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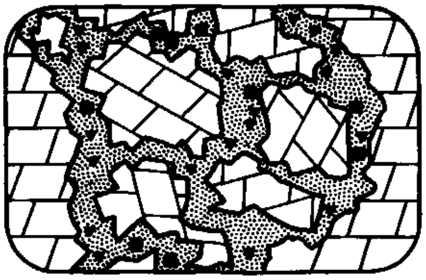
Articles



Sediments, Zinc and Lead, Rocky Mountain Belt, Canadian Cordillera

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Summary
Large numbers of zinc-lead mineral showings have been discovered recently in the northern part of the Rocky Mountain Belt, Canadian Cordillera. Many of the showings are of Mississippi Valley-type: stratabound, hosted by unmetamorphosed sedimentary carbonates, and remote from any obvious intrusive rock source. Mineralogy is simple, bitumen is a common associate, porosity and permeability are important controls, and stratigraphic control of many showings is evident. Carbonate-hosted deposits have been known for some time in the southern Rockies. The stratigraphic distribution of many of these deposits suggests that the petroleum geologist's concepts of source, migration, and trapping provide a useful framework within which Rocky Mountain Belt *mineralization* may be examined, and that basinal shales may have been important in supplying metals. More specifically, several lines of evidence suggest genetic links between mineralization and petroleum or organic matter in the Rocky Mountain Belt. Much evidence now supports the theory that oil and gas are the product of deep subsurface chemical processes. If mineralization *is* genetically related to oil maturation-migration processes, it too is likely to be a relatively late-stage event taking place under deep subsurface conditions.

Résumé
Un grand nombre d'indices de plomb-zinc ont été récemment découverts dans la partie septentrionale des Montagnes Rocheuses de la Cordillère canadienne. Beaucoup de ces indices sont du type "Mississippi-Valley" c'est-à-dire qu'ils sont confinés à une seule unité stratigraphique consistant de carbonates sédimentaires non métamorphiques et loin de toute roche intrusive. La minéralogie de ces indices est simple, souvent du bitume leur est associé, porosité et perméabilité ont été reconnus comme étant des paramètres *importants et quelquefois, le contrôle* stratigraphique de beaucoup de ces indices est évident. Dans la partie sud des Rocheuses, le même type de gisement est également connu dans des calcaires. La distribution stratigraphique de beaucoup de ces gisements suggère d'une part que les minéralisations des Montagnes Rocheuses peuvent être examineés dans le cadre du concept pétrolier de source-migration-piégeage, et d'autre part que les shistes de bassin peuvent avoir été une source importante de métaux. D'une manière plus précise, dans les Montagnes Rocheuses, plusieurs évidences suggèrent l'existence d'un lien génétique entre *minéralisation et hydrocarbures ou* matière organique. Beaucoup de faits viennent maintenant à l'appui de la théorie selon laquelle le pétrole et le gas seraient le produit de phénomènes chimiques se passant à grande profondeur. Si la minéralisation *est* génétiquement liée aux procédés de maturation-migration du pétrole, elle devrait elle aussi représenter un évènement relativement tardif se produisant à de grandes profondeurs.

Introduction

Among the most intriguing of mineral deposits are those widely known as of "Mississippi Valley-type" - dominantly of zinc-lead minerals, hosted by unmetamorphosed sedimentary carbonate rocks, and remote from any obvious intrusive igneous rock source. Although deposits hosted by volcanic rocks account for about two-thirds of the zinc and lead produced annually in Canada (Sangster and Lancaster, 1976), the large size and richness of Pine Point, a Mississippi Valley-type deposit in Devonian carbonates of the northern Interior Platform, provide continuing stimulus for exploration in carbonate terrane.

Recent exploration in the Rocky Mountain Thrust and Fold Belt has located large numbers of carbonate-hosted zinc-lead showings, particularly in the northern part of the Belt. These discoveries indicate potential for a Western Canadian district of Mississippi Valley-type deposits, and with it the opportunity to examine this type of deposit in yet another geologic setting. Following a brief review of the regional geology of the eastern Cordillera, we look at Rocky Mountain Belt zinc-lead discoveries, compare these with Mississippi Valley-type deposits, and speculate on origin.

Tectonic Setting

The Columbian Orogen comprises the eastern part of the Canadian Cordillera (Fig. 1), and consists of an intensely deformed and intruded core zone, the Omineca Crystalline Belt, and a flanking foreland zone, the Foreland Thrust and Fold Belt or Rocky Mountain Belt (*see* Wheeler *et al.*, 1972). Unmetamorphosed Proterozoic, Paleozoic, and Mesozoic sedimentary rocks make up the Rocky Mountain Belt; décollement folding and faulting are dominant. Thrust faults characterize the southern Rockies, whereas folds with relatively minor thrusts dominate the northern Rockies and Mackenzies. To the northwest, the northern Yukon tectonic complex consists of folded and faulted blocks probably bounded by strike slip faults. The entire Rocky Mountain Belt was deformed by the Columbian and Laramide Orogenies, a protracted period of mountain building which lasted from early Jurassic to early Tertiary time. Other Phanerozoic deformations are not evident in the southern part of the Rocky Mountain Belt. In the northern Rockies, Mackenzies, and northern Yukon tectonic complex, there is a clear record of Paleozoic and Mesozoic block faulting and probably related tilting and erosional bevelling. For the entire Rocky Mountain Belt and particularly for the Rockies themselves, controversy continues over the amount of crustal shortening, the westward extent of underlying crystalline basement, and whether this basement was passive or active during deformation.

Stratigraphic Framework

The stratigraphic record of the Columbian Orogen comprises two separate successions: an older, miogeocline-platform wedge that prograded westward from the North American craton into an ocean basin; and a younger, easterly-directed clastic wedge produced by Columbian and Laramide deformation. Miogeocline-platform wedge sediments apparently accumulated on a trailing continental margin, similar to the present Atlantic continental margin of North America, and these sediments probably were continuous into what is now the Omineca Crystalline Belt or core zone of metamorphic and intrusive rocks. Unmetamorphosed miogeocline-platform wedge sediments are thickest in the Rocky Mountain Belt, where they range from middle Proterozoic to middle Mesozoic in age. Although the total thickness of miogeocline-platform wedge sediments is reasonably constant along the length of the Rocky Mountain Belt, the thickness of individual sequences of a particular age or character is extremely variable. This is because the wedge consists of a series of smaller, unconformity-bounded, overlapping and northeasterly-tapering stratigraphic successions which reflect a differing depositional and tectonic history along the Belt. These successions also reflect the presence of arches, highs, or ridges along the Belt (*see* Wheeler *et al.*, 1972).

Within the Rocky Mountain Belt, the Paleozoic part of the miogeocline-platform wedge contains two assemblages: a carbonate-dominated, "cratonward" assemblage of shallow-water shelf origin; and a laterally equivalent, fine clastic and chert-bearing "oceanward" succession of more open marine, slope and trough origin and typically much thinner than the shelf assemblage.

The relatively thin, unconformity-punctuated sequences of the Interior Platform constitute the undeformed part of the miogeocline-platform wedge, and host the numerous oil and gas fields of Alberta and British Columbia. The Interior Platform also contains the Pine Point ore-field, located within almost flat-lying Middle Devonian carbonates of the southern Northwest Territories.

Zinc-lead Occurrences, Rocky Mountain Belt

Showings and deposits are located mainly in three areas: the southern Rockies, northern Rockies, and Mackenzies. Figure 1 shows some of the many known occurrences in these areas. Those of the southern Rockies are located mainly in Middle Cambrian carbonates, and include the only two occurrences of the entire Rocky Mountain Belt ever to operate as successful mines over a number of years, the Monarch and Kicking Horse deposits of the Field area, B.C. (Ney, 1954). The Oldman River occurrence (Fig. 1) is located along a thrust fault at the base of an Upper Devonian carbonate unit (Holter, in press).

Occurrences in the northern Rockies are also stratigraphically restricted in distribution, but in this region to ?Silurian and Lower and Middle Devonian platform carbonates in close proximity to carbonate-shale facies changes (Taylor *et al.*, 1975). Interest now is particularly focused on the Mackenzies of the northern Rocky Mountain Belt, where more than 400 showings in three main camps were known up to the end of the 1975 field season. These showings occur in Proterozoic and Cambrian through to Lower Carboniferous strata, although Lower Cambrian carbonate units host the majority. Developments and properties in the northern Cordillera were reviewed by Brock (1975) and Dawson (1975). Indeed the wealth of showings in the northern Cordillera has prompted Sangster and Lancaster (1976) to propose the name "Mackenzie Valley lead-zinc district" for the northern Cordillera, Interior Platform including Pine Point, and part of the Bear, Slave, and Churchill Provinces of the Canadian Shield. Does the abundance of showings in the Mackenzies mean that the area is unique within the Rocky Mountain Belt, or that many occurrences have yet to be found elsewhere in the Belt? Minor showings are known also in the Franklins, Richardsons, and Ogilvies of the northernmost part of the Rocky Mountain Belt.

Characteristics. Most zinc-lead showings of the Rocky Mountain Belt are carbonate-hosted, and many are stratabound (confined to a single stratigraphic unit). For the proposed Mackenzie Valley lead-zinc district, Sangster and Lancaster (1976) refer to two main types of showings: - a) stratabound, emplaced after lithification of host rocks, and b) stratiform (having the form of a bed) - low-grade, and synsedimentary relative to host rocks. To date the stratabound occurrences seem to be most common in the Rocky Mountain Belt, and we may generalize on these as follows:

1. Mineralogy - typically sphalerite, galena, pyrite, marcasite, dolomite, calcite, quartz, rarely barite (Fig. 2).
2. Sphalerite>galena (normally 10:1 or greater?).
3. Bitumen (dark brown to black hydrocarbon) very common (Dawson, 1975; Taylor *et al.*, 1975) (Fig. 3).

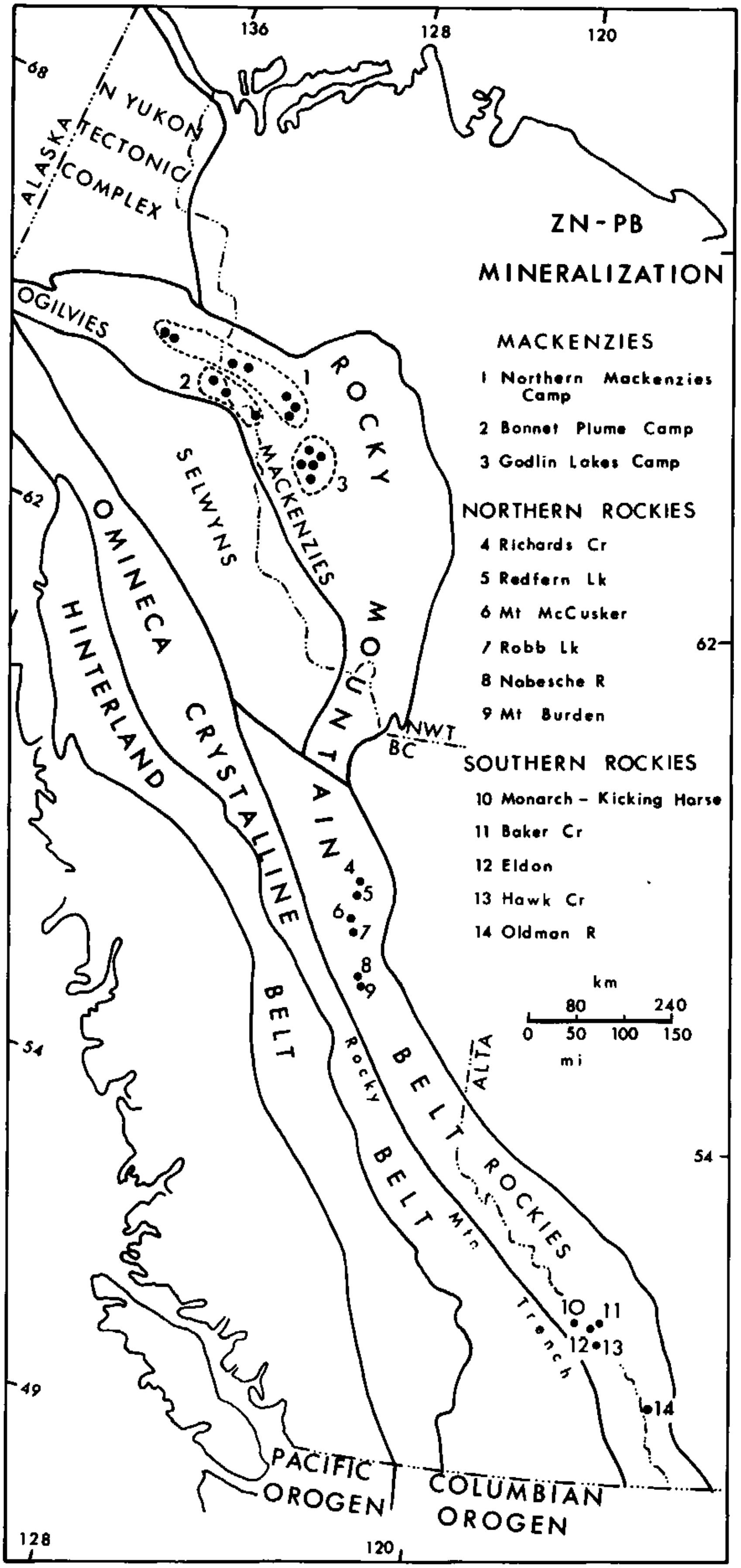

Figure 1
Tectonic elements of the Columbian Orogen (modified from Wheeler et al., *1972), and some of the more significant localities of Zn-Pb mineralization in the Rocky Mountain Belt. Over 400 showings were known in localities 1, 2 and 3 up to the end of the 1975 field season.*

4. Porosity, permeability important. Many showings occur in dolomite, not limestone; porous zones in dolomite host rocks control some occurrences (Sangster, 1970; Dawson, 1975); carbonate breccia porosity controls others (Taylor *et al.*, 1975).

5. Many deposits are open space fillings. Generally, little evidence of solution of host carbonate rocks concomittant with mineralization: porosity apparently developed before arrival of mineralizing solutions.

6. Sphalerite/galena commonly stratabound on formational scale, but cross-cutting ("epigenetic") on outcrop or hand-specimen scale.

7. Some deposits located close to platform carbonate - basinal shale facies changes (Robb Lake; Taylor *et al.*, 1975); others located some distance into the platform (Dawson, 1975).

8. Igneous rocks virtually unknown in proximity to deposits; host rocks unmetamorphosed.

9. Many occurrences show no obvious structural control. Others, e.g., some Mackenzie Mountains showings, associated with faults (Dawson, 1975).

The other class of deposits, stratiform in character, contains two types - carbonate-hosted, and shale-hosted. Carbonate-hosted stratiform deposits seem to be abundant only in the Lower Cambrian Sekwi Formation of the Mackenzie Mountains (Dawson, 1975), where they are associated with red beds and salt casts. Basinal shale-hosted stratiform deposits of galena and sphalerite are attracting real interest, however: the sizeable Howard's Pass occurrence in the Ordovician part of the Road River Formation of the easternmost Selwyn Mountains is the outstanding example (*see* Blusson, 1976). More than a dozen shale-hosted stratiform showings are known in the Road River Formation, some of them in the Selwyn Mountains to the west of the Rocky Mountain Belt, and others in the Mackenzies and Richardsons of the Belt (Fig. 1). Both types of stratiform deposits

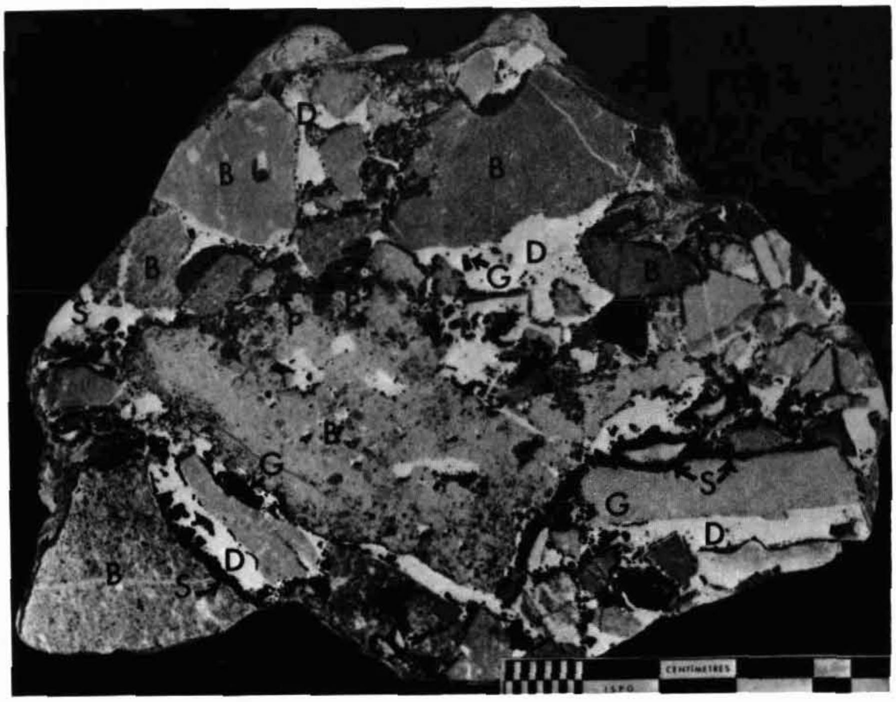

Figure 2
Polished hand-specimen of mineralized breccia from Robb Lake property, northeastern British Columbia, showing typical assemblage of sulphide minerals, white dolomite gangue, and brecciated host rock fragments. Sphalerite (S), galena (G), pyrite (P), white sparry dolomite (D), breccia fragments (B). See *Taylor* et al. *(1975).*

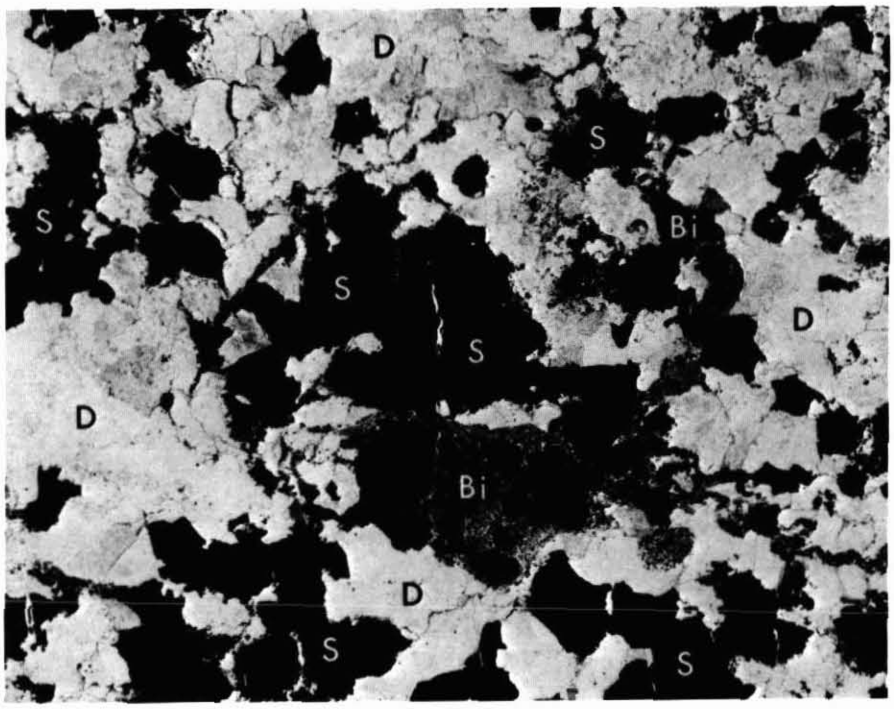

Figure 3
Thin section photomicrograph in plane light of sphalerite (S), white sparry dolomite (D), and bitumen (Bi), Robb Lake property, northeastern British Columbia. Width of field 2 cm. See *Macqueen, Thompson and Taylor (1975).*

appear to be of syngenetic or early diagenetic origin, and are not here regarded as of Mississippi Valley-type (*see* Sangster and Lancaster, 1976).

On a coarse scale, some Systems or parts of Systems have many more showings than others. Carbonates of the Lower Cambrian in the Mackenzies are particularly rich in zinc-lead showings, as are Lower Cambrian carbonates and fine-grained clastics of the Selwyn Basin and other parts of the northwestern Cordillera (Gabrielse, 1969). Those of the Lower and Middle Devonian contain a number of showings, both in the Mackenzies and northern Rockies. Ordovician and Silurian rocks have a few promising showings in the northern Cordillera, but seem not to be mineralized elsewhere. Upper Devonian and Lower Carboniferous carbonates of the southern Rocky Mountains are all but barren, although minor occurrences of sphalerite and galena are known in subsurface cores from Upper Devonian Leduc reefal carbonates of the Interior Platform, including the Bonnie Glen and Duhamel fields (Haites, 1960; Evans *et al.*, 1968). Scattered crystals of sphalerite and (less commonly) galena are encountered in a number of subsurface carbonate units of the Interior Platform, a situation which is perhaps normal for carbonate rocks. Occurrences within the Rocky Mountain Belt are not restricted to Paleozoic rocks: in the Mackenzies, significant evaporite-associated showings are located in Middle Proterozoic rocks of the Gayna River area (Dawson, 1975) and a few showings are known in Late Proterozoic carbonates.

Mississippi Valley-Type Deposits

This term is most commonly used in a general sense to describe zinc-lead mineral deposits that are hosted by unmetamorphosed carbonate rocks in areas where igneous rocks are absent or virtually so. The "type area" is the Mississippi River Valley area of the central United States, where more than 100 years of study has made these deposits well known. Important characteristics of Mississippi Valley deposits are given in Table 1. For a comparison of the geological characteristics of "type" Mississippi Valley deposits with similar deposits of the Calcareous Alps, Ireland, and our own Pine Point, *see* Jackson and Beales (1967).

At least ten different modes of origin have been proposed for these deposits, as reviewed by White (1968, p. 307; 1974). Fluid inclusion and stable isotope studies of host rocks and ore and gangue minerals have placed important constraints on the origin of Mississippi Valley deposits. In sum, these studies indicate that the main ore-bearing fluids were heated brines similar in composition to those commonly found in oil-fields, and that the lead and sulphur were derived largely from shallow crustal sources (Heyl *et al.*, 1974). These data, coupled with increased knowledge of the geological setting of "type" Mississippi Valley deposits and similar occurrences elsewhere, point increasingly to an origin that is the result of normal diagenetic processes affecting sedimentary sequences during burial, as emphasized by Frank Beales and his students.

How closely do stratabound zinc-lead deposits of the Canadian Rocky Mountain Belt compare with those of the Mississippi Valley (Table I)? Similarities seem to outweigh differences, although it is difficult to compare two areas which are at such different stages of exploration, development, and research. Many Canadian deposits tend to be located at or close to the margin of platform sequences, where such sequences pass laterally into basinal shales of the "oceanward" assemblage. Rocky Mountain Belt deposits are located in thrust-faulted and folded terrane, unlike most "type" Mississippi Valley deposits, except those of eastern Tennessee. Little is yet known on fluid inclusions, isotopic composition, or mineral zonation of the Rocky Mountain Belt showings, although Evans *et al.* (1968) did report on the four deposits of the Banff-Field area shown on Figure 1 (no. 10-13). Sulphur isotope ratios in these deposits strongly suggest a biogenic source (possibly petroleum) for sulphur, and temperatures of formation were estimated to be within the range of those encountered during burial.

Table I

Lead, zinc, fluorite, barite deposits of Mississippi Valley area (after Heyle *et al.*, 1974)

- mainly structurally controlled, open space fillings
- in all Paleozoic strata in each of the 8 principal districts
- epigenetic in present form - not strictly stratiform or stratabound
- subtly complex mineralogy, but dominated by galena, sphalerite, barite, calcite, dolomite, quartz
- show distinctive mineral zonation, particularly laterally
- lack Phanerozoic igneous rocks in 6 of the 8 principal districts
- apparently deposited by heated basinal brines (evolved connate waters), commonly at temperatures of 70° - 160°C, and in excess of 20% salt (Na-Ca-Cl)
- ores indicate mixing of at least two different sources of water
- ores contain excess radiogenic ("J-type") lead, suggesting derivation from shallow crustal sources including Precambrian basement rocks and/or Paleozoic sandstone and carbonate rocks.
- sulphur isotope ratios show a wide range of values, overlapping biogenic native sulphur, evaporites and petroleum.

Rocky Mountain Belt Stratabound Zinc-Lead Mineralization: An Approach

Two lines of reasoning look promising. The first is to consider these deposits in their total geological context; the second is to look for relationships between zinc-lead mineralization and hydrocarbon maturation and migration, at least for the stratabound deposits of Mississippi Valley-type.

In their landmark paper published in 1967, Jackson and Beales advanced a general theory of Mississippi Valley-type ore deposition through the interaction of normal diagenetic processes affecting sedimentary sequences upon burial. This approach is appealing. The Rocky Mountain Belt is simply the deformed portion of the miogeocline-platform wedge, a point often forgotten. All zinc-lead mineralization in the mountain belt and Interior Platform (e.g., Pine Point) may be seen as one result of the continuum of processes which affected miogeocline-platform wedge sediments. Mineralization also may be thought of in the same manner as a petroleum geologist thinks of an oil-field, in terms of source, migration, and accumulation (Sangster, 1970).

Links between Rocky Mountain Belt stratabound zinc-lead deposits and hydrocarbons are suggested by a commonality of factors including stratigraphic control, porosity control, and relation to facies changes; and by the spatial association of sphalerite, galena and bitumen. More generally, Mississippi Valley-type deposits commonly show fluid inclusions that contain petroleum (White, 1974, and others) and sulphur isotope ratios of galena and sphalerite overlap the range of sulphur isotope ratios normally found in petroleum, evaporites, and biogenic native sulphur (Heyl *et al.*, 1974). Additionally, the temperatures of clay mineral dewatering, hydrocarbon maturation and expulsion, and Mississippi Valley-type ore mineral deposition, all overlap as discussed below.

In the following, it is tacitly assumed (and certainly must be investigated!) that Rocky Mountain Belt stratabound deposits show fluid inclusion and isotopic characteristics similar to other Mississippi Valley-type deposits: involvement of oil-field-like brines, depositional temperatures predominantly in the range of 70°C - 160°C, and generally shallow crustal sources for lead and sulphur. These assumptions require verification if what follows is to be accepted as a working hypothesis.

Sources of metals. The ultimate source obviously is or was the interior of the earth, but here we are concerned with immediate source, and at least six immediate sources must be seriously considered. These are: basement rocks, igneous rocks, carbonates including host rock carbonates themselves, evaporites, feldspathic sandstones, and shales.

Because many Rocky Mountain Belt deposits show a stratigraphic control and do not seem to be associated with Laramide structures, the most reasonable sources for the bulk of the metals are the host rocks themselves, or more-or-less laterally equivalent sedimentary rocks, as opposed to metamorphic basement rocks or undiscovered igneous rocks at depth.

This is a basic tenet of the Jackson-Beales hypothesis (1967), and seems a sound one. If basement or igneous rocks at depth were metal sources, any Phanerozoic stratigraphic level should have an equal chance of being mineralized, yet mineralization shows a stratigraphic control. No igneous rocks are known to be associated with mineralization in Phanerozoic carbonates of the Rocky Mountain Belt: any significant metal contribution from igneous rocks would have to come from igneous rocks within laterally equivalent shales of the "oceanward" assemblage. On this point, evidence is lacking at present.

What of the host carbonates as a source? Carbonate rocks contain only a few to a few tens of parts-per-million of zinc and lead, although Recent unconsolidated carbonate sediments, consisting dominantly of the metastable forms aragonite and high magnesium calcite, are somewhat higher in metal content. By analogy with modern carbonates, during the first few tens of metres of burial the metastable carbonates present must have been eliminated from Paleozoic shelf carbonate sediments. Metals freed from host carbonates at this time (or associated evaporites or clays) generally would be on hand too early, as it is clear that stratabound occurrences within the Rocky Mountain Belt were deposited in rocks, not sediments. Disappearance of metastable carbonates may have been accompanied by dolomitization of some carbonate sequences; alternatively, dolomitization could have occurred at some depth, related to mixing of connate and meteoric waters. Liberation of metals through dolomitization cannot be ruled out as a metal source, but there appear to be concentration, storage, and timing problems. The important point about dolomitization is that it may enhance porosity, facilitating fluid movement.

Evaporites, a possible source, are difficult to evaluate, but are very rarely found in close proximity to Rocky Mountain Belt deposits. Generally, Moore (1971) has noted considerable enrichment of lead in halite rock; and Middle Devonian Elk Point evaporite sequences from the subsurface of Saskatchewan, rich in zinc, lead and copper, were identified by Thiede and Cameron (1975). Elk Point strata sampled show highest metal values in shale, dolomite, and anhydrite. If they can provide metals, evaporite sequences have the added advantage of providing metal-transporting chloride-rich brines either residually, by gypsum-anhydrite dehydration, or by groundwater leaching, as noted by Thiede and Cameron (1975).

Feldspathic sandstones are all but unknown in the Phanerozoic part of the miogeocline-platform wedge, and thus lead-bearing potash feldspars look unpromising as a significant metal source for showings in Phanerozoic rocks at least. Upper Proterozic sediments (Windermere and equivalents) are feldspathic, but are located at a stratigraphic level rather remote from many of the occurrences.

Shales, with tens to hundreds of parts-per-million zinc and lead, remain among the most likely metal sources for Rocky Mountain Belt deposits. In proximity to platformal carbonate sequences, the "oceanward" assemblage of slope and trough origin consists of calcareous shales or argillaceous carbonates, in part organic-rich, and possibly with undetected metal-rich zones. Shales rich in organic matter are commonly rich in metals. Devonian shales rich in zinc, uranium, and organic matter were reported by Macqueen, Williams, Barefoot and Foscolos (1975) from the subsurface of the Pine Point region, Interior Platform. The source(s) of metals in basinal shales is an intriguing question: do metal-rich zones represent an increased rate of metal supply by sedimentary processes (volcanic detritus, or erosion of metal-rich basement terrain), or submarine weathering processes active on contemporaneous volcanic rocks, or efficient metal concentration by organic matter combined with low rates of terrigenous sedimentation? Whatever the ultimate metal source, shales are attractive as immediate metal sources for many of the carbonate-hosted deposits. This is because, in addition to containing quantities of metals, shales undergo dramatic compositional changes at depth, including the loss of large volumes of adsorbed water from clays and amorphous materials. There is no need, of course, to consider that only a single metal source was involved for Rocky Mountain Belt deposits; nevertheless, shales remain promising stratigraphically, compositionally, and volumetrically.

Metal-rich brines. On experimental and theoretical grounds, chloride-rich brines have been known for some time to be a viable medium of metal transport. Naturally occurring metal-rich brines are now known from at least three areas: Salton Sea, California; the Red Sea; and Cheleken, U.S.S.R. (Barnes and Hem, 1973). Sources of metals in these brines are controversial, but the host sedimentary pile is indicated and brine temperatures for the latter two localities appear to be in the range of Mississippi Valley-type deposits (approx. 70-160°C). Oil-field-type brines rich in metals, and probably similar in composition to those which characterized the Rocky Mountain Belt before Laramide deformation, are known from two areas: Mississippi (Carpenter *et al.*, 1974) and northern Alberta (zinc-rich at least, lead values were not obtained owing to analytical difficulties; Billings *et al.*, 1969). Clay minerals or shales are suggested as a metal source in both situations: in the Mississippi setting, cross-formational migration of potash-rich brines is suggested to be the means by which metals are stripped from clays (Carpenter *et al.*, 1974).

Sulphur. H_2S gas, common in many carbonate reservoirs and hydrocarbon fields, is considered the most likely provider of sulphur. Other sources, considered less likely for reasons outlined above, include sulphate-bearing brines in which sulphate may be reduced by bacterial action at temperatures below about 80°C or reduced inorganically at higher temperatures; sulphate beds in the stratigraphic succession; petroleum, from which H_2S could be produced by thermal degradation; and deep-seated sulphur of magmatic origin. For deposits in the Mississippi Valley district, the wide range of sulphur isotope ratios tends to rule out a magmatic source and support shallow crustal sources including H_2S, petroleum and brine sulphate.

Precipitation of metals. There has been a longstanding problem for Mississippi Valley-type deposits: in order to transport reduced sulphur and metals at the same time, chloride-rich brines must be moderately to strongly acidic. Yet the lack of solution features in host carbonate rocks and the apparent stability of white sparry dolomite gangue during sulphide precipitation argue strongly against involvement of acidic solutions, which would dissolve carbonates on contact (Beales, 1975). Recent work by Anderson (1975) shows that a two-fluid model of sulphide precipitation is geologically more feasible despite many arguments to the contrary; brines carrying metals encounter fluids carrying reduced sulphur, and precipitation occurs. Because metal concentrations in brines are in the parts-per-million range even under ideal (and geologically reasonable) conditions, continued supply of metal-bearing brines is a requisite for sulphide formation on a significant scale. Anderson's (1975) calculations show that this is true also of sulphur; for any sizable sulphide deposit, much more sulphur is required at the depositional site than is likely to be present at any one time. Jackson and Beales (1967) argued that a critical factor in localizing sulphides in carbonates is the abundance of H_2S in carbonates but its rarity in sandstone reservoirs. Perhaps the key factor in localization is a long-continued supply of both metals *and* sulphur at the same site, as Anderson (1975) has reasoned.

Hydrocarbons: maturation and migration of organic matter. It is worth restating that many lines of evidence point to links between hydrocarbon maturation and migration, and stratabound zinc-lead mineralization in the Rocky Mountain Belt. How do oil and gas originate and migrate?

Much evidence now supports the theory that oil and gas are the product of deep, subsurface chemical processes acting on suitable sedimentary organic matter. A general scheme of hydrocarbon generation with increasing depth of burial has been given by Tissot *et al.* (1974) as shown in Figure 4. Temperature appears to be critical: if it is too low, maturation does not occur; if it is too high, volatiles are driven off and only thermal gas and reservoir bitumen remain. Thus, geothermal gradient and burial depth also are critical to the hydrocarbon maturation process. The "liquid window" concept of Pusey (1973) neatly summarizes oil occurrence and temperature-depth relationships (Fig. 5). Above the window, only biogenic gas (e.g., methane, CH_4) is likely (no maturation); below, only thermal gas and reservoir bitumen are expected (organic metamorphism). Although the liquid window concept is a very useful one, it neglects one important factor in maturation, that of time. Connan (1974) and others have shown that, in the conversion of sedimentary organic matter to petroleum, longer "cooking" times may compensate for lower temperatures, once the initial threshold of oil generation has been attained. Oil genesis is thus a relatively late-stage process, except in areas of very high geothermal gradient (Fig. 5), quite unlike the miogeocline-platform wedge of western Canada.

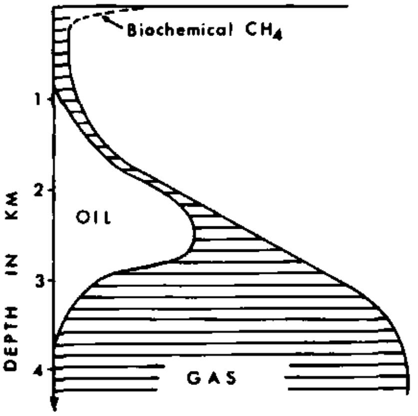

Figure 4
General scheme of hydrocarbon generation. Depth scale shown is based on examples of Paleozoic and Mesozoic source rocks. Variables affecting hydrocarbon generation in specific sedimentary basins include nature of original organic matter, burial history, geothermal gradient, and time. Simplified from Tissot et al. *(1974).*

It is important to note that not all bitumen is formed by organic (thermal) metamorphism. Other bitumen-forming processes include gas de-asphalting of oils, and water-washing and biodegradation of oil. Fortunately, these bitumens commonly can be differentiated.

Hydrocarbons, Interior Platform. The liquid window concept of petroleum maturation is illustrated in the Interior Platform. In central Alberta, there is good evidence that oil now pooled in Devonian reservoirs was not matured until Cretaceous time, because requisite temperatures (burial depths) were not attained earlier. This conclusion was reached by Deroo *et al.* (in press), from studies of oils and organic matter from the Alberta subsurface.

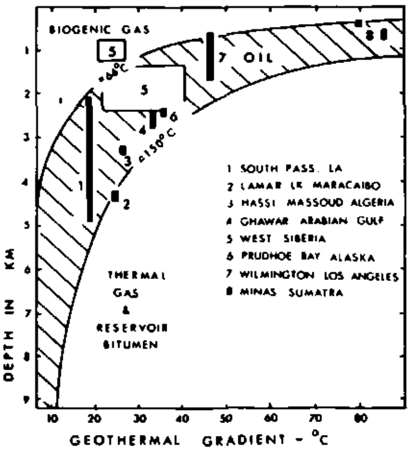

Figure 5
Liquid window concept of oil occurrence, from Pusey (1973) (redrawn). Plot of geothermal gradient against depth in km, with liquid window (cross-hatched) and selected oil fields included. Vertical bars indicate stratigraphic span of significant oil production in each field shown. According to Pusey (1973): a) A "hot" geothermal gradient does not mean high temperatures but indicates shallow production (e.g., Minas, #8); b) Over 99% of the world's oil is found at temperatures less than approx. 150°C; c) Many oil reservoirs are found at temperatures of less than approx. 66°C, but invariably they are associated with either significant uplift after heating or, less commonly, long distance migration updip. The liquid window concept appears valid, but time must also be considered in the maturation of organic matter. Longer "cooking" times may compensate for lower temperatures (Connan, 1974, and others).

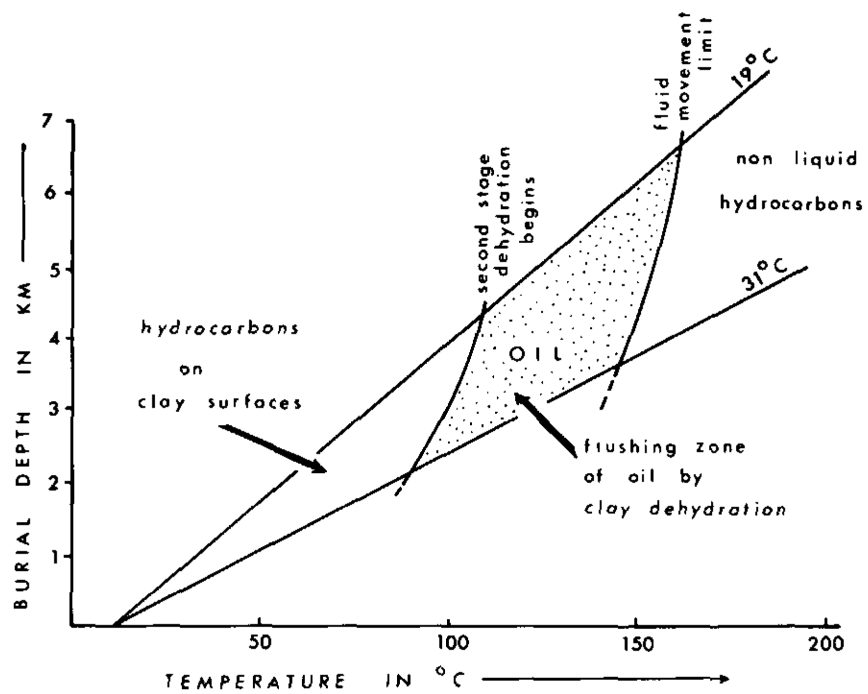

Figure 6

Correlation between burial depth, geothermal gradient for the range 19°-31°C/km, and occurrence and flushing of hydrocarbons. In organically immature zone, hydrocarbons are suggested to occur on clay surfaces; in organically mature zone, oil matures and is flushed by waters derived from second stage clay dehydration; in organically metamorphosed zone, only bitumen and thermal gas occur. Based on studies of Lower Cretaceous shales, northeastern British Columbia. Redrawn and modified from Foscolos and Kodama (1974); originally modified from Burst (1969).

In western Alberta, however, the Devonian sedimentary succession has passed *through* the liquid window, for the zone of organic metamorphism is encountered in subsurface units as the Rocky Mountain Belt is approached (Bailey *et al.*, 1974). Thus, Paleozoic rocks of the Rocky Mountain Belt, through deep burial, almost certainly were located well within the zone of organic metamorphism before Laramide deformation occurred. The important point, however, is that oil maturation and migration processes would not have occurred in Rocky Mountain Belt Paleozoic rocks until burial of about 1000 metres had occurred, allowing reasonable geothermal gradients (approx. 30-35°C/km). If mineralization *is* genetically related to oil maturation-migration processes in Rocky Mountain Belt sedimentary rocks, then it too must be a relatively late stage event. Once matured, how do hydrocarbons move from shale source beds to carbonate reservoirs?

Petroleum migration. Burst (1969) and others have shown that clay minerals of expandable lattice type (montmorillonites) lose considerable amounts of interlayer water during second-stage diagenesis and at temperatures of less than about 150°C. In the Gulf Coast area, at least, this loss of interlayer water, which seems to be temperature-dependent, is correlated with the occurrence of matured hydrocarbons, and appears to be important to primary hydrocarbon migration. Recently, Foscolos and Kodama (1974) applied Burst's (1969) concept to an assessment of the hydrocarbon-generating potential of a Lower Cretaceous shale sequence in northeastern British Columbia (Fig. 6). Although Burst's (1969) and Foscolos and Kodama's (1974) reasoning applied to expandable lattice-type clays, recent work by Barefoot and Van Elsberg (1975) suggests that loss of water from clays of *all* types and from amorphous material may be highly significant to hydrocarbon maturation and flushing. On empirical grounds, they related formation water chemistry, clay mineral stability, hydrocarbon occurrence and other properties to loss of adsorbed (interlayer) water from clays and amorphous material during burial diagenesis of Tertiary clastic sequences of the Mackenzie delta, N.W.T. Their conceptual framework of the structure of adsorbed layers on clays is of particular interest. Drawing on earlier work by others, they speculate that water is present in clays as an outer, poorly structured adsorbed layer, possibly with organic and inorganic mineral complexes; and an inner, more structured, adsorbed water layer with specific organic components and metals, such as Fe, Mn, Pb, Zn. Given this structure and composition for the adsorbed water layer on clays, is it possible that release of organic and inorganic components from clays is sequential, with metals tending to be released somewhat later than organic matter? Water released at depth from argillaceous sequences may be derived not only from clays and amorphous materials, but also from thin films of adsorbed or structured water weakly bonded to other mineral grains including carbonates (N. C. Wardlaw, pers. com., 1975); the significance of such water in petroleum migration, let alone metal transport, has yet to be assessed.

How far does oil migrate? Again in central Alberta, the geochemical character of oil now pooled in Devonian reservoirs resembles that of organic extracts taken from adjacent shale sequences (Deroo *et al.*, in press), which strongly suggests that this oil probably has not migrated more than a few miles at most from the source rocks; long-distance migration appears to take place only where suitable conduits are present in the subsurface, such as porous sandstones. Does this also mean that shale-derived metals migrate only short distances?

Brines, clays, hydrocarbons, metals: possible interrelationships. We have seen that processes of hydrocarbon maturation and migration, second stage clay mineral dewatering, and Mississippi Valley-type mineralization all occur in the range of about 60 to 150°C. For Rocky Mountain Belt stratabound zinc-lead deposits, a highly speculative diagenetic history linking all these overlapping processes is as follows, in order of increasing burial depth and geothermally derived heat:

1) Compaction, stabilization (disappearance of metastable carbonates), lithification of carbonates, including creation or enhancement of porosity by dolomitization, subsurface solution, fracturing. Loss of free (pore) water from shales by compaction, flushing. Production and migration of biogenic gas.
2) Maturation of oil, natural gas. At average geothermal gradients of 30-35°C/km, the liquid window (approx. 60-150°C) occupies an interval between depths of about 1200 to 3600 m (approx. 4000-12,000 ft), providing all heat is geothermal; time is also a factor.
3) Migration of matured oil and natural gas, within subsurface circulation system; accumulation in traps within carbonate reservoirs of miogeocline-platform wedge.
4) Metals are stripped from clay minerals within shales, or from organic-rich zones in shales (organo-metal complexes?). Metal release partly coincident with, but mainly later than, hydrocarbon maturation and flushing.
5) Brines carrying metals, probably as chloride complexes, migrate to carbonate reservoirs.
6) Sulphide precipitation occurs where metal-bearing brines encounter sulphur in carbonate reservoirs - commonly, where oil and gas accumulations are present, but the necessary condition is a continuing supply of both metals and sulphur.
7) Advanced stage of burial diagenesis organically (thermally) metamorphoses oil to reservoir bitumen, at highest geothermal temperatures reached (?200-300°C), a later diagenetic process unrelated to mineralization.
8) Deformation of thicker part of miogeocline-platform wedge. "Tectonic upgrading" of sulphides along faults (Dawson, 1975)?

Perhaps the most important consequence of such a sequence, however naive and simplistic this sequence may be, is that stratabound mineralization in the Rocky Mountain Belt is seen as a relatively late stage event, taking place under deep subsurface conditions. A corollary is that there is no need to postulate a deep convective thermal system to elevate the temperatures of metal-bearing brines, as adequate geothermal heat is available through normal burial. Such a sequence obviously cannot explain all Rocky Mountain Belt deposits in their present form, particularly those which are stratiform rather than stratabound. Nevertheless, a promising approach focuses on diagenetic history in general, including hydrocarbon maturation; and on metal source beds, migration routes, and reservoirs in particular.

Problems. Obviously, many questions remain. What governs the stratigraphic distribution of mineralization in the Rocky Mountain Belt - metal source in quantity (?metal-rich shales), sulphur supply, or a no-more-than-adequate supply of each delivered to a specific site at some critical rate? Are Lower Cambrian carbonates so well mineralized because either they or laterally equivalent basinal rocks received an extraordinary supply of metals eroded from widely exposed Canadian Shield terrain? What is the reactivity of metal-bearing solutions with hydrocarbons at temperatures of less than about 200°C: do hydrocarbons localize zinc-lead deposits? The suggestion of a link between metals and organic matter in Mississippi Valley-type deposits has been around for 50 years, but seems not to have been fully evaluated. Is Laramide tectonism as unimportant in localizing deposits as is suggested here? If clay minerals in shales are a major metal source, where do metals occur - adsorbed on clay minerals, with organic matter, or as loosely bound chloride complexes - and what triggers their release? Where are other metals which could be released, such as copper? Are potash-rich brines necessary to strip metals from clays? How efficient is the metal extraction process - inefficient, as for petroleum, for which 80 per cent or more of the organic matter remains in the source rocks? How far have metal-bearing solutions travelled? What other sources have contributed metals, and in what amounts? Was a petroleum-sulphate exothermic reaction, as recently proposed by Dunsmore (1973), of importance in ground preparation and sulphide precipitation in Rocky Mountain Belt stratabound deposits? What mechanisms are responsible for "preparing the ground" in Rocky Mountain Belt carbonates, e.g., brecciation? Are evaporites necessary to produce suitable brines for metal transport, to strip metals from clays, or to act as a source of sulphate which can be reduced to sulphur? What is the importance, if any, of meteoric water to dolomitization, dilution of brines, or sulphide precipitation? What are the genetic relations among mineralizing fluids and the common gangue minerals dolomite, quartz, and calcite? What controls the stratiform occurrences in the Rocky Mountain Belt, and is any of the above reasoning valid for these? And so on: doubtless the reader can suggest many more.

Progress in understanding Rocky Mountain Belt zinc-lead deposits will come from studies at several levels of observation. On a regional scale, the setting of the deposits and the stratigraphy and history of the host rocks place important constraints on origin. On the individual deposit or outcrop scale, the setting is equally important, as is the third dimensional aspect: very few of the new prospects have been drilled. At the level of hand-specimen analytical studies, the fluid inclusion and isotopic character of sulphides, gangues, and wall rocks should contribute significantly. Perhaps it is time to study a few of the more promising deposits in detail. A better understanding of the timing of mineralization would be a major step forward for all Mississippi Valley-type deposits: possible methods include paleomagnetic dating of sulphides, radiometric dating of microgram quantities of radiogenic isotopes, and studies of sulphur isotope ratios. It would be of great value to know more about the movement of fluids in the miogeocline-platform wedge before it was deformed in part, and perhaps this can be gained through organic or clay mineral indicators within the subsurface of the Interior Platform. The fine work of Hitchon and his colleagues on present-day formational fluids of the Interior Platform is relevant here (e.g., Hitchon and Horn, 1974). Indeed, one means of evaluating the relevance of the approach outlined herein for stratabound zinc-lead mineralization is to apply this approach to a structurally uncomplicated setting such as the northern Interior Platform of the Great Slave Lake - Pine Point region. What significance has burial history and petroleum maturation and migration to the origin of the Pine Point ore-field? Perhaps increased understanding gained from this area could then be applied within the Rocky Mountain Belt. Meanwhile, much is already known about geologic history, organic matter, clays, and fluids in subsurface settings of the Interior Platform and elsewhere. Techniques available for estimating paleotemperatures of sedimentary rocks include vitrinite reflectance, conodont colouration, bitumen compositions, and clay mineral lattice parameters and compositions. These should help in continued unravelling of the diagenetic history of the miogeocline-platform wedge, including those rocks which host zinc-lead deposits.

The petroleum geologist's "see it whole" approach toward sedimentary basins leads him to explanations of total basin behavior. From these explanations, he can make predictions on burial history, source and migration of fluids, reservoirs, trapping mechanisms, and so on, which to a significant degree govern his success as one kind of economic geologist. This general approach toward Rocky Mountain Belt zinc-lead mineralization seems even more valid today than when emphasized by Jackson and Beales in 1967. We have made a good start, but there is no shortage of puzzling problems remaining.

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