GEOLOGY OF BASE-METAL DEPOSITS

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Summary

In the geological and mining sense, the term “base metals” refers to the high-volume, low-value metallic elements and is commonly restricted to three elements: copper, lead, and zinc. Concentrations of base metals exceeding, by many orders of magnitude, the normal abundance of these elements in the earth’s crust are referred to as a mineral deposit or, if deemed to be economically viable, an orebody.

Base metals seldom occur in total isolation of the other two although the proportions vary from one deposit to another. Common associations are Cu, Cu–Zn, Cu–Pb–Zn, and Pb–Zn. Metals are normally combined with sulfur so that a base metal deposit is not only polyelemental, it is also polymineralic.

Geologists recognize many natural processes by which metallic elements in the earth’s crust are concentrated into mineral deposits, but most base metal deposits are the products of hydrothermal (i.e., literally “hot water”) processes. In hydrothermally formed mineral deposits, all the mineral components are precipitated from solution by changes in the physical-chemical conditions at the site of deposition.

Certain mineral commodities (e.g., base metals) commonly occur together in similar geological situations. This has led to the concept of a mineral deposit type, a collective term for mineral deposits that a) share a set of geological attributes, and b) contain a particular mineral commodity or combination of commodities such that a) and b) together distinguish them from other types of mineral deposits. This paper describes the main geological features of eight base-metal deposit types, listed here by the names and acronyms by which they are commonly referred to in the geological literature:

- volcanogenic massive sulfide (VMS)
- Mississippi Valley-type (MVT)
- sedimentary exhalative (sedex)
- sandstone–lead
- skarn and manto
- Ag–Pb–Zn veins in metasedimentary terranes
- porphyry copper
- sediment-hosted stratiform copper.

Each deposit-type description includes a definition, a summary of the geological environment in which it is found, the common morphology of the deposit type, its grade and tonnage characteristics, the more common minerals and their textures found in each deposit type, and concludes with a short discussion of current genetic concepts.

A brief discussion of major sources of base metals notes that vein deposits—especially those containing lead and zinc—are commonly coarse-grained and therefore were the preferred choice of miners in the last century. Copper was mainly derived from the oxidized upper portions of copper-sulfide deposits. The introduction of the selective flotation process permitted mineralogically much more complex and finer-grained ores to be processed, with the result that, in the past 90 years, copper has been derived largely from sedimentary copper, porphyry, and VMS deposit types. VMS, MVT, and sedex deposit types have been the source of the majority of the world’s lead and zinc. Within the near future, porphyry and sedimentary deposits are expected to dominate the resource scene for copper. The major source of zinc in the future will very likely be the many unexploited sedex deposits known in several parts of the world, although improved metallurgy will be required to extract this metal effectively from these characteristically fine-grained ores. The current trend toward recovery of lead is certain to increase with a resultant decline in primary-sourced lead (i.e., mined lead).

1. Introduction

The term “base metals” is not only poorly defined but its definition varies from one discipline to another. In electrochemistry, base metals are defined as any of the metals in the lower end of the electrochemical series. In metallurgy, base metal is the base on which other elements are plated. In the geological and mining sense, “base metals” is a nonspecific term referring to the high-volume, low-value metallic elements, and is commonly restricted to the three elements: copper, lead, and zinc; this is the usage that will be applied here.

Concentrations of base metals exceeding—by many orders of magnitude—the normal abundance of these elements in the earth's crust (Table 1) are referred to as a mineral deposit or, if deemed to be economically viable, an orebody.

	Oceanic crust		**Continental crust**	
	Range(ppm)	Av. (ppm)	Range (ppm)	Av. (ppm)
Cu	50–100	90	10–90	24
Pb	1–10	3	0.5–24	17
Zn	80–120	100	50–100	57

Table 1. Range and average abundances (ppm) of base metals in the earth's crust

For example, a Zn grade of 5.7% has 10^4 times the average abundance of zinc in the continental crust. One base metal rarely, if ever, occurs in total isolation from the other two, although the proportions vary from one geological deposit type to another. Common associations are Cu, Cu–Zn, Cu–Pb–Zn, and Pb–Zn. Metals are normally combined with sulfur in sulfide minerals, so that a base metal deposit is not only polyelemental, it is polymineralic as well. The more common base-metal sulfide minerals are:

- chalcopyrite (34.5% Cu)
- bornite (63.3% Cu)
- sphalerite (67% Zn)
- galena (86.6% Pb).

Thus, in a Cu–Zn deposit the copper may be contained in chalcopyrite and/or bornite, and the zinc in sphalerite. Other sulfide minerals usually found in association with these ore minerals are pyrite and/or pyrrhotite; common accessory oxide minerals are magnetite and hematite.

Geologists recognize many natural processes by which metallic elements in the earth's crust are scavenged and collected into concentrations we refer to as mineral deposits. One of the more commonly known of these processes is placer formation, in which heavy minerals, such as gold, diamonds, or platinum, are collected by fast-moving surficial waters and deposited in calm eddies, pools, or even the sea. Minerals formed at very high temperatures, such as pentlandite (a nickel mineral) and chromite (a chrome mineral), crystallize directly from a cooling magma by a process called magmatic differentiation. Although certain deposits containing copper—notably those that occur with nickel—are formed by magmatic processes, most other base-metal deposits are the products of hydrothermal (literally "hot water") processes. Although complex in detail, the hydrothermal process is simple in concept: heated water within the earth's crust leaches elements, including base metals, from the surrounding rocks, and because of its buoyancy the fluid rises into cooler portions of the crust. Mineral deposits are formed when metals are precipitated from the ore fluids by various processes, among which cooling, mixing with other fluids, and pH change are the most common. In some instances, the hydrothermal ore fluid breaks through to the earth's surface or the seafloor; in most cases, however, the cooling fluid deposits base-metal sulfides at various depths within the earth's crust. Subsequent erosional processes bring the deposits either to the present earth's surface (i.e., an outcrop) or sufficiently close to the surface that the deposit can be detected by current geophysical or geochemical exploration techniques.

Geologists have long recognized that certain mineral commodities (e.g., base metals) commonly occur together in similar geological situations. This has led to the concept of a mineral deposit type, empirically defined as:

> a collective term for mineral deposits that a) share a set of geological attributes, and b) contain a particular mineral commodity or combination of commodities such that a) and b) together distinguish them from other types of mineral deposits.

Thus, in the example cited above, "placer gold" is a mineral deposit type, and all placer-gold deposits share a set of common geological attributes. The concept of mineral deposit type—or its more common contractural equivalent "deposit type"—has proven to be particularly useful, notably in facilitating communication among earth scientists—geologists, mineralogists, metallurgists, mining engineers, and so on—by serving as a nomenclature shorthand to include a set of commonly accepted geological features characteristic of each deposit type. A corollary of the deposit-type concept is that rock assemblages that contain the attributes characteristic of a particular deposit type have the best potential to contain undiscovered deposits of that type. Thus, recognition of deposit types is an important component in modern mineral exploration.

2. Deposit Types and their Modes of Origin

The section below describes the main geological features of eight base-metal deposit types, listed here by the names and acronyms by which they are commonly referred to in the geological literature:

- volcanogenic massive sulfide (VMS)
- Mississippi Valley-type (MVT)
- sedimentary exhalative (sedex)
- sandstone–lead
- skarn and manto
- Ag–Pb–Zn veins in metasedimentary terranes
- porphyry copper
- sediment-hosted stratiform copper.

The relative abundance of the three base metal elements varies considerably within these eight deposit types. For example, VMS deposits of Precambrian age (i.e., greater than 550 million years) are normally bimetallic in Cu and Zn, whereas Phanerozoic VMS deposits (i.e., younger than 550 million years) are usually polymetallic (i.e., they contain various proportions of all three metals); Ag and Au are normal important byproducts of VMS deposits. Economically important skarn deposits may be Cu- or Pb–Zn-dominant; Ag is a common byproduct. MVT and sedex deposits are bimetallic in Pb and Zn with Zn generally predominating. Sandstone–lead deposits, as suggested by their name, are Pb-dominant. In porphyry copper and stratiform-copper deposits, copper—

virtually by definition—is the main economic base metal, although other elements occur as subsidiary byproducts.

It is important to recognize that—in bimetallic or polymetallic deposits—the base metals are not evenly or equally distributed within the deposit. In most mineral deposits, the ore elements are concentrated in zones in which one metallic element is enhanced relative to others in the deposit. Mining practices take advantage of this zoning by preferentially exploiting one part of a deposit relative to another if one base metal is economically more desirable than another.

2.1. Skarn Deposits

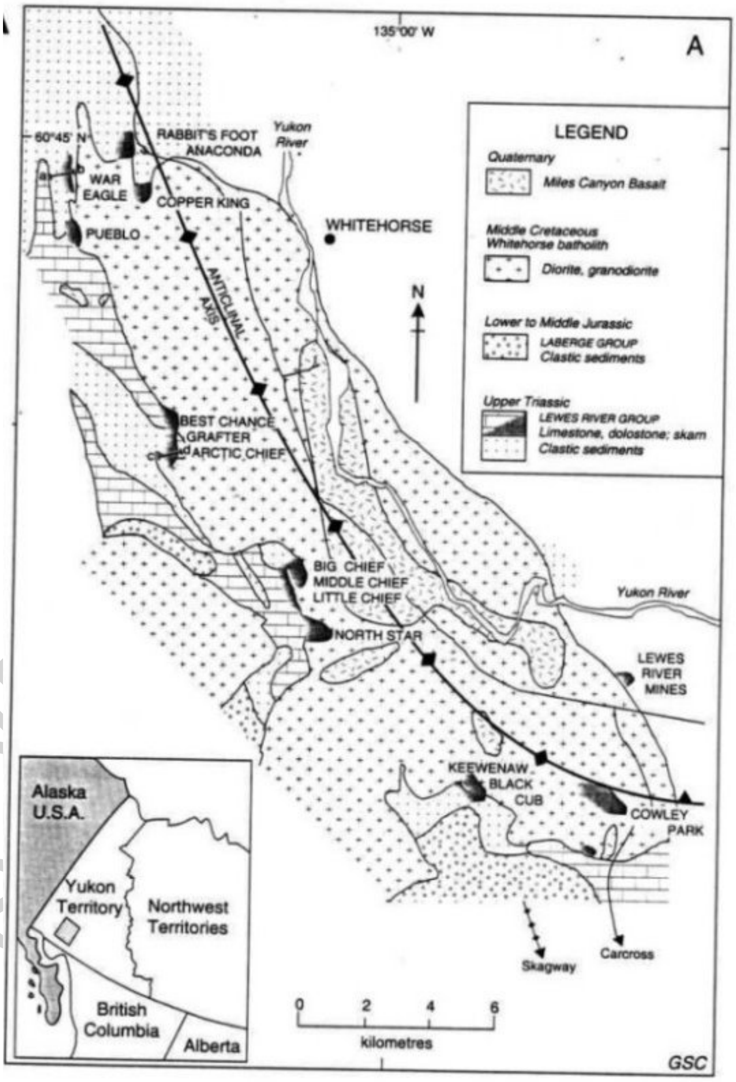

Figure 1. Distribution of small copper-skarn deposits peripheral to an igneous intrusion, Whitehorse Copper Belt, Canada. Source: from Dawson and Kirkham (1995); reproduced with the permission of the Minister of Public Works and Government Services Canada, 2001, and courtesy of the Geological Survey of Canada.

Definition: Skarn is an assemblage of dominantly calcium and magnesian silicates typically formed in carbonate rocks, such as limestone, dolostone, or marble, or carbonate-bearing rocks, such as impure shales or tuffs.

Geological setting: Base-metal skarn deposits are commonly found in areas of platform or continental-margin carbonate rocks that have been intruded by subduction-related felsic igneous rocks. A majority are of Mesozoic age or younger.

Morphology: Skarn deposits are characteristically very irregular in shape, distributed in sedimentary rocks peripheral to the genetically related igneous intrusion (Figure 1). Ores typically comprise massive replacement bodies in which little or none of the original host rock remains.

Grade tonnage characteristics: Zn + Pb skarn grades average about 10–15% (Figure 2) with byproduct silver ranging from 30 g t^{-1} to 300 g t^{-1}. In contrast, Cu skarns average about 1% Cu (Figure 1), with Ag and Au as important byproducts in some cases. Copper skarns normally occur close to the intrusive body, whereas Pb occupies a more distal position; zinc is found intermediate between the two.

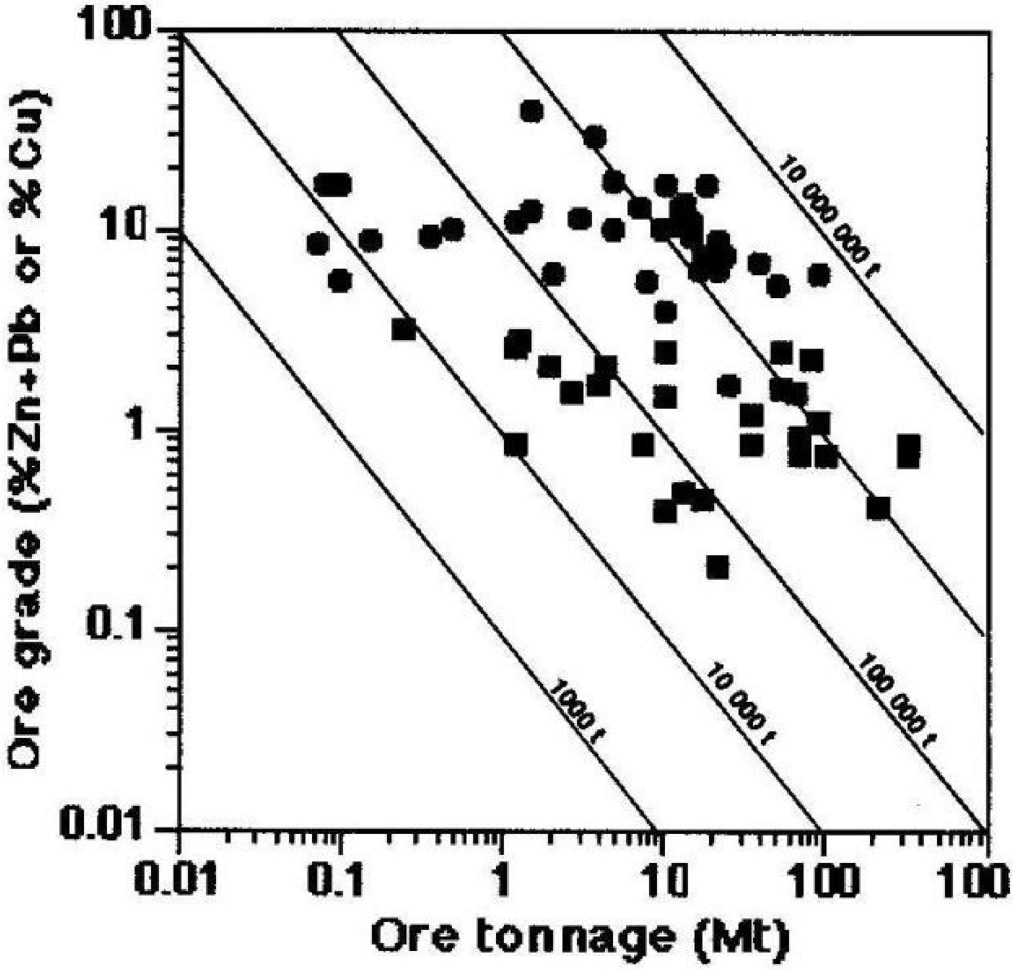

Figure 2. Typical grades and tonnages in skarns deposits. Notes: ◆ = Cu, ℓ = Zn + Pb. Diagonal lines show tonnes of contained metal.

Ore mineralogy and texture: Principal sulfide minerals in lead–zinc skarns are sphalerite, galena, and various Ag-bearing sulfosalts; major nonsulfide minerals are Mn-rich pyroxenes and garnet. Copper skarns are dominated by chalcopyrite, bornite, magnetite, and molybdenite; common silicate minerals include garnet and Mn-poor pyroxenes. Both ore and gangue minerals are generally coarse-grained, particularly where they occur in pure carbonate. Skarns in calcareous-silicate host rocks, such as shales or tuffs, tend to be finer grained.

Genesis: Precipitation of sulfides is brought about by reaction with, and replacement of, the carbonate rocks by hydrothermal fluids expelled during cooling of the adjacent or nearby igneous bodies. Skarn deposits are formed at high temperatures closest to the intrusion and comprise—in addition to the metal sulfides—very coarse-grained calcium silicate minerals formed by reaction of the ore fluids and carbonate host rocks. Lead–zinc manto deposits are similar to lead–zinc skarns in many respects but—as they formed somewhat further from the source intrusion—are somewhat cooler in their origin and lack the distinctive calcium-silicate assemblage of skarns.

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Bibliography

Beaudoin G. and Sangster D.F. (1992). A descriptive model for silver-lead-zinc veins in clastic metasedimentary terranes. *Economic Geology* **87**, 1005–1021. [A basic descriptive summary of the geological characteristics of this deposit type.]

Bjørlykke A. and Sangster D.F. (1981). An overview of sandstone–lead deposits and their relationship to red-bed copper and carbonate-hosted lead–zinc deposits. *Economic Geology*, 75th Anniversary Vol. (ed. B.J. Skinner), pp. 179–213. Lancaster, PA: Economic Geology Publishing. [A basic descriptive summary of the geological characteristics of this deposit type.]

Dawson K.M. (1995). Skarn zinc–lead–silver. *Geology of Canadian Mineral Deposit Types: Geology of Canada No. 8* (ed. O.R Eckstrand, W.D Sinclair, and R.I Thorpe), pp. 448–459. Geological Survey of Canada. [A basic descriptive summary of the geological characteristics of Canadian examples of this deposit type in Canada.]

Dawson K.M. and Kirkham R.V. (1995). Skarn copper. *Geology of Canadian Mineral Deposit Types: Geology of Canada No. 8* (ed. O.R Eckstrand, W.D Sinclair, and R.I Thorpe), pp. 460–476. Geological Survey of Canada. [A basic descriptive summary of the geological characteristics of this deposit type.]

Einaudi M.T., Meinert L.D., and Newberry R.J. (1981). Skarn deposits. *Economic Geology*, 75th Anniversary Vol. (ed. B.J. Skinner), pp. 317–391. Lancaster, PA: Economic Geology Publishing. [A basic descriptive summary of the geological characteristics of this deposit type.]

Franklin J.M. (1993). Volcanic-associated massive sulphide deposits. *Mineral Deposit Modeling: Special Paper 40* (ed. R.V Kirkham, W.D Sinclair, R.I Thorpe, and J.M Duke.), pp. 315–334. Geological

Association of Canada. [A basic descriptive summary of the geological characteristics of this deposit type.]

Franklin J.M. (1995). Volcanic-associated massive sulphide base metals. *Geology of Canadian Mineral Deposit Types: Geology of Canada No. 8* (ed. O.R Eckstrand, W.D Sinclair, and R.I. Thorpe), pp. 158–183. Geological Survey of Canada. [A basic descriptive summary of the geological characteristics of Canadian examples of this deposit type.]

Jackson J.A. (ed.) (1997). *Glossary of Geology, 4th Edition*. Alexandria, VA: American Geological Institute. [A standard reference glossary of geological and mining terms.]

Hobbs W. and Fryklund V.C. Jr. (1968). The Coeur d'Alene district, Idaho. *Ore Deposits in the United States*, *Vol. 2* (ed. J.D. Ridge), pp. 1417–1435. New York: American Institute of Mining, Metallurgical, and Petroleum Engineers. [A basic descriptive summary of the geological characteristics of a US example of this deposit type.]

Kirkham R.V. (1989). Distribution, settings, and genesis of sediment-hosted stratiform copper deposits. *Sediment-Hosted Stratiform Copper Deposits: Special Paper 36* (ed. R.W. Boyle, A.C. Brown, C.W. Jefferson, E.C. Jowett, and R.V. Kirkham), pp. 3–38. Geological Association of Canada. [A basic descriptive summary of the geological characteristics of this deposit type.]

Kirkham R.V. and Sinclair W.D. (1995). Porphyry copper, gold, molybdenum, tungsten, tin, silver. *Geology of Canadian Mineral Deposit Types: Geology of Canada No. 8*. (ed. O.R Eckstrand, W.D Sinclair, and R.I Thorpe), pp. 421–446. Geological Survey of Canada. [A descriptive summary of the geological characteristics of several types of porphyry deposits.]

Leach D.L. and Sangster D.F. (1993). Mississippi Valley-type lead-zinc deposits. *Mineral Deposit Modeling: Special Paper 40* (ed. R.V Kirkham, W.D Sinclair, R.I Thorpe, and J.M Duke), pp. 289–314. Geological Association of Canada. [A basic descriptive summary of the geological characteristics of this deposit type.]

Lydon J.W. (1995). Sedimentary exhalative sulphides (sedex). *Geology of Canadian Mineral Deposit Types: Geology of Canada No. 8* (ed. O.R Eckstrand, W.D Sinclair, and R.I Thorpe), pp. 130–152. Geological Survey of Canada. [A basic descriptive summary of the geological characteristics of this deposit type.]

Porter T.M. (1998). An overview of the world's porphyry and other hydrothermal copper and gold deposits and their distribution. *Porphyry and Hydrothermal Copper and Gold Deposits: A Global Perspective* (Australian Mineral Foundation Conference Proceedings, November 30 and December 1 1998) (ed. T.M. Porter), pp. 3–17. [Contains a general summary of the geological characteristics of porphyry copper deposits and tables of typical grades and tonnages of individual deposits.]

Sangster D.F. (1990). Mississippi Valley-type and sedex lead-zinc deposits; a comparative examination. *Institution of Mining and Metallurgy, Transactions, Section B: Applied Earth Science* **99**, 21–42.[Compares several selected geological features of the two largest lead-zinc deposit types.]

Titley S.R. (1993). Characteristics of porphyry copper occurrences in the American southwest. *Mineral Deposit Modeling: Special Paper 40* (ed. R.V. Kirkham, W.D Sinclair, R.I Thorpe, and J.M Duke.), pp. 433–464. Geological Association of Canada. [A basic descriptive summary of the geological characteristics of this deposit type in the United States.]

Biographical Sketch

D.F. Sangster retired from the Geological Survey of Canada (GSC) in 1995 after 30 years as an economic geologist specializing in the geology and genesis of lead-zinc deposits. He obtained his Ph.D. at the University of British Columbia, Canada, in 1964 and joined the GSC soon thereafter. In 1994/5 he served as President of the Society of Economic Geologists and, following retirement from the GSC, was appointed Emeritus Scientist with that organization for a further two and a half years. During his career, Dr. Sangster was awarded the Geological Association of Canada’s Duncan R. Derry Medal (1981), the Society of Economic Geologists’ Silver Medal (1984), the Mineralogical Association of Canada’s Past Presidents’ Medal (1986), and the Geological Association of Canada’s Logan Medal (1998).