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The Cobalt Mining District: Silver Sources, Transport and Deposition

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Abstract — Cobalt, Ontario, is renowned for the 12.6 billion grams (445 million ounces) of silver produced from the area since discovery in 1903 by workers of the Timiskaming and Northern Ontario Railway. Native silver generally occurs with cobalt arsenides and sulfosalts in near-vertical carbonate veins cutting the Huronian sedimentary rocks of the Gowganda Formation, the Archean metavolcanics and/or the Nipissing diabase. All major deposits have been found within a few hundred meters of the unconformity between the Archean and Huronian rocks in general proximity to the Nipissing diabase and volcanogenic sulfide mounds within the Archean meta-volcanics. Silver has been mobilized from one or more of the local country rocks by hyper-saline brines and deposited in or near zones of mixing where the saline brines encounter paleometeoric water transported to depth along the unconformity or local structures. Previous work has shown that chloride complexes are the dominant ligands responsible for silver transport. These hypersaline brines, represented as halite-bearing fluid inclusions at room temperature, have been trapped as primary fluid inclusions within vein minerals. Pressure-temperature conditions of vein formation have been derived from mineral equilibria, maximum lithostat and fluid-inclusion studies. These data are consistent with vein formation occurring over the temperature range 300°C to 350°C, with pressures constrained between 60 Mpa and 136 Mpa (600 bars and 1360 bars).

History

Alfred Larose, a blacksmith for the McMartin Brothers railway contractors, is one of the people first credited with the discovery of silver in the Cobalt area on the northern end of what is now Cobalt Lake. Larose found some float one evening and spent a few subsequent evenings locating the vein which was the source of the float. Later, he showed the vein to his employer, Duncan McMartin, and they staked a claim late in the summer of 1903 (Barnes, 1986). Unknown to Larose and McMartin was the discovery and staking of another vein by J.J. McKinley and Ernst Darragh. McKinley and Darragh were railway-tie contractors for the Timiskaming and Northern Ontario Railway, and, as a result, had been in advance of the main railway party. As a break from their work, the two men had decided to stake a claim in the area after noticing metallic particles within the rock (Barnes, 1986). On August 30, 1903, they staked a claim on the southern shores of Cobalt Lake. Although destined to produce approximately 1 billion grams of silver, both the Larose and McKinley-Darragh claims lay dormant for a while as their owners were not yet aware of what they had discovered.

In the fall of 1903, Larose had decided to take some time off and visit Hull, Quebec. While waiting to change trains in Mattawa, he visited the Timmins brothers' store where he purchased some tobacco and began talking to one the store owners, Noah Timmins. Larose showed Timmins some of his samples and then caught the train south. Noah Timmins had some knowledge of staking and was sufficiently impressed with Larose's samples to pen a letter to his brother, Henry, in Montreal, asking him to find Larose in Hull and buy a share of the claim. After some difficulty, Henry Timmins was able to locate Larose and purchase half of his claim for $3500. Coincidentally, Larose had also left some of his samples with Arthur Ferland, manager of the Matabanick hotel in Haileybury (and interestingly enough, the Timmins' brother-in-law). Ferland gave some of the samples to the director of the Ontario Bureau of Mines, T.W. Gibson, during a visit to Haileybury. Upon his return to Toronto, Gibson sent the samples to Ontario's first provincial geologist, Willet Miller, at Queen's University, and suggested he visit the area. During this same time, some of the McKinley-Darragh samples had been sent for assay, however, the results showed only bismuth and no silver. A sec-

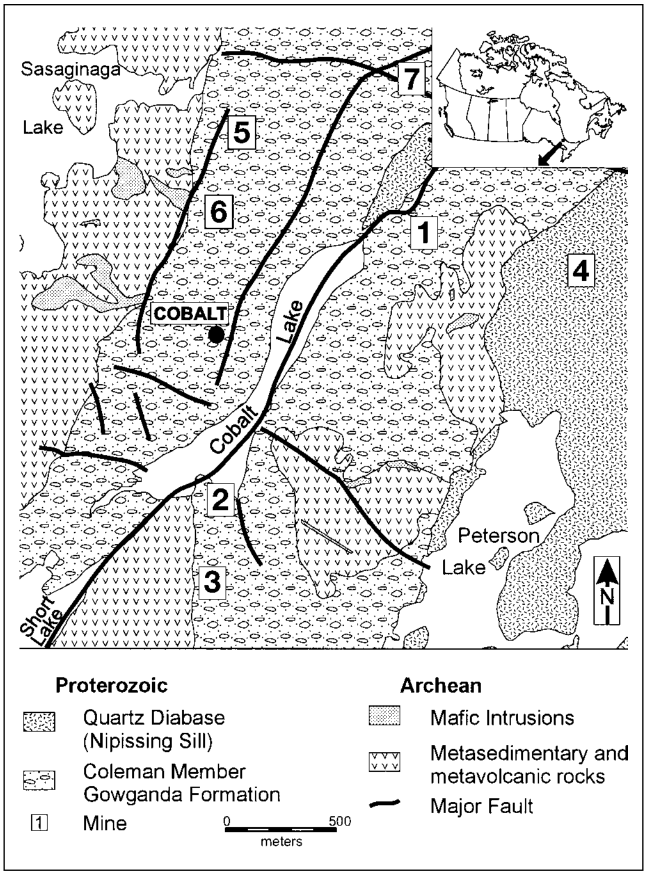

Fig. 1. Geological map of the historic mining Cobalt mining camp showing the locations of the early discoveries, major rock types and structures (after Thomson, 1964). Mines: 1. Larose; 2. McKinley-Darragh; 3. Little Silver Vein (Nipissing Mine); 4. O'Brien; 5. Trethewey; 6. Coniagas; 7. Chambers-Ferland.

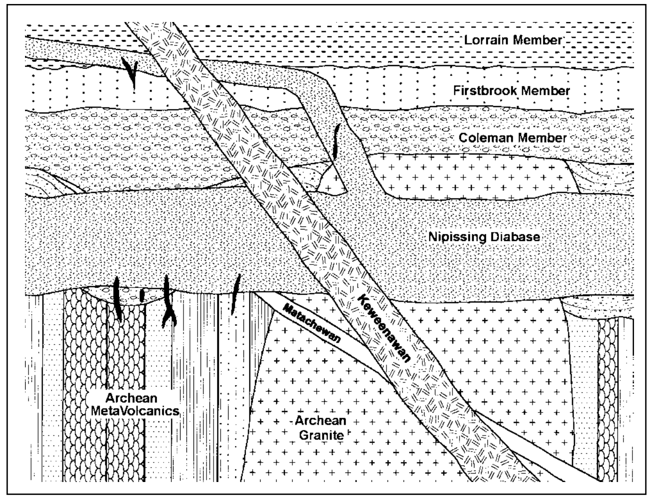

Fig. 2. Idealized geological cross-section of the major rock units in the Cobalt area. The unlabelled rock type is the Timiskaming sedimentary rocks shown in the folded smaller conglomerate pattern underlying the Coleman. The Archean metavolcanic and metasedimentary rocks are shown in the vertical dipping patterns at the bottom of the section. Silver veins are shown in black, schematically representing some of the observed associations of the silver veins with the different rock types.

ond set of samples sent to McGill University, then given to Montreal chemist, Dr. Milton Hersey, assayed at 12.5 wt% silver.

By this time, many rumors of silver at Cobalt had other people interested in the area. One of these people, Tom Hebert, a timber cruiser with the J.R. Booth Company, staked a large area directly to the north of Cobalt Lake, just to the west of the original Larose claim. He immediately approached Arthur Ferland, and a syndicate of Ferland, Herbert, and railway engineers, T. Chambers and R. Gilbraith was formed, with their claims totaling 342 ha (846 acres). Ferland then contacted an American financier named Ellis Earle, who upon having the claims evaluated, bought 341 of those hectares for 1 million dollars. That parcel became the Nipissing mine and produced more than 2.5 billion grams of silver (Nichols, 1988). One block of ore from the "Little Silver Vein" described as "not as large as a house" produced $350,000 worth of silver.

By late 1903, Miller had visited (and named) the Cobalt camp, and news of these extremely rich silver deposits had hit the world with virtually no impact. Neil King, a fire ranger in the area, staked a claim to the east of (and overlapping parts of) the Larose-McMartin claim early in 1904. King then approached and sold his claim to M.J. O'Brien of Ottawa for $4000. After some legal debate to settle the overlap with the Larose-McMartin claim, the original Neil King claim became the O'Brien mine in 1906, which yielded 35 million ounces of silver during 60 years of continuous production.

The last of the early discoveries was by W.G. Trethewey, who arrived in Cobalt in May of 1904. He had heard of silver in the area from Milton Hersey in Montreal. Being a real estate business man he had decided to attempt to buy an existing claim, however, he quickly learned that none were for sale and set out looking for his own. Trethewey searched the area to the northeast of Cobalt Lake and, while traversing a swamp, noticed a darkly tarnished vein of silver that became the Tretheway mine. A bit farther away he discovered another vein in the same network that was to become the Coniagas mine. Trethewey staked both veins later that day. The complex vein network between the two major veins eventually produced over 41 million ounces of silver (Nichols, 1988). Since 1904, the discovery of over 40 more mines in the area has resulted in the total production of over 12.6 billion grams of silver (Nichols, 1988), over 20 000 t of cobalt, 7000 t of nickel and 2000 t of copper (Jambor, 1971a) throughout the 85 year history of the Cobalt mining camp, with production peaking in 1911. Accompanying the early production at Cobalt, the town also became the staging area for further exploration in the area such as Casey township, Harris township, South Lorrain township, later discoveries at Miller Lake, Gowganda Lake, Elk Lake, Maple Mountain and the discoveries of the Larder Lake, Porcupine (Timmins) and Kirkland Lake mining camps.

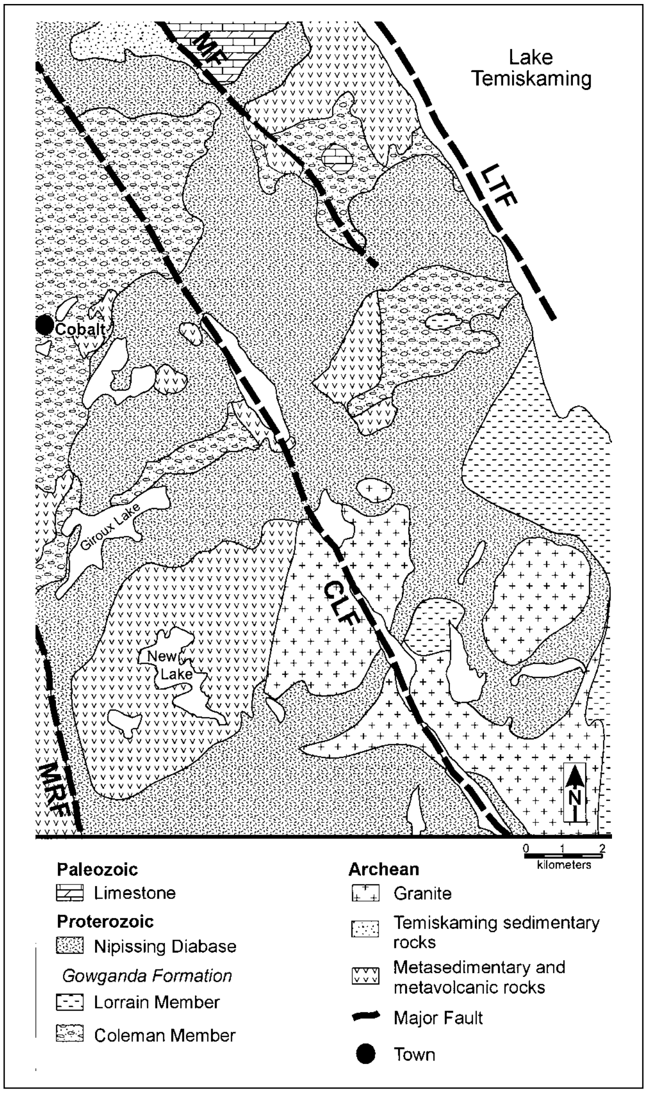

Fig. 3. Geologic map showing the basin and dome structure of the Nipissing diabase and the general relationships between the major rock types in the Cobalt area (after Jambor, 1971a).

General Geology

The Cobalt area (Fig. 1) comprises the northeastern region of the Southern Geological Province (Wilson, 1986). The oldest rocks, of Archean age, are unconformably overlain by the Proterozoic rocks of the Huronian Supergroup. The 300 m thick Nipissing diabase sill has intruded rocks of both eons but generally follows the Archean-Huronian unconformity. The Archean and Proterozoic rocks are unconformably overlain by Silurian and Ordovician limestones and Pleistocene and Recent sediments. Figure 2 depicts the geological relationships between the major rock types of the Archean and Proterozoic, and the minor units within these two eons.

Archean Rocks

The volcanic rocks and associated interflow sedimentary rocks are the oldest rocks in the Cobalt camp (Jambor, 1971a). This unit is dominantly intermediate to mafic flows with some pyroclastic units and felsic volcanic rocks, minor interflow sediments with chert and sulfide mineralization (Nichols 1988), iron formation and schists (Smyk, 1987). Timiskaming-type lithic and feldspathic arenites, wackes and conglomerates unconformably overlie the volcanic rocks (Jambor, 1971a). All these rocks have been intruded by dikes and sills of lamprophyre, mafic, and ultramafic rocks. The Archean rocks were metamorphosed to greenschist facies and were folded isoclinally during the Kenoran orogeny. Contemporaneous with the orogeny was the emplacement of Archean granites (Figs. 2 and 3).

Proterozoic Sedimentary Rocks

The Coleman Member of the Gowganda Formation unconformably overlies the Archean rocks in the Cobalt

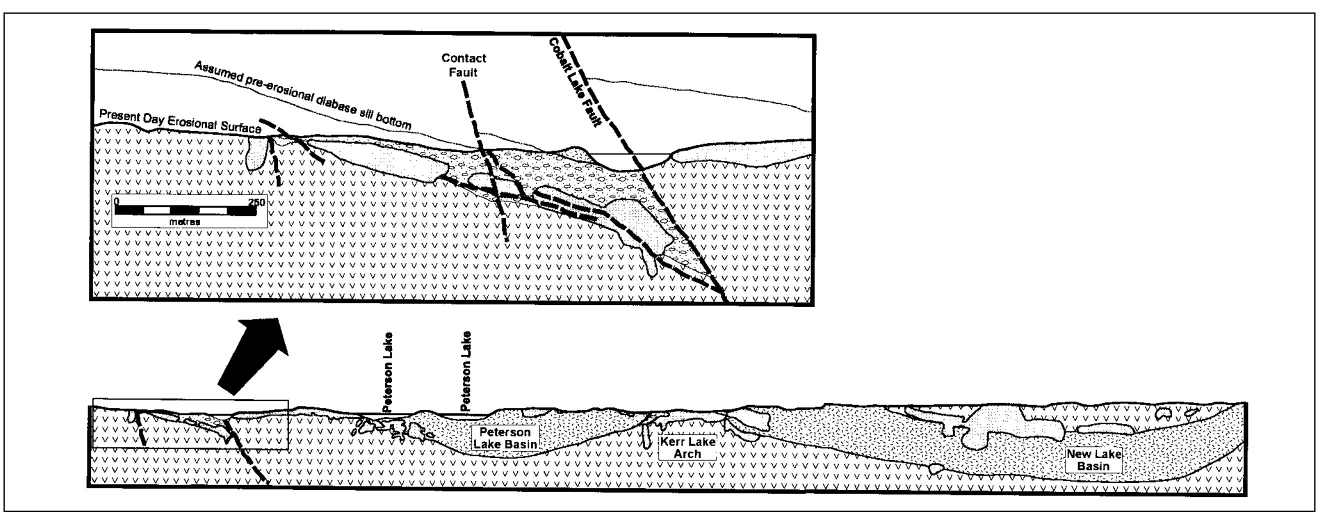

Fig. 4. Longitudinal section of the Cobalt area showing the positions of some orebodies relative to the basins and domes formed by the Nipissing diabase. An enlarged section of the northwest end of the section shows the characteristics of the deposits northwest of Cobalt Lake. See Figure 3 for legend (after Petruk, 1971a).

area. The Coleman Member is predominantly conglomerate with sandstone and laminated siltstone (Scammel, 1984; Mustard, 1985; Rainbird, 1985) with a maximum thickness of 180 m. The Coleman is conformably overlain by the Firstbrook Member, a laminated siltstone with a maximum thickness of 610 m (Jambor, 1971a). The Lorrain Formation conformably overlies the Gowganda Formation. The maximum observed thickness of 320 m (Jambor, 1971a) is cut by an erosional surface; this thickness includes only the lower arkose unit and not the overlying quartz arenite that the lower unit grades into.

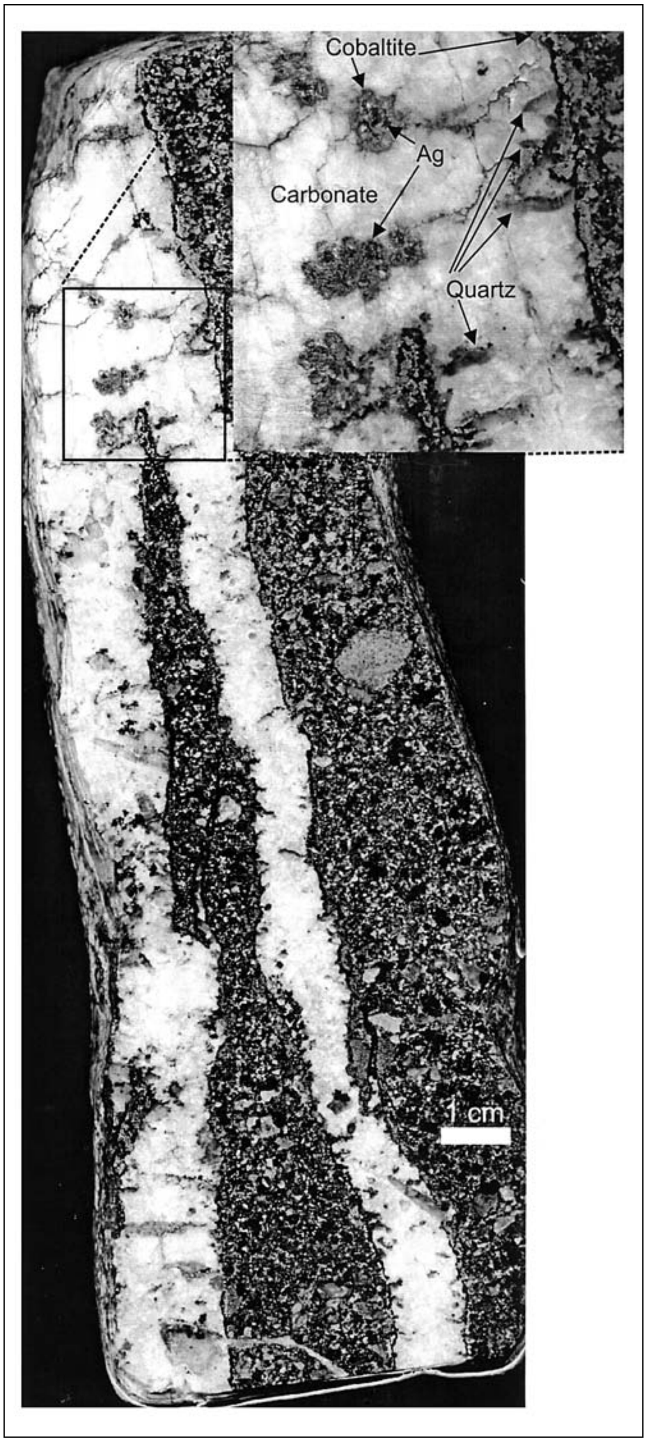

Fig. 5. Bifurcating vein from the Pan Silver mine, showing the typical carbonate-arsenide-Ag assemblage, with quartz crystals and chlorite present on the vein walls.

Nipissing Diabase

The Nipissing diabase has the bulk composition of an olivine tholeiite (Jambor, 1971b). It consists mainly of well-differentiated sills (Hriskevich, 1968; Jambor, 1971b) but dikes and gabbros are documented (Andrews, 1986). The sills generally have shallow dips that define broad basin and dome structures (Figs. 3 and 4), although locally the diabase follows pre-existing faults (Thomson, 1967).

Textural and mineralogical zoning occur within the diabase (Hriskevich, 1968; Jambor, 1971b). The lowest zone consists of a chilled margin of 5 mm to 10 mm wide. This grades upward into the lower quartz diabase that is generally 15 m to 30 m thick. The quartz diabase grades into hypersthene diabase that may occupy up to two-thirds of the sill thickness. The hypersthene diabase grades upward into variably textured diabase; this unit has variable grain size, and may be locally aplitic, granophyric or pegmatitic. The variably textured diabase is gradational into an upper quartz diabase that is generally not as thick as the lower unit. An upper chilled margin of up to 10 mm marks the contact with the intruded country rocks. Wall-rock alteration is dependent upon the intruded lithologies, ranging up to some meters into the Coleman Member, as evidenced by chlorite spotting (Jambor, 1971c).

Dikes and Sills

There are two minor sets of intrusive dikes found in the Cobalt area. The oldest set of these dikes is the Paleoproterozoic Matachewan dikes, comprised of diabase and minor lamprophyre. The youngest dikes are the Keweenawan olivine and quartz diabase dikes of the Mesoproterozoic (Jambor, 1971a).

Fault Patterns

There are three major fault patterns in the Cobalt area. A major southeast trend is represented by faults such as the Montreal River, Cross Lake, and Quinze Dam faults (Fig. 3). These faults can be traced up to hundreds of kilometers. Precambrian movement along these faults is difficult to prove, but the intrusion of a post-Nipissing diabase dike parallel to the Cross Lake fault might indicate lines of weakness in Precambrian times (Thomson, 1967). Post-Silurian movements of up to 300 m have been reported by Lovell and Caine (1970) along the Lake Temiskaming fault.

A second set of faults trends northeast. The longest fault, the Cobalt Lake fault, offsets the Nipissing diabase prior to silver deposition (Thomson, 1967). Jambor (1971a) has stated that these faults and the southeast-trending set "do not control the distribution of the silver veins and nearly all large faults are barren."

The third set of faults trends east-southeast. These are generally normal, vertical faults with displacements of up to 7.5 m (Wilson, 1986). These faults are shorter than the northeast- and southeast-trending faults, and some host silver veins (Wilson, 1986).

Veins

Two types of veins exist in the Cobalt area: the so-called vertical "ore veins" and "flat veins" (Andrews et al., 1986a) and either may be sheared or dilatant (Andrews et al., 1986a). Geological relationships indicate that the flat veins are coeval with or later than the ore veins (Andrews et al., 1986a). The ore veins are dominated by carbonate minerals with silver and sulfarsenides of cobalt, nickel, iron and bismuth and minor quartz (Fig. 5). The ore veins are commonly zoned vertically with respect to the center of the Nipissing diabase, exhibiting distinctive Ni-As, Ni-Co-As, Co-Fe-As, Fe-As and Co-As assemblages (Fig. 6) with silver grades highest in the Ni-bearing assemblages (Petruk, 1971b). The flat veins have dominantly silicate minerals, including quartz, potassic feldspar, epidote, axinite and carbonate. The intersections of some flat and ore veins can be preferred sites for ore deposition (Andrews et al., 1986a; Petruk, 1971a). The ore veins vary in width from a few millimeters to more than 30 cm with an average width of less than 5 cm (Jambor, 1971a). The silver-arsenide ore veins may be more than 300 m long and 100 m in vertical extent, although they may not be ore grade over the entire length and depth. The flat veins are up to 15 cm in thickness. Hydrothermal wall-rock alteration is of minor intensity and may vary in extent up to several cm into the host rocks (Appleyard, 1980) with a general wall-rock alteration trend of Si depletion and Ca, Na and CO_2 enrichment.

Geochronology

A K-Ar age of 2525 ± 72 Ma (Jambor, 1971a) for a quartz monzonite pluton that intruded the Archean metavolcanic rocks to the southeast of Cobalt provides an upper age constraint on the volcanic rocks. The Gowganda Formation has yielded a Rb-Sr isochron age of 2288 ± 87 Ma (Fairbairn et al., 1969). The Nipissing diabase has been dated by U-Pb at 2219 ± 3.6 Ma (Andrews et al., 1986b). The silver veins cut the diabase and are therefore younger than 2219 ± 3.6 Ma. U-Pb analyses of primary baddeleyite from the Nipissing diabase and vein-related secondary rutile yield ages of 2217.5 ± 1.6 Ma and 2217.0 ± 6 Ma, respectively (Andrews et al., 1986b). Although these data indicate no significant age difference between diabase intrusion and vein formation, an age difference of 8.1 Ma is possible within the limits of uncertainty.

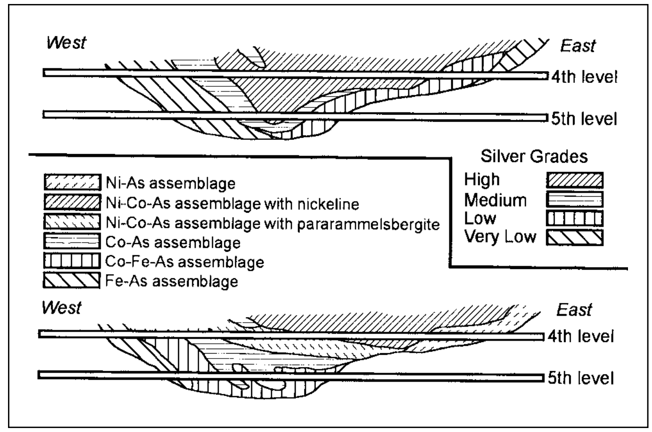

Fig. 6. Longitudinal section of the Silverfields mine, vein 1, showing the distribution of silver grades (top) and arsenides (below) (after Petruk, 1971b).

Fluid Inclusions

Fluid-inclusion studies (Scott and O'Connor, 1971; Kerrich et al., 1986; Marshall et al., 1993) reveal the presence of at least two distinct populations of fluid inclusions. The predominant fluid-inclusion type is represented at room temperature as highly saline, three-phase inclusions consisting of a halite cube, a brine, and a vapor bubble. These fluid inclusions have been observed in quartz and carbonate from ore and flat-veins, and from ore-vein axinite. Fluid-inclusion compositions were determined using microthermometry, cryogenic energy dispersive spectral (EDS) analyses, and secondary ion mass spectrometry (SIMS). The three methods consistently indicated $CaCl_2$:NaCl:KCl of approximately 3:2:1, with a salinity of approximately 35 wt% NaCl equivalent. This type of fluid inclusion has been shown petrographically to pre- and post-date the deposition of silver within the Cobalt camp (Marshall et al., 1993). A second less-abundant fluid-inclusion type is present during ore formation and is represented by two-phase fluid inclusions at room temperature. The two phases are an aqueous brine and a vapor bubble of varied proportions, with salinities ranging from almost pure water to 25 wt% NaCl equivalent. This second fluid-inclusion type has been shown to be contemporaneous with silver mineralization (Marshall et al., 1993). Additionally, no CO_2, H_2S, CH_4 or N_2 was detected in either of the two fluid-inclusion populations by Raman microscopy, microthermometry, or crushing studies.

Pressure-temperature Conditions of Vein Formation

Fluid-inclusion isochores for the three-phase fluid inclusions, stable calc-silicate mineral assemblages, and maximum

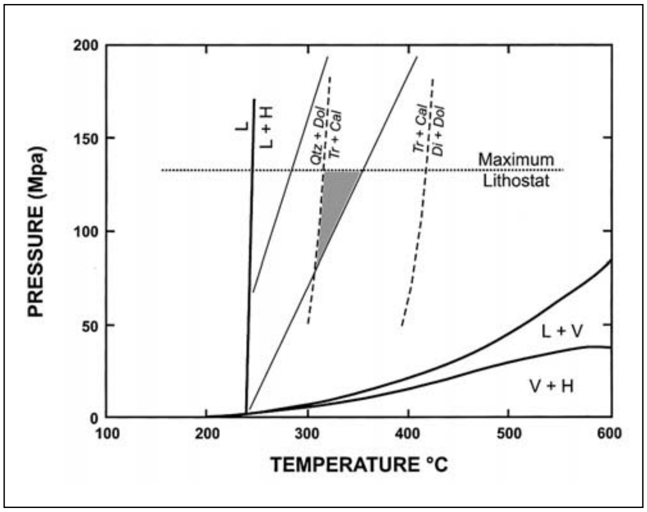

Fig. 7. Pressure-temperature diagram showing the combined constraints for the formation of the Cobalt silver veins. The mineral equilibria constraints (dashed lines) are based on calc-silicate reactions (Di: diopside, Tr: tremolite, Cal: calcite, Dol: dolomite, Qtz: quartz). The maximum lithostat limit is shown as a dotted line. The bold signature lines represent the phase stability fields for a 34 wt% NaCl isopleth in the H_2O-NaCl binary. L=liquid, V=vapor, H=halite. The light signature lines represent the maximum and minimum fluid-inclusion isochores (after Marshall et al., 1993).

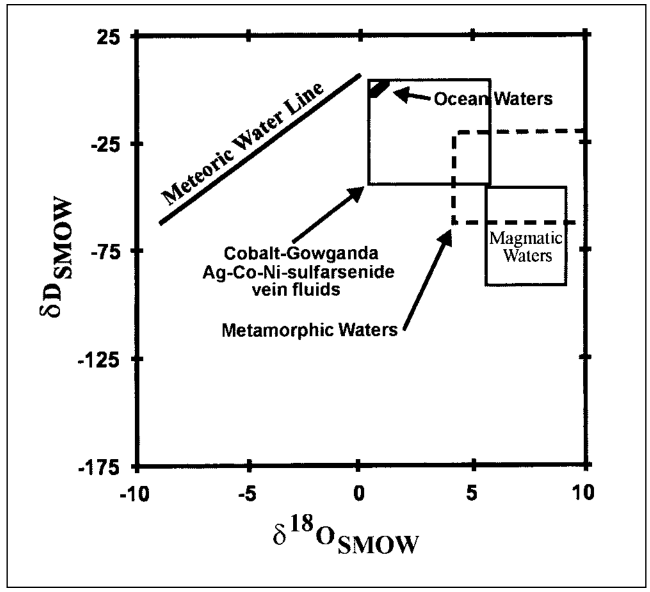

Fig. 8. Oxygen and hydrogen isotopic terrestrial fluid reservoirs for oxygen and hydrogen isotopes. The data of Kerrich et al. (1986) from the Cobalt-area minerals are displayed. These data plot ambiguously, showing a wide variation across the reservoirs for metamorphic fluids, igneous fluids, oceanic and meteoric waters. The data are calculated from mineral isotopic data.

lithostat calculations (Marshall et al., 1993) have been used to constrain pressures and temperatures of ore vein formation at Cobalt (Fig. 7). These combined techniques are consistent with vein formation between 60 Mpa and 136 Mpa, and temperatures in the range 300°C to 350°C (Marshall et al., 1993).

Mechanisms of Silver Deposition

It seems evident that the silver in the Cobalt area was transported as a chloride complex, based upon (1) the presence of highly saline brines (Scott and O'Connor, 1971; Kerrich et al., 1986; Marshall et al., 1993), and (2) the low sulfur fugacity within the veins, which is consistent with the lack of any detectable sulfur-bearing aqueous or gaseous phases in fluid inclusions, and the typically "sulfur deficient" association cobalt-nickel-silver (Meyer and Hemley, 1967). Assuming that the majority of the silver was transported as a chloride complex, there are three possible mechanisms for silver deposition: boiling of a silver-saturated solution, cooling of a silver-saturated solution, and mixing of a silver-saturated solution with a less saline fluid (possibly of meteoric origin), or some combination of all three. The relative merits of these depositional mechanisms have been discussed in Marshall et al., (1993), with additional observations on mixing and boiling presented here. The moderate temperatures and relatively shallow depths derived for vein emplacement in the Cobalt camp may have been favorable to phase separation of the identified saline brines at Cobalt, and, indeed, these conditions are not far removed from the two-phase field for the Cobalt fluids presented in Marshall et al. (1993). However, the incomplete salinity measurements from very few inclusions exhibiting boiling phenomenon (simultaneous liquid and vapor homogenization) presented in Kerrich et al. (1986) make a distinction between post-entrapment fluid-inclusion volume changes and phase separation (boiling) impossible (Bodnar, 1985). Subsequently, any interpretation including boiling is somewhat suspect.

Support of a mixing model is given in Figure 8. The δD and $\delta^{18}O$ compositions of fluids calculated from the chlorite and actinolite at equilibrium temperatures for a variety of wall rock, flat and ore vein material (Kerrich et al., 1986) are scattered, ranging from the field of magmatic waters, through metamorphic fluids and ocean waters, towards the meteoric water line. Further and more detailed support of a mixing hypothesis can be seen in Figure 9; these salinities and oxygen-isotope values were obtained directly from the quartz-hosted fluid inclusions of four samples (Kerrich et al., 1986). This limited data set shows a distinct binary mixing trend between an ^{18}O-rich, high-salinity end member and a relatively ^{18}O-poor, less saline end member.

Finally, a probable enhancement to silver precipitation accompanying any or all of the above depositional mechanisms would be the process of fluid reduction (Kissin, 1993) by units of a reducing nature, such as pre-existing Ni-As-Co-S minerals, and/or graphite or sulfur-bearing shales.

Sources of Silver

Early workers in the Cobalt camp were quick to recognize the general proximity of the Cobalt silver veins to the

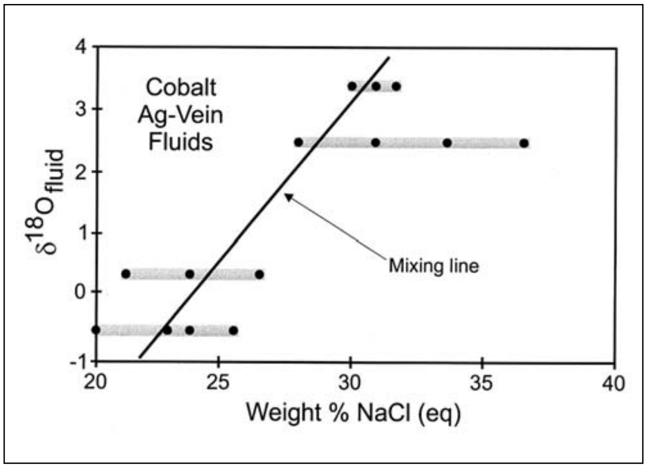

Fig. 9. Plot of $\delta^{18}O$ vs weight percent NaCl equivalent. This limited number of data points from quartz-hosted fluid inclusions form a linear array consistent with binary mixing of two end members. One end member is high salinity and enriched in ^{18}O, whereas, the other end member is less saline and relatively depleted in ^{18}O. Data (black circles) are from Kerrich et al. (1986).

Archean-Huronian unconformity and the Nipissing diabase. The diabase, the Archean rocks, the Huronian rocks, or a combination of the three, could have acted as a source of silver (Boyle and Dass, 1971; Jambor, 1971d). Additionally, deep-seated sources of magmatic/metamorphic fluids could have provided the necessary source for the Cobalt silver (Kissin, 1988). Various authors have used rare-earth elements (Andrews et al., 1986a), Sr isotopes (Kerrich et al., 1986), Pb isotopes (Thorpe et al., 1986), S isotopes (Wilson, 1986; Goodz et al., 1986; Petruk, 1971c) and mineral chemistry (Watkinson, 1986) to constrain the source of silver within the Cobalt ore veins. None of these techniques has clearly identified the source of the silver and there is no technique with more scientific merit than the others. This most probably indicates that the silver was supplied by a variety of source rocks to varying extents.

Genetic Models

A most complete set of genetic theories for the five-element (Ag, Ni, Co, As, Bi) suite has been compiled in Halls and Stumpfl (1972) and modified by Kissin (1993). The theories applicable to the Cobalt deposits have been summarized in Table 1. Any genetic model for the Cobalt camp must encompass some basic observations made by researchers working on silver veins within the camp. Firstly, silver veins generally occur within 100 m of the Nipissing diabase and the Archean-Huronian unconformity. Secondly, the veins are generally situated above an Archean massive sulfide deposit (Nichols, 1988). Thirdly, the zonation of the Co-Ni-Fe sulfarsenides with respect to silver and to the center of the Nipissing diabase (Petruk, 1971b). Fourthly, the tectonic setting during silver mineralization was one of basinal subsidence and deep crustal rifting. Finally, the silver mineralization has been dated at 2217 ± 6 Ma by U-Pb analyses of vein-related secondary rutile. This is in good agreement with a U-Pb age of 2217.5 ± 1.6 Ma from the primary baddelyite of the Nipissing diabase (Andrews et al., 1986b). Therefore, any deep-seated fluid source would have to have been intruded into the area, at the same time or shortly after the emplacement of the Nipissing diabase. Due to the similarities in age between the Nipissing diabase and the silver mineralization, it seems likely that the Nipissing diabase was a major contributor to the overall heat budget during silver mineralization.

Considering a deep-seated source versus a local source, it is instructive to approximate how much fluid would be required to deposit all of the silver mined from the Cobalt camp. A local source model has the advantage of being able to "recycle" the silver-transporting medium, whereas, a deep-seated source must move all of the silver using the transporting medium once only. Silver values obtained from hydrothermal source areas range from 0.00025 ppm at Broadlands, New Zealand, to 1.4 ppm from Salton Sea drill holes (Weissberg et al., 1979). Assuming a silver extraction efficiency of 40% (Seward, 1976; 353°C to 277°C at high salinity), this would require fluid flows on the order of 1.2 * 10^{11} to 7.0 * 10^{14} gallons. These values correspond to Missouri River annual flow rates ranging from just under a year to 85 years. These numbers are not unreasonable considering ore deposits normally form on the order of thousands of years. Therefore, in terms of fluid availability, there is no reason to discount models considering "deep-seated" sources.

The two models (Table 1) involving the hydrothermal evolution of a deep-seated granitic or mafic intrusion, proposed originally by Bastin (1939) and Tyrell (1907), respectively, have failed to garner the support of the geological community because there is no evidence for these deep-seated sources.

Table 1. Ore genesis models for the Cobalt Ag vein deposits

Theoretical Model	References
Hydrothermal evolution from a deep-seated granitic intrusion.	Bastin (1939)
Hydrothermal evolution from a deep-seated mafic intrusion.	Tyrell, 1907; Miller, 1913; Sampson and Hriskevich, 1957
Hydrothermal (in situ) evolution of the Nipissing diabase.	Tyrell, 1907; Van Hise, 1907; Jambor, 1971d
Hydrothermal/metamorphic processes concentrating components from:	
• Huronian shales	Kerrich et al., 1986
• Metal-rich Archean volcanoclastic rocks	Boyle and Dass, 1971
• Pre-existing Archean massive sulfide deposits	Goodz et al., 1986; Smyk and Watkinson, 1990
Introduction along deep fractures of juvenile five-element solutions from the crust-mantle boundary.	Halls and Stumpfl, 1972
Circulation of connate brines within continental rifts or failed rift systems.	Kissin, 1988
Mixing of hyper-saline hydrothermal brines with less saline meteoric waters.	Marshall et al., 1993

(After Kissin, 1988)

The hydrothermal in-situ evolution of the Nipissing diabase has been a favored model (Table 1) by some authors (Tyrell, 1907; Van Hise, 1907; Jambor 1971d). Cooling and mixing of silver-bearing saline brines evolved from the Nipissing diabase with meteoric fluids has been proposed by Marshall et al. (1993) and as a secondary mechanism to boiling by Kerrich et al. (1986). This mixing model, supported by fluid inclusion and stable isotope evidence, is also consistent with the U-Pb dates for the silver mineralization (Andrews et al., 1986) and the observed spatial associations of the Huronian-Archean unconformity with the Nipissing diabase. The absence of other silver deposits in other localities where there is abundant Nipissing diabase is probably due to the lack of other favorable conditions such as reduced meteoric water input (Marshall et al., 1993) or missing sulfides (Nichols, 1988).

Hydrothermal concentration of components from Huronian shales (Kerrich et al., 1986), Archean massive sulfides (Smyk, 1995; Smyk and Watkinson, 1990; Watkinson, 1986; Goodz et al., 1986; Franklin et al., 1986) and Archean volcanoclastic rocks (Boyle and Dass, 1971) is a popular model for the genesis of the Cobalt silver veins (Table 1). These models agree well with the observed spatial associations of the Huronian-Archean unconformity and Nipissing diabase. Additionally, sulfur isotope data suggest a trend of progressively heavier ^{34}S values in sulfides moving away from the veins into the Archean wall rocks. This trend suggests that some of the sulfur found in the silver-bearing veins was derived from the local Archean rocks and is consistent with the observations of Nichols (1988).

The introduction of non-magmatic crustal fluids, such as juvenile five-element solutions (Halls and Stumpfl, 1972), or the circulation of connate brines (Kissin, 1988) are possible scenarios for the genesis of the Cobalt silver veins. This model is consistent with a continental-rifting tectonic setting for the Cobalt deposits. The temperatures of formation and fluids responsible for silver transport and deposition are similar to those reported for silver mineralization attributed to this deposit genesis (Kissin, 1988).

Discussion and Conclusions

At present, there is no definitive proof that can specify the exact mode of genesis or the source of the silver for the Cobalt area. However, the similar ages of the Nipissing diabase and silver mineralization would suggest some contribution of heat, and likely fluid, from the diabase. Previous fluid-inclusion studies (Marshall et al., 1993) showed a brine, represented by three-phase (L+V+H) fluid inclusions, was present at the pre- and post-ore stages of silver mineralization. Since pre- and post-ore stages contain fluid inclusions that indicate temperatures of 300°C to 350°C, and 60 Mpa and 136 Mpa (600 bars and 1360 bars), and syn-ore fluid inclusions are consistent with these conditions, the authors infer that vein formation took place under these conditions. This highly saline brine provides the most likely method of silver transport, i.e., as silver-chloride complexes. Deposition of silver was most likely triggered by the mixing of these hyper-saline brines with a weakly saline fluid of probable meteoric origin, with boiling possibly acting as a minor depositional mechanism. Reduction of the silver-bearing fluids by local sulfide-rich or graphitic units could enhance silver deposition.

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