**Geoscience Canada**

# Five-element (Ni-Co-As-Ag-Bi) Veins

Stephen A. Kissin

Volume 19, Number 3, September 1992

URI: https://id.erudit.org/iderudit/geocan19_3art02

See table of contents

Publisher(s)

The Geological Association of Canada

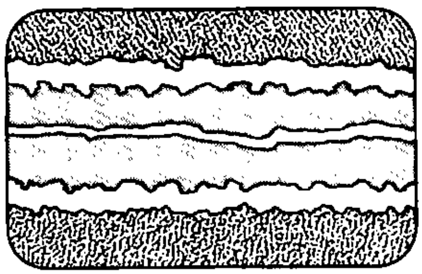
ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

Kissin, S. A. (1992). Five-element (Ni-Co-As-Ag-Bi) Veins. *Geoscience Canada*, *19*(3), 113–124.



# Five-element (Ni-Co-As-Ag-Bi) Veins

Stephen A. Kissin
*Department of Geology*
*Lakehead University*
*Thunder Bay, Ontario P7B 5E1*

## INTRODUCTION

The distinctive nickel-cobalt-native silver vein ore type, long recognized and characterized comprehensively by Bastin (1939), has also been called the five-element (Ni-Co-As-Ag-Bi) ore type (*e.g.*, Halls and Stumpfl, 1972). Both designations may be criticized for failing in universal applicability; however, the five-element type name will be employed here as convenient, if not always accurate. This designation, for example, does not take into account that a number of five-element ore districts have been important producers of uranium. Curiously, uranium is entirely absent in other districts. The mines exploiting these ores generally produce only silver, although cobalt has potential in many deposits. The deposits are fissure veins in which paragenetically separated sulphide ores may be occasional sources of copper, lead and zinc. Late-stage barite has been produced in some cases.

An inclusive definition of five-element ores that is sufficiently cognizant of the variation encountered is difficult to construct. For the purposes of this review, a five-element ore suite must include Ni-Co arsenides associated with native silver at least somewhere in a particular paragenetic sequence of a single deposit or in one deposit of an ore district. There is a great deal of variation around this fundamental definition.

The exploitation of five-element ores dates back to at least the Middle Ages (Lieber and Layerzapf, 1986), and the history of these types of ores has been linked to the development of the science of geology. The Freiberg Mining Academy (founded in 1765) is located in the Erzgebirge (Ore Mountains) district of the Czechoslovakia-Germany border, one of the largest and oldest mining districts of this ore type. In Canada, the development of mines in the Thunder Bay district in the 19th century and the Cobalt district in the early 20th century was a major economic impetus to the settlement of northern Ontario. The silver and uranium production from the Great Bear Lake area of the Northwest Territories played a similar role somewhat later in this century. The mines of the Kongsberg-Modum district of Norway were historically significant in the economy of that country as well (Johnsen, 1986).

Modern, mechanized mining methods with their advantages for the exploitation of large — even if relatively low-grade — deposits have been a factor leading to the demise of mining of five-element ores. Narrow vein widths and discontinuous, pinch-and-swell ore lodes translate into high mining costs. Sluggish silver prices, a major decline in uranium prices, and many low-cost alternative sources for nickel and cobalt have also contributed to a decline in interest in this type of deposit in the past decade. As of this writing, no mines exploiting five-element type ores are known by the author to be in operation anywhere in the world. However, on grounds of their past importance and because of their unusual mineralogy and the problem of their genesis, these deposits remain a source of great interest to many.

## GEOLOGIC SETTING

The five-element ores occur in widely scattered localities, probably on a worldwide basis, although well-established examples are found only in North America and Europe. Bastin's (1939) comprehensive listing of deposits with their mineralogy remains the best tabulation of these occurrences. In subsequent discussion in this paper, current or better-known names for some deposits are employed, and the name used by Bastin (1939) is given in parentheses. The absence of five-element vein deposits in other continents is probably only apparent, as Badham (1976) pointed out the possible existence of such deposits in South America, Africa, Asia and Australia. A number of these occurrences were drawn from lists of mineral assemblage occurrences in Ramdohr (1969), and little or no geological information is available for them.

The three major districts in Canada (Fig. 1) are all of Proterozoic age. Cobalt-Gowganda of northeastern Ontario is the largest, dwarfing the historically interesting production of the Thunder Bay district of northwestern Ontario. Some 200 km east of Thunder Bay, a group of occurrences called the Port Coldwell veins appear to be genetically related to those at Thunder Bay (Franklin *et al.*, 1986). The Echo Bay and Camsell River districts of the Great Bear Lake area of the Northwest Territories have been important producers of both uranium and silver.

The deposits of the Cobalt-Gowganda and Thunder Bay districts are described in greater detail in the next section. Those at Great Bear Lake are in metavolcanic and associated metasedimentary rocks of the Echo Bay Group and, occasionally, in the granitic rocks of the Great Bear batholithic complex, which intrudes the stratified rocks (Changakakoti *et al.*, 1986b). The veins also cut some younger diabase dykes, and radiometric dates indicate an age of mineralization of ~1500 Ma (Changakakoti *et al.*, 1986a). A minor, little-exploited district is located on the East Arm of Great Slave Lake, Northwest Territories, where the veins occur in little metamorphosed sedimentary and volcanic rocks, and also cut various Aphebian intrusive rocks of the area (Badham, 1978).

The deposits of the Idaho cobalt belt resemble five-element type deposits in some respects, but Nold (1988) stated that these are stratiform Cu-Co deposits, similar to those of the Zambian Copperbelt. They have, in places, experienced minor remobilization into veinlets due to metamorphism.

In the southwestern United States and the adjacent state of Chihuahua, Mexico, the occurrences at Wickenburg in Arizona, the Black Hawk district (Bullard's Peak) in New Mexico, and at Sabinal and Batopilas in Chihuahua are all in the Basin and Range Province. The veins cut rocks of many ages, and contemporary accounts interpret all the deposits to be the result of Laramide (Late Cretaceous–Early Tertiary) events. The Batopilas district has been described by Wilkerson (1983) and Wilkerson *et al.* (1988), and the ore deposits of the area are complex and possibly polygenetic. The veins cut early Tertiary intrusions and later dykes, but their age is unknown more exactly. Ages of the deposits are not known in detail, although those of the Black Hawk district have been shown to cut post-Laramide (Tertiary?) quartz latite and andesite dykes (Paige, 1916). However, Gerwe and Norman (1984) gave a K-Ar date of 65 Ma for alteration chlorite, too old for Basin and Range events and in agreement with the age of Laramide intrusions in the area.

In northern Europe (Fig. 1), the Kongsberg-Modum district of Norway is spatially and presumably genetically associated with events forming the Permian Oslo Graben. The deposits are, however, hosted in Archean crystalline rocks adjacent to younger rocks within the graben, although they also cut Permian dykes related to the Oslo Graben (Bugge, 1978).

Germany is the site of a number of districts, including the Schwarzwald (Black Forest) area, which contains the deposits at Wittichen, Wieden, St. Blasien and, in adjacent Alsace, Ste.-Marie-aux-Mines. A northern extension of this group of deposits occurs in the Odenwald at Nieder-Ramstadt and Nieder-Beerbach. North of the Upper Rhine Valley, minor veins bearing five-element assemblages cut older base metal and silver deposits in the Ramsbeck district. These veins, which have been called Q-veins (Querkluft), and similar veins at Nanzenbach both occur in an area called the Eastern Rheinisch Schiefergebirge. The ages of all the above deposits are uncertain, as they occur in crystalline rocks of Hercynian (as employed here, equivalent to Variscan) affinity in the Schwarzwald, or in Paleozoic sedimentary rocks in the Eastern Rheinisch Schiefergebirge. Modern interpretations, as summarized by Walther (1986), note that orientations of all these veins bear strong relationships with the generally north-south orientation of faults related to the subsidence of the Rhine Graben and are, thus, of Tertiary age. This interpretation of a young age is supported by crosscutting relationships among various generations of barren quartz and calcite, barite and fluorite, and base metal-bearing veins. Previous interpretations had considered the five-element veins, particularly those in the Schwarzwald, to be of Hercynian age.

The old and famous district of the Erzgebirge includes such well-known deposits as those of Johanngeorgenstadt, Annaberg, Schneeberg, Marienberg, Freiberg, and Jáchymov (Joachimsthal) in adjacent Czechoslovakia. The deposits have long been considered to be Hercynian (Permo-Carboniferous) in age, owing to past predilections toward magmatic-hydrothermal genetic theories, but age determinations on some vein minerals, as summarized by Tischendorf (1986), have created problems for this interpretation. The five-element veins have been considered to be Triassic-Jurassic (*e.g.*, Tischendorf, 1986) or as young as Tertiary, based on crosscutting relationships with Tertiary basaltic dykes (*e.g.*, Walther, 1986; Pouba and Ilavský, 1986). The west-northwest strike of many of the steeply dipping veins of the Erzgebirge is similar to that of "Kobaltrücken" of Thuringa and the Harz Mountains, and the three areas define a northwesterly trending region of vein mineralization. The "Kobaltrücken" of Thuringa (*e.g.*, Kamsdorf and Schweina) and the Harz Mountains (*e.g.*, Mansfeld), as well as scattered occurrences in more westerly deposits of the Kupferschiefer (*e.g.*, Bieber), are defined as veins displacing the Kupferschiefer. The "Kobaltrücken" are mineralized with five-element type ores at the Kupferschiefer horizon, but the mineralization becomes sparse above this horizon, and the veins are barren below it. The "Kobaltrücken" had been believed to be remobilized components of Kupferschiefer ores when theories of its syngenetic origin were prevalent; however, it is now recognized that the "Kobaltrücken" are epigenetic and considerably younger than the Kupferschiefer ores. Walther (1986) has summarized evidence for a Tertiary age for these veins which, although of small size, were formerly of considerable economic importance.

The Dobšiná deposit (Dobschau, Hungary) of the Western Carpathians of Czechoslovakia (Fig. 1) is an isolated occurrence of uncertain age. It occurs mainly within diorite which has intruded Devonian schists, but the veins also cut Triassic sediments that unconformably overlie the diorite (Voit, 1900). Another isolated occurrence of five-element veins is in Cornwall, where uraniferous varieties have locally been exploited. These veins are north-striking "cross-courses", which cut the principal tin and base metal veins nearly perpendicularly (Dunham *et al.*, 1978). The age of the "cross-courses" is uncertain, but they clearly post-date the Hercynian granitic bodies of Cornwall and their associated primary ore deposits.

In south-central Europe, five-element veins occur in the Alps of Switzerland and Austria (Fig. 2). In Switzerland, the Kaltenberg (Turtmannthal) and Grimentz (Val d'Anniviers) occurrences are in schists of the Pennic St. Bernard nappe. The schists are believed to be mostly of Permo-Carboniferous age; however, the age of the occurrences relative to polyphase Upper Cretaceous and Eocene-Oligocene metamorphism is unknown (Jaffé, 1986).

Austrian occurrences at Leogang (Nöckelberg, Germany) and Schmalding are in deformed Paleozoic sedimentary rocks of the

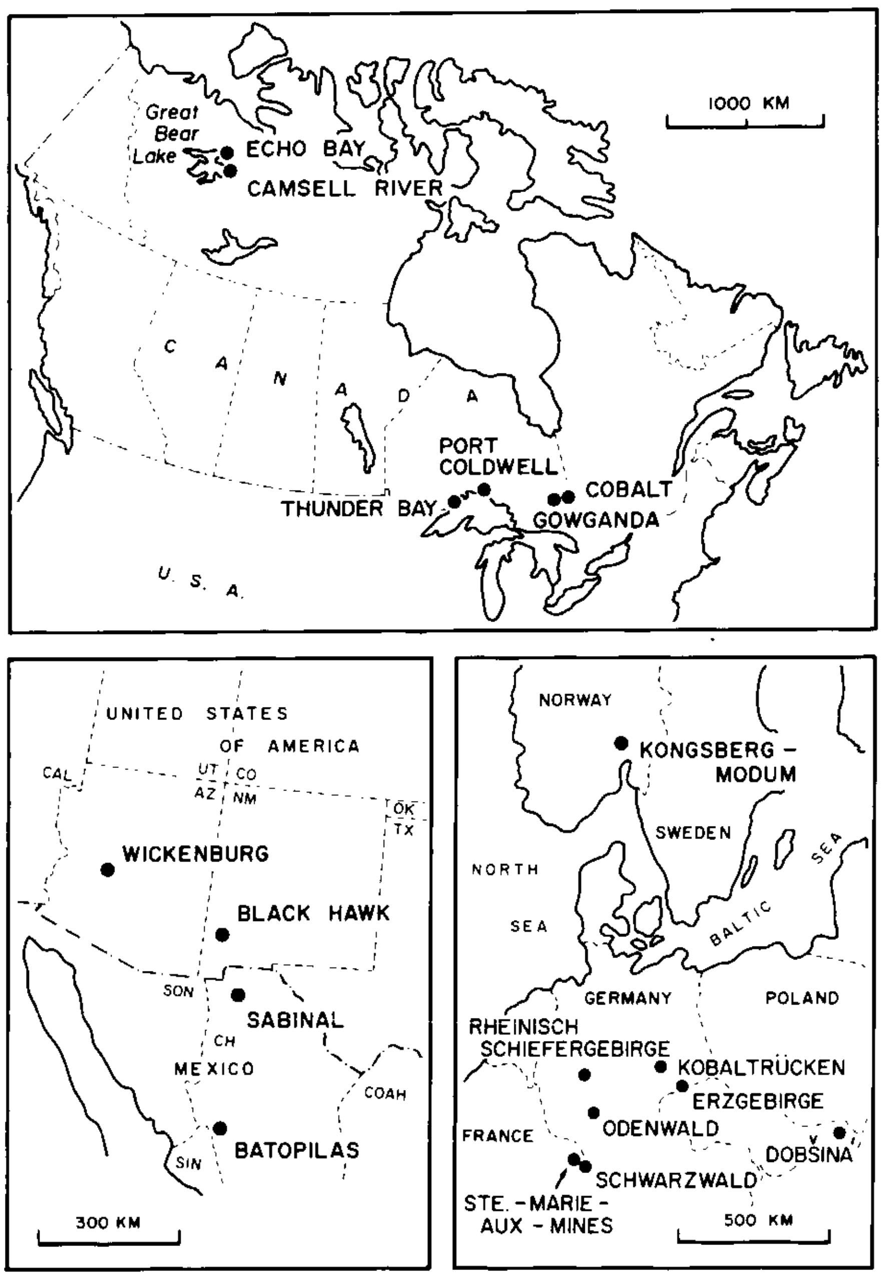



**Figure 1** *Location map for five-element vein deposits in Canada, the United States, Mexico and northern Europe. Four general localities — Rheinisch Schiefergebirge, Odenwald, Schwarzwald and Erzgebirge — are regions in Germany containing more than one deposit. The point for Kobaltrücken illustrates the general location of these veins in Thuringa and the Harz Mountains.*

Grauwacken Zone, and in metamorphic rocks of the Central Zone, respectively. In both cases, veins occupy Alpine structures, but there is controversy on the timing of emplacement, and theories of both Hercynian and Alpine timing have been proposed (Holzer, 1986).

The deposits at Allemont and Les Chalanches in France (Fig. 2) occupy fractures in the Belledonne Massif, which is composed of crystalline rocks of pre-Triassic age. These deposits are considered to have formed in the Tertiary (Ympa, 1972).

The Riu Planu is Castangias deposit of southwestern Sardinia and the Sarrabus district of southeastern Sardinia (Fig. 2) are both hosted by Ordovician-Silurian schists adjacent to Hercynian granites (Zuffardi, 1989). There is some controversy concerning the ages of both deposits; however, accounts written during the era of active mining indicate that the veins cut Oligocene porphyries in the Sarrabus district, again indicating a Tertiary age (Piepoli, 1933).

In Asiatic Russia, the Khovou-Axy deposit is hosted in Silurian and Devonian sedimentary rocks, which are cut by diabase dykes and sills. No information on the age of the deposit is available (Kroutov, 1972). The Consols-type vein at Broken Hill, New South Wales (Lawrence, 1968), is a possible but doubtful case, perhaps similar to the Kobaltrücken of the Kupferschiefer (Badham, 1976).

A few occurrences mentioned by Bastin (1939) and Badham (1976) appear doubtful as members of the five-element ore suite. The Balmoral Mine of the Republic of South Africa was a producer of cobalt from an ore composed of "smaltite". Although the deposit was interpreted to be a vein, the gangue is composed of granitic pegmatite with accessory molybdenite and chalcopyrite (Horwood, 1904). This deposit, as well as a few others mentioned by Bastin, seems to be an unusual type of pegmatitic deposit.

The Bou Azzer district of Morocco has some similarities to, but also major differences from, five-element type deposits. Although the deposits contain abundant Ni-Co arsenides, they are mostly not in the form of fissure veins and do not appear to have formed by filling of open spaces. Silver is not present as a separate mineral, but is alloyed with gold, which is a co-product of the mines. These differences suggest that the deposits are related to the mafic intrusions that host them, and are not of the five-element ore type (Leblanc, 1986).

In summary, the five-element type ores occur in a great many settings, all of which, however, are in areas of continental crust. Although there is historical disagreement in many districts on the age and timing of ore deposition, the predominant impression is that the veins formed late- or post-tectonically in any given region. There is a clear temporal and spatial relationship with continental rifting in several cases. The deposits occur in rocks of Proterozoic and younger age; however, no deposits older than the Early Proterozoic deposits of the Cobalt-Gowganda district are known. Aside from the other two Canadian Proterozoic districts — Thunder Bay and Great Bear Lake — deposits of reasonably certain Paleozoic (Kongsberg-Modum, Permian) and Cenozoic (the deposits of the Rhine Graben, Tertiary) ages occur. The ages of many deposits, however, are controversial. These controversies, more often than not, are linked to the problem of genesis, as the genetic process is tied to some time-limited agency.

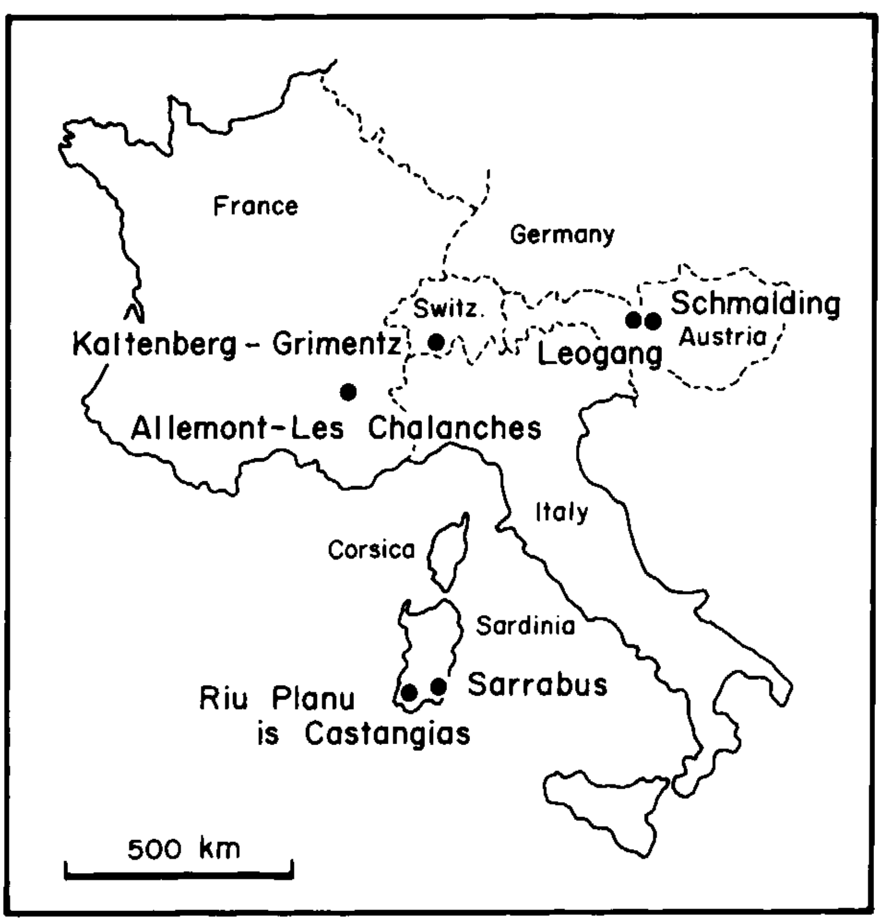



**Figure 2** *Location map for five-element vein deposits in southern Europe.*

## DEPOSIT CHARACTERISTICS

### Host Lithologies

The host rocks of five-element type veins display great diversity, although some striking similarities are apparent among some districts. On the largest scale, host rocks may be characterized as crystalline or sedimentary terrane, usually with little or no interbedded volcanics. The crystalline terrane may consist of metamorphic or granitic rocks, and, frequently, both are present. Crystalline terranes host the veins of the Alps, most German deposits, those of Sardinia, and those of Norway, whereas sedimentary host rocks are prominent at Thunder Bay and Cobalt-Gowganda, and volcanic and volcanoclastic rocks are hosts at Great Bear Lake. Several features in host rocks are considered important in controlling localization of ore. These include diabase sills (Thunder Bay (in part) and Cobalt-Gowganda); "fahlbands", *i.e.*, sulphide-rich strata in crystalline rocks (Kongsberg-Modum and Cobalt-Gowganda); carbonaceous shales (Thunder Bay and Sardinia); and sulphide-rich metavolcanic rocks (Thunder Bay (in part) and Cobalt-Gowganda).

To amplify some of these points, the geological settings of the Cobalt-Gowganda and Thunder Bay districts are displayed schematically in Figure 3. In the Cobalt-Gowganda district, some deposits (Fig. 3A) are hosted entirely within diabase sills, known locally as Nipissing diabase, cutting Archean basement rocks (1) or at upper and lower contacts of the diabase with Archean basement (2). Other deposits are hosted principally in shale-rich sections of the Coleman Formation (Fig. 3B) of the Huronian Supergroup, but extend downward into Archean basement (3), and others occur within the Coleman Formation, but below the Nipissing diabase (4). No deposits are known to occur in the Huronian sediments above the Nipissing diabase (Petruk, 1971; Andrews *et al.*, 1986). In the Archean basement, sulphide-rich strata (fahlbands) and sulphide-rich metavolcanics underlie some deposits, and carbonaceous, pyritic slates within the Archean basement are possible contributors of metals to the veins (*e.g.*, Boyle and Dass, 1971; Smyk and Watkinson, 1990).

The deposits in the Thunder Bay district occur in two curvilinear zones, the Mainland Belt and the Island Belt. Most deposits in the Mainland Belt (Fig. 3C) are localized in carbonaceous shales below diabase sills (1), whereas many of the major deposits in the Island Belt occur within a gabbro dyke (3). Some deposits of the Mainland Belt are hosted in greenstones and granites of the Archean basement (2), but there is no clear relationship with sulphide-rich zones of the former. Some deposits of the Island Belt occur in shale below diabase sills, as in the Mainland Belt (4), but attitudes of the vein systems differ in these two cases. The veins are perpendicular to northeast-striking diabase and gabbro dykes in the Island Belt, but strike northeasterly in the Mainland Belt in most cases (Franklin *et al.*, 1986).

### Form and Structure

Five-element type veins are characteristically open-space filling, and replacement of wall rock is not extensive, if present at all. Vein systems may be rather simple, as in the Thunder Bay district where steeply dipping veins have only two strike directions (Franklin *et al.*, 1986), or much more complex, as in the Cobalt-Gowganda district (Petruk, 1971). Veins are commonly completely filled with hydrothermally deposited minerals, although in the Thunder Bay district most veins are open in the centre in a vuggy zone and contain fragments of country rock of all sizes (Kissin and Sherlock, 1989). Multiple episodes of fracturing, followed by mineralization, are evident at Thunder Bay (Kissin and Jennings, 1987; Kissin and Sherlock, 1989), Gowganda (Scott, 1972) and Great Bear Lake (Robinson and Morton, 1972). The veins pinch and swell from centimetre to metre scale thickness, and mineable ores frequently occur as rich shoots separated by narrow veins. In many districts, the ores appear to be limited in depth (*e.g.*, Thunder Bay and Cobalt-Gowganda) and, although veins may persist to deeper levels, they are barren (Kissin and Sherlock, 1989; Andrews *et al.*, 1986). The silver lodes at Kongsberg, however, have a vertical extent of more than 500 m in some instances (Johnsen, 1986).

### Mineralogy

The mineralogy of five-element veins is their most distinctive feature. They characteristically contain abundant mineral species that are rare in other settings, especially Ni-Co arsenide minerals. The mineralogy of five-element deposits was reviewed by Bastin (1939), and similar information can be obtained from the description of any well-developed deposit or district of this ore type. The topic will be discussed only briefly here, in relation to paragenetic sequence.

A recurrent sequence of mineral assemblages can be seen in most deposits. This sequence can be summarized as:

***Stage 1 Early barren stage.***
Quartz, sometimes with minor base metal sulphides (pyrite, sphalerite, galena).

***Stage 2 Uraninite stage.***
Uraninite-quartz. This stage is conspicuously and completely absent in some districts (Cobalt-Gowganda, Thunder Bay, Kongsberg-Modum), but of significant economic importance in others (Great Bear Lake, Erzgebirge).

***Stage 3 Ni-Co arsenide-silver stage.***
Native silver in intimate and often spectacular association with Ni-Co arsenide minerals (rammelsbergite, safflorite, niccolite, cloanthite, maucherite). Native bismuth may also occur at this stage. The gangue is usually dolomite or calcite (Fig. 4).

***Stage 4 Sulphide stage.***
Pyrite, sphalerite, galena, chalcopyrite and other copper sulphides with native silver and argentite in predominantly calcite gangue with quartz, fluorite and barite. Native arsenic and antimony may occur at this stage. This stage is gradational from the Ni-Co arsenide stage, and transitional assemblages may contain sulpharsenides, such as arsenopyrite, and Sb-As-Ag sulphosalts, such as freibergite, pyargyrite, proustite and stephanite.

***Stage 5 Late stage.***
Usually calcite deposited at low temperatures, but occasionally accompanied by significant barite or fluorite.

These five stages represent an idealized and complete paragenetic sequence. It must be appreciated that one or more stages may be absent in any given deposit. Thus, the uraninite stage is completely absent in some districts, as noted previously. Although the Ni-Co arsenide stage is essential to the definition of the five-element ore type, its development in a particular deposit or district may be quite limited, *i.e.*, as a zone in a single

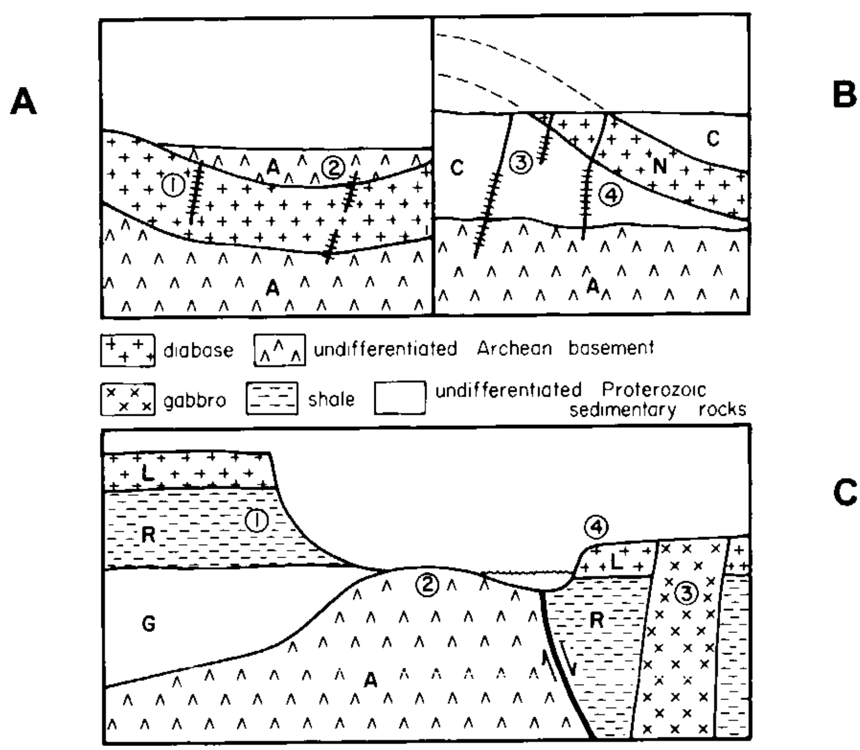



**Figure 3** *Schematic cross-sections showing the relationships of veins to geological units in the Cobalt-Gowganda district (**A, B**) and the Thunder Bay district (**C**). In A and B, the numbers locate typical settings of veins (1) mostly within Nipissing diabase (**N**) (Castle Mine), (2) at upper and lower contacts of diabase cutting Archean basement (**A**) (Beaver-Temiskaming Mine), (3) mostly within Coleman Formation (**C**) but lodes extend in the Archean and some underlie diabase (Langis Mine) and (4) within Coleman Formation below Nipissing diabase (Silverfields Mine). Hachured heavy lines indicate mineralized portions of veins. **C** represents a schematic NW-SE section through the Thunder Bay district in which (1) represents Mainland Belt veins hosted in Rove shale (**R**) below Logan diabase sills (**L**), (2) some Port Arthur group deposits of the Mainland Belt hosted in Archean basement (**A**), (3) principal Island Belt deposits (e.g., Silver Islet) hosted in gabbro dykes and (4) other Island Belt deposits hosted in Rove Shale below diabase sills. All Island Belt veins strike northwesterly, and Mainland Belt veins strike northeasterly. Several Mainland Belt veins extend downward into the Gunflint Formation (**G**).*

deposit or a few deposits in a district. For example, in the Thunder Bay district, the Ni-Co arsenide assemblage is extensively developed only in the Silver Islet Mine, whereas 40% of silver production was derived from mines in which sulphide stage assemblages with argentite and native silver were predominant (Franklin *et al.*, 1986). Late-stage veins may be abundant in a district, *e.g.*,the Schwarzwald (Walther, 1986), and occur in isolation from veins containing more complete sequences. Moreover, episodic phases of mineralization may have produced numerous superimposed cycles of deposition separated by apparent hiatuses (Kissin and Jennings, 1987; Kissin and Sherlock, 1989).

These stages of mineralization appear to represent the products of an ore-depositing solution that has evolved with time. Later stages have been deposited sequentially on earlier ones, although some (*e.g.*, Scott, 1972) have argued that early-deposited minerals have been replaced by later ones. Interpretations of extensive replacement (*e.g.*, Neumann, 1944) may lead to an alternative depositional sequence, *i.e.*, sulphide stage prior to Ni-Co arsenide stage. Most modern studies do not, however, ascribe an important role to replacement phenomena.

It is important to note not only what is present in the ores, but also what is absent. Gold has not been produced in any deposits except Les Chalanches in France and, even there, its presence is questionable, as it was recovered from gossans rather than from primary veins (Ricard, 1894), and two stages of genesis, pre-Triassic and Tertiary, have been discerned (Ympa, 1972). Other minerals associated with hydrothermal fluids of granitic origin, such as molybdenite, scheelite, selenides and tellurides, are also not reported. Even more striking is the separation chemically of the Ni-Co arsenide stage from the sulphide stage. Sulphides are completely absent in the former, and sulphur is present only as occasional sulpharsenides, such as cobaltite. Iron is also rare to absent; thus, arsenopyrite and loellingite generally do not occur in the Ni-Co arsenide assemblage. It appears that the solution that deposited the Ni-Co arsenides must have been low in reduced sulphur content. Yet, the chemistry of the solution changed markedly on reaching the sulphide stage, such that both sulphides and iron-bearing minerals could be precipitated from it. Kissin (in press) has discussed some possible constraints on such a solution.

**Alteration**

Discussion of associated alteration is frequently absent from descriptions of five-element veins. The probable reason for this is the negligible development of hydrothermal alteration in many districts. In the Cobalt-Gowganda district, alteration has been believed to have been of greater significance. Spotted chloritic alteration is widespread in host rocks to ore veins in the Cobalt-Gowganda district, and one school of thought (*e.g.*, Appleyard, 1980) has related this alteration to the emplacement of the ores. Andrews *et al.* (1986), however, have presented convincing evidence that emplacement of the ore veins post-dated the spotted chloritic alteration, which is interpreted to be related to contact metamorphic effects of the Nipissing diabase. The alteration accompanying ore deposition is confined to a narrow band surrounding a vein to a maximum of 10 cm. The geochemistry and mineralogy of this type of alteration were investigated in detail by Andrews *et al.* (1986), who distinguished three zones between an ore vein and unaltered Nipissing diabase, characterized by different alteration mineral assemblages (Fig. 5). The exact composition of the alteration zone is, however, dependent on the nature of the wall rock. Analyses and mass-balance calculations indicate that hydrothermal fluids were the main source of Ca, Na, $CO_2$, Ag, As, Nb, Y and Sr added to the altered zone, with significant but sporadic addition of K, Sr, Co, Pb, Cu and, more rarely, Hg and Au. Vein minerals are significantly enriched in rare earth elements (REEs), and altered wall rocks are enriched in REEs, relative to unaltered rock. There was consistent loss of Si, Zn, Ni, B, Li and Sc from wall rock. Erratic gains and losses were noted for total Fe, Mg, K, Al, Mn and P. The patterns of mobility of elements led Andrews *et al.* (1986) to conclude that the solutions creating the alteration were of high alkalinity and were reducing. Their source was interpeted to be remote from the site of vein deposition, based on the limited extent of the alteration and gradients in hydration and carbonatization emanating from the veins. The alteration is typical propylitic type, as is commonly associated with other hydrothermal ores.

**Fluid Inclusion Data**

Studies of fluid inclusions from five-element veins have been very informative, providing insight not only into temperatures of deposition and characteristics of the ore-depositing solution, but also into the timing of the process. Given the range of mineral assemblages present in a typical deposit, knowledge of the paragenetic position of samples is essential to the interpretation of fluid inclusion data. Extensive studies have been made at Cobalt-Gowganda (Kerrich *et al.*, 1986), Great Bear Lake (Badham *et al.*, 1972; Shegelski and Scott, 1975; Changkakoti *et al.*, 1986a, 1986b), Thunder Bay (Kissin and Jennings, 1987; Kissin and McCuaig, 1988; Kissin and Sherlock, 1989), Black Hawk (Gerwe and Norman, 1984), Les Chalanches (Ympa, 1972), and Kongsberg-Modum (Segalstad *et al.*, 1986). Reports for other deposits are brief or documentation is difficult to obtain (*e.g.*, Khovou-Axy; Kroutov, 1972).

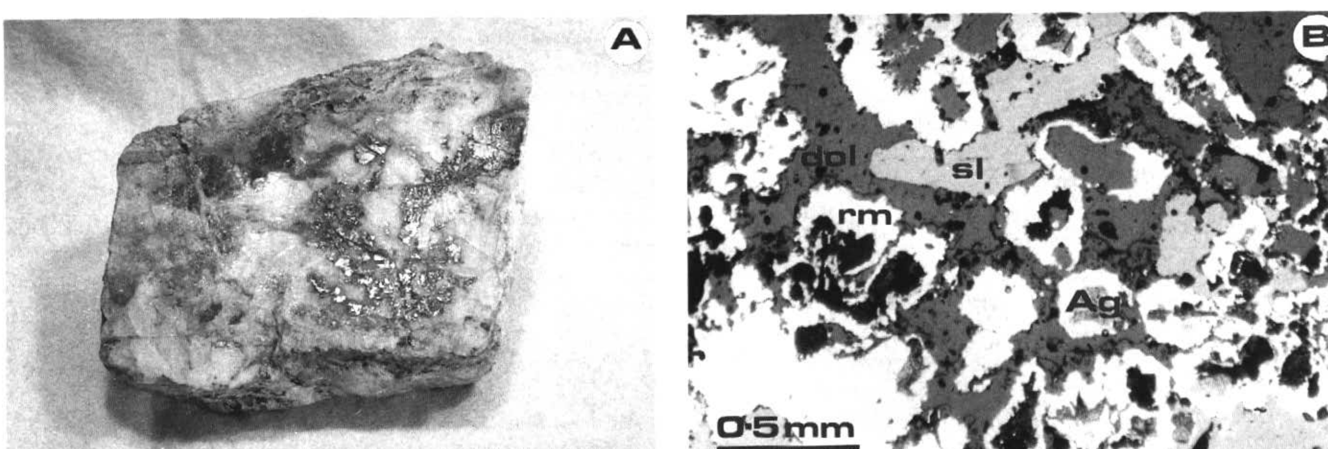



**Figure 4** (**A**) *Polished slab of ore (7.5 × 6 cm) from Silver Islet. At lower right are rosette-textured intergrowths of native silver and Ni-Co arsenides in darker, fine-grained dolomite. In upper right and centre are equant grains of argentite in later, coarse-grained, white calcite. At upper left are fragments of carbonaceous shale country rock.* (**B**) *Photomicrograph of polished section of Silver Islet ore with rosettes cored with native silver (Ag) and rimmed with pararammelsbergite (rm). Note that the silver-arsenide intergrowth is everywhere separated from later sphalerite by dolomite (dol) (from Smyk, 1984).*

In many deposits, fluid inclusions are most readily available in sulphide-stage and late-stage assemblages, with their abundant calcite, quartz, sphalerite, fluorite and barite. Temperatures and other inferences taken from fluid inclusions from these stages may not be extrapolated forward to earlier stages of deposition. Failure to consider this may produce difficulties, as exemplified by Robinson and Ohmoto's (1973) assumption of constant temperature during ore deposition. The studies cited previously consistently indicate that homogenization temperature rose rapidly from stage 1 to stage 2, peaking at 400-500°C, although somewhat lower temperatures (300-350°C) are typical of some districts. During stage 3 and into stage 4, temperatures declined to the 250-150°C range, and late-stage homogenization temperatures are invariably below 125°C. Evidence of the introduction of multiple pulses of ore-depositing fluids was obtained for Great Bear Lake (Badham *et al.*, 1972; Changkakoti *et al.*, 1986c), for Thunder Bay (Kissin and Jennings, 1987; Kissin and Sherlock, 1989), and for Kongsberg-Modum (Segalstad *et al.*, 1986). These pulses contained thermal maxima separated by cooling and fault movement, indicating that ore deposition was a long-lived, episodic process.

The fluid inclusion studies indicate the presence of a varied assemblage of fluid inclusion types. Studies at Great Bear Lake (Shegelski and Scott, 1975; Changkakoti *et al.*, 1986c), Cobalt-Gowganda (Scott and O'Conner, 1971; Kerrich *et al.*, 1986), Black Hawk (Gerwe and Norman, 1984) and Kongsberg-Modum (Segalstad *et al.*, 1986) have all determined that fluid inclusions formed during Ni-Co arsenide and native silver deposition were saturated with respect to NaCl, as evidenced by the presence of daughter crystals. Halide daughter crystals were only rarely encountered at Thunder Bay (Kissin and Jennings, 1987; Kissin and Sherlock, 1989). However, relatively little Ni-Co arsenide stage ore was sampled in this case. All studies reported a decrease in salinity in later stages of ore deposition, although wide fluctuations in cogenetic inclusions were commonly noted. These variations may be due to the admixture of low-salinity, meteoric water or, in the case of boiling, phase separation of the solution into low-salinity and high-salinity fluids.

Boiling, generally of a sporadic nature, has been reported in all the districts mentioned. Evidence for boiling has generally been direct, *i.e.*, homogenization of some coexisting inclusions to liquid and others to vapour at the same temperature, enabling a determination of a trapping pressure. Such trapping pressures have been low, on the order of 70 to 200 bars at Great Bear Lake (Changkakoti *et al.*, 1986c) and a maximum of 600 bars at Cobalt-Gowganda (Kerrich *et al.*, 1986), indicating depths of ore deposition of about 700 m at Cobalt-Gowganda, and considerably less at Great Bear Lake. The sporadic nature of boiling, and the variable pressures, suggest alternation between lithostatic and hydrostatic conditions. On the other hand, Gerwe and Norman (1984) found boiling to occur at >350°C at Black Hawk, indicating a depth of 2.4 km.

Solution salinities are generally reported in terms of equivalent wt.% NaCl, but most data indicate that components other than NaCl are also present in trapped fluids (*e.g.*, Kerrich *et al.*, 1986). Fluids are dominantly aqueous, although $CO_2$-rich inclusions are observed, particularly in the late-stage assemblage in which the gangue is predominantly carbonate (*e.g.*, Kissin and Sherlock, 1989).

**Stable Isotope Data**

Studies of stable isotopes have been carried out at Great Bear Lake (Robinson and Ohmoto, 1973; Changkakoti *et al.*, 1986b), Cobalt-Gowganda (Kerrich *et al.*, 1986; Goodz *et al.*, 1986), Thunder Bay (Kissin and Jennings, 1987; Kissin and Sherlock, 1989), and Kongsberg-Modum (Segalstad *et al.*, 1986). Studies of sulphur isotopes of sulphides have produced various interpretations. Robinson and Ohmoto (1973) concluded that their results were best explained by high-temperature reduction of seawater sulphate, with sulphides deposited in a chemical environment that changed from oxidizing to reducing, as indicated by $\delta^{34}S$ = −22‰ in early acanthite, and $\delta^{34}S$ = −4 to +20‰ in later sulphides. This wide range of sulphur isotopic compositions is in contrast to $\delta^{34}S$ = +2 to +5‰ in host rock pyrite. Robinson and Badham (1974) found $\delta^{34}S$ in sulphides to vary at approximately +1‰ and argued also for reduction of seawater sulphate as the source of sulphur. Badham (1975) subsequently argued that sulphur isotopic data indicate a magmatic source for sulphur.

In the Cobalt-Gowganda district, Goodz *et al.* (1986) found that vein sulphides of composition $\delta^{34}S$ = +2.3‰ differ significantly from the compositions of Archean basement sulphides and sulphides in brecciated wall rock. Isotopic equilibrium did not generally prevail between sulphide pairs, except for chalcopyrite and galena. The results from these pairs indicate that the source sulphur had a composition in the range $\delta^{34}S$ = +5.0 to +11.0‰. Goodz *et al.* (1986) proposed that the sulphur was produced by reaction of heated formational water with Archean basement sulphides.

Kissin and Jennings (1987) found that vein sulphides in the Thunder Bay deposits range in isotopic composition from $\delta^{34}S$ = −9.3 to +12.2‰, with some in the +25 to +30‰ range. The latter values were attributed to interaction with later meteoric water. A general sequence of $\delta^{34}S$ of galena < pyrite < barite < sphalerite is discernable, although equilibrium among sulphide-sulphide pairs and sulphide-sulphate pairs does not seem to have generally prevailed. The isotopic composition of barite is suggestive of formation of late sulphate by oxidation of reduced sulphur without fractionation. The isotopic composition of vein sulphides differs in many cases from that of sedimentary pyrite in host rocks, and direct derivation from them is unlikely. Kissin and Jennings (1987) proposed that boiling might fractionate sulphur between $SO_2$ and reduced sulphur in solution, producing some of the isotopically heavier sulphides. Subsequently, Kissin (1989) proposed that Proterozoic seawater sulphate, either as connate water in early Proterozoic sediments or directly as late Proterozoic seawater, was the ultimate source of sulphur. Segalstad *et al.* (1986) proposed seawater sulphate as the source for separate barite veins ($\delta^{34}S$ = +12‰ at

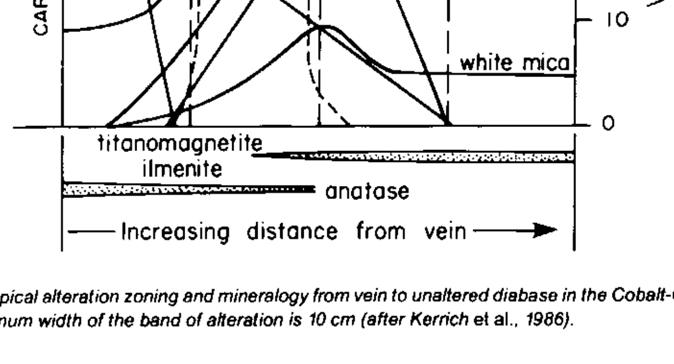



**Figure 5** *Typical alteration zoning and mineralogy from vein to unaltered diabase in the Cobalt-Gowganda district. Maximum width of the band of alteration is 10 cm (after Kerrich* et al.*, 1986).*

Kongsberg-Modum), but believed that fahlband sulphides ($\delta^{34}S$ = 0‰) were the source of vein sulphides.

Robinson and Ohmoto (1973) analyzed dolomite and calcite from the Echo Bay Mine for the isotopic composition of carbon and oxygen. Using these data, together with determinations on quartz and hematite from the El Dorado Mine (Clayton and Epstein, 1958), they concluded that $\delta^{18}O$ of water remained nearly constant at +1.0 ± 2.5‰ throughout ore deposition in the Great Bear Lake district. Their assumption of a constant temperature of 200°C during the entire period of ore deposition does not seem warranted, however. Badham *et al.* (1972), by means of their fluid inclusion studies, determined that temperatures fluctuated appreciably. Changkakoti *et al.* (1986b), using temperatures based on fluid inclusion measurements, determined that δD and $\delta^{18}O$ for analysed samples plot (Fig. 6) within the field of magmatic water ($\delta^{18}O$ = +5.5 to +10.0‰). (It should be noted that their complete $\delta^{18}O$ data fall within the range +0.47 to +9.12‰.) Carbon in the hydrothermal fluid was found to vary between $\delta^{13}C$ = -2.8 and -8.6‰ (Fig. 7), and was attributed to magmatic carbon ($\delta^{13}C$ = -5.0 ± 2.0‰).

In contrast, Kerrich *et al.* (1986) determined, on the basis of analyses of vein and alteration minerals, that the isotopic composition of the ore-depositing fluid in the Cobalt-Gowganda camp was $\delta^{18}O$ = -2.5 to +5‰ and δD = -40 to +5‰, corresponding to evolved formational brines, presumably from Huronian sediments (Fig. 6). $\delta^{13}C$ of vein carbonates is in the range -3.1 to -5.3‰ (Fig. 7) and was believed to be close to the composition of the hydrothermal fluid. The source of the carbon is unclear.

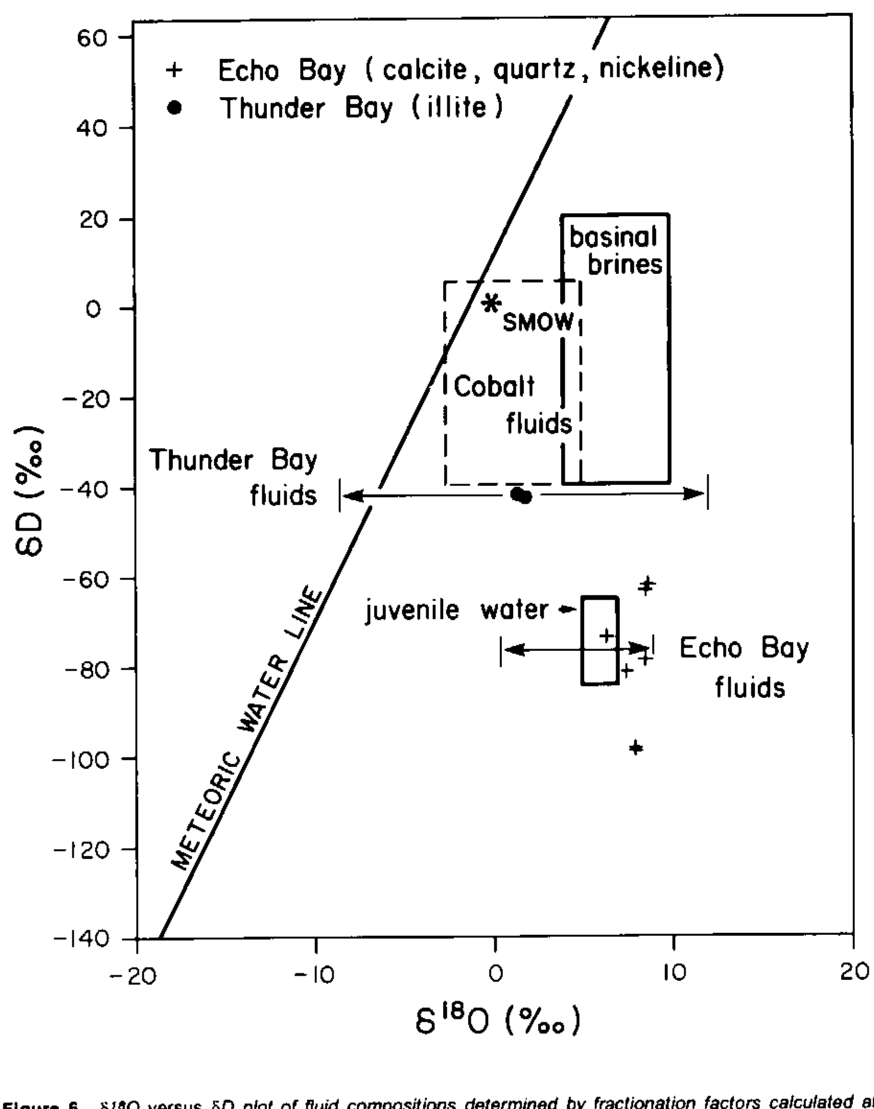



**Figure 6** $\delta^{18}O$ *versus δD plot of fluid compositions determined by fractionation factors calculated at temperatures determined from fluid inclusion studies. Arrows indicate ranges of* $\delta^{18}O$ *where no corresponding δD was determined. (δD in the Echo Bay data was determined by direct measurement of fluid inclusion waters.) Fields for basinal brines and juvenile water are from Ohmoto (1986). Data sources include: Thunder Bay-Kissin and Sherlock (1989), Cobalt-Kerrich* et al.*(1986), Echo Bay-Changakoti* et al. *(1986b). MWL = meteoric water line; SMOW = standard mean ocean water.*

For the Thunder Bay district (Fig. 6), Kissin and Sherlock (1989) determined that $\delta^{18}O$ of hydrothermal fluids that deposited quartz and calcite was in the range -8.4 to +12.8‰. This range encompasses that of basinal brines, and a series of isotopically lighter waters correlating with decreasing temperature implies progressive mixing with meteoric water. Alteration illite, with $\delta^{18}O$ = +1.9 and +1.4‰ and δD = -42.3 and -40.8‰, lies on an inferred mixing line. Vein carbonates were precipitated from fluids with $\delta^{13}C$ = -12.9 to + 0.6‰ (Fig. 7). The source of the carbon is consistent with derivation from organic carbon ($\delta^{13}C \approx$ -33‰) with fractionation of +20 to +30‰, depending on temperature, during the formation of $HCO_3^-$ in solution.

Segalstad *et al.* (1986) found "coal blende" (amorphous carbon in veins) to be of composition $\delta^{13}C$ = -28 to -30‰, suggesting derivation from shales of the Oslo region ($\delta^{13}C$ = -22 to -29‰) in the Kongsberg-Modum district. $\delta^{13}C$ of vein calcite ranges from -26 to +1‰, excluding local limestones ($\delta^{13}C$ = -10 to +3‰) as a source. Vein minerals show $\delta^{18}O$ increasing from +7 to +26‰, as anticipated from mineral-water interaction.

**Radiogenic Isotope Data**

The study of radiogenic isotopes in five-element vein deposits has a long history, extending back to the Stanton and Russell (1959) study of "anomalous leads", in which samples designated "Thunder Bay" were one of the suites analyzed. One silver deposit (Silver Mountain) was sampled in a group of lead-zinc-barite veins, now believed to be of a separate origin (Franklin and Mitchell, 1977). Newer data from Thunder Bay were presented by Franklin *et al.* (1986), who found that most data lie on a secondary isochron defined by mixing of sources from diabase sills and Proterozoic host rock. Some deposits, however, were considerably enriched in radiogenic lead, giving futuristic model ages (J-type lead), a factor attributed to contributions by granitic basement in these cases.

Thorpe *et al.* (1986) determined that most analyses from the Cobalt-Gowganda district cluster tightly near a normal lead growth, yielding an age identical within error limits to that of the Nipissing diabase. Some data, however, fall on a secondary isochron, suggesting remobilization at 1650-1945 Ma, a time not well correlated with any event in the area. The source of lead is permissibly the Nipissing diabase; however, Archean lead cannot have contributed to the lead in vein minerals.

Studies by Thorpe (1974) and Miller (1982) on galena and pitchblende, respectively, in the Great Bear Lake district led the latter to conclude that some of the data lie on a secondary isochron defined by mixing of lead from volcanogenic host rocks and diabase sills mostly post-dating the veins. A group of much more radiogenically enriched leads is also present. This general view was reinforced by Changkakoti *et al.* (1986a), who emphasized that the leads in the veins had a complex source and were modified by differing wall rock interactions during hydrothermal transport.

Strontium isotopic studies by Changkakoti *et al.* (1986a) of vein carbonates in the Great Bear Lake district do not support derivation from either the volcanogenic host rock or Proterozoic seawater. As well, simple mixing of two end member compositions cannot account for the data obtained. Changkakoti *et al.* concluded that strontium was derived from various sources of differing isotopic composition, which did not mix or equilibrate completely at the site of deposition.

Kerrich *et al.* (1986) reported $^{87}Sr/^{86}Sr$ ratios for vein minerals at Cobalt-Gowganda that are more radiogenic than those of the Huronian sediments, Archean basement or Nipissing diabase, although best agreement is with Huronian sediments. They felt, as in the case of lead data, that hydrothermal events accompanying intrusion of diabase had modified and largely homogenized both the strontium and lead systems, at least insofar as they are manifested in the five-element veins of the area.

## GENESIS

The genesis of five-element vein deposits continues to be a source of controversy and remains, in the minds of many, one of the enigmas of ore deposits geology. Table 1 summarizes the genetic theories that have been proposed either for specific deposits or districts, or for the deposit type in general. The major difficulty for all genetic theories is universal applicability of the mechanism proposed. If five-element veins are a coherent ore deposit type, then the same mechanism, subject to some degree of variation due to local geological factors, must be responsible for the origin of all deposits. The overriding problem is that a genetic mechanism that is plausible in one case may be highly implausible in another deposit or district. Moreover, in many deposits or districts, the veins have no obvious source, appearing as younger transgressive features cutting older terranes. The genetic theories in Table 1 are grouped as to overall mechanism (hydrothermal/magmatic, hydrothermal/metamorphic, syngenetic and non-magmatic) in the following discussion, with emphasis on the Canadian districts.

### Hydrothermal/Magmatic Model (Theories 1, 2 and 3, Table 1)

The generation of a hydrothermal fluid as a differentiate from a cooling granitic intrusion is historically the most widely accepted genetic theory for five-element veins (Stanton, 1972). It must be borne in mind that descriptions of many deposits date from the 19th and first half of the 20th centuries, when granites were believed to be the ultimate source of most ores. Since many five-element vein deposits occur in older crystalline terranes, it is not unexpected that many bear a spatial relationship to the granitic intrusions that are common in such terranes. Whereas earlier workers had often been content with the spatial relationship, the time relationship is also significant. In the case of the Great Bear Lake district, there is a gap of 360 m.y. between the age of the Great Bear batholith (1860 Ma) and the age of the ore veins (~1500 Ma; Changkakoti *et al.*, 1986a). The deposits of the Erzgebirge, with their close spatial association with Hercynian granites, have long been considered a result of magmatically derived hydrothermal deposition (*e.g.*, Keil, 1931); however, even modern adherents of the theory admit to a timing problem. Structural and other geological considerations indicate that the veins cannot be older than late Triassic or early Jurassic, whereas the youngest granites (275 Ma) indicate a time gap of the order of 130 m.y. (Tischendorf, 1986). Other evidence, cited earlier (Walther, 1986), suggests that the veins formed in the Tertiary.

The granitic source theory is completely incompatible with the geological evidence in both the Thunder Bay and Cobalt-Gowganda districts, where Proterozoic sedimentary host rocks unconformably overlie all known granitic intrusions. The problem is so obvious that adherents of the granitic source theory have considered the two districts to be anomalous (Bastin, 1939; Badham, 1976). Badham (1976) proposed that mixing of hydrothermal solutions derived from mafic and granitic magmas might have accounted for the unusual composition of the ore-bearing solutions, which he believed were associated with a convergent plate tectonic regime. However, as he admitted, both Thunder Bay and Cobalt-Gowganda were well removed from such activity in time and space, and even in Cornwall, where convergence of plates occurred (Badham, 1976), the Hercynian Cornubian granites are clearly older, and perhaps much older, than the five-element "cross-courses" (Darnley *et al.*, 1965).

A mafic source for hydrothermal solutions has been proposed by various workers at Cobalt-Gowganda and Thunder Bay, where diabase sills are closely spatially associated with deposits. Direct derivation from Nipissing diabase has been proposed by Scott (1972) and Jambor (1971) for the Cobalt-Gowganda district. Their arguments centre on questions as to whether a fracture in diabase could be mineralized prior to complete solidification of the sill and whether motion on mineralized faults cutting diabase occurred before or after mineralization. The

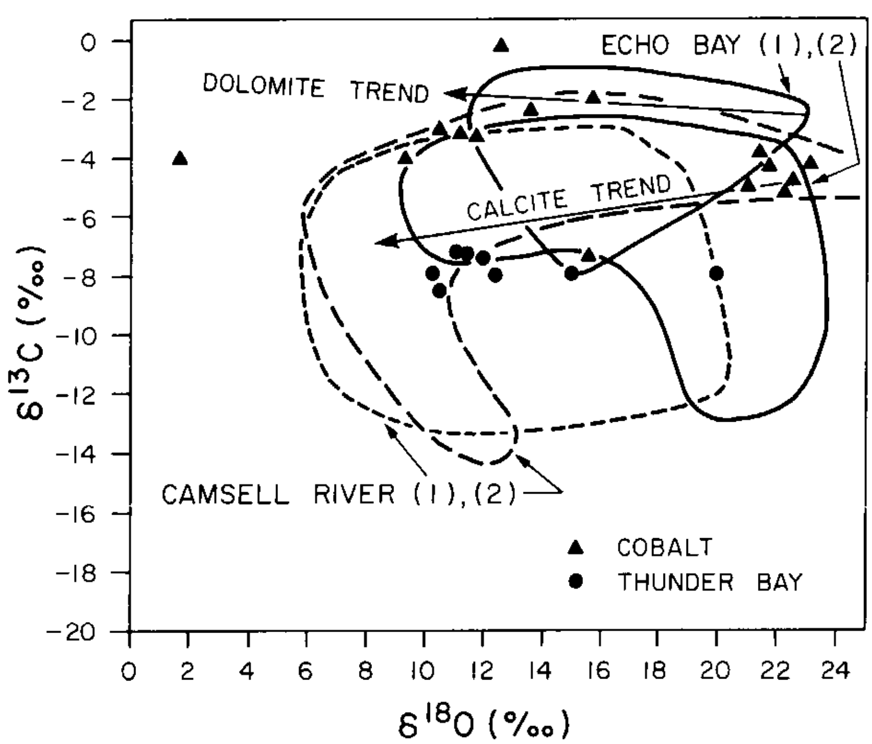



**Figure 7** *$\delta^{18}O$ versus $\delta^{13}C$ plot for carbonates. Fields for Echo Bay (1) and Camsell River (1) are from Badham* et al. *(1972); for Echo Bay (2) and Camsell River (2), from Changakoti* et al. *(1986b). Data for Cobalt and Thunder Bay are from Kerrich* et al. *(1986) and Kissin and Sherlock (1989), respectively. Arrows indicate the trends of decreasing $\delta^{18}O$ with increasing temperature in both calcite and dolomite in the Great Bear Lake district (Bradham et al., 1972).*

evidence and arguments are inconclusive, but a more serious problem for the application of a general theory is the absence of significant mafic bodies in other districts. Even at Thunder Bay, sills associated with ore veins are so thin and obviously anhydrous that *in situ* differentiation of a hydrothermal solution has not been proposed, but rather is hypothesized to have occurred at depth (Tanton, 1931). In other districts, *e.g.*, Great Bear Lake, diabase dykes are present, but are such minor features as to be highly improbable sources of major ore deposits (Badham *et al.*, 1972). Mafic intrusions are entirely absent in other deposits, *e.g.*, Black Hawk (Gillerman, 1964).

An additional problem with all variants of hydrothermal/magmatic theories is the preponderance of isotopic evidence, which strongly suggests that ore-depositing solutions are of non-magmatic origin. The hydrothermal/magmatic character of solutions at Great Bear Lake (Badham, 1975; Changkakoti *et al.*, 1986b) is disputed by others (Robinson and Ohmoto, 1973) and, as noted previously, some interpretations are ambiguous.

**Hydrothermal/Metamorphic Model (Theory 4, Table 1)**

Variations of this theory have been particularly popular at Cobalt-Gowganda, where the thermal and chemical effects of the Nipissing diabase sills affected many aspects of the geologic setting. Boyle and Dass (1971) proposed that sulphide-rich sedimentary interflow units and some volcanic rocks in the Archean basement were the source of metals in the veins. They hypothesized that the metals were mobilized by solutions heated by the intrusion of diabase. Goodz *et al.* (1986) presented evidence for a contribution from pre-existing massive sulphide concentrations in Archean basement. A similar theory was proposed for Thunder Bay by Franklin *et al.* (1986), who pointed to carbonaceous, metalliferous shales as a metal source.

This type of theory suffers, as do most others, from a lack of general applicability. The sort of contact metamorphic heating proposed is simply not viable as a theory in districts lacking intrusions of appropriate age. There are also some hydrodynamic problems with the theory, in that an intrusion hot enough to mobilize metal-scavenging solutions would cause solutions to migrate away from the heat source and to precipitate ores at the lower end of a thermal gradient. In fact, at Cobalt-Gowganda and Thunder Bay, ores are closely spatially associated with the proposed heat source (Petruk, 1971; Franklin *et al.*, 1986) and, occasionally, the diabase is mineralized in both districts.

Studies discussed previously indicate that ore deposition at Thunder Bay, Great Bear Lake and Kongsberg-Modum was cyclic and occurred during episodes of heating, separated by cooling and fracturing. Such a process is difficult to reconcile with a continuously cooling heat source, *i.e.*, a single-cycle heat engine. Thus, multiple intrusion is required, but has not been established in all cases. Moreover, Kissin and Sherlock (1989), in a study of drill core following a vein system well below the level of diabase intrusion and ore mineralization in the Thunder Bay district, found that fluid inclusion homogenization temperatures in all phases of mineralization increase with depth. A source of fluid at depth, *i.e.*, well removed from the proposed diabase heat source, seems highly likely.

**Syngenetic Model (Theory 5, Table 1)**

A syngenetic origin for deposits of the Sarrabus district of Sardinia was proposed by Schneider (1972). He suggested that these deposits, which previous observers had considered to be veins, were stratiform deposits formed syngenetically by some sort of exhalative process. His principal arguments were based on the largely stratabound nature of the deposits within lower Paleozoic black shales, quartzites and limestones. Whereas the association with a reducing environment (black shales) is probably more than fortuitous and is noted elsewhere, Schneider's (1972) overall theory is fundamentally at variance with observations of many other workers, and would require considerable elaboration to be plausible even at Sarrabus. It fails completely in accounting for the obvious epigenetic aspect of the veins universally noted elsewhere.

**Non-Magmatic Model (Theories 6 and 7, Table 1)**

Halls and Stumpfl (1972) proposed (in abstract only) that five-element solutions originated at depth, near the crust-mantle boundary. The variable occurrence of uraninite in this type of deposit was explained by passage of the solution through uraniferous granitic rock. The theory was never elaborated in full, but it has features in common with a theory relating the deposit to the environment of continental rifting.

The association of five-element type deposits with rifting has been noted by Kutina (1972), Norman (1978), Mitchell and Garson (1981) and Andrews (1986), and a more detailed, general genetic theory incorporating this association was proposed by Kissin (1988). The mechanism is the creation of a zone of anomalously high crustal heat flow along the axis of a continental rift or over broader areas involved in basin and range type tectonics. Such heat flow is capable of generating temperatures as high as 400°C at depths of 10 km. These temperatures would be capable of mobilizing formational brines and other connate waters and causing them to migrate to extensional faults peripheral to the rift axis. High salinity and high temperature in a sulphur-poor solution would be con-

**Table 1 Genetic theories for five-element veins (modified after Halls and Stumpfl, 1972).**

| Theory | Locality | Source |
|---|---|---|
| 1. By direct hydrothermal evolution from granitic intrusions | Great Bear Lake | Badham (1975) |
| 2. By direct hydrothermal evolution from mafic intrusions: | | |
| a) *in situ* | Cobalt–Gowganda | Jambor (1971) |
| b) at depth | Thunder Bay | Tanton (1931) |
| 3. Mixing of hydrothermal solutions of mafic and granitic affinities | general | Badham(1976) |
| 4. By hydrothermal/metamorphic processes concentrating components from: | | |
| a) organic-rich black shales | Cobalt–Gowganda | Kerrich *et al.* (1986) |
| b) pre-existing massive sulphides | Cobalt–Gowganda | Goodz *et al.* (1986) |
| c) metal-rich volcanoclastic rocks | Cobalt–Gowganda; Thunder Bay | Boyle and Dass (1971) |
| 5. By syngenetic processes | Sarrabus | Schneider (1972) |
| 6. By introduction along deep fractures of a juvenile five-element solution in a basalt-generating environment near the crust-mantle boundary | general | Halls and Stumpfl (1972) |
| 7. Circulation of connate brines in an environment of continental rifting | general | Kissin (1988) |

ducive to the mobilization of Ni, Co, and Ag in a solution buffered for oxygen in the vicinity of the magnetite-hematite equilibrium, as commonly found in crustal rocks. No special source rock is required, as the components of the solution would be scavenged from large volumes of various rock types. Rather, the properties of the solution explain its metal content.

Deposition occurs where the solution encounters a reductant (carbonaceous shale, pre-existing sulphides), and possibly structural, trap (sills, dykes), where boiling may augment deposition. Late mixing of meteoric water, accompanied by increasing reduction, completes a cycle from arsenide to sulphide deposit. The details of the process are discussed more fully by Kissin (in press).

The relation to rifting is strong in some districts (*e.g.*, Thunder Bay, Kongsberg–Modum), but not at all obvious in others (*e.g.*, Great Bear Lake). The association of diabase dykes and conjugate normal faults, occupied by five-element type veins in some cases (Robinson and Morton, 1972), however, is strongly suggestive of an extensional tectonic regime in the Great Bear Lake region, which has perhaps not been as fully investigated as the earlier geologic history of the Slave Province.

## SUMMARY

Five-element veins are open-space fillings, which characteristically occur as features developed late in the tectonic history of older crystalline or sedimentary-volcanic terranes. Their major characteristics include: 1) occurrence in areas of continental crust, where a spatial and temporal relation to rifting or other extensional tectonics is often prominent; 2) development from the early Proterozoic to the Tertiary (no older deposits are known); 3) association of mild propylitic alteration with sequential deposition of distinct vein assemblages (early barren, uraninite-quartz, Ni-Co arsenide-native silver, sulphide-carbonate), although some stages may be absent (particularly uraninite-quartz) and repeated cycles of deposition are frequently reported; 4) deposition at initially high (up to 450°C) temperatures from highly saline solutions, which decreased in temperature and became more reducing through the depositional sequence; 5) isotopic characteristics generally suggestive of a non-magmatic origin and derivation of components from diverse sources; and 6) frequent association of ore lodes with structural traps (capping diabase sills), reductants (black shales, pre-existing sulphide accumulations, sulphide-rich volcanic rocks), and evidence of intermittent boiling at shallow depths.

Review of pertinent data reveals a somewhat cloudy picture, in which data and observations are frequently contradictory. Selection of the correct genetic model may be further hampered by the inaccessibility of important deposits, which are long out of production, and the closure in the previous decade of the last operating mines. Nevertheless, the weight of evidence seems to suggest that the non-magmatic model, in which the driving mechanism is continental rifting, and the solution is mobilized formational water, provides the best explanation for a widely scattered group of deposits. Deposits not appearing to conform to this model may have formed by a different mechanism that produced the same result, or they may require further investigation with newer genetic concepts in mind.

## ACKNOWLEDGMENTS

Interest in this topic is an outgrowth of 16 years of residence near the five-element deposits of Thunder Bay. Many students have contributed to my knowledge and understanding of these deposits locally, and I have benefited from many discussions with colleagues from elsewhere. M.C. Smyk is thanked for providing photomicrographs of the Thunder Bay ores. The manuscript was typed by W.K. Bourke, and the figures were drafted by S.T. Spivak. The constructive reviews of D.I. Norman and S.D. Scott are gratefully acknowledged.

## REFERENCES

Andrews, A.J., 1986, Silver vein deposits: summary of recent research: Canadian Journal of Earth Sciences, v. 23, p. 1460-1462.

Andrews, A.J., Owsiacki, L., Kerrich, R. and Strong, D.F., 1986, The silver deposits at Cobalt and Gowganda, Ontario. I: Geology, petrography, and whole-rock geochemistry: Canadian Journal of Earth Sciences, v. 23, p. 1480-1506.

Appleyard, E.C., 1980, A preliminary metasomatic assessment of laminated siltstones at the Silverfields Mine, Cobalt, Ontario; Grant 70, *in* Pye, E.G., ed., Geoscience Research Grant Program, Summary of Research 1979-1980: Ontario Geological Survey, Miscellaneous Paper 93, p. 1-10.

Badham, J.P.N., 1975, Mineralogy, paragenesis and origin of the Ag-Ni, Co arsenide mineralization, Camsell River, N.W.T., Canada: Mineralium Deposita, v. 10, p. 153-175.

Badham, J.P.N., 1976, Orogenesis and metallogenesis with reference to the silver-nickel, cobalt arsenide ore association, *in* Strong, D.F., ed., Metallogeny and Plate Tectonics: Geological Association of Canada, Special Paper 14, p. 559-571.

Badham, J.P.N., 1978, Magnetite-apatite-uranium and silver-arsenide mineralizations in Lower Proterozoic igneous rocks, East Arm, Great Slave Lake, Canada: Economic Geology, v. 73, p. 1474-1491.

Badham, J.P.N., Robinson, B.W. and Morton, R.D., 1972, Geology and genesis of the Great Bear silver deposits: Proceedings, 24th International Geological Congress, Montreal, Sec. 4, p. 541-547.

Bastin, E.S., 1939, The nickel-cobalt-native silver ore-type: Economic Geology, v. 34, p. 1-40.

Boyle, R.W. and Dass, A.S., 1971, The origin of the native silver veins at Cobalt, Ontario, *in* Berry, L.J., ed., The Silver-Arsenide Deposits of the Cobalt-Gowganda Region, Ontario: The Canadian Mineralogist, v. 11, pt. 1, p. 414-417.

Bugge, J.A.W., 1978, Norway, *in* Bowie, S.H.U., Kvalheim, A. and Haslam, H.W., eds., Mineral Deposits of Europe, v. 1: Northwest Europe: The Institution of Mining and Metallurgy and the Mineralogical Society, London, p. 199-249.

Changkakoti, A., Ghosh, D.K., Krstic, D., Gray, J. and Morton, R.D., 1986a, Pb and Sr isotope compositions of hydrothermal minerals from the Great Bear Lake silver deposits, N.W.T., Canada: Economic Geology, v. 81, p. 739-743.

Changkakoti, A., Morton, R.D., Gray, J. and Yonge, C.J., 1986b, Oxygen, hydrogen, and carbon isotopic studies of the Great Bear Lake silver deposits, Northwest Territories: Canadian Journal of Earth Sciences, v. 23, p. 1463-1469.

Changkakoti, A., Morton, R.D. and Gray, J., 1986c, Hydrothermal environments during the genesis of silver deposits in the Northwest Territories of Canada: evidence from fluid inclusions: Mineralium Deposita, v. 21, p. 63-69.

Clayton, R.N. and Epstein, S., 1958, The relationship between $^{18}O/^{16}O$ ratios in coexisting quartz, carbonate and iron oxides from various geological deposits: Journal of Geology, v. 66, p. 352-373.

Darnley, A.G., English, T.H., Sprake, O., Preece, E.R. and Avery, D., 1965, Ages of uraninite and coffinite from south-west England: Mineralogical Magazine, v. 34, p. 159-176.

Dunham, K., Beer, K.E., Ellis, R.A., Gallagher, M.J., Nutt, M.J.C. and Webb, B.C., 1978, United Kingdom, *in* Bowie, S.H.U., Kvalheim, A. and Haslam, H.W., eds., Mineral Deposits of Europe, v. 1: Northwest Europe: The Institution of Mining and Metallurgy and the Mineralogical Society, London, p. 263-317.

Franklin, J.M., Kissin, S.A., Smyk, M.C. and Scott, S.D., 1986, Silver deposits associated with the Proterozoic rocks of the Thunder Bay District, Ontario: Canadian Journal of Earth Sciences, v. 23, p. 1576-1591.

Franklin, J.M. and Mitchell, R.H., 1977, Lead-zinc-barite veins of the Dorion area, Thunder Bay District, Ontario: Canadian Journal of Earth Sciences, v. 14, p. 1963-1979.

Gerwe, J.E. and Norman, D.I., 1984, Ag-Ni-Co-As-U mineralization in the Black Hawk mining district, New Mexico: Geological Society of America, Abstracts with Programs, v. 16, p. 517.

Gillerman, E., 1964, Mineral deposits of western Grant County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 83, 170 p.

Goodz, M.D., Watkinson, D.H., Smejkal, V. and Pertold, Z., 1986, Sulphur isotope geochemistry of silver-sulpharsenide vein mineralization, Cobalt, Ontario: Canadian Journal of Earth Sciences, v. 23, p. 1551-1567.

Halls, C. and Stumpfl, E.F., 1972, The five-element (Ag-Bi-Co-Ni-As) vein deposit — A critical appraisal of the geological environments in which it occurs and of the theories affecting its origin: Proceedings, 24th International Geological Congress, Montreal, Sec. 4, p. 540.

Holzer, H.F., 1986, Austria, *in* Dunning, F.W. and Evans, A.M., eds., Mineral Deposits of Europe, v. 3: Central Europe: The Institution of Mining and Metallurgy and the Mineralogical Society, London, p. 15-40.

Horwood, C.B., 1904, The red granite of Balmoral and its relation to the cobalt lodes: Geological Society of South Africa, Transactions, v. 7, p. 110-114.

Jaffé, F.C., 1986, Switzerland, *in* Dunning, F.W. and Evans, A.M., eds., Mineral Deposits of Europe, v. 3: Central Europe: The Institution of Mining and Metallurgy and the Mineralogical Society, London, p. 41-54.

Jambor, J.L., 1971, Origin of the silver veins, *in* Berry, L.J., ed., The Silver-Arsenide Deposits of the Cobalt–Gowganda Region, Ontario: The Canadian Mineralogist, v. 11, pt. 1, p. 402-413.

Johnsen, O., 1986, Famous mineral localities: the Kongsberg Silver Mines, Norway: The Mineralogical Record, p. 17, p. 19-36.

Keil, K., 1931, Beiträge zur Kenntniss der Kobalt-Nickel-Wismut-Silber-Erzgänge: Jahrbuch für Berg und Huttenweise, Sachsen, v. 105, p. 75-132.

Kerrich, R., Strong, D.F., Andrews, A.J. and Owsiacki, L., 1986, The silver deposits at Cobalt and Gowganda, Ontario. III: Hydrothermal regimes and source reservoirs — evidence from H, O, C, and Sr isotopes and fluid inclusions: Canadian Journal of Earth Sciences, v. 23, p. 1519-1550.

Kissin, S.A., 1988, Nickel-cobalt-native silver (five-element) veins: A rift-related ore type, *in* Kisvarsanyi, G. and Grant, S.K., eds., Proceedings Volume, North American Conference on Tectonic Control of Ore Deposits and the Vertical and Horizontal Extent of Ore Systems: University of Missouri-Rolla, Rolla, Mo., p. 268-279.

Kissin, S.A., 1989, Genesis of silver vein deposits on the north shore of Lake Superior, Thunder Bay District, Ontario: Geological Society of America, Abstracts with Programs, v. 21, p. A130.

Kissin, S.A., in press, The geochemistry of transport and deposition in the formation of five-element (Ag-Ni-Co-As-Bi) veins: Proceedings Volume, 8th IAGOD Symposium, Ottawa, E. Schweitzerbart'sche Verlagsbuchhandlung, Stuttgart.

Kissin, S.A. and Jennings, E.A., 1987, The genesis of silver vein deposits in the Thunder Bay area, northwestern Ontario, Grant 300, *in* Milne, V.G., ed., Geoscience Research Grant Program, Summary of Research 1986-1987: Ontario Geological Survey, Miscellaneous Paper 136, p. 230-241.

Kissin, S.A. and McCuaig, T.C., 1988, The genesis of silver vein deposits in the Thunder Bay area, northwestern Ontario, Grant 300, *in* Milne, V.G., ed., Geoscience Research Grant Program, Summary of Research 1987-1988: Ontario Geological Survey, Miscellaneous Paper 140, p. 146-156.

Kissin, S.A. and Sherlock, R.L., 1989, The genesis of silver vein deposits in the Thunder Bay area, northwestern Ontario, Grant 300, *in* Milne, V.G., ed., Geoscience Research Grant Program, Summary of Research 1986-1987: Ontario Geological Survey, Miscellaneous Paper 136, p. 230-241.

Kroutov, G.A., 1972, Le gisement des minerais As-Ni-Co au Khovou–Axy: Proceedings, 24th International Geological Congress, Montreal, Sec. 4, p. 527.

Kutina, J., 1972, Regularities in the distribution of hypogene mineralization along rift structures: Proceedings, 24th International Geological Congress, Montreal, Sec. 4, p. 65-73.

Lawrence, L.J., 1968, The mineralogy and genetic significance of a Consols-type vein in the Main Lode Horizon, Broken Hill, N.S.W.; Proceedings of the Australasian Institute of Mining and Metallurgy, No. 226, Pt. 1, p. 47-57.

Leblanc, M., 1986, Co-Ni arsenide deposits, with accessory gold, in ultramafic rocks from Morocco: Canadian Journal of Earth Sciences, v. 23, p. 1592-1602.

Lieber, W. and Leyerzapf, H., 1986, German silver, an historical perspective on silver mining in Germany: Mineralogical Record, v. 17, p. 3-18.

Miller, R.G., 1982, The geochronology of uranium deposits in the Great Bear batholith, Northwest Territories: Canadian Journal of Earth Sciences, v. 19, p. 1428-1448.

Mitchell, A.H.G. and Garson, M.S., 1981, Mineral Deposits and Global Tectonic Settings: Academic Press, London, 405 p.

Neumann, H., 1944, Silver deposits at Kongsberg: Norges Geologiske Undersøkelse, no. 162, 133 p.

Nold, J.L., 1988, The Idaho cobalt belt — A remobilized stratabound ore district, *in* Kisvarsanyi, G. and Grant, S.K., eds., Proceedings Volume, North American Conference on Tectonic Control of Ore Deposits and the Vertical and Horizontal Extent of Ore Systems: University of Missouri–Rolla, Rolla, Mo., p. 118-124.

Norman, D.I., 1978, Ore deposits related to the Keweenawan rift, *in* Neumann, E-R. and Ramberg, I.B., eds., Petrology and Geochemistry of Continental Rifts, v. 1: D. Riedel Publishing Company, Dordrecht, Holland, p. 245-253.

Ohmoto, H., 1986, Stable isotope geochemistry of ore deposits, *in* Valley, J.W., Taylor, H.P., Jr. and O'Neil, J.R., eds., Stable Isotopes in High Temperature Geological Processes, v. 16: Reviews in Mineralogy, Mineralogical Society of America, p. 491-559.

Paige, S., 1916, Description of the Silver City quadrangle: U.S. Geological Survey, Geological Atlas, Folio 199, 19 p.

Petruk, W., 1971, General characteristics of the deposits, *in* Berry, L.G., ed., The Silver-Arsenide Deposits of the Cobalt-Gowganda Region, Ontario: The Canadian Mineralogist, v. 11, pt. 1, p. 76-107.

Piepoli, M.P., 1933, Étude microscopique de quelques minerais des filons argentifères du Sarrabus: Société Française de Minéralogie, Bulletin, v. 56, p. 277-302.

Pouba, Z. and Ilavský, J., 1986, Czechoslovakia, *in* Dunning, F.W. and Evans, A.M., eds., Mineral Deposits of Europe. v. 3: Central Europe: The Institution of Mining and Metallurgy and the Mineralogical Society, London, p. 117-173.

Ramdohr, P., 1969, The Ore Minerals and their Intergrowths: Pergammon Press, Oxford, 1174 p.

Ricard, T.A., 1894, The mines of Chalanches, France: American Institute of Mining Engineers, Transactions, v. 24, p. 689-705.

Robinson, B.W. and Badham, J.P.N., 1974, Stable isotope geochemistry and the origin of the Great Bear Lake silver deposits, Northwest Territories, Canada: Canadian Journal of Earth Sciences, v. 11, p. 698-711.

Robinson, B.W. and Morton, R.D., 1972, The geology and geochronology of the Echo Bay area, N.W.T., Canada: Canadian Journal of Earth Sciences, v. 9, p. 158-172.

Robinson, B.W. and Ohmoto, H., 1973, Mineralogy, fluid inclusions and stable isotopes of the Echo Bay U-Ni-Ag-Cu deposits, Northwest Territories, Canada: Economic Geology, v. 68, p. 635-656.

Schneider, H.-J., 1972, Schichtgebundene, NE-Metall- und F-Ba-Lagerstätten im Sarrabus-Gerrei-Gebiet, SE-Sardinien. I. Bericht zur Lagerstättenkunde und Geologie: Neues Jahrbuch für Mineralogie Monatshefte, 1972, p. 529-541.

Scott, S.D., 1972, The Ag-Co-Ni-As ores of the Siscoe Metals of Ontario mine, Gowganda, Ontario, Canada: Proceedings, 24th International Geological Congress, Montreal, Sec. 4, p. 528-538.

Scott, S.D. and O'Connor, T.P., 1971, Fluid inclusions in vein quartz, Silverfields Mine, Cobalt, Ontario, *in* Berry, L.G., ed., The Silver-Arsenide Deposits of the Cobalt-Gowganda Region, Ontario: The Canadian Mineralogist, v. 11, pt. 1, p. 263-271.

Segalstad, T.V., Johansen, H. and Ohmoto, H., 1986, Geochemistry of hydrothermal processes at the Kongsberg silver deposit, southern Norway: Terra Cognita, v. 6, p. 511.

Shegelski, R.J. and Scott, S.D., 1975, Geology and mineralogy of the silver-uranium-arsenide veins of the Camsell River district Great Bear Lake, N.W.T.: Geological Society of America, Abstracts with Programs, v. 7, p. 857-858.

Smyk, M.C., 1984, A comparative study of silver occurrences, Island Belt silver region, Thunder Bay, District, Ontario: B.Sc. thesis, Lakehead University, 132 p.

Smyk, M.C. and Watkinson, D.H., 1990, Sulphide remobilization in Archean volcano-sedimentary rocks and its significance in Proterozoic silver vein genesis, Cobalt, Ontario: Canadian Journal of Earth Sciences, v. 27, p. 1170-1181.

Stanton, R.L., 1972, Ore Petrology: McGraw-Hill, New York, 713 p.

Stanton, R.L. and Russell, R.D., 1959, Anomalous leads and the emplacement of leads and the emplacement of lead sulfide ores: Economic Geology, v. 54, p. 588-607.

Tanton, T.L., 1931, Fort William and Port Arthur and Thunder Cape map areas, Thunder Bay District, Ontario: Geological Survey of Canada, Memoir 167, 222 p.

Thorpe, R.I., 1974, Lead isotope evidence on the genesis of the silver-arsenide vein deposits of the Cobalt and Great Bear Lake areas, Canada: Economic Geology, v. 69, p. 777-791.

Thorpe, R.I., Goodz, M.D., Jonasson, I.R. and Blenkinsop, J., 1986, Lead isotope study of mineralization in the Cobalt district, Ontario: Canadian Journal of Earth Sciences, v. 23, p. 1568-1575.

Tischendorf, G., 1986, Variscan ensialic magmatism and metallogenesis in the Ore Mountains — Modelling of the process: Chemie der Erde, v. 45, p. 75-104.

Voit, F.W., 1900, Geognostische Schilderung der Lagerstätten Verhaltnisse von Dobschau in Ungarn: Jahrbuch der Kaiserlich-Königlichen Geologischen Reichsanstalt, v. 50, p. 695-727.

Walther, H.W., 1986, Federal Republic of Germany, *in* Dunning, F.W. and Evans, A.M., eds., Mineral Deposits of Europe, v. 3: Central Europe: The Institution of Mining and Metallurgy and the Mineralogical Society, London, p. 175-301.

Wilkerson, G., 1983, The Batopilas mining district, Chihuahua, Mexico: Unpubl. Ph.D. thesis, University of Texas, El Paso, 642 p.

Wilkerson, G., Deng, Q., Llavon, R. and Goodell, P., 1988, Batopilas mining district, Chihuahua, Mexico: Economic Geology, v. 83, p. 1721-1736.

Ympa, P.J.M., 1972, The multistage emplacement of the Chalanches (France) Ni-Co-Bi-As-Sb-Ag deposits and the nature of the mineralizing solutions: Proceedings, 24th International Geological Congress, Montreal, Sec. 4, p. 525.

Zuffardi, P., 1989, Italy, *in* Dunning, F.W., Garrard, P., Haslam, H.W. and Ixer, R.A., eds., Mineral Deposits of Europe, v. 4/5: Southwest and Eastern Europe, with Iceland: The Institution of Mining and Metallurgy and the Mineralogical Society, London, p. 221-277.

Accepted, as revised, 1 July 1992.

## ANNOUNCEMENT

A short course on "Nonlinear Dynamics, Chaos and Fractals with Applications to Geological Systems", sponsored by the Faculty of Continuing Education, University of Calgary, will be held on May 20 and 21, immediately following the GAC–MAC joint annual meeting in Edmonton. Lecturers for the short course will include Dr. G.V. Middleton (Department of Geology, McMaster University) and Dr. David Goodings (Physics Department, McMaster University). In addition, local geologists from Calgary will present applications to the oil sands industry, among other topics. Registration will include the GAC Short Course Notes Volume 9 and chaos computer program on a 5¼″ diskette, formatted by MS–DOS, and suitable for running in most IBM-compatible computers.

The course will be followed on Saturday, May 22, by the popular series "Science on a Saturday", which will feature "Chaos and Fractals Everywhere" — a one-day seminar for the general public dealing with chaos and fractals as applied to many different fields, including earth sciences, art and computer animation, medicine, business and economy, management, weather and global change, etc.

Both the "Nonlinear Dynamics, Chaos and Fractals, with Applications to Geological Systems" short course and the "Science on a Saturday — Chaos and Fractals Everywhere" will be held at the University of Calgary in Calgary.

For further information, contact:
Faculty of Continuing Education
Telephone (403) 220–5429, FAX 284–9242
*or*
Frances J. Hein
Department of Geology and Geophysics
Telephone (403) 949–3810 (home), FAX 284–0074