April 7, 1997

**Epithermal deposits, Part 1**

by CHRISTINE NORCROSS

This is the first instalment in a new feature in The Northern Mine, which will consist of 2-part articles. In the first part, we will examine the geologic formation of a particular type of deposit. In the second part, which will run in the following week, the economic viability of such a deposit will be assessed.

An epithermal gold deposit is one in which the gold mineralization occurs within 1 to 2 km of surface and is deposited from hot fluids. The fluids are estimated to range in temperature from less than 100°C to about 300°C and, during the formation of a deposit, can appear at the surface as hot springs, similar to those found in Yellowstone National Park (in northwestern Wyoming, southern Montana and eastern Idaho). The deposits are most often formed in areas of active volcanism around the margins of continents.

Epithermal gold mineralization can be formed from two types of chemically distinct fluids -- "low sulphidation" (LS) fluids, which are reduced and have a near-neutral pH (the measure of the concentration of hydrogen ions) and "high sulphidation" (HS) fluids, which are more oxidized and acidic. LS fluids are a mixture of rainwater that has percolated into the subsurface and magmatic water (derived from a molten rock source deeper in the earth) that has risen toward the surface. Gold is carried in solution and, for LS waters, is deposited when the water approaches the surface and boils. HS fluids are mainly derived from a magmatic source and deposit gold near the surface when the solution cools or is diluted by mixing with rainwater. The gold in solution may come either directly from the magma source or it may be leached out of the host volcanic rocks as the fluids travel through them. In both LS and HS models, fluids travel toward the surface via fractures in the rock, and mineralization often occurs within these conduits. LS fluids usually form large cavity-filling veins, or a series of finer veins, called stockworks, that host the gold. The hotter, more acidic HS fluids penetrate farther into the host rock, creating mineralization that may include veins but which is mostly scattered throughout the rock. LS deposits can also contain economic quantities of silver, and minor amounts of lead, zinc and copper, whereas HS systems often produce economic quantities of copper and some silver. Other minerals associated with LS systems are quartz (including chalcedony), carbonate, pyrite, sphalerite and galena, whereas an HS system contains quartz, alunite, pyrite and copper sulphides such as enargite.
Geochemical exploration for these deposits can result in different chemical anomalies, depending on the type of mineralization involved. LS systems tend to be higher in zinc and lead, and lower in copper, with a high silver-to-gold ratio. HS systems can be higher in arsenic and copper with a lower silver-to-gold ratio. Many countries have epithermal gold deposits, including Japan, Indonesia, Chile and the western U.S., each of which occupies a portion of the "Rim of Fire," the area of volcanism that rings the Pacific Ocean from Southeast Asia to western South America. Epithermal gold is also found in British Columbia at the Baker mine, in the Toodoggone district, and near the Taseko River.

April 14, 1997
**Epithermal deposits, Part 2**
by CHRISTINE NORCROSS

Epithermal gold deposits, which contribute significantly to the world's gold supply, are an important exploration target which must be evaluated carefully based on the amount of metal they might provide, and at what cost. The amount of gold in any type of deposit is calculated based on the ore's grade (the amount of gold per tonne of rock) and tonnage (total number of tonnes) available at that grade. The higher the grade of the material, the lower the tonnage required to make recovery economical.

A high-grade deposit could have gold values ranging from 10 to more than 150 grams per tonne, whereas a low-grade deposit grades in the range of 1 to 5 grams. Low-grade deposits may have up to, and possibly more than, 200 million tonnes of rock, whereas a high-grade deposit is frequently smaller. Assay results acquired through drilling are important indicators of a deposit's grade and tonnage. High grades over short distances can be as significant as low grades over longer distances, and both types of deposit can be mined profitably.

Drill results, however, offer only a limited view of a deposit and may be difficult to reproduce. For instance, a single drill hole may intersect a high-grade zone in an otherwise low-grade (high sulphidation-Type epithermal) deposit, giving the appearance of a higher grade than actually exists. Factors other than tonnage and grade come into play in calculating the economic significance of an epithermal deposit. For instance, the presence of other metals in the ore can increase the value of a deposit, and many epithermal deposits contain a significant silver and/or copper content. The price of gold (and other metals) is also an important condition in economic evaluation, as low prices may render small or low-grade deposits uneconomic.

Many epithermal deposits occur in remote regions of under-developed countries, and the construction of infrastructure, such as roads and mills, may be necessary before deposits can be mined. These expenses increase the cost of a mining operation and must be taken into consideration when calculating the economics of a deposit.

Mining and processing methods are also important in determining economics. Since epithermal deposits are often formed at depths of less than 2 km (closer if erosion of overlying material has resulted), many are amenable to relatively less expensive open-pit mining methods. Deeper deposits that can be exploited only through underground methods are more expensive. Finally, recovery methods for epithermal gold deposits can entail either conventional milling or cyanide leaching. The cost of both procedures can increase if gold is contained in minerals that are difficult to process, such as arsenopyrite.

July 28, 1997
**Quartz-Carbonate vein gold deposits, Part 1**
by DEREK WILTON

Quartz-Carbonate vein gold deposits (also known as mesothermal lode deposits) form along, and are localized to, major regional fault and fracture systems, but are actually located in secondary or tertiary structures. These vein deposits form from hydrothermal (hot aqueous) fluids, which were derived deep in the earth's crust at a medium geological temperature (250 to 400°C).

The fluids use the fault/fracture zones as permeable channels along which to flow from their region of origin until they reach a point wherein any of a number of factors -- chemical reactions with country rock and/or changes in the temperature and/or pressure -- causes the fluids to precipitate. The gold precipitates out of solution along with the quartz vein material. These regional fault systems develop during the waning stages of continental collision and hence can form at significantly later periods than the host rocks; as such, they are termed "epigenetic."

The actual host rocks of the quartz-Carbonate veins are affected by these fault/fracture origins and can range from mylonites to fault gouge. Mylonites indicate deformation under confining pressures sufficiently high that the rock recrystallizes to a fine grain size. This is plastic or ductile behavior, and indicates that the vein formed deep in the earth's crust. Alternatively, if the fault/fracture cuts a rock at a level close to the earth's surface, then it does not have the same confining pressure and hence will break into fault gouge.
Typical quartz-Carbonate vein gold deposits consist of quartz veins with gold, pyrite and/or arsenopyrite. The gold is usually pure gold and can be present in textures ranging from solitary grains to grains intimately intergrown with sulphide minerals. In some deposits, gold is present as "invisible" intergrowths with sulphide minerals such as arsenopyrite (that is, the gold is in the crystal lattice of the sulphide mineral). In other deposits, the gold is not pure but electrum -- a mineral made up of gold, with 20% to 80% silver.

Quartz-Carbonate vein gold systems are characterized by abundant, typically iron-rich, hydrothermal carbonate alteration assemblages which spread into the host rock from the vein. They represent pulses of fluid which flowed along the fracture/fault plane into the surrounding country rock with which they are not in chemical equilibrium, producing chemical reactions and the resultant alteration halo.

Alteration associated with gold mineralization also involves sulphidation (sulphide halos are a characteristic alteration phenomenon of most quartz-Carbonate vein gold deposits) and potassium metasomatism (potassium is usually enriched in the alteration halo around the veins). These halos overprint pre-existing alteration assemblages in the host rock. Any rock type can host these vein systems, but, at best, they are developed in mafic rocks such as basalts, greenstones, gabbros and turbiditic shaley sedimentary rocks; this is attributable to the chemical contrasts between host rock and ore fluids. The ore fluids are silica-rich with carbon dioxide and potassium; hence they react best with mafic rocks, which do not contain free silica but which have calcium-iron-Magnesium silicates that can react with carbon dioxide to form carbonate alteration minerals.

Alteration associated with gold mineralization also involves sulphidation (sulphide halos are a characteristic alteration phenomenon of most quartz-Carbonate vein gold deposits) and potassium metasomatism (potassium is usually enriched in the alteration halo around the veins). These halos overprint pre-existing alteration assemblages in the host rock. Any rock type can host these vein systems, but, at best, they are developed in mafic rocks such as basalts, greenstones, gabbros and turbiditic shaley sedimentary rocks; this is attributable to the chemical contrasts between host rock and ore fluids. The ore fluids are silica-rich with carbon dioxide and potassium; hence they react best with mafic rocks, which do not contain free silica but which have calcium-iron-Magnesium silicates that can react with carbon dioxide to form carbonate alteration minerals.

Gold abundances are characteristically low in most geological materials. The average crustal abundance of gold is on the order of 3 parts per billion, and generally no single rock type is preferentially enriched in gold. As a result of the low background contents of gold, a large amount of rock must be affected by the hydrothermal fluids in order for sufficient deposits of dissolved gold to be formed. The general model for these deposits suggests that the associated regional faults have deep roots that extend down to the lower crust. Hydrothermal fluids, which contain gold dissolved from a wide region, are formed, and these are focused up along the faults to higher levels in the crust, where they react with country rock to form lode gold ores.

The author is a geology professor at Memorial University in St. John's, Nfld.

---

August 4, 1997
Quartz-Carbonate vein gold deposits, Part 2
by DEREK WILTON

In temporal terms, quartz-Carbonate vein gold deposits apparently have been restricted to specific intervals in the Earth's history, including the Late Archean, Early Proterozoic, early Paleozoic and Early Mesozoic periods. They are best developed in Archean greenstone belts within Archean cratonic areas, such as in northern regions of Ontario and Quebec, Western Australia and southern Africa.

In Canada, the best-known Archean-related mines include the Giant in the Northwest Territories and, in Ontario, the Campbell, Red Lake, Dome, Hollinger and McIntyre, as well as the Kirkland Lake camp. Examples of Proterozoic-related gold-producing regions include Saskatchewan's Star Lake and La Ronge districts. Examples of Paleozoic-Aged formations include the Meguma deposits of Nova Scotia and the Baie Vert occurrences of Newfoundland. Mesozoic-related operations include those in the Bralorne and Caribou districts of British Columbia.

These quartz-Carbonate vein deposits are Canada's primary gold producers and are one of the most important producers worldwide. In general, a minable deposit of this type contains a grade of 6 to 10 grams gold per tonne within 2 to 10 million tonnes of ore.

The drilling and assaying of this sort of deposit can be complicated and fraught with difficulty. The veins themselves usually can be readily mapped through drilling, but determination of the true gold content can be difficult as a result of the so-Called "nugget effect," in which all the gold within an interval can be concentrated in a single point. The assaying of vein material that is small in quantity but which contains a nugget can yield an erroneously large grade for the system, whereas if a gold-rich nugget within the vein is missed, erroneously low grades can result. To test a deposit properly, sampling must be thorough and completed on a statistically rigorous basis.

Since these veins have rather limited areal extents, the most economically favorable are those with a larger alteration halo. Those halos can also be auriferous, with economically exploitable gold concentrations. Exploration for quartz-Carbonate vein deposits can generally be restricted to orogenic (mountain) or greenstone belts, and the large-scale planar fault-fracture structures therein. Mapping of fault systems and alteration is essential.

Because of its low concentrations in the natural environment, gold is often difficult to detect; hence routine procedures for geochemical exploration (lake sediment surveys, for example) are often too equivocal for tracing the metal in the geological environment. Some elements, particularly antimony and arsenic, are so closely associated with gold that they can be exploration targets in the search for gold since they are much easier to detect. Such elements are known as pathfinder elements.
The best geophysical exploration techniques to use in the search for these types of ore deposits are those that map out fault structures. Techniques employing electromagnetic and magnetic technology would be of little assistance, as the amount of metallic minerals in the veins is usually limited. These vein systems are planar objects with a much greater length and depth than width, and they are hosted in solid rock. As a result, they are not usually amenable to open-pit mining operations but, rather, are exploited via underground methods.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

October 6, 1997

Placer gold deposits, Pt. 1,
by DEREK WILTON

Placer gold deposits form as a result of the breakdown and weathering of existing gold concentrations, erosion of the weathered material and, ultimately, the concentration of that material at a variable distance from its source. The term "placer" derives from the Spanish word for sand bank or stream eddy. Placer deposits, in the strictest sense, are formed in river systems, but the term is typically used to describe deposits formed in glacial and beach environments.

Placer gold deposits are formed when gold is carried from its source to its site of deposition and concentration by a surface erosional force such as rivers, glaciers, oceans and (rarely) wind. The formation of gold placers is predicated by two fundamental physical properties of gold. To begin with, gold is dense, with a specific gravity of 19.3 grams per cubic cm -- among the highest for all known minerals or native elements. Also, gold is a native element rather than a mineral (the latter being a naturally occurring inorganic chemical compound), and does not readily react with other elements.

A corollary of this second point is that gold is difficult to dissolve out of rock or minerals. The original source of the gold is unimportant, ranging, as it does, from mesothermal lode deposits to massive sulphide deposits to disseminated sulphides in bedrock to pre-existing placer systems. Placer deposits depend on an original pre-concentration of gold which can be liberated through weathering. Eluvial, or residual, placers are a type of placer deposit in which gold has undergone little transport and actually formed on, or near, the original source through the weathering or erosion of host rock. Owing to its relative chemical inertness, gold remains behind while the surrounding material is removed, essentially concentrating the gold in the weathered remnants.

Gold in placer systems is transported as discreet grains as a result of the metal's inertness. Such grains are said to be detrital, as they are derived from the physical weathering and breakdown of their host rock or mineral, a process known as detrition. Because of the high density of gold grains relative to other rock and mineral material (detritus) carried in the same erosional system, the gold grains must be transported by erosional agents operating with relatively higher energy than that needed to transport normal rock detritus. When the energy exerted by the erosional agent decreases, the gold and other dense detritus will stop moving.

In the case of fluvial (or river) placer systems, detrital gold grains are concentrated in those areas where the current of the stream slows, such as on the slow sides of bends in the river, on the downstream sides of islands or near sand bars. Gold grains move when energy is exerted on them by the transporting medium. The grains will continue to move until the medium loses sufficient energy, whereupon the gold grains will settle out of the transporting medium. An example of a fluvial placer gold deposit is a mature stream in a valley floor into which numerous subsidiary streams flow. In glacial tills, gold is transported along with other detrital material until the glacier ceases to move, dropping the gold and detritus. The driving mechanism for the formation of placer deposits, therefore, is gravity.

Another innate feature of placer gold deposits is that the material that hosts the gold is unconsolidated sediment (particulate rock that is not cemented together). The host sediment can range from gravels to sand in fluvial systems, as well as to various types of till in glacial deposits or beach sands.

A "pay streak" is the layer of sediment in a placer deposit which is enriched in particulate gold. In fluvial examples, the pay streak frequently occurs in sediments that lie directly on top of bedrock. The pay streak will also contain other dense, hard or inert minerals, such as magnetite, zircon, garnet or chromite.

There is some debate as to whether nuggets in fluvial systems represent purely detrital fragments that were rounded in transport or are the nuclei upon which dissolved gold in the stream precipitated and grew. In some instances, gold grains have greater fineness (ratio of gold to silver) towards the rim, suggesting either preferential removal of silver or precipitation of new gold.

-- The author is a geology professor at Memorial University in St. John's, Nfld.

[Back to Index]
Placer gold deposits, Pt. 2
by Derek Wilton

Although placer gold deposits have yielded less than 10% of Canada's gold production, their discovery played an important role in attracting settlers to remote areas of the country. For example, the Cariboo gold rush of the 1860s led many people to the interior of British Columbia, and the Klondike gold rush of 1897-98 did the same for the Yukon. Placer gold deposits were attractive to those early settlers because of their simplicity -- they occur when ore from a bedrock source is milled and concentrated, by natural forces, in the pay streak. Because of the unconsolidated nature of the host sediment, placer gold can be separated easily through simple techniques.

Gold, including nuggets, was first recovered from placer sources thousands of years ago by sifting through sand or gravel horizons. More sophisticated techniques, based on gravity separation and gold's higher density, were developed later.

In Greek mythology, the Golden Fleece sought by Jason and the Argonauts was actually a form of ancient sluice for the separation of detrital gold grains from river gravels; gold-bearing river gravels were flooded over sheep skins, and gold grains were entrapped in the wool.

Placer gold deposits, because of their variable grades and tonnages, are difficult to develop into large commercial operations. Conversely, the ease with which gold can be collected from the sediment makes placer deposits unusual in that individual prospectors with pans can still recover economic concentrations. Gold placers are mined in Siberia, Australia, Colombia and other areas around the world. Placer production in Canada and the U.S., however, has been curtailed somewhat as a result of stricter environmental regulations.

The most typical means of placer production is mining the sediment containing the pay streak and using gravity processing to collect the gold. The sorting usually involves flushing sediment over a separator table (mechanical trap), which collects the gold. These techniques use a considerable amount of water. The mining of placer deposits occurs mainly on surface, but, in the case of deep pay streaks, shafts are sunk through sediment accumulations. With respect to fluvial systems, mining essentially digs up the stream bed. Gold grains can form a plastic mixture, called amalgam, with mercury, which is in liquid form at room temperature. At some deposits, pay streak material can be passed through mercury baths, which removes gold particles. The amalgam is then collected and the mercury driven off, leaving the gold behind. Cyanide solutions can also be percolated through placer gravels to collect gold.

Aside from primary production of gold, placers can also point the way to bedrock gold sources, which is what happened in the California gold rush of 1849. By following fluvial placers back to their source, prospectors were able to locate richer bedrock mesothermal gold deposits. This practice has become more important in light of environmental concerns with respect to large-scale production from placer systems.

Because gold is a soft metal, the shape and size of gold found in placer deposits can vary. Detrital gold grains become more rounded the farther they travel from the source. For example, eluvial gold grains may take the form of wires reflecting the crystal or intergrowth shapes of the source gold. Abrasion and internal grinding are intrinsic to an erosional system, thus the gold grains will be worked into rounded, nodular shapes as they travel greater distances. The revelations surrounding the scandal at the Busang deposit of Bre-X Minerals in Indonesia illustrates this principle -- the gold added to core there had the rounded, nugget shape of placer gold, which was reportedly collected from a fluvial placer system. Gold grains from a bedrock source would have had the mineralogical or crystal shapes typical of intercrystalline formation.

In Ontario, Quebec and Newfoundland, geologists have been able to locate bedrock sources of gold by following patterns in the shape of till trains, coupled with determinations of the direction of ice flow in the till. -- The author is a professor of geology at Memorial University in St. John's, Nfld.

[Back to Index]
Paleoplacer uranium has been mined at Elliot Lake, Ont., and extracted from the gold deposits of the Witwatersrand district. There is a strong temporal control on paleoplacer uranium occurrences, as these occur only in rocks more than 2.5 billion years old. Gold-bearing paleoplacers are predominantly Archean-aged, but have been mined in rocks as young as 2.1 billion years. Gold in paleoplacer deposits is present as discrete grains. Uranium occurs as uraninite (UO2-U3O8). Like gold, uraninite is a dense mineral with a high specific gravity (6.5-10 grams per cubic centimeter) compared with common detrital minerals. Uraninite is unstable in oxygen-bearing surface waters, and its presence as detrital grains suggests that the earth's early atmosphere was oxygen poor. Some researchers, however, suggest that gold and uranium may be at least partly composed of hydrothermal fluid introduced along faults that bound depositional basins.

The host rock in paleoplacer deposits is quartz pebble conglomerate, a rock containing rounded grains of pure quartz up to 32 mm in diameter. The well-rounded nature and relatively equivalent size of the pebbles defines the host sediment as mature. As such, the particles have been subjected to prolonged agitation in an erosional environment. This type of sediment forms in a regime of intense weathering and corrosion, wherein quartz is the only common rock fragment to survive, owing to its hardness and resistivity to chemical weathering. Other minerals are locally concentrated with gold and uraninite. As is the case with a placer deposit, these minerals are dense, hard and/or resistant to chemical alteration. Such minerals include pyrite (in paleoplacer deposits fewer than 2.5 billion years old), platinum group metals, chromite, zircon and arsenopyrite. These minerals are intergranular to the quartz pebbles.

The host rock of a paleoplacer deposit can be composed of up to 3% pyrite. Such rocks are often referred to as pyritic quartz pebble conglomerates. Owing to the differences in their ages, the host rocks of Witwatersrand-Brazil and Ghana gold ores have subtle compositional differences. The oldest rocks, those found in Witwatersrand and Brazil, are pyritic. The younger rocks of Ghana are hematitic, further reflecting the presence of oxygen in the atmosphere. Uranium does not occur in these younger rocks.

Coal-like layers of organic matter (kerogen) are closely associated with some ore-bearing conglomerate horizons. Gold and uranium are locally concentrated in these organic layers, which are either the remnants of algal mats or the products of later hydrocarbon migration. According to some authors, this organic matter could represent paleo-angal mats. Should that analyses prove accurate, then the mats trapped gold and uranium in either of two ways: physically (from gold and uranium detritus) or chemically (from gold and uranium dissolved in stream waters).

Gold (and uranium) is concentrated in paleoplacer deposits much as it is in placer deposits, in paystreak-like concentrations. The paystreaks are thin sheets of quartz pebble conglomerate interlayered with thicker beds of sedimentary rocks.

In the Witwatersrand deposits, paystreaks can extend for up to 10 km, but are usually less than 3 metres thick. As such, these paystreaks resemble those found in river (fluvial) sediments of modern-day placer deposits. Overall, the host sedimentary rocks were deposited in high-energy fluvial conditions, such as in modern-day braided streams that flow from mountainous regions into alluvial plains. The Witwatersrand rocks are fan delta-like sedimentary horizons deposited at the base of hills from which erosion took place.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.
These deposits form through a subtle interplay between tectonic forces and paleoenvironmental conditions. The sedimentary host rocks form on erosional surfaces that have developed on old rocks. Paleoplacers form in a high-energy fluvial (river) system. Dense detrital gold and uranium grains are deposited when the river flow is no longer fast enough to keep them in motion. Exploration efforts for paleplacer deposits are usually concentrated on areas that exhibit these geographical properties.

Unlike epithermal or mesothermal lode gold occurrences, paleoplacer deposits are not associated with broad alteration halos (a chemical and mineralogical change in rocks surrounding certain types of gold deposits), which can be used to map potential deposits.

Although geophysical surveys are of little use in the exploration for paleoplacer gold deposits, radiometric surveys can be useful in the search for paleoplacer uranium deposits. These surveys, which employ radioactivity, map the distribution of uraninite, the mineral from which uranium is extracted.

February 9, 1998

**Carlin-type gold deposits, Part 1**

by Derek Wilton

Sediment-hosted disseminated gold deposits consist of fine-grained gold in silty carbonaceous sedimentary rocks. These deposits occur in the Great Basin of the southwestern U.S. Regions in which this sort of deposit occurs include the Carlin trend, a 60-km-long belt hosting numerous deposits, and the Getchell trend, which extends for 50 km. The Great Basin is a physiographic province on which rests most of Nevada, portions of Utah, Idaho and Oregon, and a small portion of eastern California. These types of deposits are also known as "Carlin-type" deposits, and occur chiefly in northern Nevada. Production from those formations began in the early 1960s.

The host rocks are predominantly thinly bedded, silty carbonaceous rocks (dolomites and limestones) or shales, though host material at some deposits includes lesser amounts of siliceous rock (silica), intrusive igneous rocks and siliceous breccias.

The gold occurs in arsenic-bearing pyrite and quartz. Gold grains are micron (0.001 mm) to submicron in size. At the Carlin deposit, coarse gold grains measuring up to 0.5 mm in dimension were found in early exploration. Typically, less than 1% fine-grained sulphides are present in the ore zones. These sulphides are generally pyrite, though orpiment (As2S3) and realgar (As4S4) may also be present. No other base metal sulphide minerals exist in these sorts of deposits and, other than arsenic (As), elevated concentrations of antimony, mercury, barium and thallium exist. The gold-bearing host rocks are typically strongly altered, with the main types of alteration being decarbonitazation, silicification and argillization. Decarbonitization is frequently best-developed on a deposit's furthest boundary, and represents the extraction of carbonate material from the host rock. Silicification is next-closest to the ore, and represents the replacement of the host rock by silica. In places, up to 95% of the rock can be replaced by silica. Such silica-rich rocks are called jasperoid. Argillization involves development of hydrothermal clay minerals such as montmorillinite and kaolinite, as well as the sericitization of feldspars. The alteration zonation is not always fully developed, and gold can be present in silicified zones and decarbonitized rocks.

The deposits are closely associated with steep (high-angle) normal faults and permeable horizons (the porous medium through which fluids can flow) in the package of sedimentary host rocks. The deposits formed when hydrothermal fluids flowed along faults until they encountered breccia zones and/or permeable horizons. The fluids then reacted with country rock, producing the alteration and depositing the gold. The process is essentially a selective replacement of carbonaceous rock by silica, pyrite and gold. Jasperoid zones can extend for up to 30 metres from a fault. These deposits have been described as a type of epithermal gold deposit (see "Geology 101," T.N.M., April 14/97) that formed through the circulation of hydrothermal fluids near the earth's surface. Sediment-hosted disseminated gold deposits are now recognized as a distinct group of deposits with greater formational depths (1.5 to 4 km) and higher formational temperatures (greater than 225C).

Current models suggest that these deposits formed from the circulation of meteoric, or atmospheric, water through basement rock. As a result, these deposits exhibit similarities to mesothermal gold deposits (see "Geology 101," T.N.M., July 28/97). Fluid movement and circulation were apparently related to large-scale tectonic processes during the deposition of gold in the Great Basin region through a combination of mixing, cooling and oxidation of fluids.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

[Back to Index]
February 16, 1998

Carlin-type gold deposits, Part 2

by Derek Wilson

Sediment-hosted gold deposits supply a significant amount of the world's gold. Although only the western United States produces gold from such deposits, these structures are also found in China and Peru.

Deposits in Nevada's Carlin trend have produced 750 tonnes of gold; known resources and reserves there are estimated at 2,400 to 3,100 tonnes of gold. Typical deposits contain 1.1 to 24 million tonnes of ore grading between 0.69 and 7.6 grams gold per tonne. Some sediment-hosted gold deposits have grades of up to 20 grams per tonne. At the Carlin trend, more than 93 tonnes of gold have been produced from 8.5 million tonnes of ore.

The deposits have low silver content, with a silver-to-gold ratio of less than 1. Recently discovered deeper deposits, namely the Hardie, contain up to 1.3 million tonnes grading 16 grams gold per tonne.

These gold deposits are exposed near surface, and are mined as open-pit operations. Such mines are generally low-grade and large-tonnage projects. The ore is crushed, piled and treated using heap-leach methods. Heap leaching is a process whereby cyanide-bearing solution is dripped through ore piles, dissolving fine-grained gold out of the rock. The gold-laden cyanide fluid is collected and subjected to further chemical treatment, which precipitates (and concentrates) gold.

Deeper deposits discovered recently along the Carlin trend appear to be hypogene (primary or unaltered concentrations) in nature. If that postulation is correct, then the main sedimentary-hosted gold deposits known today would represent oxidized replacements of hypogene ore. Hypogene deposits, or zones, have been defined at depths greater than 400 metres. Such deposits also contain higher grades (between 6 and 32 grams gold) and contain, in places, more than 10% sulphides. Hypogene deposits are amenable to standard underground mining techniques.

Although these sediment-hosted, disseminated deposits appear to be restricted to the Great Basin of the U.S., there is no reason, geologically speaking, why they couldn't occur elsewhere. Exploration may have to be directed toward the discovery of these deeper varieties, since the near-surface, oxidized sort may have been subjected to erosion. Exploration should focus on little-deformed carbonaceous sedimentary packages with prominent high-angle faulting and associated alteration (decarbonation, silicification and argillization). The identification of carbonaceous sedimentary rocks is important as these (and faults) provided permeable pathways for ore fluids, as well as chemical traps for gold precipitation.

Regional geochemical surveys for elevated concentrations of arsenic, antimony, barium, mercury and tellurium in carbonaceous rocks are also effective exploration techniques. Geophysical exploration methods would be ineffective, though some fault systems may exhibit a detectable magnetic signature during induced-polarization and resistivity surveys. Exploration for deeper hypogene ore has been conducted on the Carlin trend, particularly near known deposits, through deep drilling.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

April 27, 1998

Banded iron formation-hosted gold deposits, Part I by Derek Wilton

Banded iron formation-hosted gold deposits consist of gold intergrown with quartz and/or sulphide minerals in deformed and structurally complicated iron-rich sedimentary rocks. In general, most geologists would define these deposits as a variety of the mesothermal lode gold type.

These deposits mainly occur within Archean-aged (more than 2,600 Ma, or million years old) greenstone belts, though some are Early Proterozoic (ca. 2,100 Ma). Greenstone belts are linear volcanic and sedimentary centres that are engulfed and completely surrounded by granitic-gneissic basement rocks; these belts are typical of the shield areas of northern Ontario and Quebec and the Northwest Territories. The banded iron formation (BIF) host rocks are thinly layered (layers can be measured in centimetres) sedimentary rocks with alternating iron-rich and cherty (silicious) layers; the BIFs can have considerable lateral extents.

There are different types of BIFs, defined on the basis of the mineralogy of the iron-rich layers: if the iron-rich layer is dominantly magnetite-hematite, then the BIF is termed oxide facies (a sedimentary term meaning a distinctive group of characteristics that distinguish one sedimentary unit from another); if the layer is composed of pyrite and/or pyrrhotite (iron sulphides), then the BIF is called sulphide facies. There are also carbonate- and silicate-facies BIFs. All BIF's are classified as chemical sediments, which means that they formed through chemical precipitation from seawater on the sea floor. Other sedimentary textures in the BIFs suggest deposition in shallow water on submarine continental shelves.

Gold occurs as native (free) gold intergrown with pyrite and/or pyrrhotite; arsenopyrite and/or magnetite are also present in some deposits. Other accessory and trace minerals are similar to those found in mesothermal lode gold deposits, such as sphalerite, chalcopyrite, tetrahedrite, scheelite, and molybdenite. Mineralogy of the host-rock alteration is predicated upon the fact the rocks are iron-rich. In the case of oxide-facies BIF, primary hematite-
magnetite is replaced by pyrite-pyrrhotite with minor siderite (iron carbonate). Quartz, in the form of crosscutting veins, is also a common alteration mineral and, most typically, the gold is intergrown with sulphides in the quartz veins. Chlorite is a common alteration product of silicate minerals here.

Most generally, BIF-hosted gold deposits are thought to form by the reaction of auriferous and sulphur-bearing hydrothermal fluids with the iron oxide (or sulphide) in country rocks, causing precipitation of gold and sulphides. The gold is present in quartz veins or the immediate wallrock, wherein the precipitation reactions occur. As such, the deposits are said to be stratabound (i.e., the gold is contained within a single stratigraphic unit, but the mineralization can cut across the layering in the unit) because the specific chemical horizon responsible for gold precipitation is represented by a single sedimentary horizon. Access to the favorable chemical environments of the BIF for the hydrothermal fluids was provided by large-scale fault and shear systems in a manner similar to that visualized in mesothermal lode gold models.

There is debate as to the origin of a few BIF-hosted gold deposits. Some geologists suggest that gold actually precipitated with the original chemical sedimentary host rocks as sort of a submarine hot-spring that exhaled onto the sea floor. In this model, subsequent deformation of the gold-enriched BIF led to the local remobilization and secondary concentration of gold in highly deformed zones. In other words, the gold was originally precipitated at above-normal concentrations in the BIF but was concentrated up to ore grade with deformation of the BIF. In this case, the gold in the BIF would be classified as stratiform (truly bedded and related to the deposition of the host unit), based on its original pre-deformation form.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

May 4, 1998

**Banded Iron Formation-hosted gold deposits, Part 2**

by Derek Wilton

Banded iron formation-hosted gold deposits are important in terms of Canadian and U.S. gold production, as illustrated by mines such as the Lupin and Musselwhite in Canada and the Homestake in South Dakota.

In general, gold deposits in banded iron formations (BIFs) contain from 0.1 to 100 million tonnes of ore grading between 4 and 30 grams gold per tonne. The Homestake mine, a world-class example of this deposit type, has produced over 1,180 tonnes of gold from 118 million tonnes of ore since operations began in 1876; remaining reserves at the end of 1996 were over 21.5 million tonnes of ore grading 6.72 grams gold.

Lupin has over 9 million tonnes of ore grading 10 to 11 grams gold. The gold ore is mined in a similar manner to that of mesothermal lode gold deposits, with emphasis on veins or sulphide-rich portions of the BIFs.

Since the veins and BIFs are frequently narrow units, mining is typically an underground operation, but there is some production from open pits. The bulk ore is crushed, then fed through a processing and refining plant akin to those in use at archetypal mesothermal lode gold operations. As BIF-hosted gold deposits are restricted to greenstone belt terranes in Archean to Early Proterozoic shield areas, exploration would be directed towards regions such as the Superior and Slave provinces of the Canadian Shield. The main points in both variations to the genetic model for these deposits are that deformation either provided permeable pathways for the gold-bearing ore fluids along faults, or caused remobilization of pre-existing gold accumulations, essentially enriching and upgrading gold concentrations. Exploration would focus on highly deformed, structurally complicated portions of BIFs within greenstone belts, especially where regional fault-shear systems cut through.

The dominant structural style of the deformation manifested at most gold-bearing BIFs is folding; hence contorted fold zones in a BIF would also be a favorable exploration target. Though deformation is strongly developed in these deposits, metamorphic grade usually does not exceed greenschist facies.

Exploration should further zero in on portions of BIFs that are sulphide facies or on areas with sulphide alteration overprinting oxide facies BIF. Since BIFs account for less than 5% of the area of greenstone belts, exploration would first be directed towards locating these sedimentary rocks within the greenstone belt piles. Such exploration would be aided by airborne and ground geophysical surveys over the greenstone belts, since the greatly elevated metal contents of the host rocks make them very electrically conductive and thus discernable by electromagnetic surveys. Also, the rocks' magnetite (plus pyrrhotite) contents make them readily detectable by magnetic surveys. Induced polarization surveys would also be very advantageous in detailed exploration for, and mapping of, these conductive host rocks.

Regional geochemical surveys for iron formation and elevated concentrations of gold, iron, arsenic, bismuth and antimony could also prove effective in exploration.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.
Diamond deposits, Pt. 1 by Derek Wilton

Diamond, which is pure carbon, is the hardest substance known, yet diamonds can be broken relatively easily. Paradoxically, graphite, one of the softest minerals, is a polymorph of diamonds. The essential difference between the relative strengths of these two minerals lies in their crystal structures: in diamonds, carbon atoms are linked in an isometric form, whereas atoms in graphite form linked hexagonal sheets.

Diamond crystal structures are created when carbon is subjected to great pressures (between 45 and 55 kilobars) and high temperatures (1,050 C to 1,200 C). The zone of formation of diamonds, therefore, is below the Earth's crust, in the upper mantle. Rarely, microdiamonds can be found at meteorite impact sites, where shock-derived pressures and temperatures are sufficiently intense to transform carbon into diamonds. Diamonds can also be produced synthetically.

Diamond crystals can revert to graphite if subjected to changes in pressure and temperature over time. On the Earth's surface, diamonds are found in unusual intrusive ultramafic igneous rocks or in placer and paleoplacer concentrations. In these deposits, diamonds are not hosted by the upper mantle rocks, namely peridotite or eclogite, in which they primarily formed.

The ultramafic igneous rocks that contain diamonds at the Earth's surface are kimberlites or lamproites. Kimberlites are volatile-rich (containing H2O and CO2) potassic, ultrabasic rocks which have an unequigranular grain size, with macrocrysts (magmatic crystals and rock-crystal fragments measuring 0.5 to 15 mm across) and megacrysts (greater than 2 cm and up to 20 cm across) set in a fine-grained matrix. Lamproites are ultrapotassic, magnesium-rich rocks which, unlike kimberlites, contain no CO2.

The feature of kimberlites essential to their containing diamonds is their volatile content, as volatiles cause magmas to intrude explosively from the lower crust or upper mantle to the earth's surface. Diamonds are carried in kimberlites and lamproites as xenolithic crystals, or xenocrysts. While in transit from their melt sources, magmas pick up diamonds from their host rock and carry them upward. The magma essentially acts as a high-speed elevator, rapidly bringing the diamonds to the Earth's surface. Essentially, diamonds go through the pressure-temperature transition from the depth to surface so quickly that they can't revert to graphite. It is the great hardness of the diamonds that allows them to survive the explosive intrusion.

Kimberlite and lamproite systems have distinctive intrusive architectures. The uppermost part of an intrusive body in a Kimberlite is carrot-shaped, and has its roots in dykes and sills (hypabyssal or medium-depth intrusive rocks). Pipes, which are generally up to 2 to 3 km wide, originate at a root zone, rise through diatreme facies to the crater facies, where the Kimberlite actually breaches the Earth's surface. The walls of the diatreme dip at angles of 75 to 85 from the horizontal; the crater walls exhibit shallower dip. The crater is the widest part of the pipe, but it seldom exceeds 2 km in diameter or 250 ha in area.

In contrast, lamproites are not pipe shaped and consist of crater facies fewer than 500 metres in depth. Diamondiferous lamproite craters are up to 1.25 km in diameter with an area of about 125 ha.

Kimberlites and lamproites also contain xenocrysts of garnet and spinel. Diamonds are actually a very minor component of kimberlite and lamproite magmas, whereas other xenocrysts appear in greater abundance. Placer and paleoplacer (Geology 101, T.N.M., Jan 18-25/98) deposits, also known as alluvial deposits, form through the weathering and erosion of diamond-bearing kimberlites or lamproites. Diamonds form detrital placer grains due to their great hardness (they can withstand the erosional processes) and higher density compared with other detrital material. Diamondiferous kimberlites and lamproites are essentially secondary concentrations, whereas placer and paleoplacers deposits are tertiary.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

June 8, 1998

Diamond deposits, Pt. 2

by Derek Wilton

Diamonds fall into one of four categories. They are, in order of decreasing value: gem, near-gem, industrial and boart. Individual diamonds are measured in carats (1 carat equals 0.2 gram), whereas the grade of diamondiferous rock is expressed in carats per tonne (or carats per 100 tonnes).

World diamond production is in the order of 100 million carats per year. In 1997, the Argyle deposits of Western Australia (the world's largest producer) produced 40.2 million carats from ore grading 3.7 carats per tonne. Highly variable grades can make the value of ore in US dollars per carat quite unpredictable.

The major diamond producing nations are South Africa, Botswana, Australia, Russia and Zaire. In Canada, production from the BHP Diamonds-Dia Met Minerals operation at Lac de Gras, N.W.T., will begin later this year. The vast majority of diamond production is from kimberlites, with only the Argyle deposits providing substantial production from lamproite sources. About 3% of kimberlite pipes, which can occur in clusters of up to 50, contain diamonds, and only 1% of those occurrences are economically exploitable.
Exploration for diamonds, which occur as xenolithic crystals or fragments within kimberlites or lamproites (both of which are intrusive ultramafic igneous rock types), in heavily glaciated areas is difficult because kimberlites and lamproites are soft compared with other rock types, and are likely to be preferentially eroded as a result. The most useful exploration technique, therefore, is geochemical surveying of till and other alluvium. Positive identification of intrusive rocks from a series of samples collected during an exploration program requires detailed petrographic examination and evaluation of the constituent minerals.

Indicator minerals within kimberlite or lamproite need to be geochemically analyzed and classified to determine the intrusion's potential to contain diamonds. The precious stones are a relatively minor mineralogical constituent in those intrusives, though the indicator minerals are sufficiently abundant to be readily evaluated. Similarly, the composition of indicator minerals in soils, tills and stream sediments can be analyzed to determine if such detrital material was eroded from an area that contained diamondiferous rocks. Indicator minerals include chromite, garnet and ilmenite, each of which has a distinct geochemical signature in diamondiferous rocks.

Critical to the evaluation of diamond potential is the precise analysis of rocks or detrital material, and their indicator minerals, to define their petrological and geochemical compositions. Based on the composition of the sample analyzed, different preparation techniques are required. In order to evaluate a particular kimberlite or lamproite intrusive, bulk samples of more than 30 kg are usually collected. Indicator minerals and diamonds are separated from the sample, producing a heavy mineral concentrate (HMC) for analysis. Heavy minerals will be similarly separated from large bulk samples of detrital material for analysis. The evaluation of diamond prospects is time-consuming owing to the exacting concentration of the minor constituents from such large samples and the precision required to analyze the HMC. Kimberlite and lamproite intrusives often exhibit circular magnetic (mag) or electromagnetic (EM) geophysical anomalies that reflect the elevated mag or EM properties of the intrusives compared with the country rock, usually returning a bulb's-eye pattern. The problem with these surveys is that the craters or pipes cover such a small area that it may be difficult to distinguish the anomalies from regional gradients.

Kimberlite and lamproite craters and kimberlite diatremes are initially mined as open-pit operations because the host rocks are usually friable. Underground production is frequently initiated with increases at depth, ely in diatremes. Alluvial sources are mined as open-pit operations. The ore is crushed and diamonds, because of their hardness, are readily separable. -- The author is a professor of geology at Memorial University in St. John's, Nfld.
can cut across the layering in the unit) because the specific chemical horizon responsible for gold precipitation is represented by a single sedimentary horizon. Access to the favorable chemical environments of the BIF for the hydrothermal fluids was provided by large-scale fault and shear systems in a manner similar to that visualized in mesothermal lode gold models.

There is debate as to the origin of a few BIF-hosted gold deposits. Some geologists suggest that gold actually precipitated with the original chemical sedimentary host rocks as sort of a submarine hot-spring that exhaled onto the sea floor. In this model, subsequent deformation of the gold-enriched BIF led to the local remobilization and secondary concentration of gold in highly deformed zones. In other words, the gold was originally precipitated at above-normal concentrations in the BIF but was concentrated up to ore grade with deformation of the BIF. In this case, the gold in the BIF would be classified as stratiform (truly bedded and related to the deposition of the host unit), based on its original pre-deformation form.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

May 4, 1998

Banded Iron Formation-hosted gold deposits, Part 2
by Derek Wilton

Banded iron formation-hosted gold deposits are important in terms of Canadian and U.S. gold production, as illustrated by mines such as the Lupin and Musselwhite in Canada and the Homestake in South Dakota.

In general, gold deposits in banded iron formations (BIFs) contain from 0.1 to 100 million tonnes of ore grading between 4 and 30 grams gold per tonne. The Homestake mine, a world-class example of this deposit type, has produced over 1,180 tonnes of gold from 118 million tonnes of ore since operations began in 1876; remaining reserves at the end of 1996 were over 21.5 million tonnes of ore grading 6.72 grams gold.

Lupin has over 9 million tonnes of ore grading 10 to 11 grams gold. The gold is relatively pure, with moderate to low silver content of generally less than 6 grams. The gold ore is mined in a similar manner to that of mesothermal lode gold deposits, with emphasis on veins or sulphide-rich portions of the BIFs.

Since the veins and BIFs are frequently narrow units, mining is typically an underground operation, but there is some production from open pits. The bulk ore is crushed, then fed through a processing and refining plant akin to those in use at archetypal mesothermal lode gold operations. As BIF-hosted gold deposits are restricted to greenstone belt terranes in Archean to Early Proterozoic shield areas, exploration would be directed towards regions such as the Superior and Slave provinces of the Canadian Shield. The main points in both variations to the genetic model for these deposits are that deformation either provided permeable pathways for the gold-bearing ore fluids along faults, or caused remobilization of pre-existing gold accumulations, essentially enriching and upgrading gold concentrations.

Exploration would focus on highly deformed, structurally complicated portions of BIFs within greenstone belts, especially where regional fault-shear systems cut through.

The dominant structural style of the deformation manifested at most gold-bearing BIFs is folding; hence contorted fold zones in a BIF would also be a favorable exploration target. Though deformation is strongly developed in these deposits, metamorphic grade usually does not exceed greenschist facies.

Exploration should further zero in on portions of BIFs that are sulphide facies or on areas with sulphide alteration overprinting oxide facies BIF. Since BIF's account for less than 5% of the area of greenstone belts, exploration would first be directed towards locating these sedimentary rocks within the greenstone belt piles. Such exploration would be aided by airborne and ground geophysical surveys over the greenstone belts, since the greatly elevated metal contents of the host rocks make them very electrically conductive and thus discernable by electromagnetic surveys. Also, the rocks' magnetite (plus pyrrhotite) contents make them readily detectable by magnetic surveys. Induced polarization surveys would also be very advantageous in detailed exploration for, and mapping of, these conductive host rocks.

Regional geochemical surveys for iron formation and elevated concentrations of gold, iron, arsenic, bismuth and antimony could also prove effective in exploration.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

June 1, 1998

Diamond deposits, Pt. 1 by Derek Wilton

Diamond, which is pure carbon, is the hardest substance known, yet diamonds can be broken relatively easily. Paradoxically, graphite, one of the softest minerals, is a polymorph of diamonds. The essential difference between the relative strengths of these two minerals lies in their crystal structures: in diamonds, carbon atoms are linked in an isometric form, whereas atoms in graphite form linked hexagonal sheets.

Diamond crystal structures are created when carbon is subjected to great pressures (between 45 and 55 kilobars) and high temperatures (1,050 C to 1,200 C). The zone of formation of diamonds, therefore, is below the Earth's crust, in
the upper mantle. Rarely, microdiamonds can be found at meteorite impact sites, where shock-derived pressures and temperatures are sufficiently intense to transform carbon into diamonds. Diamonds can also be produced synthetically.

Diamond crystals can revert to graphite if subjected to changes in pressure and temperature over time.

On the Earth's surface, diamonds are found in unusual intrusive ultramafic igneous rocks or in placer and paleoplacer concentrations. In these deposits, diamonds are not hosted by the upper mantle rocks, namely peridotite or eclogite, in which they primarily formed.

The ultramafic igneous rocks that contain diamonds at the Earth's surface are kimberlites or lamproites. Kimberlites are volatile-rich (containing H2O and CO2) potassic, ultrabasic rocks which have an unequigranular grain size, with macrocrysts (magmatic crystals and rock-crystal fragments measuring 0.5 to 15 mm across) and megacrysts (greater than 2 cm and up to 20 cm across) set in a fine-grained matrix. Lamproites are ultrapotassic, magnesium-rich rocks which, unlike kimberlites, contain no CO2.

The feature of kimberlites essential to their containing diamonds is their volatile content, as volatiles cause magmas to intrude explosively from the lower crust or upper mantle to the earth's surface.

Diamonds are carried in kimberlites and lamproites as xenolithic crystals, or xenocrysts. While in transit from their melt sources, magmas pick up diamonds from their host rock and carry them upward. The magma essentially acts as a high-speed elevator, rapidly bringing the diamonds to the Earth's surface. Essentially, diamonds go through the pressure-temperature transition from the depth to surface so quickly that they can't revert to graphite. It is the great hardness of the diamonds that allows them to survive the explosive intrusion.

Kimberlite and lamproite systems have distinctive intrusive architectures. The uppermost part of an intrusive body in a kimberlite is carrot-shaped, and has its roots in dykes and sills (hypabyssal or medium-depth intrusive rocks). Pipes, which are generally up to 2 to 3 km wide, originate at a root zone, rise through diatreme facies to the crater facies, where the kimberlite actually breaches the Earth's surface. The walls of the diatreme dip at angles of 75 to 85 from the horizontal; the crater walls exhibit shallower dip. The crater is the widest part of the pipe, but it seldom exceeds 2 km in diameter or 250 ha in area.

In contrast, lamproites are not pipe shaped and consist of crater facies fewer than 500 metres in depth. Diamondiferous lamproite craters are up to 1.25 km in diameter with an area of about 125 ha.

Kimberlites and lamproites also contain xenocrysts of garnet and spinel. Diamonds are actually a very minor component of kimberlite and lamproite magmas, whereas other xenocrysts appear in greater abundance. Placer and paleoplacer (Geology 101, T.N.M., Jan 18-25/98) deposits, also known as alluvial deposits, form through the weathering and erosion of diamond-bearing kimberlites or lamproites. Diamonds form detrital placer grains due to their great hardness (they can withstand the erosional processes) and higher density compared with other detrital material. Diamondiferous kimberlites and lamproites are essentially secondary concentrations, whereas placer and paleoplacers deposits are tertiary. -- The author is a professor of geology at Memorial University in St. John's, Nfld.

September 28, 1998

Sedex massive sulphide deposits, Part 1
by Derek Wilton

Sedimentary exhalative (sedex) is a type of massive sulphide deposit associated with sedimentary rocks. Sedex deposits are major producers of lead and zinc, and constitute most of the world's largest metal deposits, including: the Sullivan mine in British Columbia; Red Dog in Alaska; Mount Isa, Broken Hill and HYC in Australia; and Rammelsberg in Germany. It has been suggested that half of the world reserves of lead and zinc occur in deposits of this type.

Sedex deposits consist of layers of massive sulphide (a rock composed of at least 60% sulphide minerals) interbedded with layers of sedimentary rock. These intercalated sedimentary rocks include chemical sediments that form through the chemical precipitation of their constituent elements (chert, which is precipitated silica; barite, which is precipitated barium sulphate; and carbonate) and clastic sediments (shale, mudstone, argillite) that form through the accumulation of sediment on the seafloor. The term "sedimentary exhalative" reflects the current thinking that the massive sulphides precipitated from hydrothermal fluids exhaled or vented on to the seafloor. A generalized morphology for these deposits depicts them as consisting of a vent zone that cuts through underlying (footwall) sedimentary rocks and passes into the massive sulphide horizons above. Feeder vents are present as vein networks and/or wallrock replacements in the footwall rocks. These vent features can be difficult to detect and are not found in all sedex deposits. In some cases, the massive sulphides either moved as a package of sediment along a topographic feature, such as a mound or hill, away from the vent, or the sulphide precipitated along the seafloor at some distance from the vent. As the layered massive sulphide is part of the overall stratigraphy of the host rocks (vertical sedimentary layering), it is usually termed "syngenetic," meaning the ore formed at the same time as the host rocks.
(the opposite structure is "epigenetic," as found in Mississippi Valley-type, or MVT, deposits). Some suggest, however, that the sulphide mineralization forms when metal-rich hydrothermal fluids move through the host sediments, replacing pyrite that has formed in the early stages of diagenesis (the cementation process that turns an unconsolidated sediment into a rock). The massive sulphides are composed of alternating layers of iron sulphide (pyrite and/or pyrrhotite) with lesser amounts of sphalerite and galena. Interlayers of clastic and chemical sediments can be present between the massive sulphide layers. Individual massive sulphide layers range in thickness from millimetres to metres, and can extend laterally hundreds or even thousands of metres from the vent. Lead, zinc and silver grades decrease with distance from the vent.

The sedimentary basins in which sedex deposits form are most often bounded by faults. The ore-forming hydrothermal fluids, like those involved in the formation of MVT deposits, are thought to have been saline brines derived from sediments deeper in the basin. However, fluids involved in the formation of sedex deposits, at around 300°C, were much hotter than those related to MVT deposits.

The brines circulated through the sedimentary pile, leaching metals out of the sediments, and then flowed to the seafloor along the basin-bounding faults.

On the seafloor, these fluids precipitated as the massive sulphide horizons. The veins and/or host rock alterations in the feeder/vent zones represent areas where the rising hydrothermal fluids were concentrated. Magmatism may play a role in initiation of the crustal stretching, as well as provide some of the heat energy that drives the fluid movement. However, unlike so-called volcanogenic massive sulphide deposits, igneous rocks are not an integral component of sedex deposits.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

October 5, 1998

**Sedex massive sulphide deposits, Part 2**
by Derek Wilton

Sedimentary exhalative deposits grade between 4% and 30% combined lead and zinc, with tonnages of up to 200 million tonnes. The giant deposits at Sullivan, in British Columbia, contained 170 million tonnes of ore with 5.5% zinc and 5.8% lead; Mt. Isa in Australia contains 125 million tonnes grading 6% zinc and 7% lead; Broken Hill in Australia contained 300 million tonnes grading 12% zinc and 13% lead; and Red Dog in Alaska has 77 million tonnes with 17.1% zinc and 5% lead.

Unlike volcanic-related massive sulphide deposits, sedex deposits contain no copper, though they do have significant amounts of lead, compared with most (but not all) Mississippi Valley-type deposits. Besides lead and zinc, sedex deposits also produce silver.

The targets of first-phase exploration are usually the large sedimentary basins in which these deposits tend to appear. The basins range in age from 300 million to 1.8 billion years. Sedex deposits generally occur in smaller, fault-bounded sub-basins within a larger basin. Follow-up targets include horizons that are the stratigraphic equivalents of known deposits, and mineralized veins and stockworks that may have acted as feeder zones. Sedimentary fill within prospective basins would include sulphur-rich shale-argillite clastic sedimentary rocks, which are interlayered with chemical sedimentary rocks, including chert, carbonate (calcite, siderite and ankerite) and barite.

Other prospective exploration targets in the search for sedex deposits are fault-bounded sub-basins, since hydrothermal exhalations were controlled by fluid movement along these faults. Synsedimentary faults can be identified by the presence of synsedimentary fault breccias, which are composed of sedimentary fragments cemented by more sedimentary material. Because the sulphide horizons are large and considerably more conductive and denser than the host sedimentary rocks, geophysics can often locate a deposit. Such geophysical exploration often includes airborne and ground surveys for magnetic, gravity and electromagnetic properties, as well as ground-based induced-polarization surveys.

Another initial exploration technique could be regional geochemical surveys for enhanced lead, zinc and barium in regions underlain by suitable sedimentary rocks.

Vent regions have geochemical halos in lead, zinc and silver, the values of which increase toward the vent. Therefore, if a regional geochemical survey detects enhanced concentrations of lead, zinc and silver, follow-up surveys for these metals could be used to track down a vent and, hence, possible massive sulphides.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

October 26, 1998

**MVT lead-zinc deposits, Part 1** By Derek Wilton

Mississippi Valley-type (MVT) deposits are named for the region of the U.S., along the Mississippi River, where these deposits were first discovered.
Mississippi Valley-type (MVT) deposits are important producers of zinc and lead, with zinc production being dominant. Some deposits, such as that of Newfoundland Zinc Mines, have contained negligible amounts of lead (galena). Typically, most MVT deposits have combined lead and zinc grades of less than 10%, more than half of which is usually zinc. Some MVT deposits are exclusively zinc producers.

Important past and present Canadian producers include: Newfoundland Zinc Mines' operation, with 7.2 million tonnes grading 8% zinc; Pine Point, in the Northwest Territories, with 75 million tonnes grading 6.5% zinc and 2.9% lead; Polaris, in the Territories, at 22 million tonnes grading 14% zinc and 4% lead; and Nanisivik, also in the Territories, with 10 million tonnes grading 10% zinc. In the MVT districts of the central U.S., many deposits -- up to 400 by some counts -- are estimated to have produced in excess of 1 billion tonnes of lead and zinc ore since the turn of the century. Silver content in MVT deposits is generally low, but appreciable silver is present in certain deposits. For example, the Nanisivik ores contain up to 60 grams silver per tonne. Cadmium, which is associated with sphalerite, has also been recovered at some MVT deposits. The orebodies represent discrete pods or lenses of massive sulphide (galena and sphalerite) in the host rocks. As such, they are amenable to both underground and open-pit operations, depending on how deep a deposit lies. The inherent porosity of the carbonate host rocks may present problems as it could allow ground water to flow into a mine. As MVT deposits are restricted to undeformed dolomitic carbonate rocks, exploration is directed towards areas underlain by such rocks. Significant deformation or metamorphism either will reduce the permeability of the rocks for the ore-bearing hydrothermal fluids or obliterate already present mineralization. A refinement to this technique is to examine carbonate successions with karst or...
Memorial University in St. John's, Nfld.

Newfoundland Zinc Mines deposit was discovered in this manner. -- The author is a professor of geology at Memorial University in St. John's, Nfld.

December 14, 1998

**VMS deposits**

by Derek Wilton

Volcanic igneous rocks play a critical role in the formation of volcanogenic massive sulphide (VMS) deposits, which are important producers of copper, lead and zinc, as well as lesser amounts of gold and silver. VMS deposits are found in every Canadian province and territory except Alberta and Prince Edward Island, and are significant producers in British Columbia, Manitoba, Ontario, Quebec, New Brunswick and Newfoundland. Like sedimentary exhalative deposits, they are a type of mineralization formed by the exhalation of hydrothermal fluids on to the sea floor. VMS occurrences are associated with submarine igneous rocks, though sedimentary rocks may also be in the vicinity. There are three main types of VMS deposits: copper-zinc, copper-zinc-lead, and Besshi. These deposits are well-defined, with a stockwork feeder zone grading into the massive sulphide. The stockwork zone is epigenic (that is, younger than the host rock) and represents the region through which hydrothermal fluids exhaled on to the sea floor. The stockwork zone appears in dormant exhalative systems as networks of predominantly quartz and sulphide veins with disseminated sulphides. These networks are central to altered country rock in that secondary mineralogy is produced when hydrothermal fluids pass beneath the massive sulphide on their way to exhalation. The massive sulphide layer forms when the dissolved components (sulphur and base metals) in the hydrothermal fluids precipitate directly on the sea floor. The massive sulphides are then bounded by enclosing volcanic and sedimentary rocks. This process is described as syngenetic, meaning that the massive sulphide formed at the same time as the host rocks. Chemical sedimentary rocks such as chert, barite, gypsum and carbonate are commonly associated with the massive sulphide horizons, and formed through the precipitation of fluids from the system that also produced the sulphide. The massive sulphide layers are stratiform (sandwiched between other rock strata) and generally stratiform (layered in appearance). Igneous rocks play a key role in the formation of VMS deposits, and can be divided into two groups: the high-temperature basaltic-gabbroic group and the lower-temperature rhyolitic-granitic group. The difference between the two is that rhyolitic rocks contain free silica (quartz), whereas those of the basaltic group do not. This chemical difference also manifests itself in the abilities of associated magmas to flow. Since basalts are less viscous than rhyolites, magma chambers filled with rhyolite are more likely to "dome up," and ultimately explode, than those filled with basalt, as the basaltic magma will flow from the chamber. Basalts are dark in color and referred to as mafic rocks, whereas the lighter-colored rhyolitic rocks are called felsic rocks. Also, mafic igneous rocks have greater copper concentrations, while felsic igneous rocks have more lead. VMS mineralization has been forming throughout Earth's history. The oldest deposits are about 3.4 billion years old, whereas the youngest form even today on the sea floor. In fact, VMS occurrences are the only significant class of mineral deposits that we can observe in the process of formation. The generic VMS model posits that such deposits form when sea water circulates through permeable rocks on the ocean floor. The sea water intake occurs at some distance from a magmatically heated zone, wherein water is drawn downwards towards the heat, becoming heated itself in the process. The heated sea water progressively reacts with the rocks through which it is flowing, dissolving metals out of rock and concentrating them. (This fluid essentially changes its composition from that of sea water.) The fluids then flow upwards along fractures in the oceanic rock to the sea floor where the now-hot fluids exale. This cyclic convection can be likened to what happens to water boiling in a pot: cold water flows from the sides of the pot down to the base, where it is heated, before rising pwards through the centre.

Igneous rocks provide the metals, sea water provides the fluid, and the cooling magma chamber provides the heat to drive the ore-forming hydrothermal system. In some deposits, it has been demonstrated that the magma chamber itself may have contributed some metals or fluids to the ore-forming system. -- The author is a professor of geology at Memorial University in St. John's, Nfld.

[Back to Index]
There are two main sub-types of copper-zinc volcanogenic massive sulphide (VMS) deposits: those that occur in Archean-Proterozoic greenstone belts (the Noranda-type) and those that formed in ocean environments less than 600 million years ago (the Cyprus- or ophiolite-type).

These deposits exhibit the typical VMS architecture, with a massive sulphide horizon overlying an alteration/stringer zone or pipe. In both types, the massive sulphide is predominantly composed of iron sulphide with less than 10% chalcopyrite (copper ore) and sphalerite (zinc ore). The iron sulphide is typically pyrite but can include pyrrhotite in metamorphosed occurrences or marcasite in lower-temperature deposits. In general, there is variation in the content of copper and zinc throughout the massive sulphide horizons, with occurrences of these metals being more frequent near the base. This zonation is thought to reflect the temperature at deposition, as copper would be carried in higher-temperature fluids and zinc in lower-temperature fluids. The sulphide mound can be envisaged as a thermal blanket. Higher temperatures at the base form copper-rich zones, whereas zinc-rich zones form higher up as the temperature gradually decreases. This may also reflect the evolution of the hydrothermal fluids, with earlier lower temperature types being relatively richer in zinc. Hydrothermal fluids that formed later and at a higher temperature contain copper. Silicate minerals intergrown with the sulphides are mainly quartz, chlorite and sericite. Chert and iron-oxide chemical sedimentary rocks overlie, and are typically associated with, these deposits, and presumably represent the final stages of exhalation from the circulating hydrothermal fluid system. The stringer or alteration zone beneath copper-zinc VMS deposits can have a larger areal extent than the massive sulphide zone itself. There is a general zonation of alteration associated with the stringer zones or pipes. In pipes below spreading ocean ridge-type deposits, where alteration is most intense, silica (quartz) is added and iron-rich chlorite overgrows the host rock. This zone grades outwards into altered and unaltered country rock. (The altered rock is composed of secondary magnesium-rich chlorite with sericite.) In Noranda-type deposits, the most intense core alteration is sericite and silica surrounded by chlorite halos. However, both types of deposits contain disseminations and veins of pyrite and chalcopyrite. Magnetite (iron oxide) may also be present, as can small amounts of sphalerite. Alteration layers composed of epidote and quartz within the footwall rocks may also extend beneath the massive sulphides. Greenstone belts are deformed layers consisting of volcanic and sedimentary rock surrounded by gneissic-granitic terrains. These can be thought of as islands of volcanic and sedimentary rocks floating in a sea of granite-gneiss. VMS deposits in greenstone belts occur in both mafic and felsic igneous rocks, but the most common host is felsic footwall rocks. The massive sulphides typically flank small domes of massive rhyolite, which may be quite brecciated. The stockwork alteration zone overprints the rhyolite, as well as other mafic to intermediate units that may underlie the dome. In the Noranda region, several massive sulphide deposits are associated with spatially or temporally distinct rhyolite domes. The spreading ridge-type VMS deposit is associated with ophiolite, or oceanic igneous rock. The ophiolite sequence slices through oceanic crust from below. The base of ophiolite, which represents upper mantle rocks, is composed of ultramafic cumulate lithologies that pass up through gabbro into sheeted dykes, the feeders for magmatic rocks on the ocean floor. The dykes then form pillow basalts, which indicate a subaqueous genesis. At the top of the sequence, sediments drape over the basalts. Within the pillow basalt zones of the ophiolite sequence, the massive sulphides occur typically in small, fault-bounded basins. -- The author is a professor of geology at Memorial University in St. John's, Nfld.

The largest greenstone-hosted volcanogenic massive sulphide (VMS) deposit in Canada is at Kidd Creek, where 115 million tonnes of ore contain an average of 2.2% copper and 7.25% zinc plus 145 grams silver per tonne. In the Noranda camp, the Millenbach deposit hosts 3.5 million tonnes grading 3.5% copper, 4.3% zinc and 56 grams silver. The Flin Flon deposit in Manitoba contains 62 million tonnes of 2.2% copper, 4.1% zinc and 43 grams silver. The oceanic spreading ridge type are smaller deposits, typically containing less than 15 million tonnes and averaging 2-3 million tonnes. Canadian examples include Tilt Cove, in Newfoundland, with more than 8 million tonnes grading 6% copper and Gullbridge, also in Newfoundland, which contained more than 4 million tonnes of 1.02% copper. Gold can be found in both types of deposits. In Canada, the greenstone deposit of the Horne mine (54 million tonnes grading 2.2% copper, 13 grams silver and 6.1 grams gold) in the Noranda district of Quebec contains gold, as does the spreading ridge type deposit at the Rambler mine in Newfoundland (400,000 tonnes grading 1.3% copper, 2.2% zinc, 23 grams silver and 5.1 grams gold).
There is considerable debate as to why some copper-zinc VMS deposits contain gold. One theory is that the original VMS mineralization was overprinted by a mesothermal lode gold system. The other posits that ore-forming fluids either had a unique composition or underwent low-pressure exhalation similar to an epithermal gold system. The massive sulphide is usually the target of mining operations, but in some deposits the massive sulphides have been removed either by erosion or deformation. When this happens, the deposit being mined would be a stockwork zone. Mining operations are usually underground with mill complexes to crush ore and separate sulphides from host rock and each other by flotation techniques. Open-pit mines are developed where the sulphide deposits occur close to the surface.

Exploration for these different types of copper-zinc VMS deposits occurs in completely different geological and tectonic environments. Exploration for the greenstone-type deposit occurs in greenstone belts in Precambrian shield areas, particularly in volcanic mafic and felsic rock sequences and rhyolitic domes with definable breccia zones (also called mill rock). Exploration for oceanic spreading ridge deposits focuses on ancient orogenic belts, such as the Appalachian or Cordilleran, or modern seafloor vents, such as those on the Juan de Fuca Ridge near Vancouver Island. These deposits were originally thought to have formed at mid-ocean ridges, but high-precision geochemical analyses points to back arc spreading ridge systems as the sites of formation. This geochemical distinction offers a potential exploration tool in oceanic terranes, in that these specific geochemical signatures can be sought in prospective rocks.

Overall, massive sulphide layers in Noranda-type deposits have a bulbous form, while those associated with spreading ridges have a bowl-shaped appearance, reflecting the structure of the footwall rocks. Sulphides in the Noranda-type deposit are typically associated with rhyolitic domes, while the spreading ridge type occur in small, fault-bounded basins within underlying basaltic oceanic rocks. Follow-up work often includes efforts to identify alteration zones or pipes in footwall rocks. These zones are typically larger than the massive sulphide itself, thus offering a better target. Aside from mapping mineralogical zonations within a potential alteration stockwork, documentation and mapping of subtle changes in geochemical signatures associated with alteration in bedrock may prove valuable in vectoring towards a massive sulphide horizon. Detailed mapping of chemical sedimentary rocks that overlie sulphide horizons could also be used as indicators. Owing to the conductive nature of their constituent metallic sulphides, these can be detected via ground and airborne electromagnetic and magnetic surveys. Airborne radiometric surveys may also prove useful, as can induced-polarization surveys.

The author is a professor of geology at Memorial University in St. John's, Nfld.

January 11-17, 1999

**Zinc-lead-copper VMS deposits, Part 1**

By Derek Wilton

Zinc-lead-copper volcanogenic massive sulphide deposits have also been called Kuroko-type, after the deposits in the Green Tuff Belt in Japan. Aside from these base metals, such deposits also produce precious metals. As with copper-zinc VMS deposits, zinc-lead-copper VMS deposits consist of a stratabound, generally stratiform, massive sulphide body underlain by a stockwork feeder zone. Although the footwall rocks in the Kuroko VMS deposits are white rhyolite domes, they are typically felsic to intermediate breccia or ashflow volcanic rocks. This composition contrasts with more refractory volcanic rocks of oceanic spreading copper-zinc VMS deposits.

Zinc-lead-copper VMS deposits form as a result of circulation of seawater through the underlying volcanic layer. The felsic volcanic nature of the zinc-lead-copper footwall indicates greater involvement of felsic igneous rocks and, hence, a source for the formation of lead and zinc. The fluids that formed copper and zinc did not have access to rocks with such lead-rich compositions.

However, it has been suggested that the absence of lead in greenstone-type copper-zinc VMS deposits reflects the lead-poor nature of the Earth's crust as it was forming. The sulphides in zinc-lead-copper VMS deposits exhibit a strong zonation, and the typical model for these deposits defines seven different mineralogical zones. However, the presence of all of these zones is rare, owing to erosion or poor development of individual layers.

These zones include: silicious ore -- the lowermost zone, consisting of stockwork pyrite, chalcopyrite and quartz; pyrite ore -- overlies silaceous ore and is stratiform massive pyrite with some veining and disseminations; oko or yellow ore -- composed of pyrite or chalcopyrite but can also include sphalerite, barite or quartz; black ore -- overlies oko ore, and consists of sphalerite, galena, chalcopyrite, pyrite and barite; barite ore -- a chemical sedimentary rock composed of massive barite (calcite, dolomite and siderite); chert-hematite -- constitutes the top of the sequence; and gypsum ore -- contains the chemical sedimentary rocks gypsum and anhydrite, and can occur on the edges of the sulphide mound laterally, away from the core.

The ores for copper, lead and zinc are chalcopyrite, galena and sphalerite, respectively.
As in the copper-zinc VMS deposits, the various zonations seem to reflect temperature differences and the outward migration of metals from the site of influx. It appears that anhydrite forms as the first phase of an exhalation system on the seafloor, and is then replaced by sphalerite and galena, followed by chalcopyrite and pyrite. The gypsum, barite and chert-hematite zones can extend laterally some distance away from the sulphide mound. Some divide the siliceous stockwork material into zones consisting of a core of siliceous pyrite that grades into siliceous yellow ore followed by siliceous black ore at the edges. A typical stockwork zone in a zinc-lead-copper VMS deposit has a quartz-sericite core (frequently with chlorite) that grades into a middle zone with sericite, clay minerals, chlorite and sometimes feldspar, and, finally, into an outer zone with zeolite and clay minerals.

These alteration systems -- particularly those consisting of sericite and chlorite, or zeolite and clay -- have been known to surround the sulphide mound and envelop the hangingwall for up to 300 metres above the sulphide body, and laterally for up to 1.5 km.

The layers containing massive sulphide mounds can exhibit soft sediment deformation features, indicating that the layers were plastic on the seafloor prior to cementation into solid rock. In some deposits, these sulphide layers moved en masse downslope from the underlying rhyolitic dome, becoming detached from their stockwork feeders. Such ore horizons are called "transported ores." "Proximal ores" are in contact with their stockwork zones, whereas the massive sulphide in "distal ores" are not connected to the stockwork.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

Zinc-lead-copper VMS deposits, Part 2
By Derek Wilton

Zinc-lead-copper volcanogenic massive sulphide deposits typically contain up to 18 million tonnes of ore, though deposits containing 100 million tonnes have been discovered.

In the Canadian portions of the Appalachian Orogenic Belt, two important zinc-lead-copper VMS districts occur. One is at Buchans, Nfld.; the other, at Bathurst, N.B. Buchans produced 16.2 million tonnes of ore grading 1.33% copper, 7.56% lead, 14.51% zinc, 126 grams silver and 1.37 grams gold per tonne from 12 orebodies that are among the richest of this sort of VMS. At Bathurst, more than 30 deposits contain 250 million tonnes of ore: the Brunswick No. 12 orebody contains 134 million tonnes of ore with 0.3% copper, 3.6% lead and 8.87% zinc, plus 100 grams silver per tonne; the Heath Steele deposit contains more than 33 million tonnes of 0.7% copper, 2.5% lead, 6.3% zinc, 60 grams silver and 0.62 gram gold; on Buttle Lake, on Vancouver Island in the Cordilleran Orogenic Belt, the H-W deposit contains 13 million tonnes grading 2.2% copper, 0.3% lead, 5.3% zinc, 38 grams silver and 2.4 grams gold.

These massive sulphides are mined by standard underground or (where possible) open-pit methods. Sometimes a combination of the two is used. These operations usually include a crushing mill. The complex polymetallic nature of the ore requires elaborate flotation and separation techniques, both to process the sulphides and remove dense barite and other waste material.

Exploration for these deposits should be undertaken in the oceanic volcanic portions of orogenic belts -- in particular, those portions that have a strong felsic-to-intermediate igneous component with a calcalkaline geochemical signature. Regional lithogeochemical surveys of volcanic rocks in the correct tectonic setting provide a first-order exploration tool. As the deposits often occur in clusters, exploration in regions with known deposits may prove successful. Exploration in prospective volcanic belts can lead to the identification of alteration halos around these deposits. The haloes, as well as the stockwork zones, may be larger than the mineralized horizons themselves. Explorers can vector toward a massive sulphide by evaluating mineralogical changes, and associated geochemical changes, in a potential alteration stockwork.

Such a technique would not work in the case of transported ore, as no stringer zone occurs in these sorts of deposits. Larger, hangingwall alteration systems would also be good mineralogical or geochemical targets. Another potential exploration target, one also larger than an actual deposit, would be a mineralized horizon of chemical sedimentary rocks, particularly barite. The evaluation of barite distributions in regional lake sediment or stream sediment surveys can be used to define the location of this horizon.

Since the deposits are electrically conductive, they can be detected via airborne electromagnetic (EM) and magnetic (MAG) surveys. Airborne radiometric surveys, which are capable of detecting the potassic content of felsic volcanic rocks or the alteration associated with the stockwork zones, can also prove useful in exploration. A more recent geophysical exploration innovation is a combined EM-MAG-radiometric airborne survey. These have been used in a recent Geological Survey of Canada mapping program in the Bathurst camp of New Brunswick. In the Buchans district of Newfoundland, Billiton Exploration recently
completed a combined EM-MAG airborne survey. Ground-based follow-up geophysical programs can include gravity, induced-polarization/spontaneous-polarization, MAG-EM and very-low-frequency surveys, any of which can be carried out in co-ordination with diamond drilling.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

May 31-June 6, 1999

Porphyry deposits, Part. 1
By Derek Wilton

Porphyry deposits are the quintessential low-grade, large-tonnage mineral deposit. These formations are called porphyries because they are commonly, but not solely, associated with intrusive igneous rocks with large, well-formed mineral crystals (typically feldspars) set in a groundmass of finer-grained crystals. The intrusive rocks that usually host the deposits are generally felsic to intermediate, ranging from granite to quartz monzonite to granodiorite. The deposits are rare in mafic intrusions, such as gabbros.

The porphyritic texture indicates that the magmas intruded and crystallized near the surface. Because of their near-surface nature, these intrusions are termed epizonal, but can also be moderately coarse-grained with uniform-sized crystals or mesozonal.

Porphyry deposits can be subdivided into different types based on their metal content. These types include copper, copper-gold, copper-molybdenum and molybdenum. In general, copper- and gold-rich porphyries are associated with intrusions derived from mafic magmas in settings such as island arcs. Molybdenum-rich deposits are associated with felsic intrusions derived from magmas with a substantial component of remelted continental crust.

Porphyry deposits are related both genetically and spatially to igneous intrusions. There are usually several bodies of intrusive rock, emplaced in multiple events, and porphyry copper deposits are often associated with dyke swarms and breccias. The country rock intruded by the porphyry can be of any lithological type.

Both the intrusion and the country rock typically exhibit strong and pervasive fracturing. The only geological requirement for porphyry mineralization is that the host rock be rigid or brittle.

Mineralization and alteration can develop in both the intrusive and country rock. The core of the mineralizing system demonstrates the most intense alteration -- called potassic alteration because potassium is added to the affected rocks. In the potassic zone the minerals biotite, potassium feldspar and quartz develop. The potassic zone grades outwards into the phyllic zone, which contains quartz and muscovite, usually in its fine-grained variety, called sericite. The phyllic zone then passes into the argillic zone, where quartz and clay minerals develop. The propylitic zone, containing chlorite, epidote and carbonate, develops next, grading outwards into unaltered country rock. These zones do not all show up in every deposit: any one can be missing. The argillic zone, typically the smallest, is often entirely absent.

Usually, mineralization has a low-grade core containing disseminated pyrite that grades out into the ore zone. In the ore zone, pyrite with lesser chalcopyrite (copper ore) and molybdenite (molybdenum ore) are present in veins and disseminations. Sometimes an outermost zone containing only pyrite develops, and then passes into unmineralized country rock.

Formation of these deposits seems to involve two processes.

One, the orthomagmatic process, involves a mechanism called "second boiling," whereby water saturates the magma as a result of crystallization. With progressive crystallization of the magma, the volume of water dissolved in it increases at a relative rate since water will not seep into silicates. For example, suppose a magma contains 2% dissolved water: once 50% of the magma has crystallized into silicate minerals, the remaining magma would contain a dissolved water content of 4%.

Because water boils at 100°C and the magma has temperatures exceeding 600-700°C, excess water will essentially boil off (hence the term second boiling) if released near the earth's surface. When this happens, sulphur, copper, molybdenum and gold can be concentrated in solution in this water. When the aqueous part of the magma boils off, the pressure can cause the intrusive and country rocks to brecciate and fracture, providing pathways for the solution to travel through the rock and be deposited. This type of brecciation and fracturing is sometimes called "ground preparation."

The second means of formation, known as the "convective process," starts when continued cooling of the intrusive magma causes groundwaters to circulate through the surrounding country rocks, much as water convects to seafloor volcanic vents and forms volcanogenic massive sulphide deposits. These late-circulating hydrothermal fluids can add more metals to the ore-forming system, or redistribute metals that had been previously deposited in the orthomagmatic stage so as to upgrade the concentration of the sulphides.

Porphyry deposits occur in a similar geological setting to epithermal-style gold deposits, and share many of the same characteristics and processes of formation. Some epithermal deposits are part of a larger porphyry-deposit system.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.
Porphyry deposits, Part 2

By Derek Wilton

Porphyry deposits can be found in orogenic areas such as the Canadian Cordillera, the Andes Mountains of Chile and Peru, and in the southwestern Pacific regions of the Philippines, Indonesia and Papua New Guinea. These deposits are the most important source of molybdenum, and of rhenium, a platinum group element associated with molybdenite crystal lattice. They are also among the most important sources of copper -- reportedly contributing up to half of the metal mined worldwide -- and gold. Silver and a number of other metals, including tungsten, tin, lead and zinc, are also recovered from porphyry operations.

These deposits contain hundreds of millions to billions of tonnes of ore grading from 0.2% to more than 1% copper, 0.005% to 0.03% moly, and 0.4 to 2 grams gold per tonne.

As an example, the porphyry copper mine at Bingham, Utah, contains an average of 0.6% copper in more than 2 billion tonnes of ore. Since operations began in 1904, the mine has produced more than 16 million tonnes of copper. Other regions with porphyry deposits include: Butte, Mont., with more than 2 billion tonnes grading 0.85% copper; Chuquicamata, Chile, with more than 10 billion tonnes grading 0.56% copper; and Ok Tedi in Papua New Guinea, with more than 375 million tonnes grading 0.7% copper and 0.66 gram gold.

In Canada, all moly production and roughly half of all copper production are derived from porphyry deposits. With the exception of Quebec's Gaspe Copper, which is mining a deposit estimated at 150 million tonnes grading 0.37% copper, Canadian porphyry production is limited to British Columbia and the Yukon.

Current and past-producing mines in those areas include: Valley Copper in British Columbia, with 690 million tonnes grading 0.41% copper; Island Copper in British Columbia, with 345 million tonnes grading 0.42% copper and 0.017% moly; Brenda in British Columbia, with 360 million tonnes grading 0.16% copper and 0.039% moly; Mount Polley in British Columbia, with 230 million tonnes grading 0.25% copper and 0.34 gram gold; and Casino in the Yukon, with 162 million tonnes grading 0.37% copper, 0.039% moly and 0.48 gram gold.

Because of their low grades, porphyry mines must be low-cost. To keep costs down, these are mined as open-pit operations, which are less costly to run than underground mines. The size of many of these deposits renders such operations huge. For example, at 800 metres deep and 4 km wide, the pit in Bingham, Utah, is the largest man-made excavation in the world.

Exploration for these deposits focuses on regions with felsic-to-intermediate intrusive rocks, particularly those with a history of multiple intrusions and brecciation or fracturing in the contact zone with country rock. More detailed exploration would zero in on defining alteration halos that grade laterally from the core of the mineralizing system. A vertical zonation in copper mineralization might also develop in hot, arid regions where surface waters tend to redistribute copper from an exposed porphyry system, concentrating it elsewhere. Such enrichments are called "supergene" and contain higher-grade copper minerals, such as chalcocite and bornite, than found in chalcopyrite. The oxidized surface waters dissolve copper from the original porphyry ore, called protore, and transport it in the water table until such time as the waters encounter a reduced zone and precipitate the copper. The presence of a supergene enrichment indicates the presence of a larger hypogene, or original, porphyry system.

Regional geochemical surveys for both metals and alteration, such as potassium, are useful exploration techniques. Regional airborne geophysical surveys, such as gamma-ray spectrometry, may prove useful in locating and defining alteration halos.

Some porphyry systems in the Andes were first detected through satellite imagery of alteration halos. Ground geophysical surveys useful in exploration include induced-polarization for disseminated and vein sulphides, and magnetic for secondary magnetite content.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

Redbed copper deposits, Part 1

By Derek Wilton

As their name suggests, red-bed copper deposits form in red host rocks. The red colouration is actually rust, which is oxidation formed after the rock's exposure to the atmosphere.

The two types of redbed mineralization are volcanic and sedimentary. The volcanic-hosted types occur in sub-aerial (land-based) lava flows and associated fragmental rocks, such as agglomerates and tuffs.

In volcanic host rocks, breccias and layers of volcaniclastic sedimentary rocks can act as permeable zones. So can flows, if they contain vesicles (holes from which gas escapes). The vesicles are typically filled with low-grade
metamorphic minerals. Such vesicles are called amygdules, and the host rocks are termed amygdaloidal flows. In many cases, the copper-bearing permeable horizons are crossed by faults or fractures.

Copper sulphide minerals -- including chalcocite, digenite, djurleite, covellite, bornite and chalcopyrite -- can form cross-cutting veins, or can be disseminated through the host rock, or can fill vesicles in volcanic rocks.

The second type of redbed deposit, sedimentary-hosted, forms in such environments as fluvial (river) systems. The red continental sediments in these oxidizing environments differ from the green-to-black, reduced sediments deposited in oxygen-poor (or anoxic) submarine environments. Typically, mineralization consists of disseminated chalcocite, with lesser bornite and chalcopyrite in permeable layers of the host rock.

The copper appears to have precipitated after encountering reduced material in the form of organic debris and pyrite. Oxic copper-bearing fluids were reduced through reaction with the iron sulphide pyrite, causing precipitation of copper sulphides.

Sometimes, copper precipitation is caused by the mixing of oxic copper-bearing fluids with hydrocarbon-rich fluids in a permeable horizon of a fluvial sequence. There is little or no alteration of the host rocks by the copper fluids, and no deformation. This combination suggests that the ore fluids were low in temperature and almost in equilibrium with the host rocks, except for oxidation potential. It is generally assumed that these fluids were diagenetic -- that is, that they were produced by dewatering of material elsewhere in the sedimentary pile.

A mineralogical zonation develops in many redbed copper occurrences, particularly in the volcanic-hosted type. Zonation is not fully developed in all occurrences and is barely present in many sedimentary-hosted types. Where fully developed, the zonation contains, at its core, native copper, which grades outwards through zones of chalcocite, copper- and iron-rich bornite, chalcopyrite and finally pyrite. The zonation is known as a "fluid front," and forms when oxidized copper-bearing fluids gradually replace reduced layers. The zone in which the reaction between reduced rock and oxidized fluid occurs is known as the "redox (reduction-oxidation) boundary."

In low-temperature, sandstone-hosted deposits, the fluid front is called a "roll front," owing to its concave shape. Copper precipitates when it reaches the redox boundary, and the continued influx of fresh ore fluid pushes the redox boundary through the permeable horizon and, at the same time, increases the copper content of the minerals behind the boundary.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

[Succinctly stated, redbed copper deposits are relatively small, and few are ever brought into production. There are no such mines in Canada, though deposits do occur in Nova Scotia and New Brunswick. Around the world, the Dzhezkazgan deposits of central Kazakhstan and the Paoli deposit of Oklahoma are producers.

Conversely, volcanic-type redbed deposits are important producers. Such mines in the Keweenawan district of Michigan have produced more than 5 million tonnes of copper since the mid-19th century from such deposits as the Calumet (70 million tonnes grading 2.64% copper) and Kearsarge (90 million tonnes of 1.05% copper). In addition to copper, redbed deposits also produce silver.

Canada's only volcanic redbed operation was the Mamainse Point mine, on the southeastern shore of Ontario's Lake Superior. It produced 850,000 tonnes grading 1.15% copper and 8 grams silver per tonne. The Sustut deposit of north-central British Columbia, which contains 43.5 million tonnes grading 0.81% copper, and the 47 zone of the Northwest Territories' Coppermine district, reported to contain 3.2 million tonnes grading 3.4% copper, are undeveloped occurrences.

More than 250 volcanic- and sedimentary-hosted redbed deposits occur in the Seal Lake area of central Labrador. The sedimentary-hosted deposits form when oxic (oxygen-rich) diagenetic fluids rise through permeable zones. The volcanic-hosted deposits form when oxic copper-bearing fluids flow along faults or fractures and encountered permeable horizons in which to precipitate copper minerals. Some models suggest that oxic fluids in volcanic-hosted deposits derive from the metamorphism of volcanic rocks from deeper stratigraphic levels. Fluids driven off by dehydration will concentrate copper in the rocks.

Kupferschiefer-type deposits are similar to the redbed type, and are found in the Central African copper belt, which straddles Zambia and the Democratic Republic of Congo, and its namesake district of Eastern Europe. These large, regionally extensive deposits form in continental shelf sedimentary environments in which continental redbeds are transgressively overlain by reduced marine sedimentary rocks (involving the gradual submergence of land by a shallow sea). These deposits formed when oxic copper-rich fluids from the underlying beds were forced up to sedimentary marine rock, creating a redox zone in which copper minerals precipitated after the reaction of the fluid with the host rock.
Exploration for sedimentary-style redbed copper deposits occurs in areas with thick, undeformed packages of fluvial sedimentary rocks, whereas exploration for volcanic-hosted redbed copper deposits focuses on sub-aerial volcanic flows and associated volcaniclastic sedimentary rocks. Exploration crews investigate fault zones and permeable horizons in oxic sequences that also contain some reduced zones or material. Delineation of mineral zonation often points the way to enriched copper horizons. Also in an explorer's arsenal are regional geochemical surveys for anomalous copper or silver and electrical-based ground geophysical surveys.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.

November 22-28, 1999

Skarn deposits, Part 1
By Derek Wilton

Skarn deposits are significant sources of tungsten, copper, iron, gold, molybdenum, lead, zinc and tin, as well as being minor sources of silver and bismuth. Industrial minerals, including wollastonite, mica, talc and graphite, are also produced from skarn deposits.

Based on the elements that are present, skarns can be divided into seven categories: iron, tungsten, copper, zinc-lead, molybdenum, gold and tin.

Mineral deposits containing skarn typically form at or near the contact between predominantly carbonate-rich rocks (limestone or dolomite) and an igneous intrusive body, or in carbonate veins along faults or fractures. They form when hot magmatic fluids from the intrusion react with the host carbonate-rich rock, producing calcium, iron, manganese and magnesium silicates (also known as calc-silicates). This process is called metasomatism, meaning that new minerals grow in the host rocks when chemically active pore fluids are introduced into it from an external source. This new growth causes only minor textural or structural disturbances in the original rock. The new minerals are typically coarse-grained crystals that grow over or replace the fine-grained or massive host rock. The calc-silicate minerals include garnet (calcium-rich grossularite and andradite to magnesium-rich pyrope), pyroxene (diopside to hedenbergite), epidote, olivine (forsterite to fayalite), wollastonite, amphibole (actinolite-tremolite to hornblende) and scapolite.

Garnet and pyroxene are the predominant minerals in most skarns, but not all other minerals develop in every skarn. The mineralogy of the skarn depends on factors including the composition of both the intrusive and carbonate rocks; the structural or relative permeable nature of the host rocks; and the level of intrusion.

In order for skarns to form, host rocks must be permeable so that metasomatic fluids can flow into and through them. If the host rock is impermeable to fluids, the build-up of heat from the cooling intrusion will cause thermal metamorphism, which bakes the rocks and leads to the formation of hornfels (fine-grained rock in which new minerals are created by thermal metamorphism of existing mineralogy). Although hornfels is typically fine-grained, it can be overgrown by such coarse-grained minerals as andalusite or cordierite. Because of the differences in the permeability of the host rock, carbonates develop skarns, while impermeable calcareous shales develop hornfels.

Skarns are classified as either calcic, if they formed in a limestone, or magnesian, if they formed in a dolomitic host rock. Silicate skarns form when intrusives come into contact with calcium-rich silicate rocks, such as amphibolite. Endoskarn is skarn that develops in the intrusive, whereas exoskarn develops in the surrounding carbonate-rich rocks. Endoskarn is igneous rock-hosted; exoskarn, sedimentary rock-hosted.

Typically, skarns are zoned, their mineralogy changing with distance from the intrusion. Closer to the intrusion, garnet is more abundant than pyroxene. Farther from the intrusion, pyroxene becomes more abundant before grading into unaltered carbonate host rocks. There are also subtle changes in the chemical compositions of the minerals, particularly in the iron-to-manganese ratio in pyroxene. Closer to the intrusive, pyroxene is iron-rich; farther away, it becomes manganese-rich. Garnets in copper and other skarns change in colour from dark-brown nearest the intrusive to yellow at greater distances.

Skarns form in three stages: First, country rock is heated by an intrusive magma, resulting in thermal metamorphism of the rock into hornfels. Dissolved metals are then deposited during a water saturation phase that follows crystallization in the magma. This process is similar to that of the boiling phases that form porphyry deposits. This vapour-fluid phase infiltrates permeable country rock, causing metasomatism, and leads to skarn formation. Metal deposition (typically as sulphides) takes place in the later, cooling stages of the metasomatic event. Finally, retrograde alteration occurs in the cooling of the system. This alteration develops through circulation of ground waters from country rock.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.
Different igneous intrusions tend to put different metals into a skarn. More mafic intrusions, such as diorites and gabbros from island arc settings, typically produce iron, copper or gold skarns. Intermediate-to-felsic intrusions form tungsten, zinc-lead, iron, copper and molybdenum skarns. The most evolved granitic intrusions, which are typically post-tectonic, produce tin, molybdenum and lead-zinc skarns.

Skarn deposits are part of the spectrum of hydrothermal and magmatic-style mineral deposits. They can be interpreted as the transitional phase between porphyry-style deposits (such as porphyry coppers) and granophile-style deposits. Copper skarns are typically associated with deeper levels in porphyry-copper deposit systems.

Most economic skarn deposits occur around intrusive bodies of Mesozoic age or younger. In Canada, with the exception of the Mines Gaspe copper skarn in Quebec and small iron skarns in Ontario, economic skarn deposits are exclusive to British Columbia and the Yukon.

Gold skarns occur in pyroxene-rich portions of calcic skarns and are characteristically part of a porphyry system surrounding an intermediate intrusive rock, such as diorite or granodiorite. They have low metal-to-gold ratios, as well as enriched arsenic, bismuth, tellurium and silver.

Gold tends to be emplaced at distance from the intrusion, in the company of sulphides, such as arsenopyrite and pyrrhotite. Throughout the world, gold skarns are said to contain an average of 4.6 million tonnes grading 10.6 grams gold per tonne. For example, the Hedley deposit in British Columbia is reported to have contained 8.4 million tonnes at 7.3 grams gold, whereas the Fortitude mine in Nevada contained 11 million tonnes grading 5.3 grams gold.

Copper skarns are the largest and most common type of mineralized skarn and are linked to porphyry copper intrusive systems. Economic mineralization develops close to the intrusion and consists primarily of iron-rich garnet. The main ore mineral is chalcopyrite, and the skarn will usually be zoned, with pyrite and chalcopyrite grading outward to a more chalcopyrite-rich fringe.

Examples of such deposits in Canada include Mines Gaspe, with 67 million tonnes grading 1.45% copper, and Copper Mountain in British Columbia, with 216 million tonnes of 0.4% copper (including porphyry mineralization). The Santa Rita deposit in New Mexico is reported to contain more than 100 million tonnes of 0.9% copper.

Tungsten skarns tend to form around coarse-grained intrusions, typically quartz monzonites with associated pegmatites. The association with deeper-seated intrusive rocks suggests that these skarns form at a higher temperature than other types of skarn. The ore mineral is scheelite, which is associated with pyrite, pyrrhotite, chalcopyrite and molybdenite in exoskarn -- that is, in skarn formed in the bedded rock outside the intrusion itself. The best Canadian examples are the Mactung deposit in the Yukon, with 32 million tonnes grading 0.92% tungsten trioxide, and the Cantung deposit in the Northwest Territories, with 9 million tonnes of 1.42% tungsten trioxide. The Shizhuyan deposit in China is reported to contain 112 million tonnes of 0.33% tungsten trioxide.

Lead-zinc mineralization in skarns is generally distant from the intrusion and develops along lithological contacts or fault-fractures in the calcareous rocks in zones of greater permeability. Silver is a common component of the ores. Typically, the silicate minerals in the skarn -- garnet, pyroxene, olivine, and amphibole -- are rich in manganese. Canadian examples include Sa Dena Hes in the Yukon, with 4.9 million tonnes of 12.7% zinc, 4% lead and 6 oz. silver per tonne, and Bluebell in British Columbia, with 4.8 million tonnes grading 6.3% zinc, 5.2% lead and 45 grams silver. Leadville in Colorado contained 23.8 million tonnes grading 3% zinc, 4.2% lead and 320 grams silver. Iron skarns are the largest of all skarns, and the ore mineral is magnetite. Intrusions rich in iron tend to form calcic iron skarns; those lower in iron tend to form magnesian iron skarns with magnesium-rich silicate skarn minerals. Garnet and pyroxene are common in these types of skarn, which, in many cases, will be composed of magnetite with lesser amounts of silicate. The Tasu deposit in British Columbia produced 21 million tonnes grading 40% iron, whereas the Marmora deposit in Ontario produced 1.1 million tonnes of 66% iron. The Sarbai deposit of Siberia is reported to contain 725 million tonnes grading 45.6% iron.

Exploration for skarns should begin in carbonate rocks intruded by water-bearing magmas. Regional geochemical surveys are also useful. Since the skarn zonation halo can be considerably larger than the metallic ore deposit, mapping of the zonation can be used to focus exploration. The high magnetite or pyrrhotite content of some skarns, particularly iron skarns, makes magnetic surveys useful in identifying and outlining these deposits, and disseminated sulphides can often be detected using induced polarization.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.
These deposits often contain cobalt, which can be of economic grade, and some have economically recoverable precious metals. Volcanogenic massive sulphide (VMS) deposits of the Besshi type are named after deposits on the southern Japanese island of Shikoku. These deposits generally contain lower base metal concentrations than other volcanogenic massive sulphides and are viewed as low-grade copper deposits; the zinc grade is typically too low to be mined economically. These deposits do, however, often contain cobalt, which can be of economic grade, and some have economically recoverable precious metals. Metal zoning is usually poorly developed in Besshi deposits. The sulphide mineralization consists predominantly of iron sulphides (pyrite and/or pyrrhotite), with lesser chalcopyrite; sphalerite may or may not be present. Unlike other VMS styles, however, Besshi sulphides can contain a highly varied and complex mineralogy, including magnetite, arsenopyrite, galena, bornite, tetrahedrite-tennantite, cobaltite, stannite and molybdenite. Quartz, carbonate, albite, sericite, chloride, amphibole and tourmaline can be found as gangue minerals in the deposits. Unlike the Kuroko-type VMS deposits, there is typically no barite present in Besshi deposits, though other chemical sedimentary rocks (carbonates or iron-oxide beds) may be associated. The Besshi massive sulphide deposits are thin, stratiform and tabular. The massive sulphides may be finely or coarsely layered, or massive; the sulphide lenses are usually just several metres thick but can extend for several kilometres. The deposits are typically deformed and metamorphosed, and highly deformed ones are almost linear in shape. Deformation can obscure the deposit’s feeder systems, but one deposit widely classified as a Besshi type, namely the Windy Craggy deposit in British Columbia, has a well-defined feeder/stockwork of extensively chlorite-quartz altered wall rock cut by sulphide veins. Crosscutting the massive sulphide horizons, there may be veins of recrystallized pyrite and/or chalcopyrite, opened and filled when the horizons were deformed. A chlorite alteration halo has developed in the country rock surrounding the sulphide horizons, which may be a relic of pre-deformational alteration. Other alteration minerals that may show up in the host rocks of Besshi deposits are quartz, carbonate, pyrite, sericite and graphite. The sulphide horizons generally occur in thick sequences of marine sedimentary rocks, ranging from black shale to arkose to greywacke. The clastic hosts themselves are generally finely laminated sedimentary rocks that resemble turbidites (sediments deposited on the ocean floor through seafloor slumping). There can also be volcanic tuffaceous interlayers. The clastic sediments are typically graphitic. There are usually no felsic volcanic rocks present, though thin layers of basalt are often present in the sequence of sediments. The basalts have a tholeiitic composition (with pyroxenes, plagioclase feldspar and olivine, which have a high iron content relative to their sodium and potassium content). The host rocks to these deposits can be metamorphosed such that the sedimentary rocks have become schists, quartzites, metacherts and/or pelites, and the basalts can be amphibolites. Their host rocks, mineralogy and chemistry place Besshi deposits along a continuum between the copper-zinc massive sulphides and the sedimentary-exhalative deposits. Although Besshi deposits are modeled as VMS-types, with the massive sulphides forming from the exhalation of hydrothermal fluids on to the seafloor, there is some debate as to the mechanism of deposition. The deposits have been characterized as the products of: seafloor accumulation in the form of sulphide chimneys and the like (that is, "black smokers"); hydrothermal brine pools that formed on the seafloor after exhalation; and replacement of clastic sedimentary rocks by sulphur-bearing hydrothermal fluids that flowed upwards in a convection cell system but did not actually exhale on the seafloor. -- The author is a professor of geology at Memorial University in St. John's, Nfld.

July 10-16, 2000

Besshi-type VMS deposits (Part II)

Besshi-type volcanogenic massive sulphide (VMS) deposits range in size from under a million to 300 million tonnes and grade between 0.64% and 3.3% copper. The Besshi deposits themselves contain 30 million tonnes of 2.5% copper and 0.3% zinc, plus 7 grams silver and 0.2 gram gold per tonne. Examples of Besshi deposits in Canada include Windy Craggy, in northwestern British Columbia, which is said to contain between 210 and 320 million tonnes of ore grading 1.66% copper, 0.09% cobalt, 3.5 grams silver and 0.2 gram gold, and Soucy, in the northern Quebec's Labrador Trough, which contains 4.3 million tonnes of 1.4% copper, 1.09% zinc, 19 grams silver and 2 grams gold.

Windy Craggy is by far the world's largest known Besshi-style deposit. Some authors suggest that the Britannia mine in southern British Columbia, which contained 48 million tonnes grading 1.9% copper, 0.65% zinc, 6.86 grams silver and 0.69 gram gold, might also be a Besshi deposit.
In the Proterozoic continental margin of the Appalachian Orogenic belt of the U.S., the Ducktown massive sulphide in Tennessee contained 163 million tonnes with an estimated 1% copper and 0.9% zinc, whereas the Gossan Lead deposits in Virginia had 20 million tonnes of 0.5% copper and 1.5% zinc. Besshi deposits occur in Proterozoic to Mesozoic rocks, while the age of most deposits is late Proterozoic to early Paleozoic (1.4 billion to 400 million years). It has been suggested that modern-day sediment-covered examples of Besshi mineralization are forming in the Guaymas Basin in the Gulf of Mexico, the Middle Valley of the Juan de Fuca Ridge (off Vancouver Island) and the Red Sea. These deposits have low base metal grades and consequently high sulphur contents. Many deposits -- Gossan Lead, for example -- were actually mined for their sulphur and not for their base metals. The high sulphur contents can present environmental problems for the mining and refining of ore.

The deposits appear to have formed in a variety of tectonic environments, from oceanic crust to early-forming rift basins in continental plates. The host rocks are thick, terrigenous clastic sedimentary sequences with lesser tholeiitic mafic magmatism. It has been suggested that the size of the deposit reflects the volume of mafic volcanic rocks in the ore-forming system; the more mafic volcanic rocks present in the basinal stratigraphy, the more copper there may be in the exhalative sulphide body. The deposits would have relative copper, zinc, silver and cobalt enrichments that could be delineated by regional lake and stream-sediment geochemical surveys.

Geochemical definition of tholeiitic basaltic magmatism in a thick sequence of clastic sedimentary rocks, or their metamorphosed equivalents, would be a useful method of regional exploration. It is a reflection of their deformational states that Besshi deposits, unlike other VMS deposit-types, do not commonly exhibit extensive feeder alteration systems in the footwall to the massive sulphide bodies. Alteration is usually a broad enveloping chloritic halo, which may be reflected by a relative magnesium enrichment in country rock. Lithogeochemical surveys of cobalt versus nickel distributions might also be useful, given that the Besshi sulphides have a distinctive cobalt-nickel ratio greater than one.

Although the deposits are composed of metallic sulphides, the abundant graphite in the sedimentary rocks (or their metamorphic equivalents) around these deposits would make it difficult to carry out airborne electromagnetic and magnetic surveys. Ground geophysical surveys using induced polarization and electromagnetics may aid in the delineation of the massive sulphide horizons.

-- The author is a professor of geology at Memorial University in St. John's, Nfld.