# 22. KIRUNA/OLYMPIC DAM-TYPE IRON, COPPER, URANIUM, GOLD, SILVER

22. KIRUNA/OLYMPIC DAM-TYPE IRON, COPPER, URANIUM, GOLD, SILVER

S.S. Gandhi and R.T. Bell

## INTRODUCTION

Deposits of this type are characterized by an abundance of magnetite and/or hematite in tabular bodies (Kiruna), breccia-fillings (Olympic Dam), veins, disseminations and replacements, all in continental, dominantly felsic volcano-plutonic settings in a late tectonic or anorogenic environment. The host rocks include all volcanic lithofacies ranging from proximal, epizonal feeder systems to distal volcaniclastic sediments, and related epizonal plutons. The deposits range from essentially monometallic (Fe) to polymetallic (Fe+Cu±U±Au±Ag±REEs). Large monometallic deposits have been mined for iron alone, but in polymetallic deposits associated metals are at the main economic interest.

The largest and most important examples occur outside Canada; these include the classic magnetite-apatite-actinolite deposits of the Kiruna district in northern Sweden and in southeastern Missouri, U.S.A. and the giant Olympic Dam Cu-U-Au-Ag-REE deposit in South Australia (Table 22-1). The breccia-hosted polymetallic Sue-Dianne deposit in the Northwest Territories is small and subeconomic, but it provides the best Canadian example of this deposit type (Fig. 22.1). All of these deposits are Proterozoic in age.

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1996: Kiruna/Olympic Dam-type iron, copper, uranium, gold, silver; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 513-522 (also Geological Society of America, The Geology of North America, v. P-1).

Large Phanerozoic deposits, mineralogically similar to the Kiruna deposits, occur in the circum-Pacific region (Chile, Mexico, China) and in Iran and Turkey. They are associated with intermediate to felsic volcanic and related plutonic rocks in orogenic settings and in relatively stable cratonic regions. Smaller occurrences of this type occur in the North American Cordillera, e.g. in the Tatoosh pluton of Mount Rainier, Washington, U.S.A., and in the Iron Mask batholith near Kamloops, British Columbia.

## IMPORTANCE

In Canada, mineable deposits of this type have not yet been found, and the known prospects are too small to form a significant mineral resource.

In Sweden, China, Chile, Mexico, U.S.A., and Iran, deposits of this type have been mined for iron, and form a small but significant proportion of world iron resources. The Olympic Dam deposit, discovered in 1975, is mined for copper, gold, silver, and uranium. It rivals the largest porphyry copper deposits in terms of contained copper, and forms the largest single resource of uranium in the world. Some of the Chinese deposits have been mined for iron and copper.

## SIZE AND GRADE OF DEPOSITS

In Canada, the Sue-Dianne deposit has drill-indicated resources of 8 million tonnes averaging 0.8% Cu, approximately 100 ppm U, and locally significant values in Au (Gandhi, 1989). Other polymetallic prospects of this type in the Great Bear Magmatic Zone are smaller, e.g. Mar, Damp, and Fab Main (Gandhi, 1989, 1994).

**Table 22-1.** Deposits of Kiruna/Olympic Dam-type in Proterozoic volcano-plutonic settings.

| Deposit characteristics / District/region | Kiruna-type deposits | Olympic Dam-type deposits | Age (Ma) |
|---|---|---|---|
| | Tabular & pipe-like bodies, dykes, and veins of magnetite±apatite±actinolite; essentially monometallic | Breccia (one or more stages); with hematite-magnetite matrix and Cu±U±Au±Ag±REE | |
| Gawler Ranges, South Australia [1] | | Olympic Dam *, Acropolis, Oak Dam, Wirrda Well | 1600-1590 |
| Kiruna and Bergslagen districts, Sweden [2] | Kiirunavaara *, Luossavaara, Rektorn, Haukivaara, Nukutusvaara, Lappmalmen, Painirova, Mertainen, Gruvberget, Grängesberg | | 1890-1880 |
| St. Francois Mountains, Missouri, U.S.A. [3] | Pea Ridge, Pilot Knob, Bourbon, Camel's Hump, Katz Spring, Iron Mountain | Boss-Bixby † | 1450-1350 |
| Great Bear Magmatic Zone, N.W.T., Canada [4] | Echo Bay, Contact Lake, Terra, Nod, Fab North, Ketcheson Lake, Blanchet Island, Labelle Peninsula, Regina Bay | Sue-Dianne, Mar, Fab Main, Damp | 1865-1855 |

* Estimated 2000 million tonnes.
† Multiple orebodies; mineralization mainly as disseminated copper in a felsic pluton (pers. comm., C.R. Allen, Cominco American Resources Incorporated, 1994).
[1] Roberts and Hudson, 1983; Paterson et al., 1986; Oreskes and Einaudi, 1990; Reeve et al., 1990; Parker, 1990; Hitzman et al., 1992.
[2] Geijer, 1930; Magnusson, 1970; Parák, 1975; Frietsch et al., 1979; Lundberg and Smellie, 1979; Lundstrom and Papunen, 1986.
[3] Emery, 1968; Panno and Hood, 1983; Hagni and Brandom, 1988; Kisvarsanyi and Kisvarsanyi, 1989; Marikos et al., 1989.
[4] Badham and Morton, 1976; Badham, 1978; Hildebrand, 1986; Gandhi, 1989, 1992, 1994.

Most foreign deposits are in the 100 to 500 million tonne range and average 45 to 65% iron (Cox and Singer, 1986, p. 172-174; Hitzman et al., 1992), but the Kiirunavaara and Olympic Dam deposits each contain 2 billion tonnes of ore. The Kiruna district has several other deposits (Table 22-1), and together with the Kiirunavaara, they constitute more than 3.4 billion tonnes of iron ore resource (Frietsch et al., 1979). Kiruna-type deposits also occur in the Bergslagen district in central Sweden, the largest being the Grängesberg deposit. In southeastern Missouri, some 30 deposits are known, and the larger ones among them (containing more than 100 million tonnes) are listed in Table 22-1. The aggregate resource of the Missouri district exceeds one billion tonnes of iron (Kisvarsanyi and Kisvarsanyi, 1989).

The larger Chilean deposits are El Romeral, El Algarrobo, and Los Colorados in the northern part of the country, and the El Laco deposits are in the Chilean Altiplano (Frutos and Oyarzùn, 1975; Bookstrom, 1977; Oyarzùn and Frutos, 1984). The Mexican examples are the Cerro de Mercado group of deposits in the west central part of the country (Lyons, 1988). Tonnage figures are not available for the individual Chinese iron deposits, but on the district level they approach the magnitude for those in other countries (Research Group on Porphyrite Iron Ore of the Middle-Lower Yangtze Valley, 1977; Li and Kuang, 1990; Xu, 1990). Occurrences in the North American Cordillera, exemplified by those in Washington and British Columbia (Fiske et al., 1963; Cann, 1979), are too small to be of economic interest. In Iran, the major deposits are the Chador Malu, Chogurt, and Seh Chahoon, located in the Bafq district in the central part of the country (Förster and Knittel, 1979; Förster and Jafarzadeh, 1984, 1994; Förster, 1990). The Murdere and Miskel deposits in Turkey are smaller examples (Helvaci, 1984).

The polymetallic Olympic Dam deposit averages 1.6% Cu, 0.05% U, 3.5 g/t Ag, 0.6 g/t Au, approximately 35% Fe, and contains notable amounts of rare-earth elements, in particular 0.2% La and 0.3% Ce (Reeve et al., 1990). Minerals carrying these metals are intimately associated with iron oxides, the proportion of which ranges from 30% to more than 80% in the deposit.

## GEOLOGICAL FEATURES

### Geological setting

The deposits are associated with continental felsic volcano-plutonic complexes that have been developed in late- and post-orogenic tectonic settings. In Sweden, this felsic magmatism occurred at the end of the Svecofennian orogeny ca. 1900 Ma (Gaál and Gorbatschev, 1987; Skiöld, 1987; Cliff et al., 1990). The granite-rhyolite terrane of southeastern

Missouri is part of a major, early to middle Proterozoic crustal zone that extends through central Labrador and south Greenland to Scandinavia, and is characterized by episodic felsic magmatism (Bickford et al., 1986; Gower et al., 1990; Gandhi and Bell, 1993). The Olympic Dam and other related deposits in South Australia are spatially related to a granite-rhyolite suite that formed in a stable cratonic environment, after the early Proterozoic Sleaford orogeny, and the Kimban orogenic and postorogenic events that occurred during the interval 1900 to 1650 Ma (Fanning et al., 1988; Mortimer et al., 1988; Johnson and Cross, 1991; Creaser and Cooper, 1993). They are concealed under some 300 m of flat-lying late Proterozoic and early Paleozoic strata, and were discovered by drill testing of coincident magnetic and gravity anomalies (Paterson et al., 1986; Reeve et al., 1990). The Great Bear Magmatic Zone in the northwestern Canadian Shield was formed during the period 1870-1840 Ma, after the Wopmay orogeny, which culminated ca. 1900 Ma (Hoffman, 1980; Hildebrand et al., 1987).

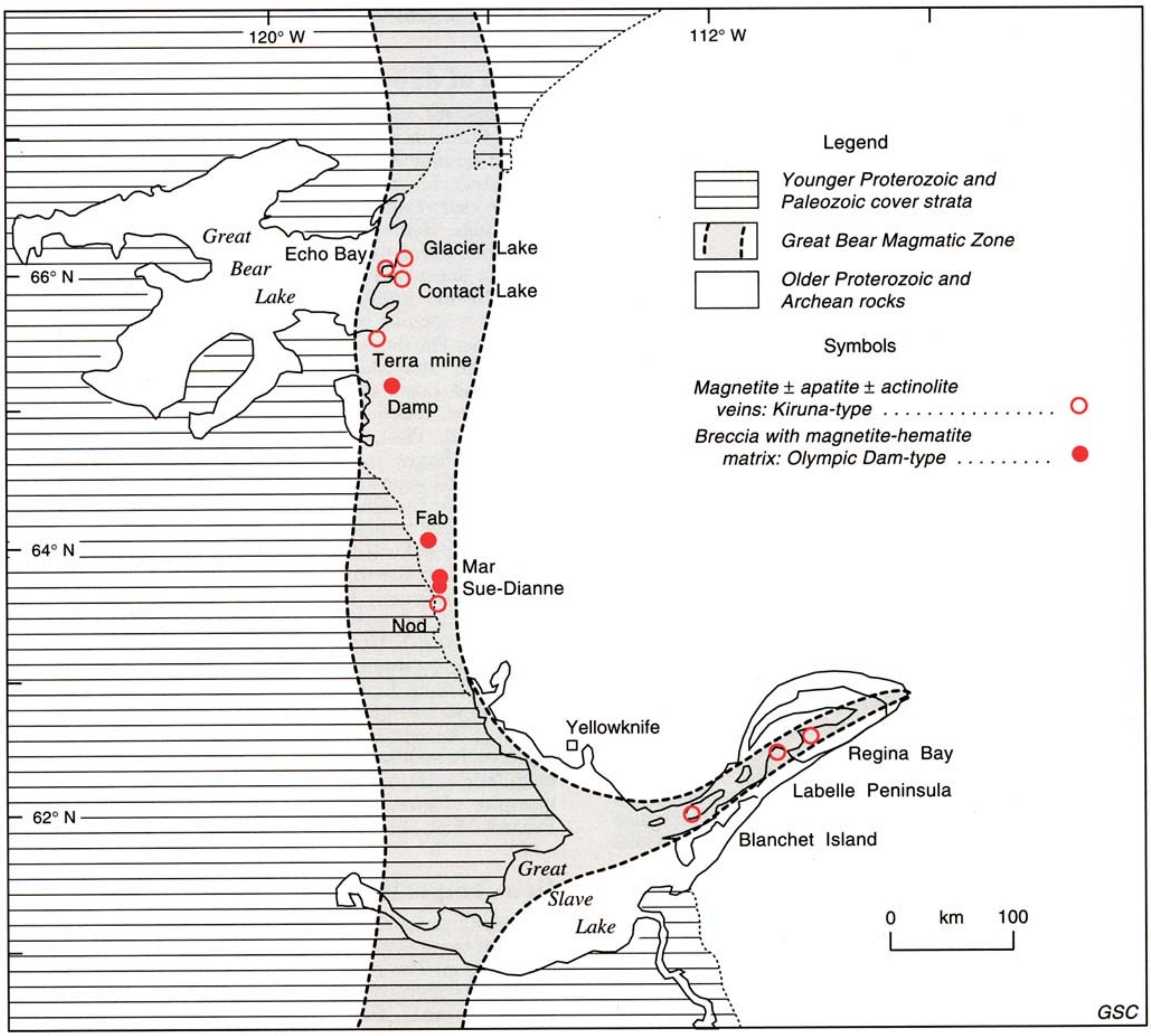


**Figure 22-1.** Areal extent of the Great Bear Magmatic Zone and location of selected occurrences of magnetite-rich veins and breccia-fillings, Great Bear Lake and Great Slave Lake area, Northwest Territories. Outline of the magmatic zone in the area covered by younger strata and lakes is based on the continuation of the magnetic anomalies, which are diagnostic of the zone in its exposed part, as noted from the regional airborne magnetic survey maps (Gandhi, 1994).

The deposits in Chile, Mexico, China, Iran, and Turkey are Phanerozoic in age. El Laco in Chile, Cerro de Mercado in Mexico, and the Iranian deposits were formed in stable cratonic environments and are closely associated with rhyolitic flows (Frutos and Oyarzùn, 1975; Förster and Jafarzadeh, 1984; Lyons, 1988). The host rocks in Mexico are part of the Tertiary Sierra Madre Occidental volcanic province, which is the world's largest continuous field of rhyolitic rocks. Other deposits in Chile and those in China are, however, in orogenic zones of Jurassic-Cretaceous age, and are associated with basalt-andesite-dacite volcanic sequences and related intrusions that are products of subduction of oceanic plates beneath continents (Oyarzùn and Frutos, 1984; Xu, 1990). In this generally compressive regime, however, extension may have played some role from time to time. For example the Chilean deposits, numbering more than fifty, occur along a large north-trending fracture zone which, according to Oyarzùn and Frutos (1984), developed at an early extensional stage, and controlled the emplacement of the host volcanic and plutonic rocks. Large granitic intrusions were emplaced during later compression. The Turkish deposits are in early Paleozoic metamorphosed volcanic strata (Helvaci, 1984).

## Age of host rocks and mineralization

The deposits range in age from 1900 Ma to recent. The age range of the Proterozoic deposits is given in Table 22-1. Older examples are not known. This may reflect the prerequisite of a thick, and laterally extensive crust for the formation of such deposits. It is noteworthy in this regard that globally the rate of crustal growth and thickening peaked in early Proterozoic time (West, 1980).

Geochronological constraints are reasonably good for the host rock/sequences based on radiometric dates and fossil records, but the precise time of mineralization in many of the deposits is less well constrained because of uncertainties inherent in isotopic studies of datable minerals in the deposits, mainly uraninite/pitchblende and apatite. Field relations and available geochronological data, however, point to the formation of the deposits essentially coeval with, or within a few million years after, the emplacement of the host rocks, as is well established for the Kiirunavaara deposit in Sweden (Cliff et al., 1990) and the Olympic Dam and Acropolis deposits in South Australia (Fanning et al., 1988; Mortimer et al., 1988; Johnson and Cross, 1991; Creaser and Cooper, 1993), and for the younger deposits, such as the Infracambrian deposits of Iran (Förster and Jafarzadeh, 1984, 1994), Oligocene deposits of Mexico (Lyons, 1988), and late Pliocene deposits of El Laco in Chile (Oyarzùn and Frutos, 1984).

## Associated structure

Block faulting, breccia development, and minor structural adjustments in the host rocks are common, but apparently neither major tectonic disturbance nor orogenic deformation occurred in these rocks immediately prior to mineralization. In some cases, major lineaments have been regarded as controlling factors, e.g. in the case of the Olympic Dam deposit (Parker, 1990).

## Relation of ore to host rocks

The ore bodies generally have sharply defined boundaries, and are commonly discordant to or cut the host volcanic, volcaniclastic, and plutonic rocks, except for some of the stratabound and stratiform deposits. Large tabular bodies in the Kiruna district are essentially concordant with the host volcanic sequence, but details of the contacts reveal some discordances as well as brecciation and veining in the host rock. In breccia deposits, the clasts are fragments of the host rocks, and the matrix is rich in the iron oxides. Replacement of wall rocks and fragments is locally intensive in some deposits as in case of the Olympic Dam deposit (Oreskes and Einaudi, 1990), but commonly it is not extensive, and is lacking in many deposits.

## Form of deposits

The deposits occur in many forms, ranging from stratabound tabular to discordant breccia zones and veins. The largest tabular deposit is the Kiirunavaara deposit, which has a strike length of 4 km and a thickness of 100 m. It dips steeply eastwards to a depth of 1.5 km, and forms a prominent ridge. Some deposits display features indicative of extrusion of iron oxide-rich melt, e.g. El Laco and Cerro de Mercado deposits (Park, 1961, 1972; Henriquez and Martin, 1978; Lyons, 1988). Other Chilean deposits are steeply dipping lenticular bodies, with associated breccia-fillings and veins. The deposits in southeastern Missouri and Iran are mostly discordant plug-like or irregular bodies with associated brecciated zones, although there are some concordant zones in the volcanic strata (Förster and Jafarzadeh, 1984, 1994; Kisvarsanyi and Kisvarsanyi, 1989). The largest complex of breccia zones is at the Olympic Dam deposit where multiple brecciation is evident (Reeve et al., 1990). The Chinese iron oxide deposits include massive irregular bodies, veins, and breccia-fillings near the boundary of subvolcanic plutons, disseminations of coarse crystals magnetite in volcanic rocks and subvolcanic intrusions, replacement bodies, and exhalative sedimentary iron-formation in a volcanic sequence (Li and Kuang, 1990). Breccia bodies in the Great Bear Magmatic Zone are lobate, circular, and tabular, as exemplified by the Sue-Dianne, Mar, and Damp deposits, respectively. They are discordant to the host volcanic strata, and contain abundant fragments of the volcanic rocks. Their vertical extent is not fully explored. In addition to these there are numerous veins in the magmatic zone, most of which are located close to the margins of quartz monzonitic intrusions (Gandhi and Prasad, 1982; Hildebrand, 1986).

## Ore composition

Two compositional varieties are common, but gradations between them also occur, forming a broad spectrum of ore composition. The most common variety is the magnetite-apatite-actinolite ore typical of the Kiruna deposits themselves. The ore is essentially monometallic, although traces of copper are not uncommon. The other compositional variety is typified by the polymetallic Olympic Dam deposit, in which the dominant iron oxide is hematite, and the ore contains significant amounts of Cu, U, Au, Ag, and REEs. The gradational varieties include magnetite-rich ore carrying

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significant amounts of Cu and U, and traces of Au, Ag, Co, Ni, and Bi, as seen in deposits of the Great Bear Magmatic Zone. Fluorite occurs in some of the deposits.

## Alteration

Hematite, chlorite, epidote, and albite are common, although individual deposits may have only one or two of these minerals. In some deposits, mostly the small ones, alteration may be negligible. In addition to the primary alteration, some of the deposits have been affected by secondary alteration. Fractures cutting some of the deposits have secondary concentrations of pitchblende that yield much younger radiometric ages, e.g. the Sue-Dianne deposit (Gandhi, 1994). Deposits subjected to paleoweathering may have undergone oxidation of magnetite to hematite, and acquired supergene enrichment of uranium and copper. The deposits in South Australia were exposed prior to the deposition of the middle Proterozoic continental siliciclastic sediments and the Paleozoic cover strata, hence they are likely to have been affected by such supergene alterations, as suggested by Oreskes and Einaudi (1990) and observed by the writers, but opinions differ regarding the importance of such alterations.

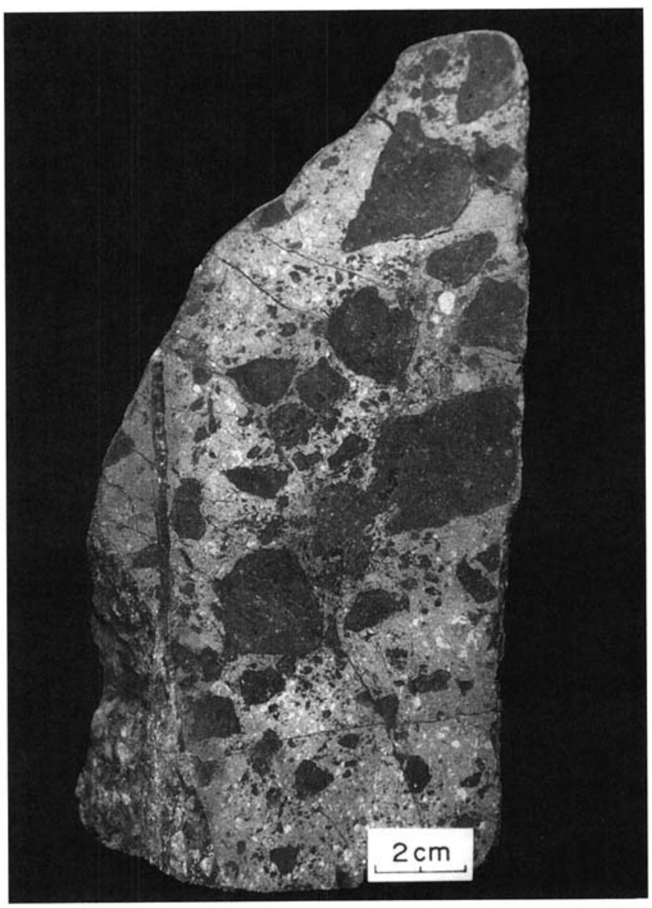


**Figure 22-2.** Photograph of a polished sample from the central part of the Mar deposit, southern Great Bear magmatic zone (Fig. 22-1), showing fragments of a feldspar porphyritic rhyodacite volcanic unit (dark grey) in magnetite matrix (medium to light grey). Note highly reflective coarse crystals and aggregates (white) in the mass of finer crystal aggregate of magnetite. Younger, veinlets contain quartz with some epidote. GSC 205427I

## Texture and mineralogy

In the monometallic Kiruna-type deposits, relative proportions of magnetite, apatite, and actinolite vary considerably. Magnetite is dominant overall, although apatite and/or actinolite form high concentrations locally in some deposits (Parák, 1975). Two or more generations of magnetite are found in many of the deposits; the earlier one occurs commonly as coarse grained, euhedral crystal aggregates, and the later ones as smaller grains. In some parts of the deposits, magnetite is altered in part, along grain boundaries and cracks, or wholly, to hematite (martite). Some of the deposits are rich in hematite, and display stratification, e.g. some of the deposits in the Kiruna, Missouri, and Mexican districts. Apatite occurs as euhedral crystals, and actinolite forms aggregates of acicular crystals. Copper sulphides, where present, form interstitial grains or aggregates. Pyrite occurs as small euhedral to subhedral crystals. The proportions of other minerals, such as calcite and quartz, are negligible. Cobalt and nickel arsenides occur in some of the veins in the Great Bear Magmatic Zone.

In the polymetallic Olympic Dam deposit, hematite predominates over magnetite, and forms 30 to 70% of the ore as breccia matrix. More than one generation of hematite is present. It occurs as fine grained aggregates and laths. Copper sulphides, pitchblende, and coffinite are intimately associated with hematite as disseminations, stringers, and aggregates (Roberts and Hudson, 1983; Oreskes and Einaudi, 1990; Reeve et al., 1990). Gold occurs locally in some of the deposits, and is commonly associated closely with copper minerals. Chalcopyrite, bornite, chalcocite, pitchblende, coffinite, and native gold are minerals of prime value, and fluorite, pyrite, bastnaesite, florencite, quartz, sericite, and barite are accessory minerals.

In the breccia deposits of the Great Bear Magmatic Zone, pitchblende, coffinite, and sulphides form aggregates, disseminations, veins, and stringers in the magnetite-specularite matrix. Fragments of volcanic rocks are common, e.g. in the Mar deposit (Fig. 22-2). Some vein-type deposits in this district display zones of coarse apatite and actinolite crystals that have grown inward from the walls (Gandhi and Prasad, 1982).

The extrusive character of some deposits, such as El Laco and Cerro de Mercado, is reflected in their lava flow-like character and prismatic crystals that reflect rapid cooling (Park, 1961, 1972; Henriquez and Martin, 1978; Lyons, 1988). Dykes and intrusive breccias, indicative of injection of iron-rich ore 'melt', are associated with deposits of the Kiruna district, and dendritic magnetite and miniature diapir-like apatite concentrations also reflect their near surface intrusive or extrusive character (Geijer, 1930; Frietsch, 1978; Nyström and Henriquez, 1994). Replacement textures have been reported in some of the Chinese deposits, and have been referred to as 'skarnoid' (Li and Kuang, 1990). Primary disseminations of magnetite occur

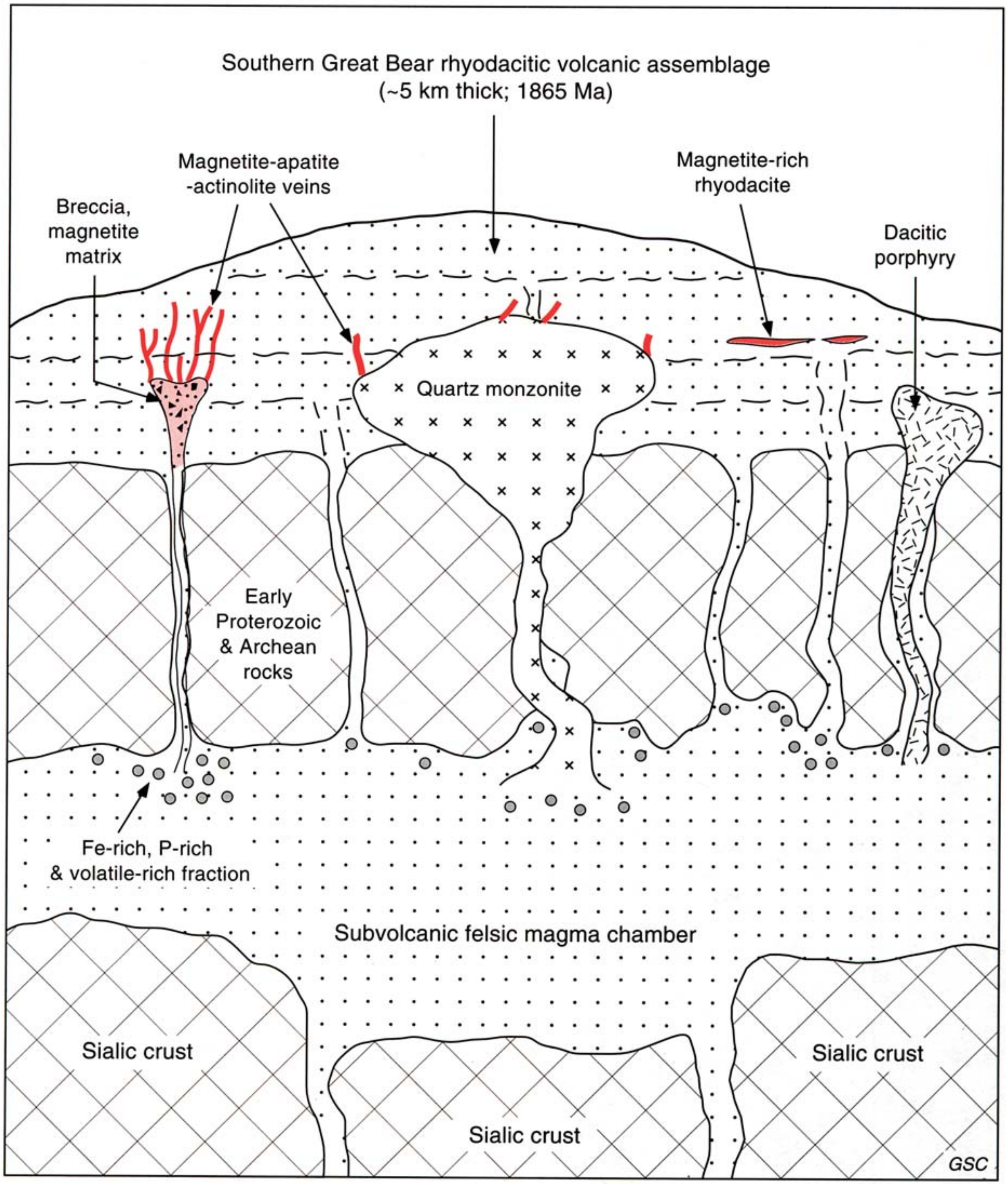


**Figure 22-3.** Diagram illustrating a genetic model for the magnetite-rich veins and breccia-fillings related to the Great Bear magmatic activity (Gandhi, 1994).

in host igneous intrusions, some parts of which contain this mineral well in excess of accessory amounts, viz., in the range of 5 to 10%.

## DEFINITIVE CHARACTERISTICS

Deposits of Proterozoic age have some definitive characteristics as listed below. Many of the Phanerozoic examples do not conform to all of these features, reflecting a wide range of geological environments in which deposits of this type can form.

i) High concentrations of magmatic or hydrothermally deposited iron are present.

ii) Host rocks are commonly felsic to intermediate volcanic rocks and related epizonal plutons, which are meta- or peraluminous and mildly to highly alkaline in character.

iii) The deposits are coeval with the volcano-plutonic activity that formed the host rocks, and are younger than 1900 Ma.

iv) Copper, gold, silver, uranium, and rare-earth elements occur in variable amounts in association with magnetite and hematite.

v) Hematitization, epidotization, carbonatization, and soda metasomatism of the host rocks are common primary alteration features of the deposits.

## GENETIC MODEL

Processes of formation of this diverse group of deposits are magmatic fractionation and hydrothermal activity, the latter in some cases involving meteoric waters. Opinions differ as to the relative importance of these and in details of mineralization for individual deposits; but there is a consensus that iron, the most abundant metal in these deposits, is derived from the same magma source that formed the host volcanic and plutonic rocks. For many deposits compelling textural and structural evidence points to crystallization from an iron-rich, volatile-charged magmatic fraction or 'melt' that intruded and/or extruded, and cooled like magma (Geijer, 1930; Park, 1961, 1972; Frietsch, 1978; Henriquez and Martin, 1978; Lyons, 1988; Nyström and Henriquez, 1994). Magnetite-rich deposits can be expected to form from such fractions at high temperatures in subsurface environments, and hematite-rich deposits at relatively lower temperatures in near surface and subaerial environments. The proportion of magmatic water in such fractions is conjectural. Mixing with oxidized meteoric waters would favour deposition of hematite. Formation of the hematite-rich Olympic Dam deposit has been attributed to magmatogenic hydrothermal solutions in the near surface environment of a volcano-plutonic complex, characterized by repeated fault-related brecciation, phreatomagmatic explosions, epiclastic sedimentation, and chemical corrosion (Reeve et al., 1990). Hematite (or specularite) can also develop by partial or complete alteration of earlier formed magnetite due to postdepositional changes in a mineralizing system. For some of the hematite-rich stratabound deposits, there are differences of opinion as to whether hematite was deposited as a primary iron oxide from hydrothermal solution, formed as a replacement of magnetite and other minerals, or was precipitated in a marine exhalative-sedimentary environment. Replacement may be due to the action of hydrothermal fluids, or of oxidized ground waters if a deposit was subjected to weathering processes.

Apatite is common in magnetite-rich deposits, and phosphorus-bearing minerals (florencite, xenotime, and monazite) occur in the Olympic Dam deposit. The role of phosphorus in lowering the crystallization temperature of magnetite in magma, and thus facilitating the generation and transport of an iron-rich magmatic fraction has been strongly emphasized by many workers (Geijer, 1930; Frietsch, 1978; Lyons, 1988). Volatiles would further enhance enrichment of iron in a residual magmatic fraction. Violent escape of volatiles would create space and conditions favourable for forceful injection or passive ingress of an iron-rich fluid, and for deposition of iron oxide. This process is manifested on a small scale as veins and breccia fillings in the roof zones and along the margins of epizonal quartz monzonite plutons in the Great Bear Magmatic Zone (Fig. 22-3). Differentiation of the plutons in situ may be adequate to explain the formation of these small occurrences (Gandhi, 1994). Large deposits, on the other hand, were most likely developed by differentiation in larger magma chambers at depth, which were the source of the volcanic rocks, subvolcanic plutons, and iron-rich fractions. Transportation of the iron-rich fractions to higher levels took place via their ascent in a pulse or pulses, either in association with silicate fractions or separately, to tectonically prepared zones or in outlets created by explosive discharge of contained volatiles. Among the volatiles, F, Cl, and $H_2O$ are considered the most important ones. With an increase in proportion of magmatic and/or meteoric water, the iron-rich fraction passes into hydrothermal solution, and forms deposits with hydrous phases as is the case with the Olympic Dam deposit. Magnetite-rich deposits, on the other hand, show a paucity of hydrous minerals that suggests low water/rock ratio and a limited role of meteoric water. Furthermore, sulphides and carbonates are present in only small amounts, reflecting the paucity of S, CO, and $CO_2$ in the mineralizing fluids. The system thus differs from the porphyry copper system, which involves development of a carapace in the roof zone of a pluton and a second boiling, prior to mineralization (Burnham and Ohmoto, 1980). The porphyry copper system has a relatively greater water/rock ratio, lower abundance of iron, lower oxygen fugacity, and higher sulphur pressure. The differences, however, become obscure in the case of alkaline porphyry gold-copper deposits, which have associated pods and veins of magnetite and apatite (±amphibole).

The ultimate source of iron and mechanisms for its concentration into mineralizing fluids are topics of considerable speculation and debate, as can be expected for a group of such diverse deposits. The sources that have been invoked are calc-alkaline mafic and/or intermediate and felsic magmas (Geijer, 1930; Frietsch, 1978; Oyarzùn and Frutos, 1984; Hildebrand, 1986), alkaline and peralkaline magmas (Förster and Jafarzadeh, 1984, 1994; Förster, 1990), and pre-existing sedimentary iron deposits (Park, 1972). The mechanisms suggested include liquid immiscibility of the silicate and iron-phosphorus melts (Badham and Morton, 1976), crystallization differentiation (Geijer, 1930; Frietsch, 1978), volatile transfer (Lyons, 1988), hydrothermal concentration (Bookstrom, 1977; Hildebrand, 1986; Oreskes and Einaudi, 1990; Reeve et al., 1990) and mixing of a relatively reduced fluid with an oxidized fluid derived from a mafic or mixed mafic and felsic volcanic provenance C. Haynes et al., 1995) in the case of magmatic sources; and high grade metamorphism and assimilation of iron-rich rocks by magma in the case of a sedimentary source. In the authors' opinion, the most likely scenario is differentiation and volatile transfer in a dacitic to rhyolitic magma chamber at depth.

## RELATED DEPOSIT TYPES

Alkaline porphyry Cu-Au deposits have veins and irregular pods of magnetite±apatite±actinolite(amphibole), and many skarn deposits are rich in magnetite and contain copper and other metals, hence both can be considered as related deposit types. Felsic volcanic-associated uranium deposits are indirectly related to the Kiruna/Olympic Dam-type in that they too occur in the continental, felsic-dominated, volcano-plutonic terrane, commonly in the late tectonic and post-tectonic environments.

Some iron oxide-rich breccias and lensoid bodies in metasedimentary rocks are mineralogically and texturally comparable with the deposits of Kiruna/Olympic Dam-type. They are, however, in settings that lack the evidence of large scale coeval magmatic activity, which is regarded here as an important feature of this deposit type. For example, breccias in the middle Proterozoic, folded sediments of the Wernecke Supergroup in Yukon Territory contain Cu, U, Co, Ag, and Au, and resemble those of the Olympic Dam deposit in many respects. There is no field evidence for any major igneous event to which the Wernecke breccias can be directly linked, but a deep seated magmatic hydrothermal source has been invoked for the formation and mineralization of the breccias (Hitzman et al., 1992; Thorkelson and Wallace, 1993, 1994). On the other hand, an evaporite diapir model, based on comparison with the Copperbelt in Zaïre and the Flinders Ranges in South Australia, has been proposed by Bell (1989). It requires dissolution and removal of the evaporites, but evidence for the presence of evaporites in or beneath the Wernecke Supergroup is weak.

Lensoid bodies of magnetite-apatite±amphibole, mineralogically similar to the Kiruna deposits, occur in some folded metasedimentary beds of early Proterozoic age, e.g. in the basement of southern Great Bear Magmatic Zone (Gandhi, 1994) and in the Singhbhum district in eastern India (Sarkar, 1984). They are essentially metamorphic segregations of the constituents deposited with the enclosing sediments.

## EXPLORATION GUIDES

Important geological guides are the features listed as "Definitive characteristics". Of these, the extensional tectonic environment is of fundamental importance, especially if accompanied by voluminous felsic volcanism. There is indeed an empirical observation that continental felsic or bimodal (basalt-rhyolite) suites formed during the interval 2000 to 1400 Ma are very important, as found in the Proterozoic terranes of the Canadian, Baltic, and Australian shields. The most important geophysical guides are coincident magnetic and gravity anomalies.

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