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Endogenic haloes of the native silver deposits, Cobalt, Ontario, Canada

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Synopsis

The economic mineral deposits of the Cobalt area are extremely rich silver-bearing veins cutting Cobalt Series sediments, Nipissing diabase, Keewatin greenstone and associated rocks. The mineral assemblage of the veins is complex, consisting of carbonates, native silver and a great variety of nickel–cobalt arsenides.

Wallrock alteration haloes enclosing the native silver–nickel–cobalt arsenide veins are well developed in the Nipissing diabase, Keewatin greenstone, rhyolite porphyry and lamprophyre, but they are much less pronounced in the Cobalt Series sediments. Chloritization, sericitization, carbonatization, albitization, pyritization and arsenopyritization took place in the wallrocks adjacent to the veins. H_2O, CO_2 and Fe_2O_3 increase and SiO_2 decreases in the wallrocks towards the veins. The iron content in chlorite increases, the sodium content of plagioclase increases and the calcium content of plagioclase decreases towards the veins.

The endogenic haloes of trace elements are coincident with the zones of vein clusters. The dispersion of Ag, As, Ni, Co, Sb, Mn and Hg outward from the veins in the Cobalt Series sediments is broad, and veins may be indicated as far as 80–100 ft away by these elements. The dispersion pattern in the Keewatin greenstone can be traced 50–60 ft outward from the veins. Haloes are very much restricted in the Nipissing diabase. The dispersion patterns of Cu, Pb and Zn are also broad and coincident with the veins.

A close association of silver–nickel–cobalt ores with the Keewatin sedimentary interflows and certain volcanic flows has been recognized. Furthermore, the Keewatin greenstone and interflow sediments contain a higher than average background amount of Ag, As, Sb, Ni, Co, Hg, Cu, Pb and Zn. These rock units may be the source of the ore constituents, the younger Nipissing diabase serving as an energy source for their mobilization. Thus, the most favourable prospecting localities may be restricted to areas where the Keewatin interflows adjoin the Nipissing diabase, or where they underlie the Cobalt Series sediments adjacent to the diabase. The pronounced trace-element dispersion patterns in the wallrocks can be used to locate the narrow silver veins in the above rock units.

This paper summarizes the results of research on endogenic haloes which occur around the veins of native silver and nickel–cobalt arsenides at Cobalt, Ontario. The chemical analyses for both major and minor elements in the altered and unaltered wallrocks, chlorites and feldspars in the altered and unaltered rocks, and the carbonate gangue minerals in the veins were carried out by spectrographic, X-ray fluorescent and wet-chemical methods.

The silver deposits of the Cobalt area occur in the Timiskaming district of northern Ontario, about 250 miles northwest of Ottawa and some 75 miles NNW of North Bay (Fig. 1 (*a*)).

Previous studies of the Cobalt area include those by Miller,[15,16] Hore,[10] Knight,[12] Hriskevich[11] and Halls and Stumpfl.[8] The mineralogy of the silver–nickel–cobalt ores of Cobalt was examined by Bastin,[1] Halls and co-workers[7] and Petruk.[18] Thomson[21] revised the geological maps

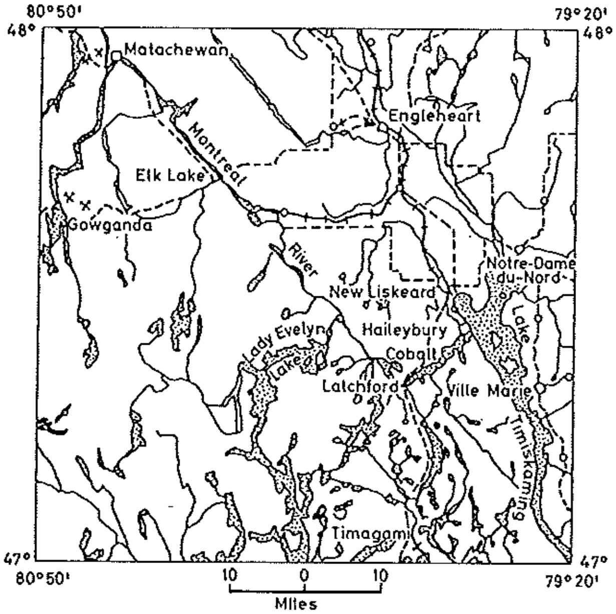

Fig. 1(a) Key map showing location of Cobalt area, Ontario

of the area. Symons[19] examined the palaeomagnetism of the Nipissing diabase at Cobalt. A volume on the geology, mineralogy and geochemistry of the Cobalt–Gowganda silver deposits has recently appeared.[2]

General geology and structure

The Cobalt area lies in the Superior Province of the Precambrian Shield. The oldest (Archaean) rocks of the area are steeply dipping Keewatin lavas (greenstones) and interflow sedimentary rocks, overlain in places by steeply dipping greywacke, quartzite and conglomerate of the Timiskaming Series (Fig. 1(*b*)). Both the Keewatin and Timiskaming rocks are intruded by Lorrain granites and hornblende syenite. The Keewatin metavolcanic rocks (greenstone), for the most part, correspond to basalts and andesites. They are fine-grained, with pillow structures in the upper part, and massive in the lower part.

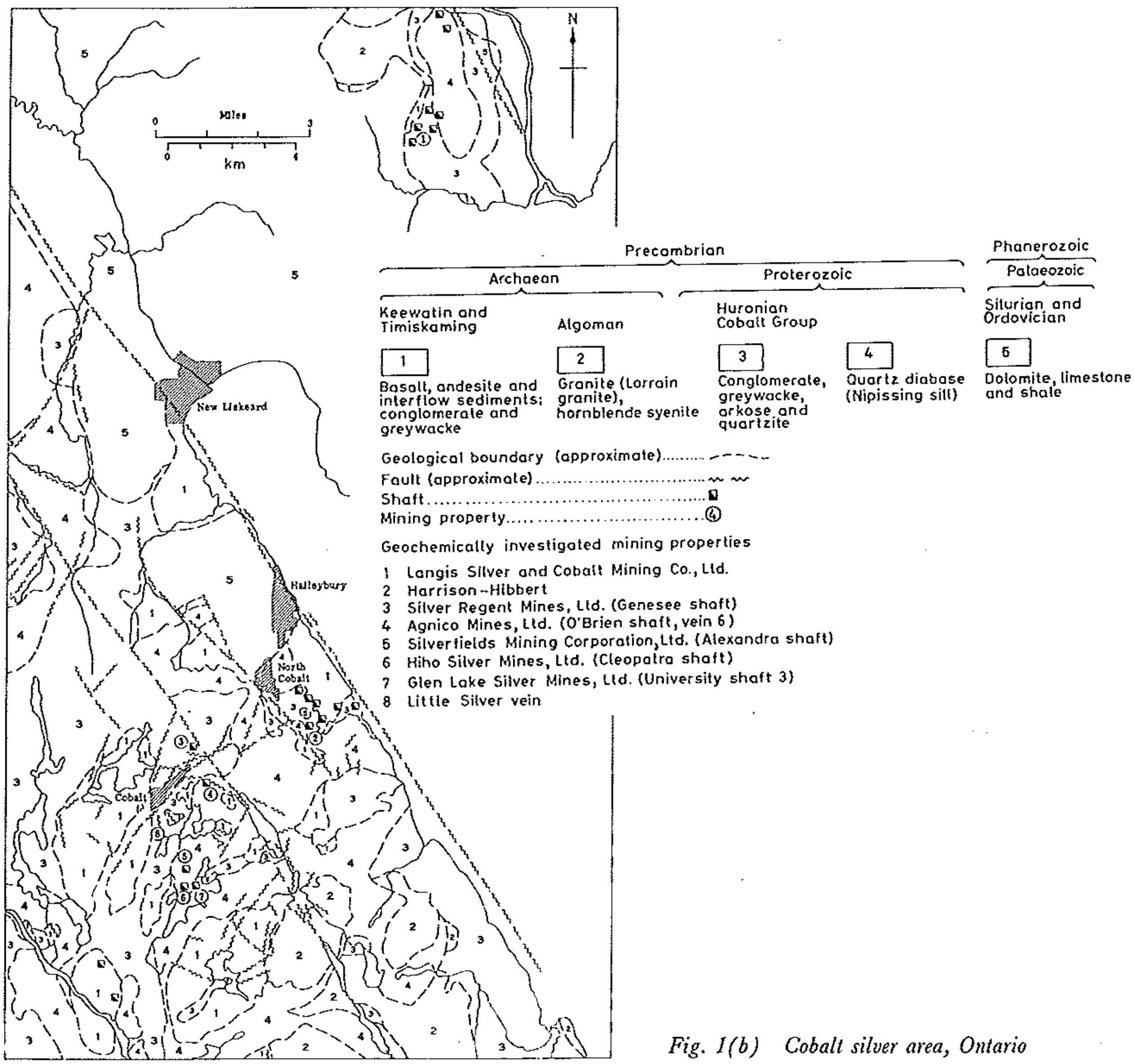

Fig. 1(b) Cobalt silver area, Ontario

Locally, they are intruded by felsite, feldspar porphyry and quartz porphyry. Metasedimentary rocks include iron formation, tuff, mica and graphitic schists, slate, chert, greywacke and quartzite. Well-developed chlorite spots, about 0·1–0·3 in in diameter, are locally present in the Keewatin greenstones.

The Proterozoic Cobalt Series, which consists of conglomerate and quartzite with a flat to gentle dip, lies with profound unconformity on the Archaean rocks. According to Moore,[17] the Cobalt Series at the Silverfields deposit is divided into four groups (from top to bottom): well-bedded greywacke, conglomerate (0–10% pebbles); grey quartzite, conglomerate (40–70% pebbles); well-bedded greywacke, conglomerate (70–90% pebbles); and bedded greywacke, conglomerate (10–40% pebbles).

Many of the rock types of the Cobalt Series contain dark chlorite spots, from 0·1 to 0·4 in in diameter, which usually follow bedding.

Both the Archaean and the Proterozoic rocks are intruded by a gently dipping Nipissing diabase sill (or composite sills). The age of the Nipissing diabase, determined by the potassium–argon method, is 2095 m.y.,[14] and by the rubidium–strontium method 2180 ± 40 m.y.[22] The main body is in the form of a large undulating sheet with gentle dip, but the dips steepen on the flanks of arches and basins. The total thickness is more than 1000 ft. The intrusion took place near the contact between the nearly horizontal beds of the Cobalt Series and the steeply dipping Keewatin rocks. No flow structures, primary lineation or foliation were noted in the diabase. It is composed (from top to bottom)[11] of the following rocks: fine-grained diabase at top contact; quartz diabase (in many places with coarse texture); hypersthene diabase ± olivine; quartz diabase; and fine-grained diabase at bottom contact.

Ordovician and Silurian limestones, dolomites, shales and sandstones lie unconformably on the Precambrian rocks, and these, in turn, are overlain unconformably by Pleistocene glacial and post-glacial deposits.

The Keewatin and Timiskaming rocks are highly folded into vertical attitudes. The axes of the folds trend northwest. The beds of the Cobalt Series have a low dip. The Nipissing diabase sill has gentle dips.

The major sets of faults, one striking northeast–southwest and the other northwest–southeast, are marked by linear, topographic depressions. The Cobalt Lake fault represents the first set, and the Cross Lake fault, Lake Timiskaming fault and Mackenzie fault represent the second. Unusual joint structures, which have a peculiar cylindroidal pattern, similar to that described by Eakins,[5] are developed in the Nipissing diabase.

Vein fissures, fractures and shear zones are well developed in the rocks of the area. Both single and multiple fractures intersect and ramify at various angles. They commonly dip steeply or vertically and vary in width from a few inches to several inches, and extend several hundreds of feet both along strike and down dip.

Mineral deposits

The economic mineral deposits of the Cobalt area are extremely rich silver-bearing veins cutting the Cobalt Series sediments, Nipissing diabase, Keewatin greenstones and associated rocks. The silver veins contain, essentially, native silver, carbonates, nickel-cobalt arsenides, a few sulphides and a variety of other minerals. The veins may be single or multiple; they ramify and intersect and pinch and swell throughout their extent. Most are short and narrow; strike lengths and dip extents are generally measured in a few hundreds of feet, and widths in inches or fractions of inches. Most veins are steep to vertically dipping, but some have dips as low as 30°. The silver veins cut all rocks in the area, and are younger than the sulphide pods and layers in the Keewatin interflow sedimentary beds.

The most important ore mineral is native silver. It is massive or forms specks in rosettes and bodies of niccolite, safflorite, skutterudite, gersdorffite, rammelsbergite and arsenopyrite. It also forms sheet or leaf at the vein–wallrock contact or in tiny fractures in the wallrocks. Proustite, associated with argentite, occurs locally. Most of the arsenides have a concretionary or tubercular texture and occur as individual rosettes, clusters of rosettes and veinlets. Cylindrical tubercles of these arsenides locally have a dendritic pattern. The arsenide minerals locally have a zoning in the veins from top to bottom: Ni–As, Ni–Co–As, Co–As, Co–Fe–As and Fe–As.[18] The high-grade silver ore is commonly confined to the Ni–Co–As and Co–As zones.

Carbonates with minor quartz are the principal gangue minerals at Cobalt. The carbonates include ankerite, dolomite, calcite and minor siderite. Along a vein the proportion of carbonates to arsenides varies within a short distance.

The other known mineral deposits of the area comprise disseminated base-metal sulphides in the interflow sedimentary beds in the Keewatin greenstones.[3] The minerals of interest in these beds include pyrite, pyrrhotite, chalcopyrite, sphalerite, galena, arsenopyrite and marcasite. The beds vary in width from a few inches to several tens of feet or more.

In addition to the above two types of mineral deposit, the lower part of the Cobalt Series sediments locally contains disseminated base-metal sulphides, mainly pyrite, galena, sphalerite and chalcopyrite.

Some of the silver veins in the district are partly oxidized to a clay-like mass consisting of limonite, wad and secondary carbonates associated with coatings of annabergite, erythrite, malachite and azurite. This type of alteration is, however, limited at Cobalt.

Basins and arches in the diabase sheet locally control the fissures and fractures. Contacts between the Keewatin and Cobalt Series, between the top of the Nipissing diabase and the overlying Keewatin, and along the bottom of the diabase sill with an undulating formation are important in localizing the deposits.[20]

Sulphide mineralization in the interflow beds is controlled essentially by stratigraphic features, later modified by contortion and dragging during folding.

Disseminated base-metal sulphides are localized in the lower part of the Cobalt Series, particularly in the more porous quartzite and the gritty conglomerate. The sulphides in these zones are pyrite, galena, sphalerite and chalcopyrite. They form aggregates and tiny discontinuous stringers in the matrix of the quartzite and conglomerate.

Wallrock alteration

Wallrock alteration haloes enclosing the native silver–nickel–cobalt arsenide veins have developed in the Nipissing diabase, Keewatin greenstone, rhyolite porphyry and lamprophyre. They are much less pronounced in the Cobalt Series sediments. Fresh rock grades transitionally veinward through a light grey bleached band to a characteristic, narrow, dark chloritic band adjacent to the vein. These bands have bilateral symmetry with respect to the vein. Alteration zones are normally 6–8 in wide, rarely exceeding 12 in. Since the physical, mineralogical and chemical changes are similar in most rock types of this area, the alteration is described for one vein system from each rock group.

Wallrock alteration in the Nipissing diabase

Alteration in the Nipissing diabase is marked by a narrow dark green band, adjacent to the vein, which grades into a light, greyish white bleached zone through a zone of chlorite spots into the grey unaltered diabase. The minerals affected during alteration are augite, hypersthene, hornblende, biotite, plagioclase and magnetite; quartz and pyrite are relatively unaltered. Weak propylitization pervades most of the diabase, resulting in a slight alteration of augite and plagioclase. Augite and hypersthene have been partly altered to hornblende. Hornblende was partly biotized and chloritized, with the formation of a minor amount of iron oxides, and plagioclase has been sericitized, with the development of some epidote.

Four zones have been recognized in the altered wallrock adjacent to the vein.[4] Zone 1 corresponds to the spotted chlorite alteration zone, which grades into the greyish white bleached zone 2 and outwards to the unaltered diabase. Zone 2 grades into the greyish white to dark green zone 3. Zone 3 is a transitional zone between zone 2 and the dark green zone 4, which occurs adjacent to the vein. Contacts between the various zones are gradational. On the basis of alteration mineral assemblages, the zonal arrangements may be grouped as follows: (1) unaltered diabase; (2) sericite–epidote–chlorite–carbonate (zones 1 and 2); and (3) chlorite–carbonate–albite (zones 3 and 4).

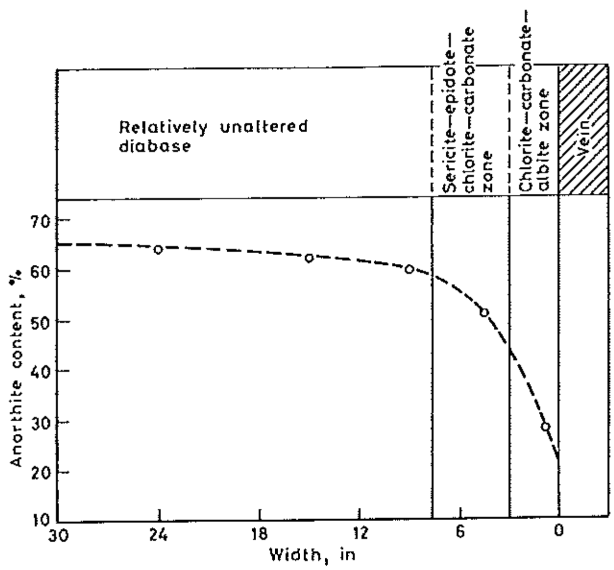

Fig. 2 Variation in composition of plagioclase in diabase wallrock, 6th level, Keeley deposit, South Lorrain

Some epidotization, carbonatization and chloritization of augite and hornblende have taken place in zones 1 and 2. Augite, hornblende, biotite and epidote have been completely altered to chlorite and some carbonate in zones 3 and 4. Chlorite forms sheaves and rosettes, and is an iron-rich variety. It belongs to the ripidolite–pycnochlorite group.[9] Feldspars have been altered to epidote, with some chlorite and carbonate, during chloritization of the ferromagnesian minerals. Within zone 3 dolomite grades to ankerite towards the vein; secondary albite begins to develop in zone 3. Titaniferous magnetite has been altered to ilmenite. Leucoxene was formed from alteration of ilmenite. Zone 3 grades into zone 4 with an increase of ankerite, albite and iron-rich chlorite. Fresh secondary albite is well developed in zone 4. Plagioclase becomes more sodic in the alteration zones towards the vein (Fig. 2). Hematite flakes are disseminated in the albite, where red alteration occurs adjacent to veins. Apatite has been nearly destroyed in this zone.

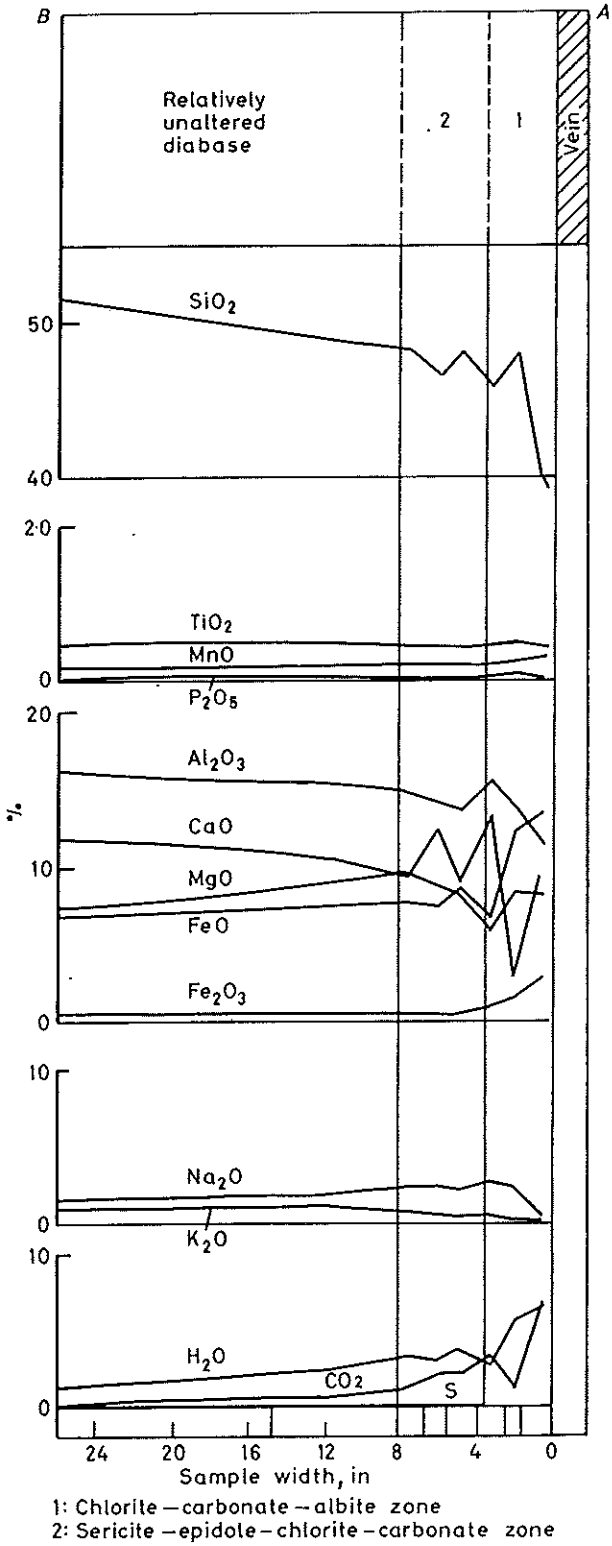

Fig. 3 Chemical variation in alteration haloes of diabase, Glen Lake adit, Glen Lake Silver Mines, Ltd.

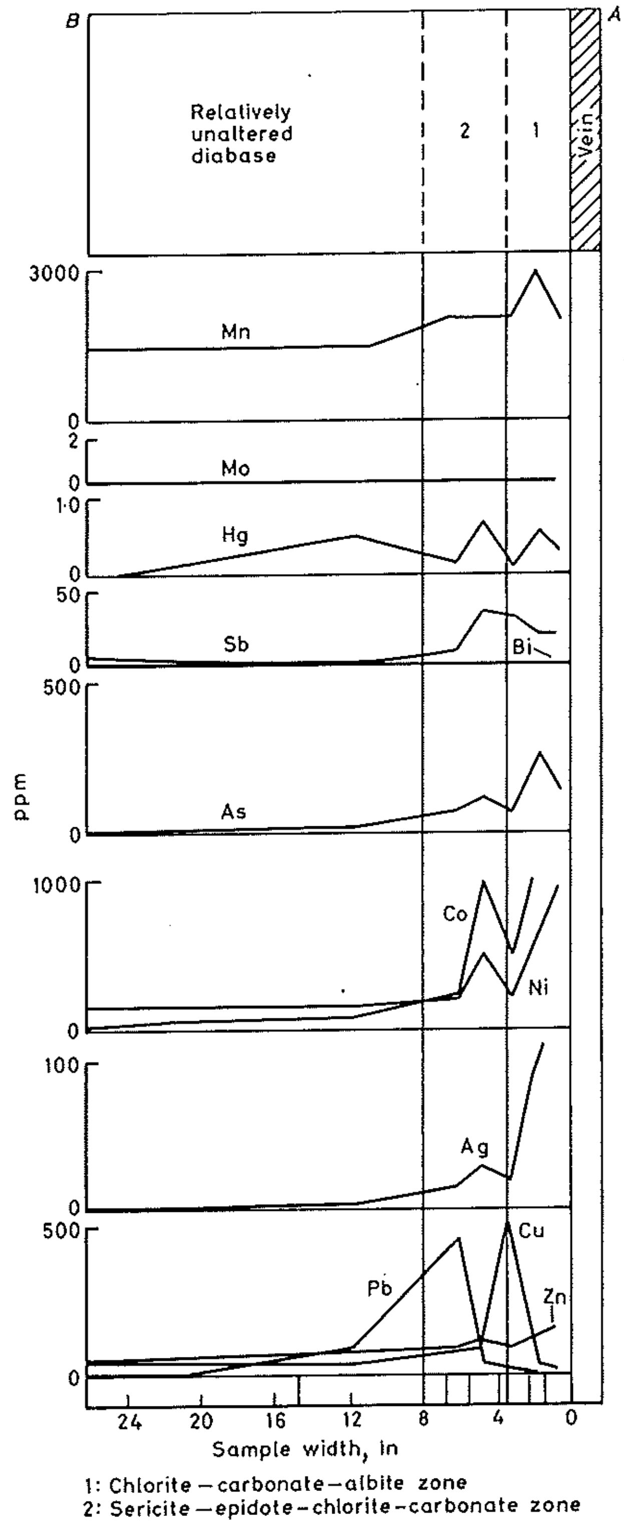

Fig. 4 Distribution of minor elements in alteration haloes of diabase, Glen Lake adit, Glen Lake Silver Mines, Ltd.

The gains and losses of elements were determined from composition–volume relationships.[6] SiO_2, Al_2O_3 and K_2O decrease in both the sericite–epidote–chlorite–carbonate and chlorite–carbonate–albite zones in comparison with the relatively unaltered diabase (Fig. 3). This decrease is paralleled by an increase in CO_2, H_2O and Fe_2O_3. Trends are not consistent for the other elements.

Distribution of cations in the chlorite of the wallrock shows that Fe^{+2}, Fe^{+3}, Al and Mg increase in the sericite–epidote–chlorite–carbonate and chlorite–carbonate–albite zones towards the veins, whereas Si, Ca, K, Mn and Ti decrease in these zones.

Distribution of the minor elements is shown in Fig. 4. The endogenic haloes of elements about the vein are restricted to the alteration zone. Ni, Co, As and Sb increase moderately in the sericite–epidote–chlorite–carbonate and chlorite–carbonate–albite zones, Ag does not change much, except in the chlorite-carbonate-albite zone, where it increases adjacent to the vein. Trends of Cu, Pb, Hg and Mn are not consistent in either of these zones. Zn, Bi and Mo do not change appreciably from background values.

Wallrock alteration in the Cobalt Series sediments

Mineral assemblages of wallrock alteration in the greywacke, conglomerate and quartzite of the Cobalt Series are grouped into (1) a quartz–sericite–carbonate zone and (2) a chlorite–carbonate–sericite zone adjacent to the vein.[4] The quartz–sericite–carbonate zone consists, essentially, of a matted aggregate of chlorite, grains of quartz, highly altered sericitized feldspar, abundant carbonate, some chlorite, and iron oxides. The ferromagnesian minerals of the mafic rock fragments have been altered to fine-grained epidote, carbonate, chlorite and iron oxides. In the chlorite–carbonate–sericite zone the ferromagnesian minerals have been completely altered to chlorite and carbonate. Sericitized feldspars have been altered to albite and fine-grained sericite. Chlorite belongs to the ripidolite–pycnochlorite group.[9] The fine-grained matrix is completely chloritized and ankeritized.

The gains and losses of elements were calculated from composition–volume relationships.[6] The SiO_2 and Al_2O_3 contents are lower in the quartz–sericite–carbonate and chlorite–carbonate–sericite zones compared with the relatively unaltered rock (Fig. 5). This decrease is paralleled by an increase of CO_2, H_2O, CaO, MgO and Fe_2O_3 (total). S, K_2O and MnO increase slightly and Na_2O and TiO_2 decrease slightly in the chlorite–carbonate–sericite zone.

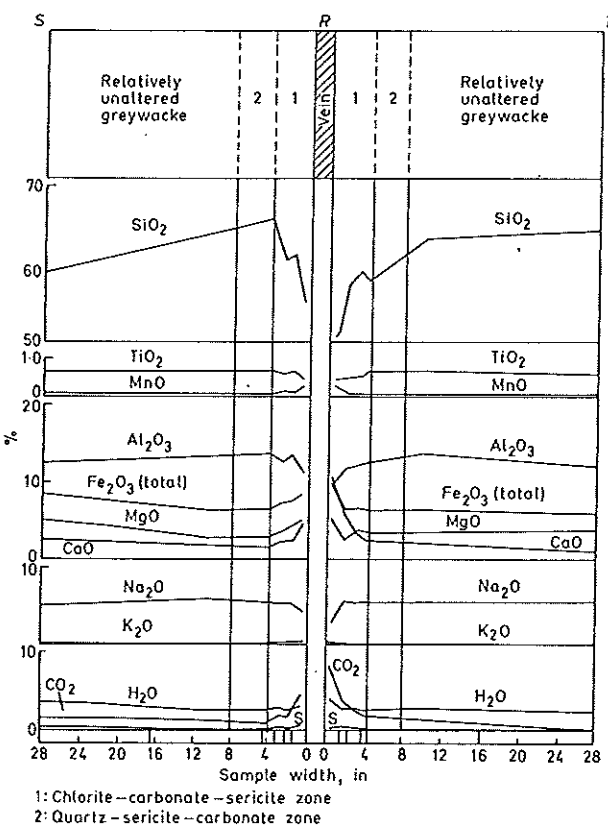

Fig. 5 Chemical variation in alteration haloes of greywacke, vein 11B, 400 W level, Silverfields Mining Corporation, Ltd.

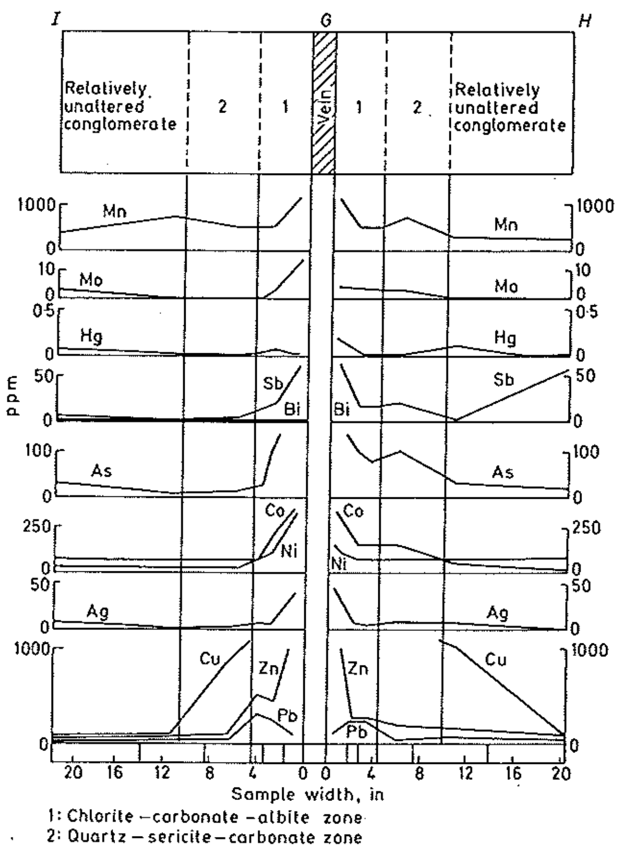

Fig. 6 Distribution of minor elements in alteration haloes of conglomerate, vein 8, 300 W level, Silverfields Mining Corporation, Ltd.

The distribution of minor elements is presented in Fig. 6. The wallrocks enclosing the vein are enriched in Cu, Zn, Ag, Ni, Co, As, Sb, Mo and Mn compared with the background values, and the endogenic haloes have a bilateral

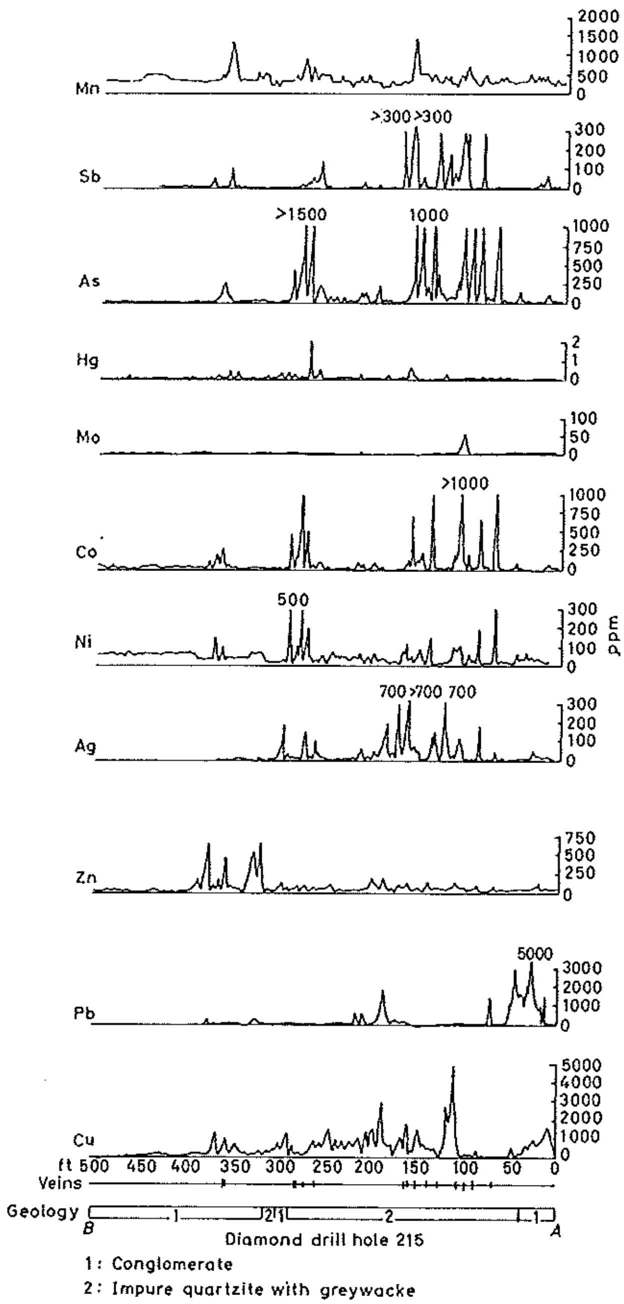

Fig. 7 Distribution of minor elements in Cobalt sediments, 300 level, Silverfields Mining Corporation, Ltd.

symmetry about the vein. Pb increases slightly towards the vein, but, locally, the distribution of Pb is erratic. Hg does not change appreciably. The concentration of Bi does not change from the background value.

Dispersion patterns in the Silverfields and Little Silver deposits indicate that the endogenic haloes of Ag, Ni, Co, As and Sb adjacent to veins extend outwards up to 90 ft or more (Figs. 7 and 8).

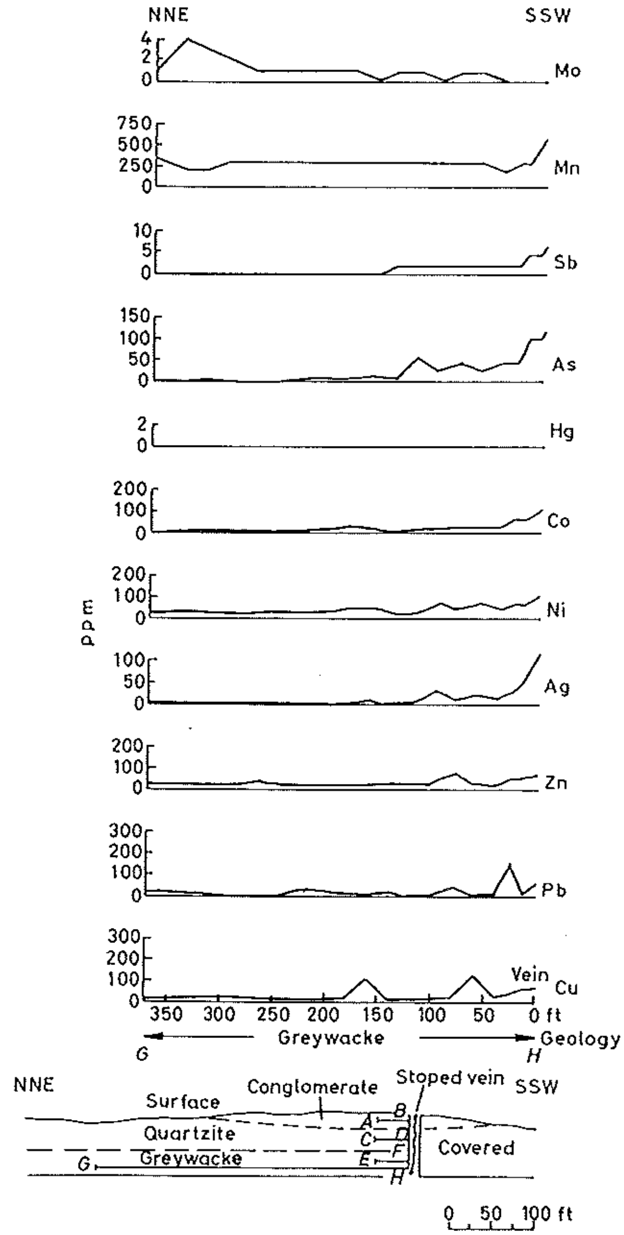

Fig. 8 Distribution of minor elements in Cobalt sediments (greywacke), Little Silver vein, and geological section in vicinity of vein

Wallrock alteration in the Keewatin rocks

Mineral assemblages of wallrock alteration in the Keewatin greenstones are grouped into (1) a chlorite–epidote–carbonate–sericite zone and (2) a sericite–carbonate–chlorite zone adjacent to the vein.[4] The chlorite–epidote–carbonate–sericite zone corresponds to the greenish-grey to greyish-white bleached band. Plagioclase has been sericitized and epidotized. The chlorite is mostly iron-poor. Titaniferous magnetite has been altered to ilmenite. The sericite–carbonate–chlorite zone corresponds to the dark green band at the vein–

wallrock contact. Carbonatization and sericitization are intense and widespread, the carbonates and sericite replacing most of the feldspar and epidote and part of the chlorite. The proportion of sericite and carbonate increases and chlorite decreases towards the vein. The carbonate is mainly ankerite. The chlorite is mostly iron-rich and belongs to the ripidolite–pycnochlorite group.[9]

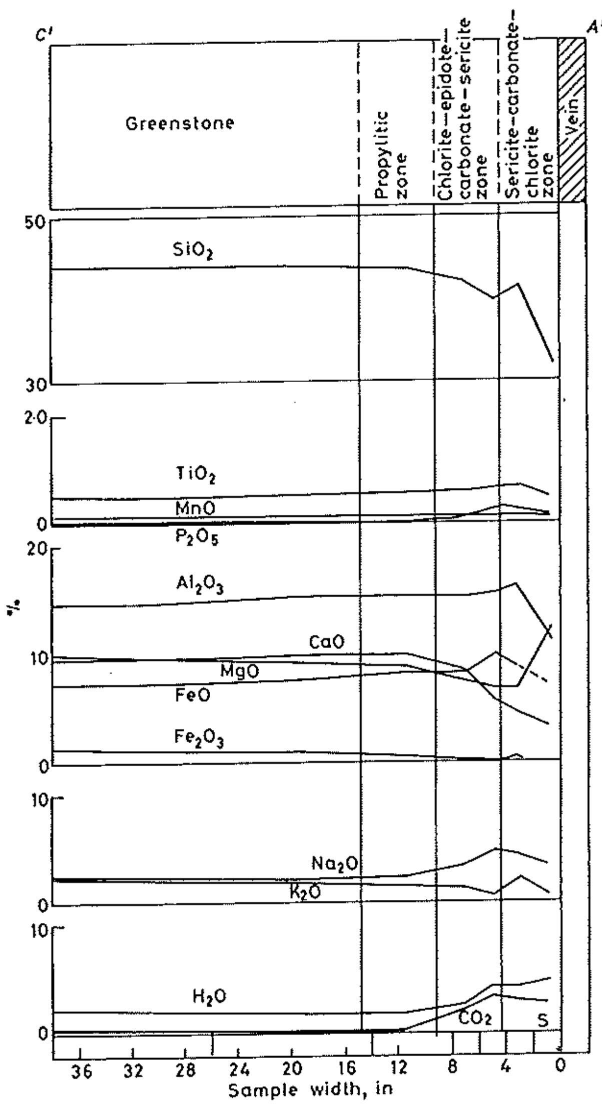

Fig. 9 Chemical variation in alteration haloes of greenstone, 291 level, Hiho Silver Mines, Ltd.

The distribution of the major elements in the alteration zones is presented in Fig. 9. The SiO_2, CaO and Fe_2O_3 contents decrease in the chlorite–epidote–carbonate–sericite and sericite–carbonate–chlorite zones compared with the relatively unaltered rock. This decrease is paralleled by an increase of H_2O and CO_2. Na_2O, Al_2O_3, FeO, TiO_2 and P_2O_5 increase in the chlorite–epidote–carbonate–sericite zone and decrease in the sericite–carbonate–chlorite zone, whereas the reverse is true for MgO. S and MnO do not vary.

The distribution of the cations in the chlorite of the Keewatin wallrock indicates that Si, Ca, K and Ti decrease in the chlorite–epidote–carbonate–sericite and sericite–carbonate–albite zones, whereas the reverse is true for Al, Mg and Fe^{+2}. Mn and Fe^{+3} increase slightly in the sericite–carbonate–chlorite zone.

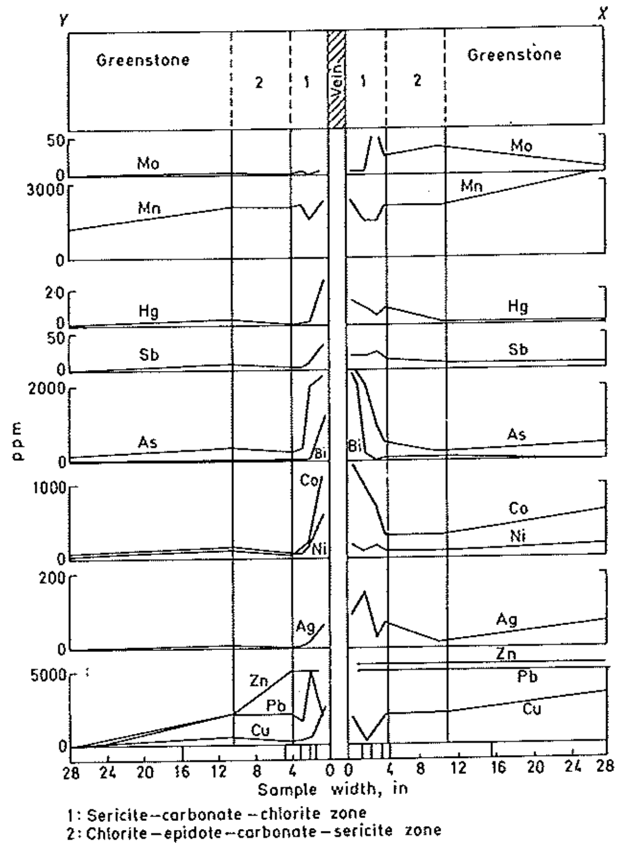

Fig. 10 Distribution of minor elements in alteration haloes of greenstone, vein 8, 500 level, Silverfields Mining Corporation, Ltd.

The distribution of minor elements in the Keewatin wallrock is given in Fig. 10. Co, As and Hg are enriched in the sericite-carbonate–chlorite zone compared with the background values. Ni, Ag, Bi and Sb increase slightly in the sericite-carbonate-chlorite zone, and Zn and Pb increase in both zones. Cu, Mn and Mo have an erratic distribution.

Discussion

Wallrock alteration haloes enclosing the Cobalt deposits demonstrate convergent alteration in that intense alteration has changed andesite, basalt, lamprophyre, rhyolite porphyry, diabase, greywacke, conglomerate and quartzite to a uniform rock type, which consists of chlorite, sericite and ankerite. The lateral zonation adjacent to the veins appears to have developed contemporaneously, or nearly so, with the deposition of the vein minerals. The evidence in favour of a contemporaneous origin is (1) that certain constituents, such as carbonates, chlorite, various sulphides and arsenides, present in the altered zones, are the same as those in the veins, and (2) that the same type of alteration zones are present in both the ore-bearing and gangue-bearing veins without ore.

Two generations of chlorite are present: chlorite spots in the Cobalt Series sediments and Keewatin rocks, developed at an early stage by low-grade contact metamorphism, associated with intrusion of the Nipissing diabase, and younger chlorite, developed as a result of wallrock alteration adjacent to the vein during vein formation. Hematitization associated with albitization involves the development of red alteration haloes in places. The red haloes were formed by wallrock alteration processes, and the red colour is due to a large concentration of minutely disseminated hematite flakes in albite.

The combined effects of chloritization, carbonatization, albitization, sericitization, pyritization and arsenopyritization involve an introduction of CO_2, H_2O, S, As and minor Na and Mn, and a removal of Si and Al. Some Ca, Mg, Fe, K, P and Ti were redistributed within the alteration zones, and some migrated into the vein.

Wallrock alteration resulted mainly from the transfer of H_2O, CO_2 and S into the walls from the vein fluid. Migration of constituents took place where a chemical potential gradient developed between the vein system and the wallrock.[4] Migration of elements from the vein to the wall took place by two possible processes: (1) mass transport in solution and (2) diffusion of material through the solution. Mass transport in solution took place along fractures, pores, grain boundaries and other discontinuities in rocks, under a pressure gradient. Where mass transport in the solution was slow, migration took place by diffusion in an aqueous medium. According to Korzhinskii,[13] in diffusion processes the chemical potentials of components in two adjacent zones tend to equalization, whereas the concentrations of components in pore solutions of two adjacent zones may be different. In flow of solution these conditions are reversed.

Guides for exploration

Three features may be used in the Cobalt area as a guide to the discovery of silver veins: wallrock alteration, vein gangue materials and association of certain rock types.

Wallrock alteration

Wallrock alteration products can be used under certain circumstances for the exploration of silver veins. The alteration zones are only a few inches wide, and their use as a guide to ore is, therefore, limited. The primary dispersion of minor elements in the wallrocks is extensive, however, and this parameter has considerable potential as an exploration tool.

Physical

The well-developed dark chlorite zone which adjoins the vein grades outward into a light greyish-white bleached zone, which exhibits good bilateral symmetry with respect to the vein. These coloured zones are only a few inches wide, and although these are very diagnostic, they can be used only in a detailed exploration programme and not on a regional scale.

Mineralogical

The mineralogical regularity in the wallrock alteration is evidenced by the tendency of dissimilar host rocks, such as the Nipissing diabase, Cobalt Series sediments and Keewatin rocks, to converge to a uniform type of alteration closely related to the silver veins. Although these mineralogical zones are distinct, they are narrow, and can only be used in a detailed exploration programme and not on a regional scale.

Spotted chloritic alteration is widespread in the mineralized zones of the Cobalt Series sediments and Keewatin rocks adjacent to the upper and lower contacts of the Nipissing diabase. No significant correlation could be made between the spotted chloritic alteration and an individual vein, but the distribution of silver veins is confined to this zone of spotted alteration. The spotted alteration is, therefore, useful in a general way as a guide in the search for silver deposits.

Chemical

The distribution of minor elements in various rocks may serve as a valuable guide to ore. The primary dispersion of minor elements in the wallrocks depends on the nature of the host rock. The primary halo is widespread in the Cobalt Series sediments, less extensive in the Keewatin rocks, and relatively local in the Nipissing diabase.

The dispersion of Ag, As, Ni, Co, Sb, Mn and Hg outward from the veins in the Cobalt Series sediments is broad, and veins may be indicated as far as 80–100 ft away by these elements. The dispersion patterns of these elements in the Keewatin rocks have a similar trend and can be traced 50–60 ft outward from the vein. The distribution in diabase outward from the vein is much restricted and can be traced only a few feet. Thus, the pronounced trace-element dispersion patterns in certain rock types can be used on a broad scale to locate the narrow silver veins.

Vein gangue materials

Various types of carbonate gangue minerals are associated with different grades of silver veins, and these may be used in a detailed exploration programme.

Grey to pinkish-grey ankerite and dolomite with minor calcite are dominant in the high-grade silver veins in the Cobalt Series sediments, buff to pinkish-white calcite with minor ankerite and dolomite dominate in the intermediate grade, and calcite with recrystallized quartz is dominant in the barren veins.

The silver ores in the Nipissing diabase are associated with grey to dark grey and pink rhombohedral and sugary calcite with minor ankerite and dolomite, whereas the fine-grained pure white to salmon-pink calcite with quartz is devoid of silver.

In the Keewatin rocks grey to dark grey ankerite and dolomite, with some pink calcite, dominate in rich to intermediate-grade silver veins.

Association of certain rock types

A close association of the silver–nickel–cobalt ores with the Keewatin interflow sedimentary rocks and certain volcanic flows has been recognized. Furthermore, the Keewatin greenstones and interflow sedimentary rocks contain higher than average background amounts of Ag, As, Sb and Hg. These rocks are postulated as the source of the vein metals, the younger Nipissing diabase serving as an energy source for their mobilization. Thus, the most favourable prospecting localities may be restricted to areas where the Keewatin interflows adjoin the Nipissing diabase, or where they underlie the Cobalt Series sediments adjacent to the diabase.

Such conditions are found in the Cobalt, South Lorrain, Casey Township and Gowganda areas, and it is suggested that prospecting and exploration should be concentrated on those areas.

Summary and conclusions

The economic mineral deposits of the Cobalt area are predominantly rich silver-bearing veins cutting the Cobalt Series sediments, Nipissing diabase, Keewatin greenstones and associated rocks. The silver veins contain, essentially, native silver, carbonates, nickel–cobalt arsenides, a few sulphides and a variety of other minerals.

Wallrock alteration haloes which enclose the veins have developed in all the host rocks, and the physical, mineralogical and chemical changes are similar in most. Alteration is marked in the Nipissing diabase, Keewatin greenstones, rhyolite porphyry and lamprophyre, but is much less pronounced in the Cobalt Series sediments. Wallrock alteration demonstrates convergent alteration in that intense alteration has changed andesite, basalt, lamprophyre, rhyolite porphyry, diabase, greywacke, conglomerate and quartzite to a uniform rock type—mainly chlorite, sericite and ankerite. The combined effects of chloritization, carbonatization, albitization, sericitization, pyritization and arsenopyritization involved an introduction of CO_2, H_2O, S, As and minor Na and Mn, and a removal of Si and Al. Some Ca, Mg, Fe, K, P and Ti were redistributed within the alteration zones, and some migrated into the vein.

The dispersion of Ag, As, Sb, Ni, Co, Mn and Hg in the Cobalt Series sediments outwards from the vein is broad, and the endogenic haloes extend outward up to 90 ft in places. A somewhat similar pattern is present in the Keewatin rocks, but the endogenic haloes are generally more restricted. The dispersion is narrow in the Nipissing diabase.

Wallrock alteration resulted mainly from the transfer of materials into the walls from the vein fluid, and migration of constituents took place where a chemical potential gradient developed between the vein system and the wallrock. Migration of elements in the wallrock from the vein took place by mass transport in solution and diffusion of material through solution. Wallrock alteration products can be used under certain circumstances for the exploration of silver veins. The endogenic haloes of minor elements in the wallrocks are extensive, and this parameter has considerable potential as an exploration tool. Mineralogical zones can be used in a detailed exploration programme. Spotted chloritic alteration is widespread in the mineralized zones in the Cobalt Series sediments and Keewatin rocks adjacent to the upper and lower contacts of the Nipissing diabase. This type of alteration is useful in a general way as a guide in the search for silver deposits. Various types of carbonate gangue minerals may be used in a detailed exploration programme.

A close association of silver–nickel–cobalt ores with the Keewatin sedimentary interflows and certain volcanic flows has been recognized, and the most favourable prospecting localities should be restricted to areas where the Keewatin interflows adjoin the Nipissing diabase, or where they underlie the Cobalt Series sediments adjacent to the diabase.

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