ORIGIN OF THE SILVER VEINS OF THE COBALT - GOWGANDA REGION

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Abstract

The origin of the silver-bearing veins in the region is discussed in terms of a deep-seated parental magma source, a distillation of the metals from Archean rocks as a result of Nipissing diabase intrusion, and a direct derivation from differentiated Nipissing diabase. It is concluded that the Nipissing intrusions were the source of the metals: ore veins occur in all types and ages of pre-Nipissing host rocks close to the diabase intrusions; where there was no diabase, Ni-Co arsenide-native silver veins have not been found.

Introduction

The close spatial relationship of the Nipissing diabase and the silver-arsenide veins has been recognized since Cobalt's infancy. In more than 60 years of silver production from the region, this fundamental relationship has continued to be corroborated. Any genetic theory that does not incorporate or provide alternative explanations for this association has therefore failed to integrate a dominant geological fact. Because isotopic data (p. 30-31) also point to a probable temporal association of the ores and Nipissing diabase, only 3 of the many proposed genetic theories will be considered here. These are: (1) the ores were derived from the parent magma of the diabase; (2) the ores were extracted from pre-Nipissing rocks, with the mobilizing agent being the Nipissing diabase; (3) the ores were derived by fractionation of the Nipissing diabase.

Parent Magma Source

Tyrrell (1907) seems to have been among the first to have advocated a deep-seated source for the ores, but the theory was more precisely stated and attained prominence through the writing of Miller (1913), Reid (1918), Whitehead (1920), Boydell (1931), Moore (1934, 1956), Bastin (1935, 1939), and Sampson & Hriskevich (1957). Specifically, almost all of these writers have suggested that the solutions which deposited the vein matter were derived from a deep-seated magma which may have been the parent of the Nipissing diabase. Bastin (1939) wrote at length on nickel-cobalt-native silver ore occurrences throughout the world, and on this basis concluded that the deep-seated magmatic source was granitic or intermediate in composition rather than diabasic.

Supporting evidence for a parent magma rested primarily on the fact that the ore veins cut the Nipissing diabase and that ore occurred in the Cobalt Lake fault. A more elaborate study was undertaken by Moore (1934) who stated (pp. 754-755) :

> "The writer concludes, from the petrographic, structural and other features — that the source of silver for most of the ore was in the parent magma and not in the sills. The role played by the sills in the emplacement of the deposits is regarded as entirely a structural one. The extent of the differentiation in the sills has not been sufficient, in the writer's opinion, to produce the bulk of the ore. The presence of aplite and granophyre with the diabase in some localities indicates that soda-rich solutions escaped from the diabase sills, but whether they originated in the sills or in the parent magma has not been proven."

Some 20 years after the above paper was written, Moore (1956) examined the silver deposits at Gowganda and modified his original conclusions (1956, pp. 30-31) :

> "Summing up the data on the relations of silver, diabase, and granophyre, it is evident that they are inconclusive in one or the other of the two categories mentioned above. The granophyre carries more silver than the diabase, but this might be because one rock is more easily impregnated with the ore-bearing solutions than the other. The distinct relation of the silver and granophyre in the Morrison veins, described above, however, strongly supports the hypothesis that the veins in that mine, at least, are the result of differentiation in the diabase. Further, the occurrence of many small, but rich, veins in the sill west of Gowganda Lake and about 5 miles from the centre of the Miller Lake basin favours the concept of the source being in the sill. This is strengthened by the fact that there is considerable granophyre associated with some of these veins. There may, of course, be another feeder for the sill beneath this area, and since the sill is highly fractured there, the ore-bearing solutions could come up to its upper part. There is strong evidence that at least some of the silver is due to differentiation in the sill.
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> Favouring a deeper source for most of the silver is its abundance near the centre of the Miller Lake basin where most of the sill originated and in mines in which granophyre is rare. Further, the diabase in these mines is highly fractured by faults of considerable size, and by extensive columnar jointing. It is recognized that ore is more likely to be found in the sill where most jointage occurs. This jointing certainly preceded the formation of the ore deposits, and although the faults appear to be post-ore in age, many of them must have been in existence before the veins were formed, since there is such a definite relation between them. This highly fractured condition of the sill would account for a difference in the position of the veins, with respect to the sill, in the Cobalt and Gowganda areas. It would permit the silver-bearing solutions to rise through the sill to its upper part where they would be trapped by the tight Keewatin at its contact".

Bastin (1935, 1939) wrote at length on the parent magma concept and summarized his conclusions as follows (1939, p. 39) :

> "The prevailing association of the nickel-cobalt-silver veins with relatively flat-lying diabase is probably due in part to a blanketing effect of the sills and the

associated flat-lying Cobalt series on ascending mineralizing solutions causing them to spread laterally beneath these formations until they encountered fractures suitable for ore deposition.

The Nipissing diabases were not only completely crystallized but had been fractured by faults, some of them of considerable displacement, prior to mineralization. It is unlikely, therefore, that the mineralizing solutions came from the diabase sills.

This conclusion is also supported by evidence that certain so-called aplites that border some of the veins are not the final products of the crystallization of the diabase sills as formerly believed but were formed by hydrothermal alteration after the diabase was completely solidified."

In refuting Bastin's origin for aplites, Sampson & Hriskevich (1957) concluded that aplites and their associated arsenide minerals were derived from Nipissing diabase. They carefully documented the fact that vug-like masses in the dykes contain carbonate and ore minerals which were an integral part of the aplitic magma. Sampson & Hriskevich chose, however, to distinguish between "normal" veins having a carbonate gangue, and "aplites" which contain essentially the same mineralization. For the "normal" veins lacking aplite, Sampson & Hriskevich invoked a parent magma source because (1957, p. 75) :

"The mineralization is substantially later than the diabase, as veins occur in faults that displace the diabase."

Because this is a recurring theme in many papers, the present writer has attempted to document the cases where such displacements occur. The path, however, invariably leads only to the Cobalt Lake fault. The question of whether significant displacement of the diabase occurred along the Cobalt Lake fault after intrusion and prior to ore deposition has already been discussed (see p. 31) ; post-diabase, pre-ore movement along the fault has not been well-established. It should be noted, moreover, that the aplite dykes and their associated mineralization as described by Sampson & Hriskevich cut the diabase, which must have been sufficiently competent to sustain fracturing prior to complete crystallization of all the components of the intrusion. Acknowledging that fracturing did occur, movement along such planes would constitute faults. Presumably therefore, faulting is permissable and the major uncertainty is the amount of movement considered tolerable in such circumstances.

The remaining factors cited as favouring a deep-seated source need be mentioned only briefly. Bastin's (1935, 1939) arguments regarding hydrothermal alteration of the Nipissing diabase by solutions from a deep-seated source are rejected because the development of this feature coincides with diabase fractionation rather than with volatiles rising from beneath the sheets. Similarly, the occurrence of hundreds of small veinlets at the top of, and above the diabase sheets, is difficult to relate structurally to a deep-seated source. One could assume that these came from the Nipissing diabase whereas ore veins below the sheet came from a deep source, but such a two-fold origin is improbable. There is also no reasonable way that a deep source would account for Petruk's data which show that the ore minerals are symmetrically zoned with respect to the centre line of the Nipissing diabase sheets.

Distillation from Archean Rocks

Although most of the early writers on Cobalt favoured the Nipissing diabase as the source of the ores, consideration was also given to the possibility that the metals might have been leached out of the older rocks. Van Hise (1907), for example, suggested that the ore minerals came from the diabase, and the carbonate gangue from the Archean rocks and Proterozoic conglomerates. Recently, Halls & Stumpfl (1969) proposed that the metals may have been extracted from the basement rocks at considerable depths.

The theory that the silver ores of the region are late distillates from the Archean country rocks has received considerable attention (Boyle, 1968a, b, c ; Boyle *et al.*, 1969 ; Boyle & Johnston, 1970 ; Dass, 1970). A brief reiteration of this theory is given in the final paper of this volume. The principal factors cited in support of an Archean source for the metals are as follows : (1) the rocks richest in As, Sb, Ag, Hg, Bi, Cu, Pb, Zn, Ni, and Co are the Keewatin interflow sediments ; (2) many nickel-cobalt-arsenide-native silver deposits in other parts of the world cut rocks containing pre-existing sulphides.

These two lines of support are somewhat general in nature. They provide the necessary setting for a philosophy of genesis rather than providing evidence that the operation occurred. The present writer has no objection to mobilization or distillation of pre-existing sulphides as one of many possible methods of vein genesis. Under these circumstances, a discussion of deposits other than in the Cobalt-Gowganda region is a digression. It seems appropriate to point out, however, that the Cobalt-type veins and older sulphides in other countries may not have the intimate genetic association that has been implied. The deposits at Kongsberg, Norway, have cited as an example to support the theory that the veins at Cobalt were derived from pre-existing sulphides. This origin for the Kongsberg ores may meet with considerably less than universal acceptance. Gammon (1966), for example, states (p. 180) that certain fahlbands

> "... have attracted special attention because they are associated with workable ore deposits, being closely associated with silver at Kongsberg and cobalt at Modum,

> It is commonly supposed that these workable mineralizations are genetically connected with the fahlbands, but this seems not to be the case."

Further (p. 181) :

> "It seems clear that the silver mineralization is of Permian date and has no more than a spatial relationship to the much earlier formed [Precambrian] fahlband zones."

In discussing the Modum deposits, Gammon states (1966, pp. 181-182) :

> "The most important of the Modum cobalt workings are at Skuterud.... The large amphibolite body to the east of the workings has olivine-rich rocks concentrated at its eastern boundary with the metasediments. It is postulated that this contact represents the original base of a thick olivine-dolerite sill emplaced before the metamorphism and isoclinal folding. It is interesting to note that if the cobalt mineralization was present at this time, it would have been connected with the top contact of this olivine-dolerite sill. Similar relations are observable in the cobalt-silver deposits of the Cobalt-Gowganda-South Lorraine area, Ontario...."

Gammon's conclusion that the Kongsberg and Modum deposits are only spatially associated with fahlbands does not preclude a genetic relationship between the Cobalt silver ores and interflow sediments. In other words, the present writer is advocating that the origin of the Cobalt-Gowganda ores must be determined primarily from evidence gathered by examining the deposits in this region. The mere presence of pre-existing sulphides in older rocks is not in itself an indication that the younger Ag-Co-As veins represent their derivatives. The suggestion that such extraction has occurred in other parts of the world is not evidence that this process has operated at Cobalt.

Aside from these general considerations, there are several features of the ore deposits that indicate that Archean rocks may not have been the source of the metals in the veins. Although many veins occur on the upward projection of interflow bands, many do not. An explanation must be found for the latter situation, particularly where veins occur in Cobalt sediments above the diabase, or in diabase which has intruded Algoman granite. Many small veinlets and prospects of Co-Ni arsenides and native silver having a negligible vertical persistence occur in areas where Archean rocks are not exposed. Distillation and transport from Archean rocks at unknown depths *below* the diabase is an improbable source for these.

Some parts of the Archean, notably the cherty interflow sediments, are much enriched in sulphides of the base metal type — pyrite, pyrrhotite, sphalerite, galena, and chalcopyrite. These base metal occurrences constitute concentrations of Cu, Zn, Pb, Fe, and S, whereas the silver-bearing veins that in places cut the base metal deposits represent markedly contrasting concentrations of Co, Ni, Ag, and As. In fact, the Archean rocks are low in Ni, Co, Ag, and As when one takes into account the volume of sulphides incorporated in the analyses of the interflow sediments (Tables 91 and 101). Thus, although they are structurally important in some places, the interflow sediments are an inappropriate source for the ore veins. This interpretation is also based partly on the fact that these rocks constitute a very minor part of the Archean sequence. Local distillation is inadequate; extraction over a considerable depth would be necessary, but by an undefined mechanism. If distillation occurred, it must therefore have been predominantly from other Archean rocks. To selectively extract trace levels of the appropriate elements from Archean greenstones, but not the Nipissing diabase, is a formidable operation.

A final comment on the lack of an effective mechanism to achieve the distillation is warranted. The Archean rocks and their contained sulphides were folded into their present positions and intruded by granitic bodies of batholithic proportions. Although dilation zones were formed, there is no indication that selective mobilization of the necessary elements occurred. Resorting to the Nipissing diabase as the activating force for distillation also presents some additional problems. For example, in the paleomagnetic study by Symons (1967), the $500 \pm 75°C$ isotherm of contact metamorphism was found to be 20 to 25 feet below the diabase at the Silverfields mine. This means that the volume of rock affected by relatively high metamorphic temperatures is small. Furthermore, Boyle (1968a), Boyle & Johnston (1970), and Dass (1970) have objected to a diabase source because the veins cut diabase which must therefore have been "completely crystallized". By the time the diabase had "completely crystallized" and was subsequently fractured, temperatures in the enclosing country rocks must have dropped considerably. Under these circumstances the diabase would be either a poor choice as a stimulus for distillation or, alternatively, the distillation was effected at relatively low temperatures. In the latter case there is the problem of explaining the relatively high temperature arsenide geothermometric data for veins outside the diabase.

Nipissing Diabase Source

Because the Nipissing diabase is so closely associated with the ore veins, most proponents of theories involving other sources must have considered and subsequently rejected a diabase source. The fact that the veins cut the diabase and that ore occurs along the Cobalt Lake fault may have been dominating factors which influenced the search for alternative geneses. As has been discussed, these are not considered to be valid reasons for rejecting the diabase as the source of the ores.

The detailed mineralogical studies presented in this volume have added support to the theory that the ores were derived from the Nipissing diabase intrusions. The observation by Petruk that the arsenide veins are zoned with respect to the centre line of the diabase clearly points to the intrusions being the focal point of ore deposition. The gangue minerals and the wall rock alteration are virtually identical to products formed by diabase fractionation. The predominantly carbonate vein gangue also occurs in abundance in miarolitic cavities and as an alteration product of pyrogenic diabase minerals. Compositional zoning of chlorites in two veins in Huronian sediments beneath the diabase suggests that the material moved down from the diabase into the underlying Huronian sediments rather than up from the Archean.

Notwithstanding statements to the contrary, silver is present in the diabase in amounts comparable to that of Archean rocks. More important, nickel, cobalt, arsenic, silver and sulphur have been mobile in the diabase so that in some cases anomalies occur near the upper and lower contacts and in the most fractionated parts of the intrusions. If the total silver production from all mines throughout the region is taken as 600 million ounces, then a rough calculation can provide an idea of the volume of rock necessary to account for the silver ores. For the Nipissing diabase, measurements of the Henwood intrusions indicate that the average specific gravity is about 3.0. If the area covered by the diabase basin is taken as 11 miles by 5 miles (which is an under-estimate), and the thickness of the intrusion as 800 feet, then a silver content of 0.3 ppm would yield approximately 828 million troy ounces of silver. Adding to this the residual silver in the diabase, which is less than 0.2 ppm, then an initial silver abundance of less than 0.5 ppm in the Henwood magma alone would account for considerably more metal than has been produced throughout the history of the mining in the whole of the Cobalt-Gowganda region.

It is recognized, however, that such calculations are not particularly meaningful as there is no way of ascertaining whether the present trace elements levels are indeed residual. On the other hand, the results do indicate that either extremely high concentrations of silver or distillation from great depths would have been necessary for the interflow sediments to be an adequate source of this element.

The distribution of the appropriate trace elements in the diabase (pp. 320-357) strongly suggests that these are efficiently scavenged or retained by the volatiles rich in alkalis, water, and carbonated compounds. The suggestion is also supported by the appearance of anomalous metal values, including arsenic, in some granophyres. This enrichment is related to diabase fractionation, and is independent of the type or age of the rocks intruded by the diabase. In the Henwood Upper sheet, for example, abundant calcite and traces of dolomite are present near the upper contact both as vertical stringers 1-2 mm wide and as a diffuse replacement of the diabase. At footage 1,675 (4 feet from the top contact) minute grains of cobaltite are present in vertical calcite stringers. Microprobe analyses indicate that the grains are variable in composition. One representative grain gave Co 32.6, Ni 4.6, Fe 0.9, As 45, S 16.9 wt. %. In terms of quantity, the occurrence is completely insignificant. It is significant, however, that cobalt mineralization is not only present, but is in the form of an arsenide which is an important constituent in ore veins.

Concluding, therefore, as Sampson & Hriskevich (1957) have, that the Nipissing diabase magma was capable of forming minerals identical to those in the ore veins, what factors point instead to an extraneous source for the ores? In advocating a source at depth, Moore (1956) noted that most productive veins at Gowganda occur in areas where granophyre is not abundant. Although some veins do occur in granophyres, Moore's observation is in a general sense valid throughout the Cobalt-Gowganda region. It is the present writer's view that during crystallization the volatile-rich fractions moved toward dilation zones and the cooled parts of the sheets as well as being accumulated as a residuum. The granophyres constitute a part of the residual fraction relatively enriched in trapped volatiles, and the relevant ore elements thus occur predominantly as dispersed phases. As a rock type, granophyres are therefore appropriately poor in mines but locally rich in dispersed metals. Moore's observation has thus served to point out a very important association, namely, that there is a relationship between the occurrence of ore veins and the specific type of Nipissing diabase present.

Somewhat indirectly related to the above is Moore's (1956) remaining argument for a parental source, in which the silver-bearing solutions are visualized as moving through the Miller Lake sheet to its upper part. Here the solutions "...would be trapped by the tight Keewatin at its contact." In fact, of the approximately 60 million ounces of silver produced from Miller Lake, almost all has come from within the diabase sheet rather than from the upper and lower contacts. Why is this so different from vein occurrences in other parts of the region? A possible explanation is that in all other localities the crystallization of the diabases responded to cooling which was predominantly from the bottom toward the top. Exclusively at Miller Lake is there evidence of substantial cooling from both the top and bottom of the sheet. The development of hypersthene diabase at both these positions and the confinement of most veins to within the sheet are coincidentally unique.

Finally, in light of what has been said about the character and distribution of the ore veins, the main argument favouring a direct Nipissing diabase source may be simply stated : where there was no diabase, Ni-Co arsenide-native silver veins have not been found ; where there was diabase, these veins may occur regardless of the type or age of host rock intruded by the diabase.

Structural Localization of the Ore Veins

Thomson (1965) has summarized and discussed the empirically-derived exploration guidelines applicable at Cobalt. Many writers have briefly commented on the structural development of the ore veins, but relatively few have treated this subject in detail. The veins are relatively small features and, as Thomson (1957) has pointed out, their distribution does not seem to be related to the major faults in the region. The veins are characteristically of limited depth, and almost all ramify and disappear as local crackle zones once the Archean has been penetrated for a few tens of feet. Localization of veins along major faults, such as the Beaver at South Lorrain and the Nipissing No. 64 at Cobalt, is unusual, and the vast majority of ore veins are not of this type. In a few cases the localization of individual veins can be attributed to the presence of re-activated, deep, pre-diabase faults, but for most veins the writer would propose an origin based on the concept of diabase intrusion under a small compressional stress, with subsequent cooling leading to the development of tensional fractures. Cooling and shrinkage of an intrusion in a typical basin and arch structure would involve a contraction of 5 to 10 per cent of the thickness of the diabase sheet. Tensional joints and fractures could therefore develop as a result of : (a) shrinkage of the diabase and subsidence of the cover rocks ; (b) the attendant relaxation of the compressive stress on the basement rocks.

Complications arise because of the heterogeneous nature of the country rocks and the lack of knowledge as to where the feeders for the diabase basins are located. If the feeder sites were known a better understanding of the feasibility of incorporating two additional factors could be assessed. These are : (1) the development of tensional features due to subsidence toward the magma source ; (2) the generation of compressional forces by attempted resurgence from the feeder sites. Indications of local basin subsidence are the imperfect development of radial faults in the Peterson Lake and North Lorrain basins at Cobalt, and an equally imperfect tendency for the ore veins to be either parallel or normal to the basin rims. The exact nature of the forces leading to fracture development thus remains hypothetical, but the concepts of compressional intrusion and subsequent shrinkage nevertheless provide some possibly useful guidelines for the development of vein fractures. The ore veins are confined to the approximate outer limits of the diabase thermal aureole as marked by spotted chloritic alteration. Arches or domes were heated both from the sides and top so that, when combined with the time lag in cooling of different parts of a fractionated sheet, the arches should have had the best potential for the development of deep Ni-Co arsenide veins in rocks below an intrusion.

In an eroded diabase basin structure completely encompassed by flat-lying sediments, the response to the application and release of compression would be minimal. However, tensional fracturing from shrinkage should be well-developed in sediments above the diabase near the rim of the basin. This position should be the most favourable site for ore veins in the specified environment. If the diabase basin was completely filled with steeply-dipping Archean rocks rather than flat-lying sediments, subsidence would be partly or largely accommodated by slipping along stratigraphic features. Tensional fracturing would be subordinate and the focal point of ore deposition should be predominantly near the diabase contact rather than extending for some distance above it. In a situation where the basin contained a lens of Archean rocks between the diabase and Proterozoic sediments, the subsidence would be transmitted from the Archean to the overlying horizontal sediments. Ore veins could occur at the diabase-Archean contact, but the best location for extensive fracturing and the development of good vein structures should be the Archean–Proterozoic unconformity. The best site along the unconformity would be the sediments above the diabase rim.

For structures beneath the diabase the situation is somewhat similar. The least favourable site from the point of view of diabase differentiation is the deepest part of the basin ; the most favourable areas for deposition lie toward the basin rim. If a considerable thickness (several hundred feet) of Proterozoic sediments underlie the diabase, then ore shoots should be largely confined to the vicinity of the intrusive contact. If Archean rocks underlie the diabase, then veins should again be largely confined to the vicinity of the diabase contact. The best sites along the contact are where the competency of the basement rocks changes markedly (e.g. lamprophyre dykes, interflow sediments) near the diabase rim. In the case of a lens of Proterozoic sediments intervening between the Archean and the diabase, the best site would be in these sediments near the Archean-Proterozoic unconformity. The development of the tensional fractures is visualized as a rebound effect following dissipation of the compressional stress. Transmission of the rebound from the top of the Archean to the overlying Proterozoic sediments is enhanced by an irregular rather than a flat paleotopography. The optimum sites for fracturing are in the sediments above rocks showing marked changes in competency. Thus shallow troughs of Proterozoic sediments under diabase rims, and wedges of these rocks at arch positions are indeed favourable locations for ore veins.

With respect to the character of the resultant fractures, neither shrinkage nor rebound would be expected to occur in a single, uniformly smooth movement. Adjustment is more likely to occur in a series of step-like movements as tension is contemporaneously built up at one position and relieved in another. Rather than major faulting, many small fractures and joints would develop. These might be subject to a series of minor jostling movements until thermal contraction of the diabase ceased.

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