paths of hydrocarbons accumulated in the Lower Cretaceous sandstone "giant" tar accumulations of Alberta-II; Journal of Petroleum Geology, v. 8, no. 1, pp. 101-114.

Dunsmore, H.E. and D.J. Shearman (1977): Mississippi Valley-type lead-zinc orebodies: a sedimentary and diagenetic origin: in Proceedings on the Forum on Oil and Ore in Sediments, P. Garrard (ed.); Department of Geology, Imperial College, Prince Consort Road, London, pp. 190-205.

Dyck, A.V. (ed.) (1975): Borehole geophysics applied to mineral prospecting: a review; Geological Survey of Canada, Paper 75-31, 67 p.

Evans, H.B. (1970): Status and trends in logging; Geophysics, v. 35, no. 1, pp. 93-112.

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

Fowler, A.D. (1986): The role of fluid flow in the genesis of the Pine Point deposit, western Canada Sedimentary Basin - A discussion; Economic Geology, v. 81, pp. 1014-1024.

Garland, G.D. and M.E. Bower (1959): Interpretation of aeromagnetic anomalies in northeastern Alberta; 5th World Petroleum Congress, Section 1, Paper 42, pp. 787-800.

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

Gauvin, M.J. (1986): Zinc: in Canadian Minerals Yearbook 1985 Review and Outlook, G. Cathcart (ed.), Energy, Mines and Resources Canada, Mineral Report 34, p. 66.1-66.12.

Gibbins, W.A. (1983): Mississippi Valley type lead-zinc districts of northern Canada: in International Conference on Mississippi Valley Type Lead-Zinc Deposits, Kisvarsanyi, G., Grant, S.K., Pratt, W.P. and J.W. Koenig (eds.); Proceedings Volume, University of Missouri-Rolla, Rolla, Missouri, pp. 403-414.

Giordano, T.H. (1985): A preliminary evaluation of organic ligands and metal-organic complexing of Mississippi Valley-type ore solutions; Economic Geology, v. 80, pp. 96-106.

Giordano, T.H. and H.L. Barnes (1981): Lead transport in Mississippi Valley-type ore solutions; Economic Geology, v. 76, pp. 2200-2211.

Godfrey, J.D. (1985): Lead and zinc - commodity profile; Internal report to AENR, Alberta Research Council Internal Report, 22 p.

Gregg, J.M. and R.D. Hagni (1987): Irregular cathodoluminescent banding in late dolomite cements: Evidence for complex faceting and metalliferous brines; Geological Society of America

Bulletin, v. 98, pp. 86-91.

Hadley, M.G. (1986): Devonian stratigraphy of northern Alberta, northeastern B.C. and District of Mackenzie; Unpublished paper, Geology 608, University of Alberta, 85 p.

Haites, T.B. (1960): Transcurrent faults in western Canada; Journal of the Alberta Society of Petroleum Geologists, v. 8, no. 2, pp. 33-78.

Haynes, S.J. and M.A. Mostaghel (1982): Present-day precipitation of lead and zinc from groundwaters; Mineralium Deposita, v. 17, pp. 213-228.

Heyl, A.V. and W.S. West (1982): Outlying mineral occurrences related to the Upper Mississippi Valley Mineral District, Wisconsin, Iowa, Illinois, and Minnesota; Economic Geology, v.77, pp. 1803-1817.

Hitchon, B. (1969a): Fluid flow in the Western Canada Sedimentary Basin: 1. Effect of topography; Water Resources Research, v. 5, no. 1, pp. 186-195.

Hitchon, B. (1969b): Fluid flow in the Western Canada Sedimentary Basin :2. Effect of geology; Water Resources Research, v.5, no. 2, pp. 460-469.

Hitchon, B. (1977): Geochemical links between oil fields and ore deposits in sedimentary rocks: in Proceedings on the Forum on Oil and Ore in Sediments, P. Garrard (ed.); Department of Geology, Imperial College, Prince Consort Road, London, pp. 1-37.

Hitchon, B. (1980): Some economic aspects of rock-water interaction: in, Problems of Petroleum Migration, W.H. Roberts III and R.J. Cordell (eds.); American Association of Petroleum Geologists, Studies in Geology no. 10, pp. 109-119.

Hitchon, B., Levinson, A.A., and S.W. Reeder (1969c): Regional variations of River Water Composition Resulting from Halite Solution, Mackenzie River Drainage Basin, Canada; Water Resources Research, v. 5, no. 6, pp. 1395-1403.

Hoffman, C.F. and O.P. Strausz (1986): Bitumen accumulation in Grosmont Platform Complex, Upper Devonian, Alberta, Canada; American Association of Petroleum Geologists Bulletin, v. 70, no. 9, pp. 1113-1128.

Holcombe, C.J. (1985): Paleoflow modeling for sedimentary orebodies; Economic Geology, v. 80, pp. 172-179.

Hood, P.J. (ed.) (1979): Geophysics and geochemistry in the search for metallic ores; Geological Survey of Canada, Economic Geology Report 31, 809 p.

Hoy, T. (1982): Stratigraphy and structural setting of stratiform lead-zinc deposits in southeastern B.C.; Canadian Institute of Mining and Metallurgy Bulletin, v. 75, no. 840, pp. 114-134.

Jackson, S.A. and F.W.Beales (1967): An aspect of sedimentary basin evolution: the concentration of Mississippi Valley-type ores during late stages of diagenesis; Canadian Petroleum Geology Bulletin, v. 15, pp. 383-433.

Jackson, S.A. and R.E. Folinsbee (1969): The Pine Point lead-zinc Deposits, N.W.T., Canada: Introduction and paleoecology of the Presquile Reef; Economic Geology, v.64, no. 7, pp. 711-717.

Kerr, J.W. (1976): Cornwallis lead-zinc District; Mississippi Valley-type deposits controlled by stratigraphy and tectonics; Canadian Journal of Earth Sciences, v.14, pp. 1402-1426.

Krebs, W. amd R.W. Macqueen (1984): Sequence of diagenetic and mineralization events, Pine Point; Canadian Society of Petroleum Geologists Bulletin, v.32, no. 4, pp. 434-464.

Kyle, J.R. (1976): Brecciation, alteration and mineralization in the Central Tennessee Zinc District; Economic Geology, v. 71, pp. 892-903.

Kyle, J.R. (1983): Temporal and spatial aspects of mineralization in the K57 Orebody, Pine Point District, N.W.T., Canada: in International Conference on Mississippi Valley Type Lead-Zinc Deposits, Kisvarsanyi, G., Grant, S.K., Pratt, W.P. and J.W. Koenig (eds.); Proceedings Volume, University of Missouri-Rolla, Rolla, Missouri, pp. 338-345.

Lajoie, J.J. and J. Klein (1979): Geophysical exploration at Pine Point Mines Ltd. zinc-lead property, Northwest Territories, Canada: in Geophysics and Geochemistry in the Search for Metallic Ores; P.J. Hood (ed.), Geological Survey of Canada, Economic Geology Report 31, pp. 653-664.

Lindblom, S. (1986): Textural and fluid inclusion evidence for ore deposition in the Pb-Zn deposit at Laisvall, Sweden; Economic Geology, v.81, pp. 46-64.

Long, K.R., Kelly, W.C., Ohle, E.L. and K. Lohmann (1986): Ground preparation and zinc mineralization in bedded and breccia ores of the Monte Cristo Mine, North Arkansas; Economic Geology, v.81, pp. 809-830.

MacIntyre, D.G. (1982): Geologic setiing of recently discovered stratiform barite-sulphide deposits in northeast British Columbia; Canadian Institute of Mining and Metallurgy Bulletin, v. 75, no. 840, pp. 99-113.

Macqueen, R.W. (1976): Sediments, zinc and lead, Rocky Mountain

Belt, Canadian Cordillera; Geoscience Canada, v. 3, pp. 71-81.

Macqueen, R.W. (1979): Base metal deposits in sedimentary rocks: Some approaches; Geoscience Canada, v. 6, pp. 3-9.

Macqueen, R.W. and R.I. Thompson (1978): Carbonate-hosted lead-zinc occurrences in northeastern British Columbia with emphasis on the Robb Lake Deposit; Canadian Journal of Earth Sciences, v. 15, pp. 1737-1762.

Macqueen, R.W. amd T.G. Powell (1983): Organic geochemistry of the Pine Point Lead-zinc Ore Field and region, N.W.T., Canada; Economic Geology, v. 78, no. 1, pp. 1-25.

Masters, J.A. (1984): Lower Cretaceous oil and gas in Western Canada; in J.A. Masters (ed.); Deep Basin Gas: American Association of Petroleum Geologists , Memoir 38, pp. 1-38.

Mazzullo, S.J. (1986): Mississippi Valley-type sulphides in lower Permian dolomites, Delaware Basin, Texas: Implications for basin evolution; American Association of Petroleum Geologists Bulletin, v. 70, no. 8, pp. 943-952.

McCamis, J.G. and L.S. Griffith (1967): Middle Devonian facies relationships, Zama area, Alberta; Bulletin of Canadian Petroleum Geology, v.15, no. 4, pp. 434-467.

McNaughton, K. and T.E. Smith (1986): A fluid inclusion study of sphalerite and dolomite form the Nanasivik Lead-Zinc Deposit, Baffin Island, N.W.T., Canada; Economic Geology, v. 81, pp. 713-720.

Moshier, S.O. and D.W. Waples (1985): Quantitative evaluation of Lower Creaceous Mannville Group as source rock for Alberta's Oil Sands; American Association of Petroleum Geologists Bulletin, v. 69, no. 2, pp. 161-172.

Norris, A.W. (1963): Devonian stratigraphy of northeastern Alberta and northwestern Saskatchewan; Geological Survey of Canada, Memoir 313, 168 p.

Norris, A.W. (1973): Paleozoic (Devonian) geology of northeastern Alberta and northwestern Saskatchewan in, Guide to the Athabasca Oil Sands area, M.A. Carrigy and J.W. Kramers (eds.); Alberta Research Council, Information Series no. 65, 61 p.

Ohle, E.L. (1980): Some considerations in determining the origin of ore deposits of the Mississippi Valley-tyo - Part II; Economic Geology, v. 75, pp. 161-171.

Olson, R.A.O. (1984): Genesis of paleokarst and strata-bound zinc-lead sulphide deposits in a Proterozoic dolostone, northern Baffin Island, Canada; Economic Geology, v. 79, pp. 1056-1103.

Park, D.G. and B. Jones (1985): Nature and genesis of breccia bodies in Devonian strata, Peace Point area, Wood Buffalo Park, northeast Alberta; Canadian Society of Petroleum Geologists Bulletin, v. 33, no. 3, pp. 275-294.

Porter, J.W., Price, R.A. and R.G. McCrossan (1982): The Western Canada Sedimentary Basin; Royal Society [London] Philisophical Transactions, v. 305, pp. 169-192.

Powell, T.G. and R.W. Macqueen (1984): Precipitation of sulphide ores and organic matter: Sulphate reactions at Pine Point, Canada; Science, v. 224, pp. 63-66.

Rhodes, D., Lantos, E.A., Lantos, J.A., Webb, R.J. and D.C. Owens (1984): Pine Point orebodies and their relationship to the stratigraphy, structure, dolomitization, and karstification of the Middle Devonian Barrier Complex; Economic Geology, v. 79, pp. 991-1055.

Roedder, E. (1968): Temperature, salinity, and origin of the ore-froming fluids at Pine Point, N.W.T., Canada, from fluid inclusion studies; Economic Geology, v. 63, pp. 439-450.

Sangster, D.F. (1986): Classification, distribution and grade-tonnage summaries of Canadian lead-zinc deposits; Geological Survey of Canada, Economic Geology Report 37, 68 p.

Sangster, D.F. (1983): Mississippi Valley-type deposits: A geological melange: in International Conference on Mississippi Valley Type Lead-Zinc Deposits, Kisvarsanyi, G., Grant, S.K., Pratt, W.P. and J.W. Koenig (eds.); Proceedings Volume, University of Missouri-Rolla, Rolla, Missouri, pp. 7-19.

Sangster, D.F. and R.D. Lancaster (1976): Geology of Canadian lead and zinc deposits: Geological Survey of Canada, Report of Activities, Paper 76-1A, Pt. A, pp. 301-310.

Sawkins, F.G. (1984): Ore genesis by episodic dewatering of sedimentary basins: Application to giant Proterozoic lead-zinc deposits; Geology, v. 12, pp. 451-454.

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

Sheriff, R.E. (1970): Glossary of terms used in well logging: Gephysics, v. 35, pp. 1116-1139.

Skall, H. (1975): The paleoenvironment of the Pine Point Lead-zinc District; Economic Geology, v. 70, pp. 24-47.

Smith, N.G., Kyle, J.R. and K. Magara (1983): Geophysical log documentation of fluid migration from compacting shales: A mineralization model from the Devonian Strata of the Pine Point area, Canada: Economic Geology, v. 78, pp. 1364-1374.

Snow, G.G. and B.W. Mackenzie (1981): The environment of exploration: Economic, organizational, and social constraints; Economic Geology, 75th Anniversary Volume, pp. 871-896.

Spirakis, C.S. (1983): A possible precipitation mechanism for sulphide minerals in Mississippi Valley-type Lead-Zinc deposits: in International Conference on Mississippi Valley Type Lead-Zinc Deposits, Kisvarsanyi, G., Grant, S.K., Pratt, W.P. and J.W. Koenig (eds.); Proceedings Volume, University of Missouri-Rolla, Rolla, Missouri, pp. 211-215.

Sverjensky, D.A. (1981): The origin of a Mississippi Valley-type deposit in the Viburnum Trend, Southeast Missouri; Economic Geology, v. 76, pp. 1848-1872.

Sverjensky, D.A. (1984): Oil field brines as ore-forming solutions; Economic Geology, v. 79, pp. 23-37.

Telford, W.M., Geldhart, R.E. and D.A. Keys (1976): Applied Geophysics; Cambridge University Press, Cambridge, 860 p.

Threadgold, P. (1970): Applications of well-logging techniques to mining exploration boreholes: in, Mining and Petroleum Geology, M.J. Jones (ed.), Institute of Mining and Metallurgy, pp. 731-747.

Vaasjoki, M. and B.L. Gulson (1986): Carbonate-hosted base metal deposits: Lead isotope data bearing on their genesis and exploration; Economic Geology, v. 81, pp. 156-172.

Wallis, R.H. (1970): A geological interpretation of gravity and magnetic data, northwest Saskatchewan; Canadian Journal of Earth Sciences, v. 7, pp. 858-868.

Watts, N.R. (1987): The role of carbonate diagenesis in exploration and production form Devonian Nisku reefs, Alberta, Canada; in Bloy, G.R. and J.C. Hopkins (eds.), Principles and concepts for explorarion and exploitation of reefs in the Western Canada Basin, Canadian Society of Petroleum Geologists Short Course, Canadian Reef Inventory Project, no page number.

Williams, G.K. (1984): Some musings on the Devonian Elk Point Basin, western Canada; Bulletin of Canadian Petroleum Geology, v. 32, no. 2, pp. 216-232.