THE ROBB LAKE CARBONATE-HOSTED LEAD-ZINC DEPOSIT, NORTHEASTERN BRITISH COLUMBIA: A CORDILLERAN MVT DEPOSIT

JoAnne L. Nelson (Geological Survey Branch, B.C. Ministry of Energy and Mines),
Suzanne Paradis (Geological Survey of Canada, Mineral Resources Division, Sidney, B.C.),
Willem Zantvoort (SEOS, University of Victoria)

KEYWORDS: MVT, Lead-zinc, Northern B.C., Robb Lake, Silurian, Devonian

INTRODUCTION

The Robb Lake Pb-Zn deposit is hosted by platform carbonate rocks in the Rocky Mountains of northeastern British Columbia (56°56N, 123°43W; 94B/13; Fig. 1). The deposit, hosted by Silurian-Devonian dolostone of the Muncho-McConnell Formation, consists of a series of interconnected bedding-parallel and crosscutting breccia bodies with sparry dolomite, sphalerite, galena, pyrite, quartz, calcite, and pyrobitumen in their matrix. It is the most promising and the best developed lead-zinc occurrence in the northern Rockies, with significant showings over an 8 km^2 area.

The timing and mode of origin of the Robb Lake mineralization are controversial. The host breccias were attributed to early karst collapse by Taylor (1977) and to collapse related to evaporite dissolution by Manns (1981). In these models, mineralization was a late diagenetic or early post-diagenetic process of mainly passive infilling and replacement. On the other hand, Macqueen and Thompson (1978) advocated hydraulic cracking as the mechanism of brecciation. They hypothesised a Laramide age for the deposit based on the co-occurrence of metals and petroleum, and on the observation that burial depths necessary to produce temperatures greater that 200°C in Siluro-Devonian strata were not achieved until the Mesozoic time.

This re-evaluation of the Robb Lake deposit is a joint Geological Survey of Canada – British Columbia Geological Survey project, part of the Central Foreland Natmap Project. Its aims are: 1) to map the deposit area at a scale of 1:20,000, 2) to describe the surface showings and their host rocks and 3) to produce an absolute age by Rb-Sr methods on sphalerite (Christensen *et al*., 1996). This paper summarizes the field work done during the summer of 1998, and introduces the Rb-Sr analytical study that will be completed in 1999.

PREVIOUS WORK

Lead-zinc mineralization was discovered near Robb Lake in 1971 by Arrow-Interamerican Corp., Barrier Reef Resources Ltd., and Ecstall Mining Ltd. This discovery sparked an exploration and staking rush in the northern Rocky Mountains of British Columbia that led to the discovery of numerous lead-zinc occurrences (Figure 1) and recognition of a potential new lead-zinc belt.

The geological resource at Robb Lake is quoted as 6.5 million tonnes at 7.11% combined lead and zinc, (2.4 metre mining width, 5% cut-off grade; Consolidated Barrier Reef Resources, Rights Offering Circular, November 29, 1984). Drilling between 1972 and 1975 led to the incomplete delineation of three prospective ore bodies, the “lower zone”, the East Webb ridge zone, and the West Webb ridge zone (Figure 2). Drilling was continued by Texasgulf in the summers of 1980 and 1981. Since then, no exploration work has been done. Core is stored at an airstrip at the confluence of Mississippi Creek and the Halfway River (Figure 2).

In 1959, Irish (1970) began reconnaissance mapping of the Halfway River map area, an area of the Canadian Rocky Mountains that is located between the Peace (lat. 56°00’N) and the Halfway (lat. 57°00’N) rivers. Four field seasons led to the first published geological map of the Halfway River area. This map was immediately used by mineral explorationists, who in the late summer of 1971 discovered lead-zinc mineralization at Robb Lake. This discovery sparked a staking and exploration rush that lasted until 1974. By that time, a host of new geological problems, requiring investigation at a more refined scale, needed attention, and R.I.

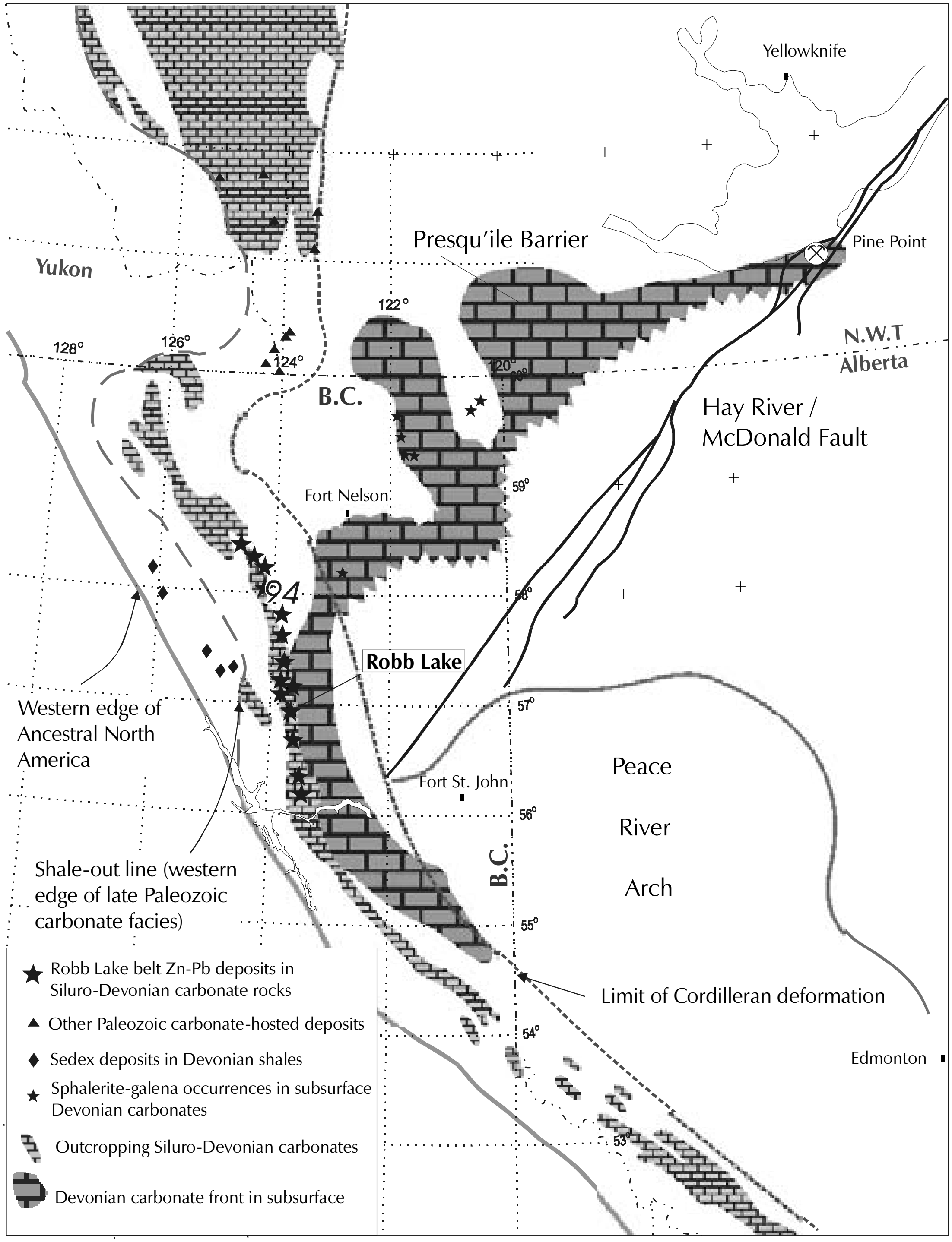

Figure 1. Location of Robb Lake and related deposits, and regional features of the North American continental margin in Siluro-Devonian time.

Thompson (1989) began mapping in 1975. Two theses were done in the course of the following years on specific geological problems. A. Taylor (1977) studied the carbonate stratigraphy and petrology, and suggested a peritidal environment for the sedimentary succession. He concluded that the formation of breccias was due to intrastratal karst and that the mineralization occurred subsequent to brecciation from formation waters that issued from compacting shales. Manns (1981) studied the stratigraphic aspects of the Silurian-Devonian sequence hosting the

Robb Lake lead-zinc mineralization. He concluded that the host breccias were collapse structures due to solution of evaporite interbeds, and that mineralization resulted from migration of petroleum-bearing formation fluids into an evaporitic dolostone platform at an unknown time prior to the Laramide Orogeny. Sangster (1973, 1979), and Sangster and Lancaster (1976) favoured a paleokarst solution collapse origin, linked to an unconformities within and above the Siluro-Devonian carbonate sequence. Macqueen and Thompson (1978) rejected this hypothesis, and ascribed the breccias to hydraulic fracturing that resulted from compaction and dewatering of the shale basin to the west during Laramide deformation.

PROPERTY GEOLOGY

The Robb Lake Pb-Zn deposit is part of a belt of Mississippi Valley-type (MVT) deposits in the northern Rocky Mountains (Figure 1). The deposits are hosted by Silurian-Devonian platform dolostones that form part of the outcropping Paleozoic carbonate front (Thompson, 1989). In the subsurface, the Devonian carbonate front turns eastward to become the Presqu'ile Barrier, which hosts the Pine Point lead-zinc deposit.

Most of the lead-zinc mineralization at Robb Lake occurs within the Muncho-McConnell Formation, although a few occurrences lie within a thin overlying sequence attributed to the Stone-Dunedin formations. As noted by Macqueen and Thompson (1978) and Thompson (1989), and documented in our detailed mapping (Figure 2), the deposit is located next to the tectonically telescoped shelf-slope facies boundary. The strata that host Robb Lake lie in the immediate footwall of a major thrust fault, which carries deep water early Paleozoic strata in its hanging wall.

The main stratigraphic units encountered in the Robb Lake area are described below, and their distribution is illustrated on Figures 2 and 3. They are divided into two disparate stratigraphic sequences, separated by the major thrust fault southwest of Mississippi Creek. Basinal units in the hanging wall of the fault include the Cambro-Ordovician Kechika Group, the Ordovician Skoki Formation, the Ordovician-Silurian Road River Group, and unnamed Siluro-Devonian quartzite-dolomite and Silurian dolostone breccia units. Northeast of the fault a platformal succession includes the Silurian Nonda Formation, the Siluro-Devonian Muncho-McConnell Formation, very thin and mostly undivided Lower Devonian Stone and Middle Devonian Dunedin Formations, and Upper Devonian Besa River Formation.

Basinal Units

Kechika Group?

Strata here assigned to the Kechika Group are restricted to a single cliff and ridge top exposure in the immediate hanging wall of the major thrust fault southwest of Mississippi Creek. This sequence consists of medium to dark grey, orange-brown to olive weathered, calcareous shale and slate characterised by very distinct colour laminations in the millimetre to centimetre range. It is very well-cleaved, forming papery to slabby cleavage fragments. These rocks somewhat resemble the eastern facies of the Besa River Formation and were assigned to it by Thompson (1989); however we have assigned them to the Kechika Group based on a) their slatey, almost phyllitic character, which contrasts with the softer, muddier Besa River shales, b) their complete contrast with black Besa River siliceous argillites less than a kilometer along strike (Figure 2) and c) their contact with the underlying Muncho-McConnell Formation, which is non-outcropping and structurally discordant. If this contact is a thrust fault, then the complete absence of Stone/Dunedin strata along it is explained.

These strata are overlain directly by the Road River Group; the Skoki Formation, which outcrops in the overlying thrust sheet above the headwaters of Mississippi Creek, is missing. Since the Skoki Formation in northern Halfway River map area is over 600 metres thick, the assignment of these rocks to the Kechika Group poses a distasteful regional problem. They may belong to the upper part of the Beaverfoot Formation (A. Legun, personal communication 1998) or, in spite of the local contradictions that this engenders, to the Besa River Formation as previously mapped.

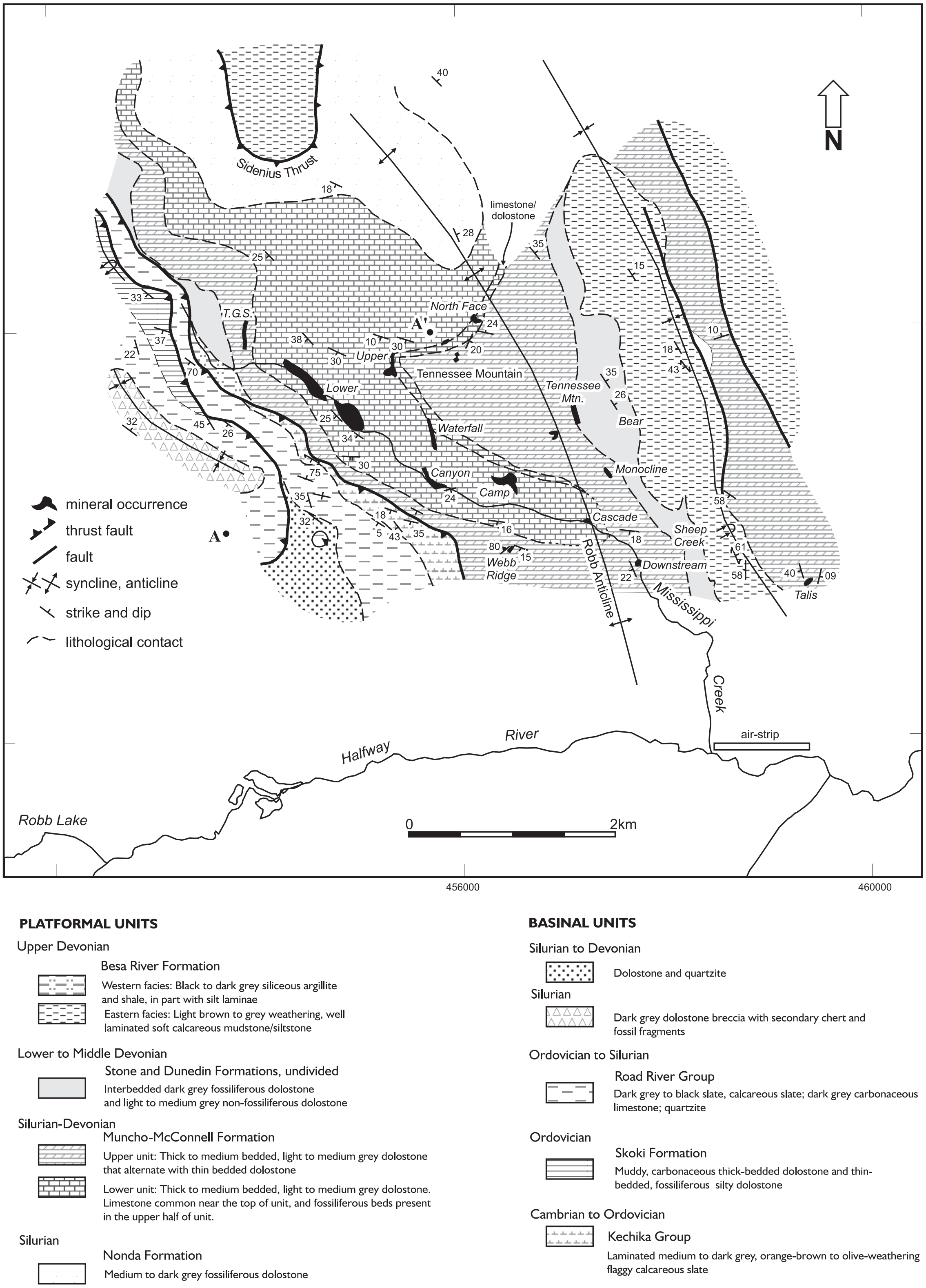

Figure 2. Geology of the Robb Lake deposit area. Surface showings from unpublished property map, Cordilleran Engineering Ltd. (1972).

Skoki Formation

The Skoki Formation, which outcrops on the southwest wall of the cirque that heads Mississippi Creek, is subdivided into two distinct units. The lower part of the Skoki is 70 metres of thickly bedded, cliff forming dolostone. It is light to medium grey, muddy and carbonaceous. The upper Skoki is a recessive unit of light brown to chalky orange weathering, light to medium grey, thinly bedded silty dolostone. Beds are up to 50 centimetres thick. This unit contains bivalves and abundant burrow structures; and one trilobite fossil was noted.

Road River Group

The Road River Group is dominated by sooty, non-fossiliferous flaggy slate and calcareous slate, and well cleaved, dark grey to black carbonaceous limestone. Less abundant are white quartzite, and beds several metres thick of highly fossiliferous, carbonaceous limestone that contain corals and brachiopods. Large carbonate concretions produce cleavage fragments the size of dinner plates. This highly heterogeneous section is typical of the Road River Group strata near shelf margins. It is overlain by unit SDdq in the lower of the two thrust sheets, and by the Silurian breccia in the upper one.

Siluro-Devonian dolostone and quartzite, unit SDdq

This unnamed unit lies in well-exposed stratigraphic contact above the Road River Group on the ridge southwest of Mississippi Creek. Its basal grey sandstone overlies black limy shale along a slightly undulating contact with a suggestion of load casting. The basal thick-bedded grey quartzite is overlain by light grey thick-bedded dolostone and quartzite. No fossils were seen. It is correlated with the Silurian-Devonian shelf dolostone-sandstone units farther northeast.

Silurian sedimentary breccia, unit Sbx

The Silurian breccia is a thin, cliff forming dolomite breccia that extends for 30 km from Lady Laurier Lake to Mt. Kenny, immediately west of Robb Lake (Thompson, 1989). The breccia overlies the Road River Group on ridge tops at the headwaters of Mississippi Creek (Figure 2). Breccia beds consist of medium to dark grey, angular to subangular dolostone and black chert fragments in a grey dolomite cement. They also contain abundant and well-preserved fossil fragments of halysites, favosites, and colonial corals. The dolostone fragments exhibit grey-black colour laminations on the millimetre to centimetre scale. The breccia itself is bedded on the centimetre- to 10 metre-scale; sets of thin dolostone calcilutite and calcarenite and small-clast breccia alternate with thick units of unsorted, matrix-supported megabreccia.

According to Thompson (1989), the fragments are all derived from the Nonda Formation, and the unit is interpreted as a debris flow (or succession of debris flows) deposited on the foreslope of a Nonda reef.

Platformal Units

Nonda Formation

The Nonda Formation is a very distinctive medium grey to very dark grey weathering, fossiliferous dolostone. Fossils include crinoids, and the corals halycites and favosites. The alternating medium to dark grey coloured beds make the Nonda Formation unmistakable. Bedding thickness ranges from .15 to 2.0 metres. Locally fine calcareous laminations are observed. Chert nodules and silicified fossils are common throughout the unit.

The Nonda Formation exposed at Robb Lake forms the core of the Robb Anticline.

Muncho-McConnell Formation

The Muncho-McConnell Formation forms most of the high peaks adjacent to the mountain front (Thompson, 1989). It consists almost entirely of light grey weathering, resistant dolostone and sandy dolostone, except for few beds of dark grey micritic limestone. The Muncho-McConnell is over 400 metres thick in the Robb Lake area, and consists of fine-grained primary crystalline dolomite that formed largely in a low energy, high salinity lagoonal, intertidal and supratidal environment. Because of its completeness, and uniform fine grain size, the “regional” dolomitization is probably early diagenetic.

Although the Muncho-McConnell is generally unfossiliferous, large brachiopods (average 5 to 10 cm long) are prominent within some exposures along Mississippi Creek, and gastropods, amphiporids, stromatolites, fragments of bivalves, and other unidentified fossils have also been noted (Manns, 1981). Taylor (1977) links the presence of fossils within the Muncho-McConnell near Robb Lake to the proximity of the Silurian-Devonian facies front.

In the vicinity of the Robb Lake deposit, the Muncho-McConnell Formation can be subdivided into upper and lower units based on bedding thickness, and outcrop and bedding characters. The lower unit (SDMl) is a massive, cliff forming unit that has thick and subtly defined bedding, and is locally blocky in character. By contrast, the upper unit (SDMu) has well defined bedding with locally distinct very fine carbonaceous laminations.

The lower unit (SDMl) is a light to medium grey, thickly bedded dolostone approximately 250 metres thick. Sedimentary textures include abundant fenestrae, less common algal laminations and rare, thin intervals that show current laminations and rip-up clast breccias. A 10-15 metre thick sandstone unit, which marks the base of the lower unit, may be equivalent to a regional sandstone marker unit (Legun, this volume). Beds of silty dolostone, sandy dolostone, and shale are interspersed with the dolostone. A marker bed, known as the "angular sand marker" (ASM), occurs within the dolostone sequence about 110 metres below the top of the unit. According to Manns (1981), this marker is present in all drill holes but is rarely seen in surface rocks. It corresponds to a local disconformity. The general character of the lower Muncho McConnell Formation is consistent with a sabkha environment, as noted by Manns (1981).

The uppermost 30 to 50 metres of the lower unit are particularly thick-bedded and often form major cliffs. On Tennessee Mountain (i.e., near the North Face and Camp showings), parts of this upper section consists of thick-bedded to massive limestone pods that pass laterally and vertically into the typical thick dolostone beds. It is overlain by dark, thin-bedded, muddy dolostone of the upper unit. This unit is important to the Robb Lake deposit in that the stratabound-style showings on Tennessee Mountain are all located immediately below it (Figure 2).

The upper unit (SDMu) is a 200 metre thick, light to medium grey dolostone with well defined bedding and distinct carbonaceous current laminations. The rhythmic sequence of the upper unit is better developed than in the lower unit, and the thin bedded dolostone intervals are more extensive, giving outcrops a terraced appearance that contrasts with the cliffier lower unit. The basal sequence (0-25 m) of SDMu is composed of thick laminated dark grey silty dolomite mudstone with local sand concentrations (Manns, 1981). A marker bed known as the "pale sand marker" (PSM), 1-2 m thick, was identified in drill holes in Webb Ridge (Manns, 1981). The "TGS Breccia" (Manns 1981) is the lowermost unit of SDM2 on the eastern end of Texas Ridge. This breccia unit is over 20 meters thick. In it, large, subangular to subrounded clasts up to several metres across are surrounded by a matrix of fine dolomite mudstone. They show a diversity of colours and bedding characteristics: within the limited lithologic variation of local sources, this is a polymictic breccia. A series of large limestone clasts, probably fragments of a single disrupted bed, occurs along its base. Higher in the breccia, beds of fine-grained, thin-bedded dolostone drape over large breccia clasts. We interpret this unit as a synsedimentary slump deposit.

In unit SDMu, thicker, algal laminated beds alternate with thin, strongly current-laminated intervals. The latter may contain rip-up clast breccias, or current cross-laminae. Fenestrae are common, particularily near the tops of the algal-laminated beds. Mudcracks were observed in talus. These features indicate a sabkha environment affected by periodic strong wave action.

Taylor (1977) and Manns (1981) interpreted the top of the lower unit and at the top of the upper unit as disconformable. Evidence for significant erosion surfaces includes the presence of sand markers (ASM and PSM), scour surfaces, soft sediment deformation features, and local breccias such as the TGS.

Stone/Dunedin formations

The Lower to Middle Devonian Stone and Dunedin formations could not be distinguished in the Robb Lake area, so they are described together in this section. They consist of interbedded medium dark grey fossiliferous, partly calcareous, dolostone and light to medium grey buff weathering fossiliferous and non- fossiliferous dolostone. Some fossiliferous limestone occurs as a black (reef-front ?) breccia. Fossils include brachiopods, gastropods, crinoids, rugosa and colonial corals, and local crinoid wackestone.

This unit is thin and discontinuous (Figure 2). It is nowhere capped by a single thick dark grey fossiliferous carbonate unit assignable to the Dunedin Formation. Nevertheless it may be partly time-equivalent to the Dunedin. The position of Robb Lake next to the interpreted carbonate shelf margin may explain the anomalously thin Lower to Middle Devonian section.

Besa River Formation

The Besa River Formation outcrops in three areas: in the core of a syncline east of the main showing area, in the footwall of the Sidenius thrust fault in the core of the Robb Anticline, and in a narrow band in the immediate footwall of the major thrust fault exposed in the headwaters of Mississippi Creek (Figure 2). In its eastern exposures, the Besa River Formation consists of soft brown/grey weathering, finely laminated dark grey to black calcareous to noncalcareous argillite/shale and siltstone.

The western facies of the Besa River Formation includes dark grey to black, siliceous argillite and shale with silt laminae. In outcrop, the thrust fault is a zone of strong shearing that truncates bedding and cleavage in both the underlying black Besa River argillites and the overlying calcareous, carbonaceous shales of the Road River Group.

Mineralization

The Robb Lake deposit consists of numerous stratabound and cross-cutting lead-zinc showings hosted by the Muncho-McConnell Formation, and a few occurrences in the overlying Stone-Dunedin formations. Most of the showings occur along the valley of Mississippi Creek and adjacent mountain slopes (Fig. 2). Mineralization at Robb Lake takes two forms: mineralized breccias, and veins/vein stockworks. Breccia mineralization is by far the most important. The breccias are interconnected, bedding-parallel and/or crosscutting bodies in as much as 200 metres of stratigraphic section (Fig. 3). Not all the breccias are mineralized. The favorable mineralized sections form a broad stratabound zone occupying the upper 200 metres of the lower unit of the Muncho-McConnell Formation and the lower 130 metres of upper unit; a 70 metre thick, barren section separates the mineralized zones (Boronowski and James, 1982).

The mineralized zones have a northwesterly elongation and alignment, parallel to the strike direction and to the structural and paleofacies features. The breccia bodies form relatively thin and narrow horizons and pods that are both parallel to and crosscut bedding (Figs. 2, 3). The largest of these bodies may extend for more than 300 metres along bedding or crosscut more than 50 metres of section. The base of the upper cliff-forming unit exerted a strong control on the location of the main stratiform breccia bodies, as is illustrated on the cross-section of the valley of Mississippi Creek (Fig. 4). This cross section shows that the south slope of Tennessee Mountain is more or less a dip slope, and the

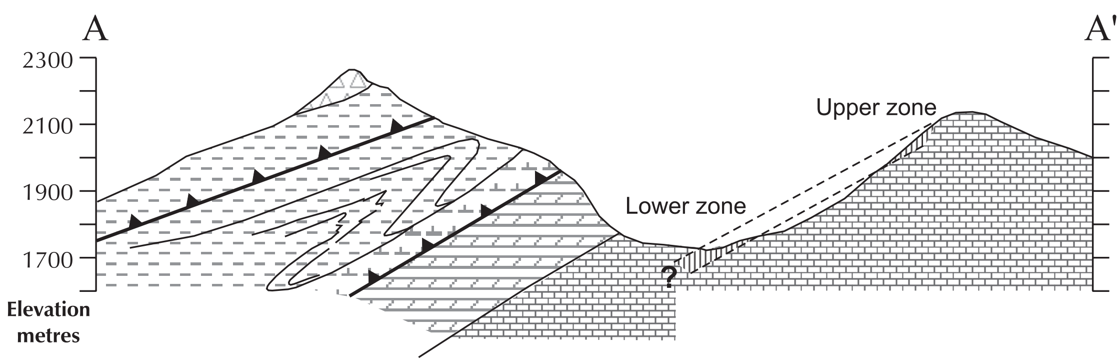

Figure 3. Cross-section A-A' of the Mississippi Creek valley, looking northwest. Shows that, assuming an average bedding dip of 30o, the upper and lower mineralized zone are at the same stratigraphic level. For legend and location of section see Figure 2.

showings along the creek, such as the Lower, Canyon, and Cascade zones, are stratigraphically equivalent to those on the south side of Tennessee Mountain (the Upper, Waterfall, and Camp zones, and also the North Face zone). In the East and West Webb zones on Webb Ridge, drilling has outlined up to four major mineralized horizons and numerous isolated pods in the lower and upper units of the Muncho-McConnell Formation. They are stacked and may be connected at different levels laterally and vertically (Boronowski and James, 1982).

A broad mineral zonation has been recognized in the distribution of the sulphides and other minerals at Robb Lake. The sphalerite/galena ratio decreases stratigraphically upward, with approximate ratios of zinc to lead of 7:1 at the Lower showing, 1.5:1 at the West Webb showing, and 4.5:1 at the East Webb showing (Manns, 1981). The best overall grade mineralization, intersected in hole 113-82, was15.02% Pb+Zn over 3 metres, with a Zn:Pb ratio of 2:1: this was predominantly associated with the pyrobitumen- and carbonaceous-rich matrix of the rock-matrix ("trash") breccias (Boronowski and James, 1982).

Characteristics and morphology of the breccias

The breccias at Robb Lake have long been a focus of study (Sangster, 1973, MacQueen and Thompson 1978, Manns, 1981), although not a topic of consensus. There are a number of breccia types within the Muncho McConnell Formation of primary and of secondary origin; some are unrelated and some intimately related to sulphide mineralization. The most important ones with regard to the mineralization are the sparry dolomite-cemented crackle, mosaic and rubble breccias, and the rock-matrix ("trash") breccias. The following classification is texturally based.

Dolostone-chip breccias associated with current-laminated beds in SDM2. These thin layers, generally less than 10 centimetres thick, contain thin bedding fragments of dolostone roughly imbricated or stacked in a fine dolostone mud matrix. Their occurrence suggests that they are of synsedimentary storm origin. No mineralization is associated with them.

Dolostone-matrix breccias in SDM1 and SDM2, including TGS Breccia. In these breccia layers, sparse to abundant, generally subangular clasts of dolostone contrast in color with their dolostone matrix. The matrix lacks internal bedding, except rarely within the TGS breccia. Breccias may be either monomict or polymict; in any case the clasts are all assignable to the Muncho McConnell Formation. A synsedimentary origin is reasonable based on their character and occurrence. In a few cases - the TGS breccia and at the upper end of the North Face showing - mineralization is associated with these breccias.

Crackle and mosaic breccias. These terms represent end members of a continuum. The crackle breccias show little displacement of the fragments in coarse-grained sparry white dolomite cement (Fig. 5A). The fragments consist exclusively of highly angular clasts of the variably altered crosscut dolostone host-rock. The mosaic breccias have fragments that are largely but not wholly displaced (Fig. 5B). The fragments also consist of highly angular clasts of the dolostone host-rock in a coarse-grained sparry white dolomite cement. Generally, mosaic breccias grade out through crackle breccias into unfractured dolostone. It is notable that in these breccias, individual clasts tend to be of somewhat uniform size, typically 5 to 20 centimetres across; although the fragments can range in size from one millimetre to several metres in longest dimension. Megabreccias of this type are rare. A substantial portion of the mineralization at Robb Lake occurs within the dolomite cement of the mosaic and crackle breccias.

Rubble breccias. In contrast with the crackle and mosaic breccias, the rubble breccias are polymictic, and the fragments are completely displaced, showing no match with each other. By textural definition, this category includes the rock-matrix ("trash") breccias, which are rubble breccias with fragmental matrix instead of dolomite cement. The rubble breccias are by far the most volumetrically important types of breccias and the most varied. They contain a variety of clasts that are included in a fine-grained dark grey fragmental matrix or in white sparry dolomite cement or in a mix of both. The breccias are generally grain-supported and locally matrix-supported. The fragments consist of a variety of altered and unaltered dolostone (90 volume per cent), white sparry dolomite

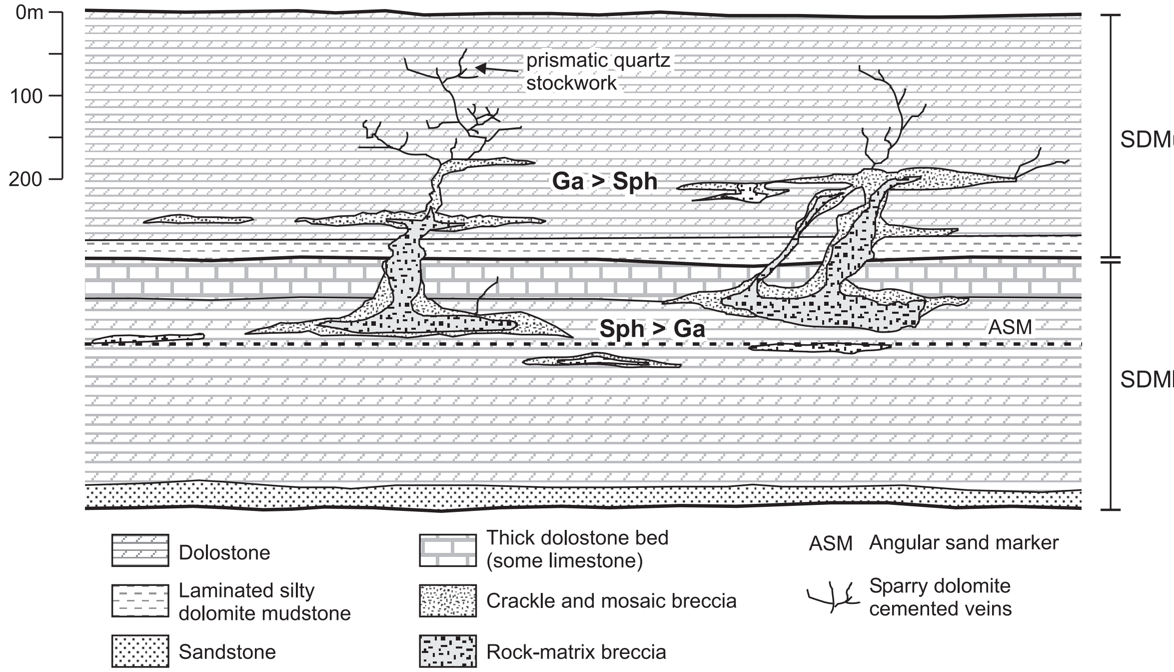

Figure 4. Textural and mineralogical zoning in the Robb Lake system.

(i.e., subangular fragments and thin curviplanar segments of vein selvages; 5 volume per cent), shale/mudstone (2 volume per cent), finely laminated shaly carbonate (1 volume per cent), chert (1 volume per cent), pyrobitumen-rich material (<1 volume per cent); sulphides (<1 volume per cent), individual rounded sand grains with overgrowths (<1 volume per cent), and fossils (brachiopods and gastropods; <1 volume per cent). The fragments are highly angular to subangular and vary in size from less than one millimetre to several metres. Most breccias are dominated by fragments less than 10 centimetres in diameter. The matrix of the "trash" breccias is a dark grey to black carbonaceous dolostone. On close inspection, this matrix is composed of fine fragments, cemented by overgrowths and interstitial dolospar and quartz. Some of the fine fragments are possibly pyrobituminous shale, however much of the dark colour of the matrix can be accounted for by the dark to medium grey dolostone fragments, occasional shale fragments, and the fine disseminated sulphides. The sulphides, sphalerite, galena and pyrite, are concentrated in the matrix as individual grains and clusters, and as fracture filling material.

In terms of relative paragenesis, the rock-matrix ("trash") breccias crosscut the dolomite-cemented mosaic and crackle breccias; but conversely the dolomite cement of the crackle and mosaic breccias enclose fragments of the rock-matrix ("trash") breccia, and dolomite veins crosscut the "trash breccia". We interpret these apparently conflicting temporal relationships to mean that the breccias originated as an overlapping, multi-episodic sequence of events prior to and during mineralization. The incorporation of sulphide clasts in the rock-matrix ("trash") breccias is evidence that brecciation and mineralization were at least in part contemporaneous.

Figure 4 depicts the spatial relationships between the different classes of mineralized breccias. The rock-matrix ("trash") breccias with combined zinc-lead grades in the order of 6% (Boronowski and James, 1982) are preferentially located within the upper half of lower unit of the Muncho-McConnell. Some of these breccias are also found in the upper unit but they rarely achieve ore grade mineralization. In general, the rock-matrix ("trash") breccias occur at the base of the breccia bodies and are overlain and fringed by the rubble, mosaic, and crackle breccias that are cemented by white sparry dolomite. Also, in the overall system, the rock-matrix ("trash") breccias tend to be located within the lower unit, whereas the dolomite-cemented rubble, mosaic and crackle breccias tend to overlie the "trash" breccias and are more abundant in the upper unit.

Mineralogy, textural relationships, and mineralogical zonation

Sphalerite, galena, and pyrite are the main sulphide minerals; marcasite has been observed in thin sections by Taylor (1977), and Manns (1981). Sphalerite is pale yellow, dark orange, red, or brown. It occurs as fine to coarse single or aggregates of anhedral crystals (1 mm to 1 cm) in white sparry dolomite cement of the crackle, mosaic, and rubble breccia, and in the fine-grained carbonaceous dolostone matrix of the rock-matrix ("trash") breccia. Anhedral crystals or aggregates of crystals of sphalerite occur as rims on one or several sides of the angular dolostone fragments, or as scattered crystals within the white sparry dolomite cement. According to Manns (1981), geopetal sphalerite (i.e., "snow on the roof" texture) is abundant at Robb Lake, but in our observations on the various showings, sphalerite was also seen to coat indifferently any or every side of fragments. "Snow-on the-roof" is only well-developed in surface showings within the TGS breccia, where mosaic breccias cross-cut the original synsedimentary breccia. Sphalerite crystals and aggregates range from less than 1mm to 1.5 cm. Very fine-grained sphalerite (i.e., < 1mm) is only present in the matrix of the rock-matrix breccia. Sphalerite crystals are usually anhedral and are commonly fractured. Colloform sphalerite has been reported at the Waterfall showing (locality 3; Fig. 2) (Macqueen and Thompson, 1978; Manns, 1981).

Overall, galena is less abundant than sphalerite and pyrite. It commonly occurs as euhedral crystals (< 1cm to 2 cm) and less commonly as anhedral aggregates in the white sparry dolomite cement of the rubble, mosaic, and crackle breccias, and in the carbonaceous dolomite matrix of the rock-matrix ("trash" breccia. Galena also occurs as fracture-filling, without sphalerite or quartz. Sangster and Carrière (1991) observed galena veinlets crosscutting sphalerite crystals, and grains of sphalerite completely enclosed by galena. In showings located in the lower sequence of the Muncho-McConnell (SDMl), galena is typically associated with sphalerite, and may have co-precipitated or precipitated slightly later. In the upper sequence (SDMu), galena often occurs by itself, as euhedral and anhedral crystals disseminated in the white sparry dolomite, and in one instance filling fractures in sparry dolomite. It is also commonly associated with quartz. When quartz is present and associated with galena, it occurs as fractures cutting galena or as inclusions in galena (Sangster and Carrière, 1991).

Pyrite and marcasite occur as disseminated fine-grained euhedral to subhedral crystals and aggregates in the rock-matrix ("trash") breccia, and as massive aggregates of fine-grained pyrite along stylolites and bedding planes, and as fracture fillings. Irregular pyrite veins cut the breccia at the "Lower zone".

Pyrobitumen commonly occurs within the various breccias where it fills small cavities, and fractures. It locally forms a component of the rock-matrix breccia, giving the dark grey colour to its matrix.

Besides zoning stratigraphically upwards from stratabound to cross-cutting style of mineralization, the Robb Lake system exhibits mineralogical zonation (Figure 4) . Sphalerite, the dominant sulphide mineral, is most abundant within breccias in the stratabound showings. Both locally and in the system as a whole, the galena-sphalerite ratio appears to increase upwards and outwards. On the scale of metres at the North Face showing, sphalerite-rich rock matrix ("trash") breccia passes outwards into mosaic breccia cemented by sparry dolomite and galena. Regional zoning is demonstrated at one of the stratigraphically highest showings, the Bear, located within the Stone Formation high on the southeast ridge of Tennessee Mountain. There, sphalerite is insignificant, and large galena clumps in sparry dolomite veins pass outwards into drusy, crystalline quartz. Crystalline quartz appears to be the most distal expression of the Robb Lake system, occurring in veins and voids throughout the upper part of the Muncho McConnell Formation.

Alteration

Megascopically, three distinct phases of dolomitization affected the carbonate rocks in the Robb Lake area. An early phase consists of a light grey weathering, medium and dark grey replacement dolostone composed of fine-grained crystalline dolomite. This dolomite dominates the sequence regionally and is considered to be the result of very early diagenetic alteration of primary calcite. A texturally later, coarse sparry and prismatic white to grey dolomite coats some dolostone fragments and is associated with zebra texture. Zebra dolomite, a common feature of carbonate rocks associated with MVT deposits, is well displayed at the Robb Lake deposit. It consists of thin dolostone layers (mm to cm scale) identical to, and connecting with, the surrounding homogeneous dolostone, but separated from each other by coarse sparry and prismatic white dolomite layers (mm to cm scale) or, in some cases, by voids of the same shape as the white layers, or by pyrobitumen, or by a combination of the three. The layering is either oriented parallel to bedding or in herringbone patterns that resemble cross bedding, the template for which is cryptic. It never extends continuously either vertically or laterally for more than 50 cm. Zebra texture affects all the dolostone units of the Robb Lake area, and fragments of the zebra texture are incorporated in the mineralized breccias. It forms broad altered selvages to vein-type mineralization, for instance around the showing on Webb Ridge. The third phase of secondary dolomite in the Robb Lake area is a white sparry dolomite that forms the cement of the breccias, and fills the joints, fractures, vugs, and primary porosity such as fenestrae and fossil interiors.

With the help of cathodoluminescence petrography, Manns (1981) was able to distinguish four generations of dolomite: (1) fine-grained inert dolomite forming the regional host-rock dolostone, (2) inert coarse white sparry and prismatic dolomite lining cavities, coating dolostone fragments in breccias, and associated with the zebra texture, (3) luminescent dolomite forming the cement of the mineralized breccias and associated with sphalerite, galena, pyrite, and local pyrobitumen, and (4) inert dolomite filling the central portions of large cavities.

Accompanying laboratory studies

A total of 10 samples from various lead-zinc showings of the Robb Lake area were submitted to the University of Michigan for Rb-Sr dating of sphalerite. Rb-Sr dating of the Robb Lake mineralization, if successful, will provide an absolute age on the mineralization and a constraint on the geochronology of ancient crustal fluid flow in the Presqu'ile Barrier.

Until recently, radiometric geochronology has been of little use in evaluating models for the formation of MVT deposits because of lack of alternative minerals that are amenable to dating by conventional isotopic methods (Halliday *et al*., 1990). Over the past years, a handful of apparently robust radiometric ages for carbonate-hosted Pb-Zn deposits have become available. Rb/Sr dating of sphalerite is a technique that provides a direct age for the primary sulphides and consequently has a direct impact to the understanding of causes and effects of fluid migration in relation to basin evolution and tectonic events. This technique has been successfully used to date other MVT deposits, such as Pine Point (Nakai *et al*., 1993), Polaris (Christensen *et al*., 1995b), Blendevale in Australia (Christensen *et al*., 1994, 1995a), and deposits in East Tennessee (Nakai *et al*., 1990, 1993) and Upper Mississippi Valley (Brannon *et al*., 1992). However Rb/Sr methods have not always been successful in dating certain MVT deposits, primarily because the low Rb content of sphalerite poses a sometimes unsurmountable analytical/interpretational challenge. The theory, methods, success, and pitfalls of the technique are explained in Christensen *et al*. (1996).

DISCUSSION

Brecciation and open-space filling are very important processes in the formation of Robb Lake as in most Mississippi Valley-type deposits. Temporal and genetic relationships between brecciation and mineralization at Robb Lake are controversial. Are the breccias that host mineralization the result of wall-rock dissolution by Mississippi Valley-type mineralizing brines or were they formed by other, earlier fluids, possibly related to regional weathering and karstification, which created an extensive paleoaquifer system for later MVT brines (Sangster, 1988)? Did alteration and dissolution of carbonate wall rock in the breccias cause ore deposition at Robb Lake? These questions largely remain unanswered at Robb Lake, as indeed at other MVT deposits around the world.

In some MVT districts, it is documented that solution of carbonate by ore-related brines has allowed collapse and brecciation of the overlying beds, and that gravity was an important force in the shattering. However, the fine median size and high degree of angularity of the fragments within the trash breccias and of the breccia bodies at Robb Lake suggest that other forces such as hydraulic fracturing may have supplemented simple collapse. Although like other MVT deposits, Robb Lake is intimately associated with carbonate breccias, a number of key textures that in other cases have clearly linked brecciation to karsting and solution collapse are not observed in the deposit. These include intrakarst sediments, sagging of overlying strata, and open-space sulphide textures such as stalactites and sulphide-carbonate laminites. On the contrary, mineralization is intimately associated with brecciation, particularily with the synmineral trash breccias, both in time and in space.

One possible explanation for the textural differences between Robb Lake and, for instance, Pine Point, is that the Robb Lake deposit formed from fluids under higher confining pressure, with hydrostatic and lithostatic pressure equivalent, whereas Pine Point formed in a near-surface environment in which significant open spaces were maintained over time.

Questions that we will try to resolve in the future with respect to the Robb Lake deposit include the following:

The age of mineralization is unknown and could be as old as late Devonian (equivalent to Pine Point deposit) or as young as Cretaceous or even younger. It is hoped that the proposed Rb-Sr sphalerite study will illuminate this issue.

How did the rock-matrix ("trash") breccias form? How does solution collapse promote the fine clast size and highly angular clast shapes seen in these; and by what collapse mechanism are entire vein selvages detached? On the other hand, what other mechanism of brecciation could be operative in the context of relatively cool brines (87° to 154°C with a mean of 119°C; Sangster and Carrière, 1991)?

Why do the mineralized and unmineralized breccias preferentially favor a stratigraphic interval, the base of the upper thick unit, which is otherwise lithologically indistinguishable from others in the Muncho-McConnell Formation?

Are the deposits of the Robb Lake belt, Pb-Zn mineralization in the subsurface Presqu'ile Barrier and Pine Point cogenetic, the result of a single eastward "flush" of MVT brines; or are they polygenetic? Are the MVT deposits of the Robb Lake belt genetically related to the SEDEX deposits of the Kechika Trough?

ACKNOWLEDGMENTS

The authors are very grateful to D.J. Robertson and J.M. Der Weduwen of Falconbridge Ltd. for lively exchange of ideas, and for providing access to property and data. We are grateful to Amy Thibeault for her assistance in the field. Drafting was done by Richard Franklin. R.I. Thompson, A. Legun and W. J. McMillan reviewed the manuscript.

REFERENCES

Brannon, J.C., Podosek, F.A., and McLimans, R.K. (1992): A Permian Rb-Sr age for sphalerite from the Upper Mississippi zinc-lead district, Wisconsin; *Nature*, Volume 356, pages 509-511.

Christensen, J.N., Halliday, A.N., and Kesler, S.E. (1996): Rb-Sr dating of sphalerite and the ages of Mississippi-Valley-type Pb-Zn deposits; *Society of Economic Geologists*, Special Publication No. 4, pages 527-535.

Christensen, J.N., Halliday, A.N., Vearncombe, J., and Kesler, S.E. (1995a): Testing models of large-scale crustal fluid flow using direct dating of sulfides: Rb-Sr evidence for early dewatering and formation of MVT deposits, Canning Basin, Australia; *Economic Geology*, Volume 90, pages 877-884.

Christensen, J.N., Halliday, A.N., Kesler, S.E., Liegh, K.E., and Randell, R.N. (1995b): Direct dating of sulphides by Rb-Sr - a critical test using the Polaris Mississippi Valley-type Zn-Pb deposit; *Geochimica et Cosmochimica Acta*, Volume 59, pages 5191-5197.

Christensen, J.N., Halliday, A.N., Kesler, S.E., and Vearncombe, J. (1994): Age of MVT mineralization in the Canning Basin, Australia: Rb-Sr analysis of sphalerite from the Blendevale deposit; *Geological Society of America*, Abstracts with Programs, Volume 26, pages A381.

Halliday, A.N., Ohr, M., Mezger, K., Chesley, J.T., Nakai, S., and DeWolf, C.P. (1990): Recent developments in dating ancient crustal fluid flow; *Reviews of Geophysics*, Volume 29, pages 577-584.

Haynes, S.J. (1979): Carbonate-hosted lead-zinc occurrences in northeastern British Columbia with emphasis on the Robb Lake deposits: Discussion; *Canadian Journal of Earth Sciences*, Volume 16, pages 1641-1642.

Legun, A. (1998): Geology of the Mt. McCusker area, northeastern British Columbia (94G/4W); *in* Geological Fieldwork 1998, *B.C. Ministry of Energy and Mines*, Paper 1999-1, this volume.

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

Macqueen, R.W. and Thompson, R.I. (1979a): Carbonate-hosted lead zinc occurrences in northeastern British Columbia with emphasis on the Robb Lake deposit: Reply; *Canadian Journal of Earth Sciences*, Volume 16, pages 1634-1644.

Macqueen, R.W. and Thompson, R.I. (1979b): Carbonate-hosted lead zinc occurrences in northeastern British Columbia with emphasis on the Robb Lake deposit: Reply; *Canadian Journal of Earth Sciences*, Volume 16, pages 2067-2068.

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

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

Sangster, D.F. (1973): Geology of Canadian lead and zinc deposits; *Geological Survey of Canada*, Paper 73-1, Part A, pages 129-130.

Sangster, D.F. (1979): Carbonate-hosted lead zinc occurrences in northeastern British Columbia with emphasis on the Robb Lake deposit: Discussion; *Canadian Journal of Earth Sciences*, Volume 16, pages 2063-2066.

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

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

Taylor, A.H. (1977): Carbonate stratigraphy and petrology: Robb Lake zinc-lead property, northeastern British Columbia; unpublished M.Sc. thesis, *Carleton Universit*y, Ottawa, Ontario.

Thompson, R.I. (1974): Geology of the Robb Lake property; *B.C. Department of Mines and Petroleum Resources*, Annual Report 1972, pages 463-467.

Thompson, R.I. (1989): Stratigraphy, tectonic evolution and structural analysis of the Halfway River map area (94B), northern Rocky Mountains, British Columbia; *Geological Survey of Canada*, Memoir 425, 119 pages.