
Geological Features and Genetic Models of Mineral Deposits

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INTRODUCTION

Mineral deposits are natural concentrations of one or more mineral commodities that may be termed *ore deposits* if they reach levels where economic extraction is viable. They form as a result of many geological processes, but they form within specified geological settings. Similar genetic processes may operate to form deposits that have similar characteristics and, thus, may define a “class” of deposits. The geological processes that may concentrate minerals include fractional crystallization of magmas, release of volatiles from a crystallizing magma, magmatic interaction with host rocks, metamorphic reactions producing fluids, chemical changes in circulating heated groundwater, organic interactions, and weathering, among others. Eckstrand et al. (1995) neatly summarize that “mineral deposit types” are mineral deposits that share a set of geological attributes and contain a particular commodity (or commodities) that collectively distinguish them from other types.

Ideally, mineral deposit types should reflect how the mineral deposit was actually formed, and in this case, one might be able to use the term *genetic model*. However, in many cases there is considerable debate among geologists as to how a specific deposit was formed, and thus classifications based purely on a given genetic model will encounter problems. An alternative is to classify deposits based on empirical features (minerals, host-rock association, etc.), which will lead to the unique fingerprint of a particular deposit (i.e., a descriptive model). Even though no two mineral deposits are identical, empirical descriptions of deposits tend to show natural groupings into a small number of loosely definable categories or types. In turn, these categories tend to coincide with genetically derived models; so even by using purely physically descriptive classifications, there is often a close coincidence between these and models defined using genetic criteria.

Prior to the 20th century, models for the formation of mineral deposits were subject to the often-polarized views of either plutonist (all deep igneous origins) or neptunist (all sedimentary origins) theories for the origin of rocks, and it was really only in the 20th century that modern views of mineral deposit formation emerged.

From the late 1960s, plate tectonic theory has revolutionized geological thinking, and in the mid-1980s, Guilbert and

Park (1986) devised a mineral deposit classification scheme based on plate tectonics.

Figure 3.1-1 is a very broad attempt to show an interpretation of the environment of formation of key mineral hypogene deposit types with respect to plate tectonic settings in their broadest sense.

ORE GENESIS (FORMATION PROCESSES)

Linking deposit types directly to ore-forming processes is certainly the preferred way to classify, as it will provide better criteria for the understanding of the deposit with respect to associated features (such as how its formation relates to associated igneous rock suites, alteration patterns, etc.). In turn, this will lead to better exploration models for their discovery and evaluation. Nevertheless, descriptive models are needed in practical terms to aid engineers in the evaluation of particular deposits (choice of exploration tool, elements to analyze in geochemical exploration, etc.).

Evans (1993) divides ore-forming processes into the four main categories of internal processes, hydrothermal processes, metamorphic processes, and superficial processes. The former three processes relate to subsurface phenomena, while the last of these obviously covers those processes occurring at the earth’s surface. In this chapter it is preferred to use the three main divisions of orthomagmatic, hydrothermal, and surficial deposits in line with Einaudi (2000) and broadly encompassing the range of Evans’ criteria (Evans 1993). Hydrothermal should be further subdivided into magmatic hydrothermal, metamorphic hydrothermal, diagenetic hydrothermal, and surface hydrothermal to refine the nature of the hydrothermal process.

Further qualifying terms such as syngenetic and epigenetic are useful in discussing the genesis of ore deposits. Syngenetic is used for mineral deposits that are interpreted to have formed at the same time as the enclosing rocks. Syngenetic deposits are bounded by the host rocks themselves as in the case of a deposit formed by crystallization of magma, the result of precipitation within sediments on the seafloor from a hydrothermal vent, or perhaps by the physical sedimentation of heavy mineral sand. Conversely, epigenetic is used for mineral deposits that formed later than the enclosing rocks, and as a result the deposits are found as masses, layers,

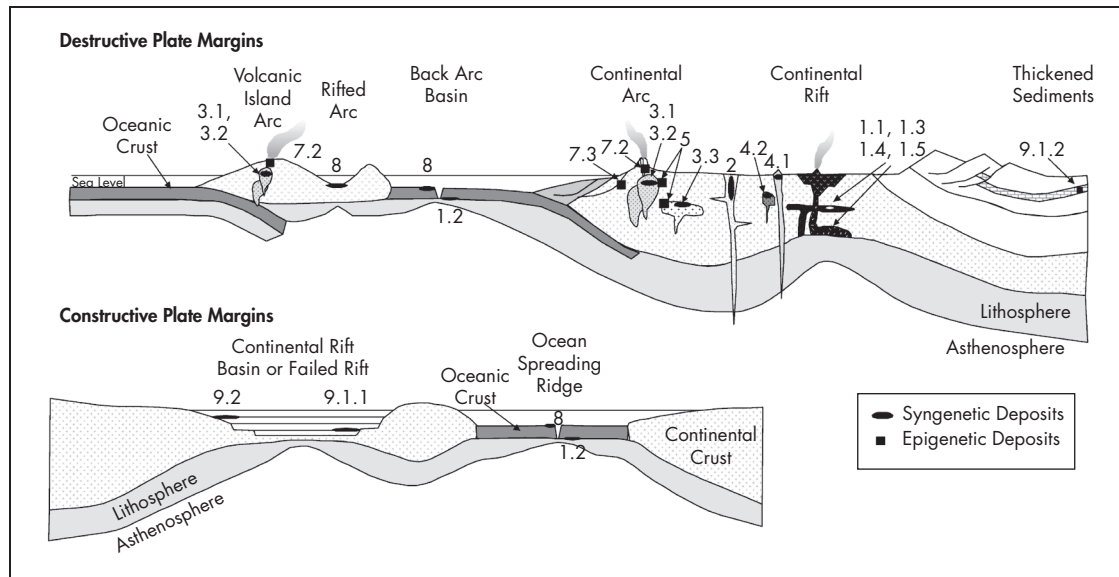


Figure 3.1-1 Plate tectonic settings for key magmatic and hydrothermal deposit types (numbers refer to deposit classes and types shown in Table 3.1-1)

or disseminations that are seen to cut or overprint the original rock. An example of this might be a gold-quartz vein crossing a deformed greenstone.

Hypogene is another useful term used to describe mineralization formed by processes deep in the earth, whereas *supergene* refers to processes superimposed on original mineralization. Often these terms are synonymous in their use with the terms *primary* and *secondary*, respectively. In the context of a sulfide deposit formed, for instance, as a magmatic segregation of chalcopyrite that is then partly oxidized by weathering to, for example, chalcocite, the chalcopyrite is considered to be hypogene (or primary), while the weathering product chalcocite would be termed supergene (or secondary).

KEY DEPOSIT-FORMING PROCESSES

Orthomagmatic Deposits

Orthomagmatic deposits are those that form from primary magmatic processes (i.e., cooling and crystallizing magmas). They are hosted within the rocks from which they formed. Therefore, they are by definition also syngenetic. Deposits may form as a result of

- Solid phases crystallizing as a differentiate as the magma cools;
- Minerals crystallizing from the enriched residual fluids formed as magma cools and crystallizes;
- The formation of a sulfide melt that developed by immiscibility from a coexisting silicate melt; or
- Where a magma transports xenolithic or xenocrystic phases that it has picked up on its passage through the earth's crust.

Hydrothermal Deposits

Hydrothermal deposits are those that literally form from hot water (hydrothermal fluids) circulated through the earth's crust. Direct evidence for the presence of these fluids in the earth's crust are surface manifestations such as hot springs and fumaroles, but indirect evidence is provided by the presence

of hydrous minerals in even crystalline rocks. Hydrothermal fluids may have their origin in igneous plutons or from metamorphic reactions deep in the crust, but they can also be the result of deeply circulated and heated meteoric or seawater, or they may be the release of trapped water from sedimentary basins undergoing diagenetic change.

Tracking the original source for this range of fluids is now largely possible using studies of fluid inclusions trapped in minerals and the use of a range of isotopic markers. At one end of the range of hydrothermal deposits there are fluids directly related to or exsolving from cooling igneous intrusions, and at the other end there are surface waters heated as they have been circulated into deeper, hotter parts of the earth's crust. Technically speaking, the term *hydrothermal* should only be used for water-dominated fluids, whereas fluids in the gaseous state should be referred to as *pneumatolytic*. Hydrothermal deposits can be either syngenetic or epigenetic, depending on where and when the deposit formed.

Magmatic Hydrothermal

Magmatic-hydrothermal fluids form as a body of magma cools and crystallizes. In some cases the magmatic system may simply be a passive source of heat that drives the circulation of fluids exotic to the magma through adjacent fractured crust into which the magma is intruding. In many other cases the magma, particularly felsic magmas such as those that form granitic rocks, contain very significant amounts of miscible water, which is carried in the magma itself. As this magma cools and crystallizes it becomes more concentrated and eventually forms an immiscible fluid phase, which in the process collects other components that prefer to partition from a silicate melt into a hydrous-fluid phase. Gases are also miscible in silicate melts at higher temperatures and pressures. But again, as the magma cools and is intruded into shallower portions of the crust, the gases become immiscible and may partition into a fluid phase or may escape entirely as a vapor (pneumatolytic fluids). Components concentrating in a fluid phase that may exsolve from magma include chloride ions, which leads

Table 3.1-1 Major classes of economically important mineral deposits

Class	Type/Subtype	Formation		
1 Deposits in mafic magmas	1.1 Layered chromite deposits	Syngenetic		
	1.2 Podiform chromite deposits	Syngenetic		
	1.3 Titanomagnetite deposits	Syngenetic		
	1.4 Magmatic platinum group metal deposits	Syngenetic		
	1.5 Nickel sulfide deposits	1.5.1 Sudbury	Syngenetic	
1.5.2 Flood basalt association		Syngenetic		
1.5.3 Ultramafic volcanic association		Syngenetic		
1.5.4 Other mafic and ultramafic intrusive associations		Syngenetic		
2 Magmatic diamond deposits	Kimberlites and lamproites	Syngenetic (xenocrystic)		
3 Deposits associated with felsic magmas	3.1 Porphyry Cu-Mo-Au deposits	Epigenetic (with respect to host rocks), contemporaneous with magmatic activity		
	3.2 Porphyry Mo (W) deposits	Epigenetic (with respect to host rocks), contemporaneous with magmatic activity		
	3.3 Granite-hosted Sn-W deposits	Epigenetic (with respect to host rocks), contemporaneous with magmatic activity		
	3.4 Intrusion-related gold deposits	Epigenetic (with respect to host rocks), contemporaneous with magmatic activity		
4 Deposits associated with peralkaline and carbonatite magmas	4.1 Peralkaline Ta-Nb, rare earth element deposits	Syngenetic with late magmatic activity and epigenetic		
	4.2 Carbonatite Cu, rare earth element, Nd, Fe, P deposits	Syngenetic and epigenetic		
5 Skarn and carbonate replacement deposits		Epigenetic		
6 Iron oxide copper-gold deposits		Epigenetic		
7 Hydrothermal gold and silver deposits	7.1 Sediment-hosted gold deposits	Epigenetic		
	7.2 Epithermal gold and silver deposits	High-sulfidation epithermal	Epigenetic	
		Low-sulfidation epithermal	Epigenetic	
7.3 Lode (or orogenic) gold deposits		Epigenetic		
8 Volcanic-hosted or volcanogenic massive sulfide deposits	Mafic	Syngenetic		
	Bimodal mafic	Syngenetic		
	Pelitic mafic	Syngenetic		
	Bimodal felsic	Syngenetic		
	Siliciclastic felsic	Syngenetic		
9 Sediment-hosted deposits	9.1 Sediment-hosted sulfide deposits	9.1.1 Sedimentary exhalative Pb-Zn (Cu) in clastic sediments (+Broken-Hill type deposits)	Syngenetic (<i>Epigenetic</i>)	
		9.1.2 Mississippi Valley type (MVT) Pb-Zn	Epigenetic	
		9.1.3 "Irish" type Pb-Zn (Cu)	Syngenetic-epigenetic	
		9.1.4 Clastic sediment-hosted Cu	Epigenetic	
	9.2 Sediment-hosted iron and manganese deposits	9.2.1 Ironstones		Syngenetic
		9.2.2 Banded iron formation (BIF)	9.2.2.1 Algoma BIF	Syngenetic (+epigenetic)
			9.2.2.2 Superior BIF	
			9.2.2.3 Rapitan BIF	
		9.2.3 Manganese ore		Syngenetic
	9.3 Sedimentary uranium deposits	9.3.1 Unconformity vein type uranium		Epigenetic
		9.3.2 Sandstone-hosted uranium		Epigenetic
	9.4 Gold and uranium in conglomerates			Syngenetic (+epigenetic?)
	9.5 Chemical sediments	9.5.1 Evaporites		Epigenetic
9.5.2 Manganese nodules			Syngenetic	
10 Ores related to weathering	10.1 Laterites	10.1.1 Bauxite	Epigenetic	
		10.1.2 Nickel (cobalt) laterite	Epigenetic	
		10.1.3 Lateritic gold	Epigenetic	
	10.2 Supergene weathering	10.2.1 Secondary copper		Epigenetic
		10.2.2 Secondary zinc		Epigenetic
11 Placer deposits			Syngenetic	

to the formation of high-temperature brines that are effective solvents for many metals such as iron, copper, lead, and zinc (Brimhall and Crerar 1987). These metal-rich fluid phases can then migrate away from the magma and can begin to interact with minerals and fluids in previously crystallized magma or outside rocks, which can cause these to become altered by chemical reaction and lead to precipitation of new mineral phases, including the ore minerals. These fluids can also concentrate miscible gases, for example, carbon dioxide (CO₂), sulfur dioxide (SO₂), and hydrogen sulfide (H₂S), which can also aid in the transport of dissolved components with vapor-dominated fluids derived from magmas implicated in the transport of some metal deposits (Williams-Jones et al. 2002).

All mineral deposits that formed by replacement or in fractures around the cooled magma chamber are by definition epigenetic because they overprint the host rocks, although they are contemporaneous with associated magmatic activity. Other rarer metals may remain miscible in the silicate magmas much longer but may become concentrated in the final hydrous fluid phase, trapped at the very final moment within the cooling magma chamber itself. In this case, the deposits are defined as syngenetic, because the deposit fills interstices in the magma as it crystallizes in a similar fashion to orthomagmatic deposits. Depending on the crystallization path for the magma and its interaction with external components, a range of deposits may form from these processes.

Metamorphic Hydrothermal

Metamorphic-hydrothermal fluids form as metamorphism results in mineral-chemical processes that may release volatiles, often dominated by water but which may include gases such as CO₂. Metamorphism is induced in rocks by external heat or pressure or (usually) by a combination of both. Heat may be provided by the deep burial of a rock mass through time or alternatively by the intrusion of a magma body nearby. Pressure to cause metamorphism may be provided again during deep burial or else by tectonic processes. By definition, all of these deposit types are epigenetic because the effects are seen to overprint rocks that have already formed.

Diagenetic Hydrothermal

Diagenetic-hydrothermal fluids are formed as pore waters trapped during sedimentation, then loosely bonded to clays and other minerals, which are released during compaction and lithification. This process may develop on a large scale in a sedimentary basin undergoing burial and lithification and is a related process to hydrocarbon generation. The released water can pick up dissolved salts (becoming a brine), which then has a greater ability to transport many cations and ligands to a point of deposition to form an ore deposit (Brimhall and Crerar 1987). In these sedimentary basins, evaporite beds may be a specific source of salts that can be dissolved by the basinal water.

Basins undergoing diagenesis become heated, and thus the basinal brine may become a highly effective solvent for dissolving large quantities of metals. These basinal brines may then migrate via crustal faults and permeable horizons to depositional environments. Syngenetic deposits can form when these fluids are expelled in a submarine or lacustrine environment, where chemical precipitation can result in layered deposits of minerals. Epigenetic deposits can also be formed where the fluid interacts with already lithified rocks causing alteration and the precipitation of minerals.

Surface or Seafloor Hydrothermal

Surface or seafloor hydrothermal fluids are generated as deeply penetrating meteoric- or seawater-derived waters descend and become heated deeper in the crust. This process is particularly apparent in regions where there is elevated crustal heat flow, often where the earth's crust is being thinned. In the case of the seafloor, this phenomenon is common where a new ocean is formed by the seafloor spreading through the formation of submarine volcanoes. On land, such hydrothermal fluids can be generated in zones of crustal attenuation, often associated with subaerial volcanism. These phenomena may not directly relate to igneous activity, however, as fluids may be simply interacting with residual and convecting heat in the deep crust.

Surface manifestations of this process may be the presence of hot springs on land or seafloor hydrothermal vents. Deposits formed by these processes can be epigenetic, where they replace rocks already formed, or they may be syngenetic, for example, in the case of seafloor hydrothermal vents where exhaled fluids may result in layers and masses of chemically precipitated ore minerals. Syngenetic deposits can also form on land where hot springs vent to the surface and minerals are deposited in layered masses.

SURFACE UPGRADE (LOW TEMPERATURE)

Low-temperature (<50°C) surface processes can also be responsible for the formation of economic ore deposits. Physical processes such as physical erosion, transportation, and deposition lead directly to the redistribution and accumulation of specific minerals. Such deposits are formed as a result of the differing physical and chemical behavior of the minerals forming the original rock. These physical processes can be either hydraulic (water) or aeolian (wind).

Weathering is also a very important ore-forming process resulting in chemical change and redistribution of components in surface rocks by migrating solutions. The differential chemical properties of minerals at the earth's surface and within the surface-crustal interface can lead to residual upgrades or chemical dissolution and reprecipitation mechanisms to concentrate the metal/mineral of interest. In such cases, ore formation is driven by the circulation of largely meteorically derived water at the earth's surface, although similar analogous processes can take place on the seafloor. These subsurface waters can dissolve components, reprecipitating them at favorable mineral sites or surface interfaces. Another process important for ore formation that is a surface phenomenon is the process of evaporation. Dissolved salts precipitate as water is lost in an evaporating basin for example, or by the evaporation of water from the ground's surface due to heat energy from the sun.

SPECIFIC DEPOSIT TYPES

Deposits have been classified in a number of ways by different authors. Table 3.1-1 shows the classification scheme preferred here, which is largely based on empirical features of the deposits but which happily coincides with genetic classification in many cases. A number of less-important deposit types are not covered in this section. Their omission (e.g., vein-style base metal deposits) is largely on the grounds that current economic considerations do not make these deposits attractive targets for mining operations. References for this section are in the "Source References" section at the end of the chapter.

CLASS 1: DEPOSITS IN MAFIC MAGMAS**Type 1.1: Layered Chromite Deposits**

- Bushveldt, South Africa
1,100 Mt (million metric tons) at 42% to 45% Cr₂O₃
(chromium oxide)
- Great Dyke, Zimbabwe
113 Mt at 26% to 51% Cr₂O₃
- Kemi, Finland
59 Mt at 26% Cr₂O₃
- Campo Formoso, Brazil
17 Mt at 17% to 21% Cr₂O₃
- Bird River, Canada
60 Mt at 4.6% Cr₂O₃

Age and Distribution

Most significant deposits of this type are Achaean or Early Proterozoic in age and are known in cratonic regions of Canada and the United States, South Africa, South America, and Finland.

General Characteristics

These deposits occur in large layered intrusions that show a differentiation into a lower ultramafic zone and an upper mafic zone. They generally occur in two forms: the first are emplaced like tabular sills where igneous layering is parallel to the intrusion floor (or roof), whereas the second are funnel-shaped, with the layering dipping into the center like a saucer shape. Bodies can be enormous (e.g., Bushveldt, which is 480 × 380 km; Great Dyke, which is 530 × 6 km) or they can be quite small (e.g., Kemi, which is 15 × 2 km). The intrusions are developed in different tectonic settings and can relate to cratonic rifts or be synvolcanic intrusions.

The deposits themselves generally take the form of laterally continuous chromite-rich layers that vary from one centimeter to several meters thick. Laterally, they can extend for many hundreds of kilometers. The chromite may be interlayered with other rock types such as dunite, peridotite, pyroxenite, anorthosite, or norite, but those with the best grades are usually associated with primitive peridotites.

Type 1.2: Podiform Chromite Deposits

- Kempirsai, Kazakhstan
>90 Mt at 50% Cr₂O₃
- Kavak, Turkey
2 Mt at 20% to 28% Cr₂O₃

Age and Distribution

Podiform chromite deposits are all typically Phanerozoic in age, occurring in the tectonized mantle parts of ophiolite complexes. Significant deposits are recorded in the Philippines (Tertiary), Albania (Jurassic), Turkey (Jurassic-Cretaceous), Kazakhstan (Silurian), and many small occurrences in the Caledonian-Appalachian orogen.

General Characteristics

The chromite is found in the basal part of an ophiolite sequence, namely, the ultramafic tectonite (usually a harzburgite). Ophiolites are the obducted fragments of oceanic crust usually preserved in orogenic belts, where thrusting has exposed the basal mantle sections of the sequence. These ultramafics are likely to be the residual mantle, and the upper

contact of this unit with overlying cumulate ultramafic dunites is normally taken to be the petrological Moho.

The deposits take the form of lens-like bodies of massive to heavily disseminated chromite, although often the bodies are highly discordant and rod-like. The variable morphology undoubtedly reflects the tectonized nature of these upper mantle rocks. Ores are dominated by chromite that occurs with interstitial olivine, orthopyroxene, clinopyroxene, and plagioclase. This assemblage is often partially serpentinized or altered to more hydrous minerals such as chlorite, amphibole, talc, and carbonate. Textures may appear to be magmatic or clearly overprinted by deformation.

Type 1.3: Titanomagnetite Deposits

- Lac Tio, Canada
125 Mt at 32% to 35% TiO₂ (titanium oxide)
- Tellnes, Norway
>380 Mt at 18% TiO₂
- Kachkanar, Russia
6,937 Mt at 53% Fe, 5.3% TiO₂, 0.2% V

Age and Distribution

Large anorthosite intrusions of Mesoproterozoic age hosting titanium, vanadium, and iron extend from North America to the Sveconorwegian province of Scandinavia. Similar deposits are found in many tectonic belts around the world, such as in the Ural Mountains in Russia.

General Characteristics

Deposits relate to large differentiated intrusive complexes composed largely of anorthosite, gabbro, norite, and monzonite. Concentrations of metallic oxide minerals occur in the following styles: disseminated oxides in the host rocks, conformable lenses with sharp to indistinct boundaries with earlier crystallized phases of anorthosite and gabbro, late-stage dykes rich in oxide minerals cutting host gabbro and anorthosite, and as replacements linked to alteration zones on the margins of host intrusions. Ore minerals may be disseminated and interstitial to silicate minerals or else form massive aggregates separated from the silicates. The giant Lac Tio deposit in Canada is an irregular, tabular, 1,100-m-long, 1,000-m-wide intrusion, whereas the Tellnes deposit in Norway takes the form of a 14-km-long dyke.

Type 1.4: Magmatic Platinum Group Metal (PGM) Deposits

- Bushveldt Merensky Reef, South Africa
2,160 Mt at 8.1 g/t PGM + Au
- Bushveldt UG2, South Africa
3,700 Mt at 8.7 g/t PGM + Au
- Bushveldt Platreef, South Africa
1,700 Mt at 7.3 g/t PGM + Au
- Stillwater (J-M Reef), United States
421 Mt at 18.8 g/t PGM + Au
- Great Dyke, Zimbabwe
1,680 Mt at 4.7 g/t PGM + Au
- Lac des Iles, Canada
6.7 Mt at 5.4 g/t PGM + Au

Age and Distribution

The bulk of the intrusions hosting these deposits are Archaean to Proterozoic. Stillwater and a group of smaller Canadian

examples are Achaean, whereas the Great Dyke and Bushveldt are early and mid-Proterozoic, respectively. The Skaergaard intrusion in Greenland is Tertiary in age and is the youngest known. The deposits occur in large intra-continental rifts or at the margins of rifted continents, and thus they are usually hosted in older continental crust.

General Characteristics

The mineralization in all cases is largely stratiform, but there are some differences in the degree of conformity to enclosing host rock. Broad common features occur in all deposits. For example, PGMs are almost entirely found within sulfides and specific PGMs. The morphologies and mineral associations are diverse, however.

The Proterozoic-age Bushveldt-layered intrusion is the world's largest PGM repository. The intrusion forms a clover-leaf-shaped outcrop measuring 400×240 km, and it comprises mafic and ultramafic cumulate rocks located around a granitic core. The lower cumulate rocks, the Rustenburg Layered Suite, is up to 7 km thick, with the lowermost Critical zone the main host to PGM deposits in the Merensky Reef and UG2 layers. Mineralization is also developed in a unit known as the Platreef, which forms the base of the Critical zone in the northeastern lobe of the Bushveldt.

Type 1.5: Nickel Sulfide Deposits

The four categories of nickel sulfide deposits are Sudbury, flood basalt association, ultramafic volcanic association, and other mafic intrusive associations. These are discussed as follows.

Subtype 1.5.1: Sudbury

- Sudbury, Canada (global)
1,648 Mt at 1.2% Ni, 1.03% Cu (+ PGMs and Au)

Age and Distribution

The Sudbury Igneous Complex formed during the Proterozoic age as the likely result of a meteorite impact. This impact ruptured the earth's crust and allowed the intrusion of a mantle-derived mafic magma body, which differentiated to form the igneous complex and its nickel-copper sulfide deposits.

General Characteristics

The rather unique Sudbury nickel-copper sulfide deposits are largely confined to the so-called "sublayer" unit of the Sudbury Igneous Complex at its contact with the rocks into which it was intruded. The complex is a 65-km-long, 25-km-wide oval-shaped outcrop. In section across the narrow dimension, it forms a funnel-shaped body widening at the surface. Two types of sublayer are host to the nickel-copper deposits in two settings. The contact sublayer is a discontinuous gabbro-norite at the basal contact with nickel-copper sulfides and xenoliths of footwall and exotic ultramafic units. The offset sublayer comprises apophyses of quartz-diorite, which crosscut into the footwall. The sublayer has a distinctive mineralogy of quartz, plagioclase, biotite, hornblende, and copper-nickel sulfides and may contain exotic xenoliths of the wall rocks.

The nickel sulfide ores in both cases are dominated by pyrrhotite-pentlandite-chalcocopyrite with pyrite and magnetite. Bornite is common in the copper-rich zones. Arsenic-bearing sulfides are common in places. Copper-rich vein ores are

known in the footwall of the complex and are dominated by chalcocopyrite and cubanite. PGMs include complex tellurides and arsenides.

Subtype 1.5.2: Flood Basalt Association

- Norilsk, Russia
900 Mt at average grade of 2.70% nickel
- Jinchuan, China
515 Mt at average grade of 1.06% nickel

Age and Distribution

Flood basalt provinces are fairly widespread through the geological record, but not all have nickel sulfide deposits associated with them. Special conditions appear necessary to produce the nickel sulfides and then to trap and retain them in ore deposits.

General Characteristics

The deposits can comprise both massive sulfide and disseminated sulfides. The relative proportions of the two styles of mineralization vary widely, with massive mineralization dominant at Norilsk but minor mineralization at Jinchuan. The principal minerals are pyrrhotite (FeS), pentlandite (Fe,NiS), and chalcocopyrite (CuFeS₂), though there are minor amounts of many other minerals.

The igneous provinces that host these deposits are typically very large, commonly more than 1,000 km in diameter. They are dominantly tholeiitic in composition although alkaline volcanic rocks are often associated, and the occurrence of olivine-rich rocks indicates they formed from high-temperature melts.

Subtype 1.5.3: Ultramafic Volcanic Association

- Kambalda District, Australia
48 Mt at 3.6% Ni, 0.25% Cu
- Thompson Belt, Canada
69 Mt at 2.5% Ni, 0.13% Cu
- Raglan, Canada
18.5 Mt at 3.13% Ni, 0.88% Cu
- Shangani, Zimbabwe
22 Mt at 0.71% Ni

Age and Distribution

Komatiites are mainly restricted to Archaean sequences, and Kambalda-type deposits are almost exclusively developed in Precambrian sequences. In addition to the type locality in Western Australia, good examples occur in similar rocks in Zimbabwe and Canada, and deposits are recorded in Brazil and Russia. Most deposits occur in mid-Archaean to late-Archaean rocks, with only a few minor deposits developed in the oldest greenstone sequences of southern Africa or the Pilbara in Australia. Younger komatiite-like rocks are barren of significant nickel sulfide deposits.

General Characteristics

The nickel sulfide ore bodies in this class can be stratiform or stratabound. Stratiform deposits typically form tabular or ribbon-shaped bodies situated at the base of the host ultramafic units. Such deposits have dimensions from a few hundred meters to 5 km in length, but mostly the stratigraphic thickness of the sulfide zone is less than 10 m, with distinct lower and upper contacts. In some cases they show marked

elongation parallel to the regional volcanic or tectonic grain, with length-to-width aspect ratios of up to 20 at Kambalda.

Stratabound massive and disseminated mineralization is not confined to the base of ultramafic units but can be distributed through the lower to central portion of the host cumulate unit. The shape and size of stratabound deposits are more difficult to quantify because of their diffuse, gradational character; the margins are defined by arbitrary economic cutoff grades. Broadly, they have oblate to elongate lens shapes, depending on the shape and size of the host unit. Dimensions are generally much larger than equivalent stratiform deposits, particularly stratigraphic thickness, which may be up to several hundred meters.

Ore minerals are pentlandite, present as granular aggregates, and, to a much lesser extent, locked in pyrrhotite. Chalcopyrite, pyrite, and ferrochromite are the other principal minerals present. Nickel tenors within the sulfide component (as opposed to the Ni grade of the whole rock) can vary from less than 5% to more than 20%, but they are usually constant in an ore lens. Copper, cobalt, and the platinum-group elements are minor components of the mineralization. Arsenic is present and can occur in significant concentrations, resulting in adverse environmental impact when nickel concentrates are sent to a smelter.

Subtype 1.5.4: Other Mafic and Ultramafic Intrusive Associations

- Voisey's Bay, Canada
136 Mt at 1.59% Ni, 0.85% Cu
- Selebi-Phikwe, Botswana
110 Mt at 0.75% Ni, 1% Cu
- Lynn Lake, Canada
20 Mt at 1.02% Ni, 0.54% Cu

Age and Distribution

This type is generally found in areas of thickened crust in late Achaean to Proterozoic terranes, usually in highly deformed regions where reconstruction of the tectonic setting is difficult. Key examples are Lynn Lake, Canada; Selebi-Phikwe, Botswana; Monchegorsk, Russia; and Kotalahti, Finland. Voisey's Bay, Canada, is possibly also in this type but shows many features similar to the Norilsk deposit (see "Subtype 1.5.2: Flood Basalt Association" section).

General Characteristics

The host mafic/ultramafic intrusions associated with these Ni-Cu sulfide deposits include a variety of types: multiphase stocks, multiphase chonoliths, multiphase sills, and highly deformed sills. The styles of mineralization are also varied, including massive sulfides, breccia sulfides, stringers and veins, and disseminated sulfides. The sulfide minerals are usually pyrrhotite-pentlandite-chalcopyrite-pyrite assemblages and may form massive, matrix, or disseminated types. Pyrrhotite is often dominant, and as a result of this, nickel tenors are generally lower than other magmatic deposits. Nickel-copper ratios are typically between 3:1 and 1:1.

CLASS 2: MAGMATIC DIAMOND DEPOSITS

- Argyle, Australia
83 Mt at 2.7 ct/t (carat per metric ton)
- Ekati, Canada
60 Mt at 0.9 ct/t

- Jwaneng, Botswana
287 Mt at 1.44 ct/t

Age and Distribution

Economic diamond deposits occur with volcanic centers of unusual, highly alkaline volcanic and subvolcanic intrusive rocks, which are known as kimberlites and lamproites.

Diamond-bearing kimberlites and lamproites only occur around the margins of or within stable cratonic blocks that have not undergone major deformation or metamorphism. Productive kimberlites vary widely in age from Precambrian to Mesozoic. Some of the lamproites that host diamond deposits are as young as 55 Ma (million years). Thus, it is likely that the formation of primary diamond deposits has gone on throughout geological time.

General Characteristics

Both kimberlites and lamproites are formed from very volatile-rich magmas that are generated at great depth (about 200 km deep for lamproites and between 200 and 300 km deep for kimberlites). Kimberlites are more gas-charged (with carbon dioxide) than lamproites, so they are more likely to form large diatreme structures close to the surface. In both cases they occur as dykes, sills, and minor plugs formed at depths of several kilometers. However, these are generally small, and so they cannot provide the tonnage required for an economic deposit.

Kimberlite magmas tend to form a deep conical explosion crater or diatreme (pipe). These so-called pipes typically range from 50 to 500 m in diameter with four contrasting rock facies. The diatreme facies consists of fragmented wall rocks and material brought up from deep below. The maar facies contains bedded material that fell back into the crater after an eruption. The crater facies includes finely bedded ash and crater-lake sediments, possibly containing fossils. The pyroclastic facies forms as a tuff ring around the vent. All facies may be diamondiferous, but because diamonds are not actually formed as a part of the magmatic process but are xenocrysts simply carried by the magma from the mantle where they formed, their grades can be highly variable.

The shape of kimberlite pipes is typically steeply conical, rather like a carrot. Lamproites, by contrast, form shallower conical to irregular bodies that commonly do not extend to depth.

CLASS 3: DEPOSITS ASSOCIATED WITH FELSIC MAGMAS

Felsic ("granitic") magmas are often generated in subduction-zone settings, and within this setting, different types of granitic magmas are linked to different metal associations. Subduction-related ore-forming magmas have been classified into two broad chemistries of granitoids: S-type and I-type granites, reflecting contrasting sources for the magmas deep in the crust. It is apparent that Sn-W deposits are associated with S-type granites, whereas Cu-Mo-Au mineralization is associated with I-type granites. A further A-type of granite has been discriminated, and these are associated with Mo-W mineralization.

Type 3.1: Porphyry Cu-Mo-Au Deposits

- Chuquibambilla, Chile
15,000 Mt at 0.77% Cu, 0.01% Mo, 0.0133 g/t Au
- El Teniente, Chile
11,850 Mt at 0.92% Cu, 0.02% Mo, 0.0236 g/t Au

- Kalmakyr, Uzbekistan
5,625 Mt at 0.4% Cu, 0.509 g/t Au
- Morenci, Arizona, United States
4,693 Mt at 0.52% Cu, 0.00639 g/t Au
- Grasberg, Indonesia
3,409 Mt at 1.12% Cu, 1.07 g/t Au
- Oyu Tolgoi, Mongolia
2,700 Mt at 1.15% Cu, 0.4 g/t Au
- Sar Cheshmeh, Iran
1,200 Mt at 1.02% Cu, 0.03% Mo, 0.27 g/t Au
- Madjanpek, Serbia
1,000 Mt at 0.6% Cu, 0.3 g/t Au

Age and Distribution

Most porphyry deposits are Mesozoic or younger, but deposits are known from rocks older than 3,000 Ma. Porphyry copper deposits have been directly related to the process of subduction and formation of volcanic arcs, and this accounts for their distribution along active subduction margins of the Cordillera of the Americas and western Pacific. Porphyry copper deposits are also found distributed along ancient volcanic arcs, now preserved in such structures as the Tethyan orogenic belt and the Central Asian orogenic collage.

General Characteristics

Typically porphyry copper deposits take the form of low-grade disseminations and fracture-hosted sulfide mineralization usually developed within or at the margin of high-level felsic intrusive rocks. The deposits may take the form of irregular to ovoid bodies in plan and from solid to cup or hollow cylindrical shapes in section. Individual ore bodies may be discrete, they may overlap or even be stacked, and they may have dimensions up to thousands of meters in each direction, such as in the case of the “supergiant” deposits at El Teniente. Ore bodies are characteristically zoned according to ore minerals and alteration assemblages with several “classic” models proposed to describe the distribution of such zonation. In reality, these zones are often far more complex and overlapping, commonly with the superimposition of alteration zones.

Principal ore minerals are chalcopyrite, bornite, chalcocite, tennantite, enargite, molybdenite, and electrum. Associated minerals include pyrite, magnetite, quartz, biotite, potassium-feldspar, anhydrite, muscovite, epidote, chlorite, and clay minerals. In gold-rich porphyries, tellurides and arsenopyrite may be part of the ore assemblage, while accessories such as scapolite, calcite, albite, fluorite, and even garnet may be present.

Hydrothermal alteration is extensive and zoned, and at a deposit scale, it ideally comprises an inner potassic zone characterized by the presence of biotite and/or K-feldspar often accompanied by one or more of magnetite, amphibole, and anhydrite. Outside this is a propylitic zone comprising quartz, chlorite, epidote, calcite, and sometimes albite, with local development of pyrite. A further alteration type, phyllic, may be developed between the potassic and propylitic zones, but it may be more irregular or tabular and show evidence for being often “changed” later than the initial alteration stages. The economic sulfides are usually closely associated with the potassic alteration, although in some cases the presence of strong sodic alteration is important.

Type 3.2: Porphyry Mo (W) Deposits

- Climax, Colorado, United States
907 Mt at 0.24% Mo, 0.02% W
- Henderson, Colorado, United States
727 Mt at 0.171% Mo
- Quartz Hill, Alaska, United States
1,700 Mt at 0.136% Mo
- Malmbjerg, Greenland
136 Mt at 0.138% Mo, 0.016% W

Age and Distribution

Most porphyry molybdenum deposits are Mesozoic or younger. Located in continental arc terranes, the deposits are hosted in A-type (or anorogenic) granites normally related to a rift or extensional setting related to a mature subduction-zone setting. Most economic deposits are located in the Cordillera of the Americas, with a few in the Pacific region, and there is an important prospect in Greenland.

General Characteristics

The key examples of the type, Climax and Henderson, are genetically related to a small cupola of a regional intrusive batholith emplaced during regional extension. The batholith is an anorogenic or A-type pluton. Host intrusions vary from quartz monzodiorite through to granite. Mineralization is more likely to form as a stockwork than as disseminations. The intrusive bodies at Climax are highly evolved granite magmas rich in tin, tungsten, fluorite, and rubidium, while other bodies are adamellite in their composition.

Ore bodies can be associated with simple, composite, or multiple intrusions associated with dykes and breccia pipes. Multiple intrusions are common, which has given rise to multiple, often stacked, ore bodies (known as “shells”) in some of the deposits. The shapes of the ore bodies often form inverted cups, shallow bowls, or hollow cylinders mantling an intrusive stock.

The principal ore minerals are molybdenite, scheelite, wolframite, and sometimes associated cassiterite and bismuthinite. Fluorite and topaz are common accessories not seen in typical porphyry copper deposits. Molybdenite occurs in quartz veinlets that carry other sulfides and gangue, in small fissure veins, in fracture coatings, in breccia matrix, and very rarely as disseminations.

Alteration patterns are very similar to porphyry copper deposits (mentioned earlier), with potassic alteration and silicification particularly important in the cores of the deposits.

Type 3.3: Granite-Hosted Sn-W Deposits

- East Kemptville, Nova Scotia
56 Mt at 0.165% Sn (+ Cu, Zn)
- Ardlethan, Australia
9 Mt at 0.5% Sn
- Wheal Jane, Cornwall, United Kingdom
5 Mt at 1.2% Sn
- Hemerdon, Cornwall, United Kingdom
42 Mt at 0.18% WO₃ (tungsten trioxide), 0.025% Sn
- Panasqueira, Portugal
31 Mt at 0.3% WO₃, 0.02% Sn
- Cerro Rico, Bolivia
828 Mt at 0.35% Sn, 200 g/t Ag

Age and Distribution

The age of these deposits ranges from Archaean to Tertiary, with the bulk of the deposits of Mesozoic age. The Hercynian orogenic belt of Europe (Cornwall to Central Europe) is host to a significant proportion of these deposits, and important deposits are associated with granites in the Appalachian-Caledonide belt of North America. The common feature to all these belts is the association with late-stage magmatism in collisional orogens, where the deposits group in distinct metallogenic provinces.

Well-known locations of Sn-W deposits occur in Cornwall (England), Portugal, Erzgebirge of Central Europe, Malaysia, Bolivia, Tasmania (Australia), and Brazil. The deposits are all related to granitoids but show a range of styles from porphyry Sn (Bolivia), tin greisen deposits, to lode-type Sn-Cu (Cornwall and Tasmania). Tin skarns are often developed in the same terranes (see next section).

General Characteristics

Primary tin deposits can occur within granites or within pegmatites or aplites (dyke-like rocks) associated with the granite. They also occur in rocks surrounding the margins of the intrusive rocks as veins, disseminations, skarns (discussed later), or more distal carbonate replacements (generated by magmatic fluids). Pegmatites, fault-controlled veins, stockworks, and breccias are common, as well as the development of distinctive altered granite contact zones known as greisens. Greisen is a metasomatic-hydrothermal rock that results from high T-alteration of granite by fluorine-rich fluids that exsolved from enriched magma during the last stages of solidification. Greisens are associated with silicification and areas where alkali feldspar is replaced by quartz and muscovite. Wolframite- and cassiterite-bearing quartz veins often form swarms within the alteration, and tourmaline is a common accessory silicate. The outer margins of greisen tend to be marked by zones of intense kaolinization. Mineralization tends to form near the top of granite intrusions (often within the margin of a cupola), but also occurs in large quartz-cassiterite-sulfide veins that may pass from the granite into the metamorphosed margin to the granite.

Type 3.4: Intrusion-Related Gold Deposits

- Fort Knox, Alaska, United States
220 Mt at 0.9 g/t Au
- Salave, Spain
15 Mt at 2.99 g/t Au
- Mokrsko, Czech Republic
57 Mt at 1.9 g/t Au
- Vasilkovskoe, Kazakhstan
100 Mt at 2.4 g/t Au
- Kidston, Australia
94 Mt at 1.48 g/t Au

Age and Distribution

Most intrusion-related gold (IRG) deposits so far identified are Phanerozoic, particularly the Cretaceous and mid-Paleozoic. Key belts are the mid-Cretaceous Tintina Gold Province in western Canada and Alaska, the New England-Lachlan Fold Belt of eastern Australia, parts of the Paleotethys belts of Europe, and regions of the Tien Shan in Central Eurasia. Further Paleozoic deposits are recorded in New Brunswick, Canada.

General Characteristics

The deposits are highly variable in precise features, but they generally can comprise a range of mineralization styles reflecting their location with respect to distance from a felsic, ilmenite-series (reduced) pluton. A general zonation of the mineralization is seen with distance away from any associated intrusion, with characteristically a more proximal W-Mo-bearing assemblage passing laterally to a more distal Au-As-Bi assemblage.

Intrusion-proximal deposits may comprise sheeted veins associated with thin aplite and pegmatite dykes developed in the brittle carapace of the reduced pluton itself. In the best example of this type, Fort Knox, gold relates to both higher-temperature magmatic features and more distal hydrothermal veins. The ore assemblage contains gold typically intergrown with bismuth- and tellurium-bearing phases and commonly molybdenum or tungsten minerals. There is generally a low sulfide content, but where present, the more common associated sulfide phases are consistent with a reduced magmatic source often comprising pyrrhotite, pyrite, loellingite, and arsenopyrite. Some of the deposits are like skarns, where mineralization replaces adjacent host rocks. The more distal examples of this deposit type share many features found in deposits classed as lode or orogenic gold deposits in metamorphic rocks, where causal intrusions have not been unequivocally identified (see “Type 7.3: Lode Gold Deposits” section). Because of this, discrimination between gold deposits in metamorphic rocks (lode gold deposits) and IRG remains controversial.

CLASS 4: DEPOSITS ASSOCIATED WITH PERALKALINE/CARBONATITE MAGMAS**Type 4.1: Peralkaline Ta-Nb Rare Earth Element Deposits**

- Lovozero, Russia
>1,000 Mt at 0.3% Nb₂O₅, >1% REE

General Characteristics

Peralkaline rocks are important repositories of rare metals such as zirconium, niobium, beryllium, uranium, thorium, tantalum, rare earth elements (REE), yttrium, and gallium. Currently, only deposits in Russia are being mined for niobium. Peralkaline rocks form plutons in stable cratonic, anorogenic regions. Their occurrences are controlled by regional fault systems, and they may form ring complexes. The concentrations of rare metals occur as a closed magmatic system and slowly crystallize with rare metals concentrated in the latest cooling phases. High fluorine in the magma lowers the freezing point and the viscosity, allowing the complexes to fractionate to extreme compositions, concentrating rare metals in the residuum.

Type 4.2: Carbonatite Cu, Rare Earth Element, Nd, Fe, P Deposits

- Mountain Pass, California, United States
36.3 Mt at 7.67% REE
- Palabora, South Africa
286 Mt at 0.69% Cu
- Aley, Canada
20 Mt at 0.7% Nb₂O₅ (niobium pentoxide)

Age and Distribution

Four recognized frequency highs of carbonatite magmatism related to tectonic activity are as follows:

- Mid-Proterozoic: 1,800 to 1,550 million years ago (coincident with the Hudson-Svecokarelian orogeny)
- Mid- to late-Proterozoic: 1,100 million years ago (Grenville orogeny)
- Late-Proterozoic to Paleozoic: 750 to 500 million years ago (Caledonide orogeny)
- Breakup of Pangea: 200 million years ago

The major hard rock niobium deposits are in Brazil, Canada, Palabora, and the major Kovdor apatite deposit in northern Russia.

General Characteristics

Carbonatites are igneous rocks that contain at least 50% (modal) carbonate minerals. These comprise calcite, dolomite, and ankerite, as well as sodium- or potassium-bearing carbonates along with diopside, sodic pyroxenes, or amphibole; phlogopite; apatite; and olivine. They are generally found in stable intraplate areas but are located along major tectonic features, usually associated with topographic doming constrained by crustal-scale faults.

Carbonatites form modest-sized intrusive bodies, flows, or tuffs, and they are closely associated with a range of alkali silicate rocks such as syenites. Carbonatites are usually surrounded by an aureole of metasomatic rock called fenite. Mineralization associated with carbonatites can be either magmatic or metasomatic, where mineralization occurs in the altered assemblage.

Mineralization relates to magmatic layering and flow structures, with the mineralization in the case of the niobium deposits taking the form of irregular lenses. Ore minerals include pyrochlore (niobium), rare earth fluorocarbonates or phosphates, perovskite-magnetite, and apatite. Host rocks also contain many unusual accessory minerals. Barite is common in almost all carbonatites. Phosphorus-rich deposits contain apatite with olivine and magnetite.

CLASS 5: SKARN AND CARBONATE REPLACEMENT DEPOSITS**Examples of Skarns**

- Hedley District, Canada
7.0 Mt at 1.7 g/t Au, 17.1 g/t Ag
- Fortitude, Nevada, United States
5.1 Mt at 10.45g/t Au, 27.8 g/t Ag, 0.2% Cu
- Mactung, Canada
33 Mt at 0.88% WO₃
- Antamina, Peru
745 Mt at 1.24% Cu, 1.03% Zn
- Moina, Tasmania
30 Mt at > 0.15% Sn
- Las Bambas, Peru
339 Mt at 1.3% Cu, 0.15g/t Au

Examples of Carbonate Replacements

- Cerro de Pasco, Peru
175 Mt at 7% Zn, 2% Pb, 103 g/t Ag and
50 Mt at 2% Cu (+ Au, Ag)
- Colquijirca, Peru
25 Mt at 7% Zn

General Characteristics

A skarn is defined as an assemblage of zoned, coarse-grained, generally iron-rich mixture of calcium or magnesium silicates resulting from the alteration of an original rock-type. Main types of skarn are those resulting from the following:

- Metamorphic recrystallization of silica-carbonate rocks
- Local exchange of components between lithologies during high-grade metamorphism
- Local exchange of components between magmas and carbonate rocks at high temperatures
- Large-scale transfer of components over a broad range of conditions between magmas and predominantly carbonate rocks

Replacement skarns can form a carapace of altered intrusive rock (endoskarn) surrounded by a zone of alteration in the wall rock (exoskarn). Skarns may be associated with both I-type and S-type magmas (as discussed previously), and the type of magma associated may in part dictate the metal budget of the skarn. Carbonate replacement deposits may lack the typical skarn alteration assemblages.

Because of the complications of describing skarns based on the alteration minerals (which are a combined function of wall-rock chemistry and the superimposed system), mineralized skarns are best classified in terms of component of interest. Seven major types are recognized: iron, gold, tungsten, copper, zinc, molybdenum, and tin.

Carbonate replacement deposits, often termed *mantos* in the literature, tend to be hosted in carbonates or calcareous sediments and are largely polymetallic zinc-lead rich, often with copper and silver. Alteration of the host rocks in this deposit type can be quite cryptic and may be represented by minor calcite and dolomite and quartz, developed close to the ore body itself.

CLASS 6: IRON OXIDE COPPER-GOLD (WITH OR WITHOUT URANIUM) DEPOSITS

- Olympic Dam, Australia
8,300 Mt at 0.8% Cu, 280g/t U₃O₈ (uranium oxide concentrate), 0.76g/t Au, 3.95g/t Ag
- Candelaria, Chile
600 Mt at 0.95% Cu, 0.2g/t Au, 3.1g/t Ag
- Ernest Henry, Australia
122 Mt at 1.18% Cu, 0.55g/t Au
- Salobo, Brazil
986 Mt at 0.82% Cu, 0.49g/t Au

Age and Distribution

Within Australia and parts of South America, where the largest of these deposits is found, the deposits tend to be hosted in Mesoproterozoic to Neoproterozoic rocks (1,800 to 850 Ma). However, many deposits are found in the Phanerozoic, with the important Chilean iron oxide copper-gold (IOCG) belt hosting the Mesozoic Candelaria deposit. Worldwide, recorded ages of IOCG deposits range from 1,800 to 15 Ma for the deposit group.

General Characteristics

The deposits included in this class range from around 10 Mt to more than 8,000 Mt of contained ore at grades around 1% Cu plus gold, which brings them into the size of porphyry copper deposits. In the case of the giant Olympic Dam deposit, the

setting is interpreted as a diatreme breccia within a caldera, and many authors regard the presence of breccias as a key diagnostic for this deposit type. Other deposits clearly relate to major crustal structures or else have a strong association with the aureole of a distinctive intrusive suite. Kiruna-type iron ore deposits have been proposed by some to represent the copper-poor end members to this deposit class.

The deposits are characterized by the development of large volumes of low-titanium magnetite and/or hematite with a simple assemblage of copper, usually as chalcopyrite and associated gold and sometimes uranium. In the copper-rich deposits, paragenetically late chalcopyrite and bornite occurs within or near the iron oxide phases. The oxides are often zoned from an earlier magnetite to a later or more distal hematite. Other associated minerals are phosphates, dominated by apatite and usually highly enriched REE and sometimes a cobalt and silver enrichment. Silicate gangue minerals include actinolite, pyroxene, epidote, chlorite, and tourmaline. Apatite and other phosphate minerals are common, as well as the rare earth-rich epidote mineral allanite.

Wall-rock alteration is a characteristic of the deposit type. This is often developed on a regional scale (>100 km²) and may comprise regionally extensive sodic and calcic alteration (up to tens of kilometers away from mineralized districts) and more focused, proximal potassic alteration more closely associated with mineralization. In some cases, the alteration resembles skarn seen associated with magmatic intrusive suites.

CLASS 7: HYDROTHERMAL GOLD AND SILVER DEPOSITS

All the deposits in this class are epigenetic and are subdivided into three broad groups based on host-rock association and depth of formation within the earth's crust.

Type 7.1: Sediment-Hosted Gold Deposits

- North Carlin trend, Nevada, United States
491 Mt at 5.86 g/t Au
- Twin Creeks, Nevada, United States
90 Mt at 2.5 g/t Au
- Jerritt Canyon, Nevada, United States
33 Mt at 6.9 g/t Au
- Bau, Malaysia
ca. 40 Mt at ~2 g/t Au
- Barneys Canyon, Utah, United States
2.8 Mt at 2.4 g/t Au
- Zarshuran, Iran
2.5 Mt at 10 g/t Au

Age and Distribution

Deposits with common features in this class are generally Mesozoic or younger. The type locality is the Carlin District of the United States, which has produced more than 50 million ounces (1,600 t) of gold up to 2002. Here, the deposits are hosted in Paleozoic rocks (largely Devonian) although the mineralization is dated at 42 to 36 Ma. The most comparable deposits are found in the West Qinling and Dian-Qian-Gui areas of southern China, while other analogs are found in Utah, Chile, Malaysia, Indonesia, and Iran. Nevada is by far the most productive district for this deposit type to date.

General Characteristics

Carlin-type deposits are characterized by auriferous pyrite associated with a range of anomalous trace elements occurring as replacements in carbonate-rich host rocks. The deposits may take a variety of forms (e.g., tabular, branched, carrot-like, and irregular), and they may be stratabound or clearly crosscutting. The mineralization appears to be hosted in locally porous lithologies, particularly developed where such lithologies intersect high- and low-angle faults related to regional thrust faults.

Deposits are up to 3 km long, with mineralization occurring in a depth range of up to 1,000 m, although this may comprise several stacked ore bodies. Barren zones between ore bodies are generally formed of less-permeable horizons. Impermeable units generally cap ore zones, and the best mineralization is developed in structural-lithological settings similar to favorable traps for oil reservoirs.

At Carlin, gold is associated with As, Sb, Tl, and Hg and was deposited in main-stage arsenian pyrite and marcasite. Quartz, kaolinite, dickite, and illite are minor gangue phases.

Type 7.2: Epithermal Gold and Silver Deposits

Examples of High Sulfidation

- El Indio, Chile
23.2 Mt at 4.6 g/t Au, 10 g/t Ag
- La Coipa, Chile
52.1 Mt at 1.58 g/t Au, 50 g/t Ag
- Lepanto, Philippines
38 Mt at 3.53 g/t Au
- Pueblo Viejo, Dominican Republic
150 Mt at 7 g/t Au

Examples of Low Sulfidation

- Martha Hill, New Zealand
83.3 Mt at 3.2 g/t Au, 33 g/t Ag
- McLaughlin, Nevada, United States
17.5 Mt at 5.2 g/t Au
- Hishikari, Japan
3.2 Mt at 63 g/t Au
- Gunung Pongkor, Indonesia
6 Mt at 17 g/t Au, 162 g/t Ag

Age and Distribution

Epithermal and related deposits occur in modern volcanic arcs such as the circum-Pacific "Rim of Fire" of active volcanism. Other deposits are found in similar volcanic arc settings in other parts of the world, where processes similar to those active around the Pacific Ocean occurred in the past. Ancient volcanic arcs such as parts of the Tethys and the arcs of Central Asia also yield such deposits.

Many of the epithermal deposits occur in regions where copper-gold porphyries and skarns form (see previous sections), and there is sometimes a direct genetic relationship.

General Characteristics

Epithermal deposits formed at shallow crustal levels (typically from the water table to about 1,000 m below at the time of formation). The temperatures that correspond to this depth range (controlled by the boiling point of water with depth) are from less than 100°C to about 350°C.

A major difference is recognized between two contrasting classes of epithermal deposit usually referred to as low sulfidation and high sulfidation, which reflect the nature of the hydrothermal fluid. Low sulfidation means an association of the minerals quartz ± calcite ± adularia ± illite, while in high-sulfidation systems, alteration is dominated by the minerals quartz ± alunite ± pyrophyllite ± dickite ± kaolinite.

Both deposit types can occur in subaerial volcanic settings of calc-alkaline to alkalic and intermediate to acid composition. High-sulfidation deposits tend to occur in proximal volcanic settings, whereas low-sulfidation deposits can occur in any setting and may be hosted in basement rocks. Both deposit types are localized by structures, but any suitable structure may be used including favorable volcanic features such as calderas.

For low-sulfidation deposits, the most important features are their typically open-space vein-fill character, their diverse range of distinctive textures, and the characteristic alteration pattern. Silica (quartz) veins and the presence of surface sinters (hot-spring deposits) are typical in low-sulfidation systems. For high-sulfidation deposits, the most important features are their typically massive, disseminated character; their mineralogy (especially the ore mineral enargite and gangue mineral alunite); and the characteristic alteration pattern. Quartz is uncommon as a vein mineral in high-sulfidation systems but may be present as distinctive vuggy or sometimes massive-quartz alteration.

Hydrothermal alteration around low-sulfidation deposits is characteristic of that produced by neutral-pH fluids. The characteristic ore minerals in low-sulfidation deposits are pyrite, gold (often electrum), other base-metal sulfides (chalcopyrite, high-Fe sphalerite and galena), and often selenides along with gangue minerals quartz, chalcedony, calcite (and other carbonates), adularia, and illite. Hydrothermal alteration in high-sulfidation deposits results from very acid fluids, and the zonation results from their progressive neutralization. The characteristic ore mineral phases of this deposit type are pyrite, enargite (copper arsenic sulfide), pyrite, chalcopyrite, tennantite, covellite, and gold. Tellurides are uncommon but present in some deposits.

Type 7.3: Lode (or Orogenic) Gold Deposits

- Muruntau, Uzbekistan
1,320 Mt at 4.0 g/t Au
- Ashanti, Ghana
430 Mt at 4.73 g/t Au
- Golden Mile, Australia
1,000 Mt at 1.98 g/t Au
- Homestake, South Dakota, United States
148 Mt at 8.34 g/t Au
- Sukhoi Log, Russia
388 Mt at 2.7 g/t Au
- McIntyre-Hollinger, Canada
104 Mt at 9.47 g/t Au

Age and Distribution

These deposits are widespread in metamorphic, orogenic terranes around the world, and settings include Precambrian shields, more specifically Archaean greenstone belts, Paleoproterozoic fold belts, late Proterozoic, and younger orogens. These younger orogens are located along the former margins of the supercontinents of Gondwana and Laurentia, and there are more recent belts related to orogens at the

margins of the Pacific. Deposit frequency highs occur in the periods 2,800 to 2,550 million years ago, 2,100 to 1,800 million years ago, and 600 to 50 million years ago.

General Characteristics

Lode gold deposits are normally located adjacent to regionally extensive, often broad first-order deep crustal structures that have a complex geological history. The gold deposits themselves are usually located along second- or third-order structures linked to the regional first-order features, often in sites where the structures bend, change direction, or branch.

Mineralization styles vary from quartz-sulfide stockworks and breccias to quartz dominated vein deposits, showing simple to complex banded textures to disseminations without discrete vein development in sheared rocks. Mineralization is most commonly developed in rocks of greenschist metamorphic grade, although important deposits are found in both lower- and higher-grade rocks.

The wall rocks around the mineralization are often altered, with the commonest type of alteration dominated by sericite, carbonate minerals, and sulfides. Silicification is also common as are tourmaline, K-feldspar, biotite, and albite in some cases. Alteration intensity and width vary with the style of deposit and the nature of the host rocks. In deposits developed in higher metamorphic grades, the alteration can resemble skarn-like assemblages.

The largest of the deposits are typically 2 to 10 km in their longest dimension and up to 1 km wide. The deposits are characterized by generally low amounts of contained sulfide (typically 2% to 5%), with gold-silver ratios generally between 1:5 and 1:10. Pyrite and arsenopyrite are dominant sulfides, although pyrrhotite is common in deposits in higher-grade metamorphic rocks. Tungsten, bismuth, and tellurium are often geochemically anomalous in the deposits, with discrete minerals containing these elements often present.

CLASS 8: VOLCANIC-HOSTED OR VOLCANOGENIC MASSIVE SULFIDE DEPOSITS

- Rio Tinto, Spain
500 Mt at 2.5% Zn, 0.8% Pb, 0.7% Cu, 0.8 g/t Au, 30 g/t Ag
- Gai, Russia
380 Mt at 1.57% Cu, 0.74% Zn, 0.06% Pb
- Kidd Creek, Canada
300 Mt at 9.50% Zn, 1.5% Cu, 0.4% Pb, 130 g/t Ag
- Bathurst, Canada
110 Mt at 7.3% Zn, 2.4 % Pb, 1% Cu, 65 g/t Ag
- Rosebery, Australia
9.4 Mt at 16.2% Zn, 5% Pb, 0.74% Cu, 2.9 g/t Au, 155 g/t Ag

Age and Distribution

Volcanogenic massive sulfide (VMS) deposits are one of the few mineral deposit styles that occur throughout the geological record up to the present day. The oldest known sulfide deposits of this type are located in the pre-3,700 million year old Isua group in Greenland, and the youngest are actively forming today in the deep oceans and are the subject of active mineral exploration. Much is understood about the deposits, as there have been many detailed studies of modern seafloor hydrothermal systems where these deposits are seen to form in generally deep ocean areas of active volcanism, either

at mid-ocean ridges or in volcanic back-arc basins. Rare examples are known from the relatively shallow water of the Mediterranean. In the geological record, 80% of VMS deposits are hosted in former volcanic-arc sequences.

General Characteristics

In broad terms, the deposits ideally comprise a broadly stratiform, stratabound mass or lens of sulfide that most likely is hosted in volcanic rocks or sediments. The sulfide lens may vary from less than a meter to several tens of meters thick and have highly variable length and widths. The deposit may thicken in the center, and below this a stockwork zone of altered and mineralized rock may be developed. Above the massive sulfide lens, the deposit may be covered by volcanic rocks or sediments with commonly a very distinct change in the nature of the footwall and hanging wall rocks. Individual deposits vary widely in size and shape. Multiple sulfide lenses are common. Most mines consist of several closely spaced ore bodies.

Plots of the dominant metals in VMS deposits define three major groups of deposits, namely, a copper-zinc, a zinc-lead-copper, and a lead-zinc group. The metal contents of the deposits relate to the nature of the host-rock package, and thus a fivefold classification of mafic, bimodal-mafic, mafic-siliciclastic, bimodal-felsic, and felsic-siliciclastic deposits is proposed. In the broadest sense, the first three groups are dominated by deposits where iron and copper sulfides dominate, while in the last two groups, more polymetallic sulfide assemblages dominate.

In the copper-zinc deposits, the massive sulfide lenses are usually dominated by pyrite, with pyrrhotite, chalcopyrite, and sphalerite normally forming the other major sulfide minerals. Magnetite is a common accessory mineral. Quartz, chlorite, barite, gypsum, and carbonates are the main gangue minerals. The ore bodies are commonly strongly zoned with copper enriched at the base of the deposit with zinc (and lead) at the top. This is usually marked by a mineralogical zonation, particularly in the sulfides. The regional ore-equivalent stratigraphy is sometimes marked by a metalliferous sediment. In the more polymetallic deposits, galena, sulfosalts, and barite are common.

Gold and silver are common credits in VMS deposits, particularly the more polymetallic types. The stockwork feeder zone to the deposits and the peripheral margin to the massive sulfide lenses are likewise commonly gold enriched.

CLASS 9: SEDIMENT-HOSTED DEPOSITS

Examples of this deposit type can be broadly subdivided into sulfide deposits, iron and manganese oxide deposits, sedimentary uranium deposits, chemical sediments, and gold- and uranium-bearing conglomerates.

Type 9.1: Sediment-Hosted Sulfide Deposits

This group of deposits ranges from clastic-hosted copper deposits, such as the Kupferschiefer and the African copper belt, to the clastic-hosted sedimentary exhalative (SEDEX) Zn-Pb (Cu) deposits, where a syngenetic, seafloor origin is proposed, and the clearly epigenetic carbonate, or rarely sandstone replacement Mississippi Valley type (MVT) Pb-Zn deposits. The “Irish type” carbonate-hosted deposits are a subgroup with much in common with SEDEX Zn-Pb deposits, but they also have a few aspects of MVT deposits making them a distinctive group.

Subtype 9.1.1: Sedimentary Exhalative Pb-Zn (Cu) in Clastic Sediments

- Red Dog, Alaska, United States
150 Mt at 5% Pb, 17.1% Zn, 82.3 g/t Ag
- Gamsburg, South Africa
150 Mt at 0.5% Pb, 7.1% Zn, 6 g/t Ag
- McArthur River, Australia
227 Mt at 4.1% Pb, 9.5% Zn, 40 g/t Ag
- Rammelsburg, Germany
27.2 Mt at 1.0% Cu, 7.8% Pb, 16.4% Zn, 103 g/t Ag

Age and Distribution

These deposits are found in large sedimentary basinal sequences from the mid-Proterozoic to the present. Although SEDEX deposits are probably found in rocks from the Archaean to the present, there are two frequency peaks in the mid-Proterozoic and Palaeozoic. The Proterozoic is host to a series of deposits in Australia (e.g., Mt. Isa), Canada (Sullivan), and South Africa (Gamsburg). The Paleozoic of western Canada and Alaska is host to a number of deposits, including Cirque, Howards Pass, and Red Dog. The Paleozoic of Western Europe hosts the Meggen and Rammelsburg deposits.

The common theme of association is the formation of deposits during periods of major continental rifting. In the case of the Proterozoic, there is a link to the breakup of a large supercontinent to separate Australia, Antarctica, North America, and South Africa. The deposits in the Rhenish of Western Europe and Selwyn Basin of Canada and Alaska are linked to major continental rifting in the Devonian to Carboniferous.

General Characteristics

The deposits form largely conformable to semiconformable stratiform lenses of sulfides and associated hydrothermal products. Deposits typically have a length-to-thickness ratio in the order of 1:20, and many are underlain by some form of vein system that can be interpreted as a feeder. The deposits are usually compositionally layered to some degree on a millimeter-to-meter scale. Breccias, irregular veining, and disseminated textures are common.

Mineralogically, the deposits comprise sulfides together with carbonates and very commonly barite. Pyrite often dominates as the major sulfide, although in many of the Proterozoic deposits, pyrrhotite is the main phase. Sphalerite and galena are usually the main economic sulfides. Siderite and ankerite are common gangue minerals.

Zonation in the deposits is often both lateral and vertical, with transitions from sulfides to oxides common from the core to periphery, both laterally and vertically. Carbonate alteration haloes are common in these deposits, and very commonly the Zn-Ba and Zn-Mn ratios decrease in carbonate with distance from the “feeder” system or core of the deposit. Silicate alteration and silicification may occur in some deposits.

Subtype 9.1.2: Mississippi Valley Type Pb-Zn

- Polaris, Canada
22 Mt at 4% Pb and 14% Zn
- Pine Point, Canada
76.1 Mt at 2.9% Pb and 6.5% Zn
- Tri-State District, United States
500 Mt at 0.6% Pb and 2.4% Zn

- Viburnum Trend, Missouri, United States
111 Mt at 0.8% Zn and 5.8% Pb
- Jinding, China
90 Mt at 7.8% Zn, 1.6% Pb
- Angouran, Iran
14.5 Mt at 26.6% Zn, 4.6% Pb
- Silesia, Poland
200 Mt at 4% to 5% Zn, 1% to 2% Pb

Age and Distribution

Mississippi Valley type (MVT) deposits are generally restricted to post-Proterozoic rocks, with the exception of the Pering deposit in South Africa. They are known in Paleozoic to recent carbonate-rich sedimentary packages with important deposits in Canada at Polaris, Pine Point, Gays River, and Newfoundland Zinc. The platform carbonate sequences of the United States host these deposits, including the district that gives the deposit its name (Mississippi Valley), Tennessee, Missouri, and the Tri-State District. Major deposits of this type are also found in the Lennard Shelf of Australia, Silesia in Poland, and the Cevennes of France.

General Characteristics

The deposits are generally carbonate-hosted, usually in a dolostone or limestone, although, rarely, they can be sandstone-hosted. The deposits occur mostly in relatively undeformed platform carbonate sequences at the flanks of large sedimentary basin sequences. Districts are often large (up to thousands of square kilometers), but they may comprise clustered small (<10 Mt) individual deposits.

The deposits are normally stratabound, but they are sometimes stratiform where they can resemble SEDEX deposits. Mineralization generally cuts across the stratigraphy but often forms bodies within specific horizons or beds. Ore minerals are dominated by sphalerite and galena with an iron sulfide (pyrite or marcasite). Ore grades in deposits rarely exceed 15% combined Pb-Zn, and mineralization is often accompanied by abundant gangue minerals, dominated by carbonates (calcite, dolomite, siderite, etc.). Fluorite and barite are common; the former mineral seems to be absent from SEDEX deposits, which may be a key discriminating feature.

The deposits range from bedded types to discordant bodies commonly taking the form of mineralized breccias. There are often strong physical controls to the development of mineralization, including the location of basement highs, faults, fractures, and the fault-controlled development of solution collapse breccias.

Subtype 9.1.3: Irish-Type Pb-Zn (Cu)

- Navan, Ireland
70 Mt at 10.1% Zn, 2.6% Pb (+14 Mt at 9.85% Zn)
- Lisheen, Ireland
23 Mt at 13.1% Zn, 2.2% Pb
- Reocin, Spain
80 Mt at 10% Zn, 1% Pb

General Characteristics

The type locality for this deposit subtype is Ireland, although other deposits are known at Reocin and the Kootenay arc in Canada. Deposits are generally stratabound but sometimes occur stratiform, typically wedge-shaped lenses abutting a

fault. The mineralized lenses may be up to 30 m thick and extend 200 m from bounding fault. Larger deposits may comprise individual or stacked lenses that are roughly concordant to bedding.

The mineralization often comprises massive sulfides, but in some deposits layered textures are present. Mineralization comprises sphalerite and galena, the principal ore minerals with iron sulfides (generally pyrite and marcasite) variable from being the dominant sulfide to being a minor constituent. Barite is common in most of the deposits forming massive lenses in some cases.

Subtype 9.1.4: Clastic Sediment-Hosted Copper

- Lubin, Poland
>3,400 Mt at 2.0% Cu, 40 g/t Ag, 0.2% Pb, 0.1% Zn
- Kolwezi, Democratic Republic of Congo
880 Mt at 4.5% Cu, 0.4% Co
- Konkola, Zambia
1,000 Mt at 2.5% Cu
- Nchanga, Zambia
710 Mt at 2.5% Cu
- Udokan, Russia
1,310 Mt at 1.51% Cu, 9.6 g/t Ag, 0.5 g/t Au
- Dzhezkazgan, Kazakhstan
2,000 Mt at 1.02% Cu, 0.82% Zn, 0.8% Pb, 13 g/t Ag
- Aynak, Afghanistan
705 Mt at 1.56% Cu
- White Pine, Michigan, United States
>150 Mt at 1.2% Cu

Age and Distribution

These deposits are found in rocks ranging in age from early Proterozoic to Tertiary but are most frequent in late Mesoproterozoic to late Neoproterozoic rocks and in late Paleozoic sequences. These were all periods of major continental breakup, glaciation events, and times when there is evidence for the dissolution of thick evaporite sequences. The following six giant districts are known around the world:

- Neoproterozoic Katangan Basin of Central Africa (Central African copper belt)
- Permian basin of Europe (Kupferschiefer)
- Paleoproterozoic Kodara-Udokan Basin of Siberia (Udokan)
- Paleozoic Chu-Sarysu basin of Kazakhstan (Dzhezkazgan)
- Middle Proterozoic mid-continent rift of the United States (White Pine)
- Neoproterozoic-Cambrian Basin in Afghanistan (Aynak)

Other smaller districts are known in Australia and North Africa, among others.

General Characteristics

Two associations are generally involved for this deposit type. One type (Kupferschiefer) is hosted in reduced, organic-rich sedimentary rocks formed in shallow marine or lacustrine environments comprised of silts, shales, sandstones, and dolomites. These units are typically overlain by oxidized coarser units of oxidized red-bed type sequences. The second type of deposit ("red-bed copper") is hosted within continental red-bed sequences where mineralization occurs at the interface between gray (relatively reduced, often pyrite-bearing) and red (oxidized, hematite-bearing) sandstones, arkose, or

conglomerates. Some deposits in the Central African copper belt are found in highly metamorphosed rocks that appear to be the basement sequences to the basinal deposits seen elsewhere hosting copper mineralization. In some cases, such as the Kupferschiefer, thick sequences of oxidized volcanic-rich sediments are present.

In most cases, deposits are generally thin (usually less than 3 m and never greater than 30 m thick), stratiform, sediment-hosted mineralization comprising Cu (\pm Co, Ag, Pb, Zn, Pt, Pd). The grade of the mineralization is typically 1.5% to 3% Cu, but mineralization is laterally very continuous with huge tonnages developed (the Central African copper belt contained more than 3 Gt of proven ore grading close to 3% Cu). The deposits are dominated by fine-grained disseminated sulfides, comprising largely chalcocite (Cu_2S), digenite (Cu_9S_5), bornite, chalcopyrite, carrollite (CuCo_2S_4), galena, sphalerite, and pyrite.

Type 9.2: Sediment-Hosted Iron and Manganese Deposits

Subtype 9.2.1 Ironstones

These deposits include the Minette-type iron ores of Lorraine and Luxembourg; the Northamptonshire ironstone in England; and the Clinton-type ironstones of Newfoundland, Alabama, and the Appalachians. The giant Lisakov deposit in the southern Urals is an oolitic ironstone. The Minette-type oolitic deposits have been major sources of iron in the past, but their low grades (typically 25% to 35% Fe) have made them increasingly uneconomic as a source of iron.

Age and Distribution

Both Clinton-type and Minette-type iron ores are restricted to the Phanerozoic. Clinton-types are developed in Cambro-Ordovician sequences of North America. Minette-type ironstones are common throughout the Mesozoic of Europe, in western Kazakhstan, and in parts of northern Africa. Major Oligocene ironstones are present at Kerch in Ukraine and at Lisakovsk in Kazakhstan, among others.

General Characteristics

Minette ores are characterized by regionally extensive horizons of siderite and chamosite within dominantly limestone sequences. In Europe they are found in the Jurassic, extending from the United Kingdom through to central Germany. The chamosite is often distinctive, as it usually takes the form of oolites in a mixed silicate and carbonate matrix. The ores are thus lime-rich (up to 20%), which leads to these ores being generally self-fluxing. Clinton ores extend for at least 1,000 km along strike across the Appalachians. They are frequently associated with black shales and have been deposited in continental shelf and estuarine basins. Beds in the ores are generally less than 1 m thick, separated by ferruginous shales. The ores are typified by oolitic hematite-rich beds, with features suggesting a shallow depositional environment although minor sulfide-rich (pyrite) facies are developed.

Subtype 9.2.2: Banded Iron Formation

Three types of banded iron formation (BIF) are recognized that broadly equate to three major time periods in the earth's history, from the Archaean to Proterozoic, and three distinctive tectonic settings. Algoma-type deposits formed in rocks

3,500 and 3,000 million years old, Lake Superior (Superior)-type deposits occur in rocks 2,500 to 2,000 million years old, and the smaller group of Rapitan-type deposits are found in rocks 1,000 to 500 million years old.

Sub-subtype 9.2.2.1: Algoma BIF

- Cerro Bolivar, Venezuela
500 Mt at >60% Fe
- Koolyanobbing, Australia
116 Mt at 62% Fe

Age and Distribution

Algoma-type deposits are typically found in Archaean greenstone belts with the type locality in the Abitibi greenstone belt of Canada. Other deposits include Kudremuk, India; Cerro Bolivar, Venezuela; and Koolyanobbing, Australia. Similar deposits are known in the Paleozoic of the Bathurst District, Canada, and modern analogs may be present on the current seafloor.

General Characteristics

Algoma-type iron deposits are formed as part of sedimentary sequences, but they show a close relationship to volcanic rocks of mafic to felsic composition. The deposits are geographically related to proximal and distal volcanic centers. Mineralization comprises micro- to macro-interlayered iron mineral (oxides, sulfides, or silicates) and silica bands. These silica-iron bands are typically interbedded with clastic sediments and volcanics. The host horizons are regionally extensive features that are often laterally zoned into silicate, oxide, carbonate, and sulfide-dominated facies. Deposits become mineable usually where metamorphosed to a coarser grade or where thickened by tectonic events, or else where they are residually enriched by secondary processes such as weathering.

Sub-subtype 9.2.2.2: Superior BIF

- Hammersley Province, Australia
25,000 Mt at >55% Fe
- Quadrilatero Ferrifero, Brazil
6,000 Mt at >50% Fe
- Serra Norte, Brazil
17,300 Mt at 66% Fe

Age and Distribution

Superior-type deposits are generally Proterozoic in age, largely in the time period 2,500 to 2,000 million years old, and examples are found distributed around the world. Examples include the following: Transvaal Basin, South Africa; Labrador, Canada; Minnesota, United States; Damara, South Africa; and Krivoy Rog in the Kursk region of Ukraine and Russia.

General Characteristics

Mineable deposits of Superior-type BIF comprise discrete stratigraphic units of oxide lithofacies. Stratigraphic thicknesses may be 30 to 300 m, with strike lengths in the order of kilometers. Folding and faulting may result in favorably thickened packages.

BIFs are characterized by alternating bands of silica and iron minerals that when unmetamorphosed are very fine grained. The primary minerals are largely magnetite, hematite, quartz and minor iron silicates, carbonates, and occasionally

sulfides. In manganiferous facies, pyrolusite, manganite, and hollandite may be present. Primary sedimentary features may be present, such as oolites in a cherty or carbonate matrix, rare cross-bedding features, intraformational breccias, slumping, compaction structures, and stromatolite textures. Non-metamorphosed BIFs are referred to as taconite, whereas metamorphosed BIFs generally become coarser grained and are known as metataconite or itabirite.

Taconite rarely makes mineable ore unless upgraded by secondary processes. Itabirite is much coarser grained and can be upgraded by physical sorting, although in most cases both types need to be upgraded by secondary processes to produce mineable ore. Secondary upgrading serves to remove silica and to cause iron enrichment by oxidation.

Sub-subtype 9.2.2.3: Rapitan BIF

- Crest, Yukon, Canada
18,600 Mt at 43.8% Fe

Age and Distribution

Rapitan deposits are known from the Mackenzie Mountains in Canada; Jacadigo, Brazil; and the Adelaide Geosyncline, Australia. They are late Proterozoic to early Paleozoic in age.

General Characteristics

The Rapitan BIFs are generally formed of bedded chert-hematite, much like other Superior-type iron formations. However, their associations are significantly different as they are generally associated with diamictites (tillites), dropstones, sandstones, conglomerates, and argillites. The tectonic setting is one of graben and fault scarps located on the margins of continents or ancient cratons.

Subtype 9.2.3: Manganese Ore

- Mamatwan, South Africa
13,600 Mt at >20% Mn

Age and Distribution

The largest single manganese resource is the Kalahari manganese field of South Africa, which is Proterozoic and related to an iron-rich BIF. Manganese facies of iron-formation ores are also developed in the Lake Superior region and in the Devonian sequences of Kazakhstan and Russia. Manganese is produced from BIF in Gabon. Other important deposits occur in the Oligocene Nikopol Basin in Ukraine and in the Chiatura Basin in Georgia. Important Cretaceous deposits are found in northern Australia (Groote Eylandt) and in the Molango District of Mexico.

General Characteristics

In BIF-type associations, the manganese-rich bodies lie stratigraphically above the iron-rich facies with manganese minerals such as pyrolusite and hollandite present instead of the iron oxides. Textures in the ores are similar to the BIFs described in the previous sections.

In the case of the important Oligocene deposits of the Ukraine and Georgia, the ores consist of irregular concretions, nodules, and masses of manganese oxides with or without carbonates in a silt to clay matrix. The manganiferous bed averages 2 to 3.5 m thick, runs 15% to 30% Mn, and is traceable for at least 250 km along the strike, although postdeposition erosion frequently disrupts the bed.

The main minerals in the ore zone are pyrolusite and psilomelane, together with manganocalcite and rhodochrosite. The deposits are laterally zoned from oxides to carbonate facies.

Type 9.3: Sedimentary Uranium Deposits

Sedimentary uranium deposits can be classified in two categories: unconformity vein-type deposits and sandstone-hosted uranium deposits.

Subtype 9.3.1: Unconformity Vein-Type Uranium

- Cigar Lake, Canada
160,000 t at 19% U_3O_8
- McArthur River, Canada
150,000 t at 21% U_3O_8
- Jabiluka No. 2, Australia
163,000 t at 0.55% U_3O_8
- Crouzille, France
13,400 t at 0.25% U_3O_8

Age and Distribution

These deposits are generally Proterozoic in age (2,500 to 600 Ma) and are found in a number of countries around the world. The most famous are the deposits in the Proterozoic Athabasca and Thelon basins of Canada, but other important fields are found in Australia (East Alligator, Jabiluka) and formerly the Crouzille region of France.

General Characteristics

Deposits are generally small but can range up to 50 Mt in size. The deposits can also be very high grade. Cigar Lake and McArthur River in Canada have the highest grades of any uranium deposits, averaging 19% and 24% U_3O_8 , respectively. Deposits often produce important by-products, and in the case of Jabiluka in Australia, the deposit carries 15 g/t Au. Key Lake in Canada has a nickel resource but is too radioactive to exploit.

Deposits are largely hosted in sandstone units overlying older, metamorphosed, generally Proterozoic basements (Paleozoic in the case of the French deposits). Mineralization is developed at and below the unconformity, especially where the sequence is intersected by faults passing down into the basement. The ore bodies are generally tubular to flattened cigar-shaped high-grade zones passing into a more disseminated style mineralization. Mineralization is strongly controlled by subvertical faults, shear and fracture zones, as well as the subhorizontal plane of unconformity.

Mineralization appears as either polymetallic mineralization containing uranium, nickel, cobalt, and arsenic, or it is monomineralic containing uranium only. Monomineralic-type mineralization is usually formed of euhedral grains of uraninite and pitchblende within the host rock, which may be arkose, semipelite, graphitic schist, pelite, or in some cases mylonite. Polymetallic mineralization is typical for sub-unconformity mineralization in the Athabasca Basin. At the high-grade Cigar Lake deposit, this consists of pods and lenses of pitchblende and coffinite with arsenides and sulfarsenides of nickel and cobalt, together with nickel, cobalt, lead, molybdenum, iron, and zinc sulfides. Gold and platinum group metals (PGMs) can also be present. Monomineralic mineralization is commonly hosted in lenses around structures, or as thin stockwork veinlet zones.

Alteration is common and may take the form of chloritization, argillization, carbonation (dolomite), silicification, pyritization, and tourmaline alteration.

Subtype 9.3.2: Sandstone-Hosted Uranium

- Chu-Sarysu and Syrdarya, Kazakhstan
1.3 Mt contained U_3O_8
- Callabonna, Australia
41.2 kt contained U_3O_8
- Wyoming Basin, United States
320 kt contained U_3O_8
- Southern Texas, United States
~80 kt contained U_3O_8
- Franceville Basin, Gabon
~38 kt contained U_3O_8

Age and Distribution

Sandstone-hosted deposits span a range of host rock ages and are distributed globally with principal deposits found in the Wyoming Basin, Kazakhstan, New Mexico, and Australia.

General Characteristics

These deposits are generally hosted within sandstones as the name suggests, and they are generally medium- to coarse-grained, continental fluvial to marginal marine sediments and are ideal for in-situ leach mining. Foreland basin settings are the most prospective for this deposit type as tectonic activity is a key component to promote fluid flow through the sediments to precipitate uranium. A key feature is also the presence of impermeable units, either a shale or mudstone, interbedded in the host stratigraphy, which helped to focus and contain fluid flow into favorable trap sites.

The deposits are subdivided into the following three main types based on morphology: tabular, roll-front, or basal channel. The tabular-type deposits form elongate lenses of mineralization within sediments that show selective reduction. This reduction may be caused by the presence of organic matter in the host sediments. The mineralization develops parallel to the postulated groundwater flow through the host rocks. Roll-front deposits form disseminations in permeable and porous sandstone beds. The mineralization is developed within the sandstone at an interpreted redox front. Roll-front deposits usually form the largest deposits, and the fact they are hosted in porous sandstone makes them ideal for in-situ leaching. Basal channel deposits are similar to roll-front deposits, but they are specifically hosted in the coarse channel gravels of ancient fluvial sediments.

The primary mineralization is pitchblende and coffinite, but secondary minerals (e.g., autunite, uranophane, carnotite, and tobernite) are often present due to later weathering events. Grades in the deposits are usually quite low (commonly $<0.4\% U_3O_8$), but they can usually be mined by low-cost leach technology, making them economic targets for extraction and processing.

Type 9.4: Gold and Uranium in Conglomerates

- Witwatersrand Basin, South Africa
4,000 Mt at $9.2\text{g/t Au} > 200\text{ g/t U}$
- Elliot Lake, Canada
140 Mt at $0.09\% U$

Age and Distribution

These deposits are found in rocks as old as 3.0 billion years in southern Africa and India. Gold-bearing conglomerates in South Africa are 3,070 million years old, whereas the bulk of the Witwatersrand deposits, which have accounted for more than 35% of all gold mine production, are hosted in rocks between 2,950 and 2,710 million years old. The Elliot Lake conglomerates in Canada are 2,450 million years old and the Tarkwian gold-bearing conglomerates in West Africa are 2,130 million years old. Tertiary-aged gold-bearing pebble conglomerates are known in New Zealand with many features similar to the more ancient examples. The bulk of the economic deposits are Archaean to Proterozoic, although if they represent paleoplacer deposits (which is the traditional model for their formation), then modern analogs could be the gold-bearing alluvial gravels found in many goldfields still actively forming today.

General Characteristics

The most significant deposits of this group are the gold-uranium deposits of the Witwatersrand Basin in South Africa and the uranium-bearing conglomerates of Elliot Lake in Canada. The following observations are based on these deposits.

In the Witwatersrand, gold is hosted within a sequence of quartz arenite-dominated rocks that are chemically, mineralogically, and texturally submature to supermature. Quartz pebble rocks dominate, but feldspathic quartzites are also relatively common, suggesting a granitic source for much of the detritus. At Elliot Lake, the mineralization is hosted in similar quartz-rich pebble conglomerates where the detritus appears to have been derived from the reworking of pegmatitic granites.

In the Witwatersrand, a number of host rock types are associated with the gold-bearing conglomerates. At the base of the section, submature arenites are developed in a stream system on granitic basement rocks. Further up, the West Rand Group contains shale, sandstone, and iron formation. The main host part of the package, the Central Rand Group, formed as part of major braided stream systems, clearly developed in broad valleys as parts of alluvial fans. Unidirectional and herringbone cross bedding is recorded, indicative of both single flow directions and a degree of reworking in shallow intertidal conditions. Argillites, siltstones, and minor limestones are testament to standing water during parts of the sedimentation, and in places, glaciogenic deposits and iron formations are developed. Finally, the uppermost part of the sequence comprises a unit called the Black Reef, which contains gold where it has reworked the Central Rand Group rocks.

The ores in the Witwatersrand are typically free-milling, with gold largely present as native grains containing 7% to 14% Ag. The ore material is made up of the following three types of ores: coarse pebble conglomerates ("blanket reef"), carbon seams, and pyritic quartzites. Gold may take one of five different forms: free gold particles with minor sulfides (e.g., sphalerite, linneite, gersdorffite, cobaltite, and chalcopyrite), gold associated with carbonaceous matter, redistributed gold along fractures or on the surface of other grains, gold in pyrite or arsenopyrite, or gold in later secondary quartz veins.

At Elliot Lake, a somewhat similar package of fluvial sediments hosts mineralization where uraninite occurs as poorly rounded to euhedral grains up to 0.2 mm across within the matrix of a quartz-pebble conglomerate.

Type 9.5: Chemical Sediments

Chemical sediment deposits are divided into evaporites and manganese nodules. These are discussed as follows.

Subtype 9.5.1: Evaporites

Evaporites are the main source of rock salt, potash, borates, nitrates, agricultural fertilizers, and lithium.

Age and Distribution

Evaporites are only known to have formed from the Proterozoic onwards, although in the bulk of cases in the Proterozoic, the evaporite horizons are now no longer present. Basins hosting major exploited evaporite deposits include the Permian Zechstein Formation, present through most of northern Europe and the eastern United States. Other basins are the modern intracontinental lacustrine basins of Chile, Bolivia, Argentina, California, and Utah, where borates, nitrates, and lithium deposits are mined. One of the world's largest borate-producing regions is located in western Turkey.

Subtype 9.5.2: Manganese Nodules

This deposit type is unique, as it occurs largely in international waters of the ocean. The deposits have never been mined owing to the combination of the water depths and the lack of a comprehensive legal framework for the exploitation of the nodules.

Age and Distribution

The nodules occur in the deep pelagic parts of all major modern oceans, but they especially occur in the Pacific Ocean, where exploration indicates there may be up to 100 nodules per square meter. They represent an enormous future resource of nickel, copper, cobalt, and manganese.

General Characteristics

The nodules occur in the deep oceans where normal clastic sedimentation is low to absent. In the Pacific, where the nodules are best developed, they contain up to 2% combined Ni and Cu with substantial Co and Zn. Deposits are very extensive; the most attractive resource is in the so-called Clarion-Clipperton region of the Eastern Pacific, in a belt bounded by longitude 60°W to 180°W and latitude 15°S and 15°N.

CLASS 10: ORES RELATED TO WEATHERING

Type 10.1: Laterites

Lateritization is a weathering process occurring under humid tropical conditions leading to the dissolution of most soluble elements, such as K, Na, Mg, Ca, and some Si, and accumulating less soluble elements, such as Al and Fe. Principal deposits formed by this process are nickel-cobalt, bauxite (Al), and lateritic gold. Lateritization of existing lower-grade iron ores can result in significant upgrades to the deposits, largely as a result of silica removal. Important phosphate and niobium deposits have been upgraded in this way at Mabounie in Brazil, in Gabon, and at Lueshe in the Democratic Republic of Congo.

Subtype 10.1.1: Bauxite

Two main types of bauxite are karstic and lateritic. Karstic bauxites form by the dissolution of carbonate sequences with concomitant weathering of associated aluminosilicates. Lateritic bauxites are developed over a variety of

aluminum-bearing rocks and form a characteristic zoned profile. Karstic bauxites are commonly developed in carbonate sequences in the Mediterranean region, for example, at Les Baux in France, from where the deposit type gets its name. Lateritic bauxites are developed in five major regions of the world: Guiana and the Brazilian shield in South America, a province in West Africa, India, Southeast Asia, and Australia. These lateritic bauxites account for around 90% of world's bauxite resources.

General Characteristics

In a typical lateritic bauxite, the fresh parent rock is overlain by a saprolite composed largely of kaolinite with some iron hydroxides and residual parent minerals (e.g., quartz, zircon, and magnetite). Saprolite is where the texture of the original rock is still discernable and where the volume is preserved despite removal of soluble components. This saprolite varies in thickness up to 100 m in deeply weathered terrains. Above the kaolinitic saprolite, gibbsite replaces kaolinite, and this is the bauxite horizon. This horizon, which constitutes the ore zone, is typically a few meters thick and usually has very high aluminum grades and low iron values. Above this, the profile is capped by either a duricrust (which may be bauxitic or ferruginous) or a clay-rich zone. Any duricrust is likely to be composed of oxyhydroxide minerals and kaolinite.

Three types of lateritic bauxite are recognized: orthobauxite, metabauxite, and cryptobauxite. Orthobauxites are those interpreted to have formed in situ by a single-stage weathering process. Metabauxites are more aluminum-rich, having developed on quartz-poor rocks as an upgrade reworking under drier conditions of an already formed orthobauxite. Cryptobauxites are used to describe bauxites buried under clay cover, again resulting from the reworking of an orthobauxite under probably more humid conditions.

Subtype 10.1.2: Nickel (Cobalt) Laterite

- Koniambo, New Caledonia (silicate)
150 Mt at 2.57% Ni
- Cerro Matoso, Colombia (silicate)
40 Mt at 2.5% Ni
- Murrin Murrin, Australia (clay-silicate)
125 Mt at 1.02% Ni
- San Felipe, Cuba (clay-silicate)
230 Mt at 1.33% Ni
- Euboea, Greece (oxide)
185 Mt at 1.3% Ni
- Goro, New Caledonia (oxide)
200 Mt at 1.57% Ni
- Buruktal, Russia (oxide, clay-silicate)
110 Mt at 1.2% Ni
- Vermelho, Brazil (oxide, silicate)
410 Mt at 1.23% Ni

Age and Distribution

A number of known nickel laterites occur in the currently tropical zones of the earth, and it is clear that many are actively forming today. Major deposits occur throughout Central America, Africa, Southeast Asia, and the Pacific, and they can be attributed to recent weathering periods. Southern Europe (Balkans and Greece) through to Turkey and many parts of Russia and adjacent states host nickel laterites, which are the result of late

Mesozoic and Tertiary weathering periods. In addition, many deposits are located on ancient crust (e.g., Australia and Brazil), where the weathering history is likely to have been very protracted and difficult to ascribe to one particular time period.

General Characteristics

In broad terms, in-situ nickel laterites form simple zoned profiles over unweathered parent rock. In a number of cases the laterite may be transported to some degree where the nickeliferous unit is no longer autochthonous on its parent. In all cases, the initial parent rock was an ultramafic, and in a rare case, mafic igneous parent rock was largely composed of Mg- and Fe-bearing silicates where nickel substituted for Mg to some degree. Typically, nickel values in unweathered parent rock are 0.2% (by weight) Ni. Apparently there is no necessity for the parent rock to be unusually enriched in nickel. Ultramafic rocks suitable for forming nickel laterites include dunites, peridotites, and serpentized equivalents, where nickel resides in olivine, pyroxene, and serpentine-group minerals.

A typical laterite profile comprises an unweathered ultramafic parent rock passing up into a saprolite zone (weathered but still retaining a fair degree of competence, original texture, and volume). Above the saprolite zone is an oxide zone that may have a variable component of clay (usually mixed-layer and iron-rich). This oxide zone is often zoned into a lower limonitic (goethite-rich) and upper hematitic facies, which is likely to have silica present as aggregates or distinct ledges. The whole profile is capped by a ferruginous or siliceous duricrust where present.

Nickel is usually enriched in the saprolite zone where Ni substitutes for Mg in a range of hydrous layer silicate minerals (such as serpentine, talc, sepiolite, and chlorite). Nickel is also enriched in the oxide zone, where nickel may be hosted in mixed-layer clays, more commonly in goethite, and also in a range of manganese oxides, including asbolane. Cobalt is an important associated metal in these deposits, and this is strongly fixed by the manganese oxide phases. Hematitic parts of the profile are generally nickel-poor and silicification decreases grade.

Subtype 10.1.3: Lateritic Gold

Artisanal miners in West Africa and Brazil have mined this deposit type for centuries. In these deposits weathering has both liberated gold and also resulted in the physical concentration of gold particles. Major gold resources of this type have been identified at Ity in Cote d'Ivoire, Ashanti in Ghana, and Igarape Bahia in Brazil.

In parts of Australia, nugget-bearing weathering zones have produced spectacular numbers of gold nuggets, and bauxitic deposits in Queensland carry gold where no mineralization is detected in the basement rocks. A major gold resource of 45 Mt at 1.8 g/t Au was identified at the Boddington bauxite mine, Western Australia, in 1988 after material was finally sent for assay.

Type 10.2: Supergene Weathering

Supergene weathering deposits are divided into secondary copper deposits and secondary zinc deposits.

Subtype 10.2.1: Secondary Copper

- Bingham Canyon, Utah, United States (porphyry Cu)
338 Mt at 1.5% Cu

- Morenci, Arizona, United States (porphyry Cu)
379.4 Mt at 1.02% Cu
- Potrerillos, Chile (porphyry Cu)
137.4 Mt at 1.51% Cu
- Chuquicamata, Chile (porphyry Cu)
684.3 Mt at 2.12% Cu
- El Teniente, Chile (porphyry Cu)
234.8 Mt at 2.18% Cu
- Phoenix, Cyprus (VMS)
9.2 MT at 0.78% Cu + 6 Mt at 0.31% Cu

Age and Distribution

Many major porphyry copper camps around the world have a developed supergene zone that makes them attractive targets for exploitation. Many large VMS deposits also have supergene blankets (e.g., Paleozoic of the Urals), although these have not been exploited to date. The Phoenix ore body in Cyprus is an example of a supergene-enriched VMS that has been exploited for the oxidized ores.

General Characteristics

At the base of a typical supergene profile is the primary hypogene ore, which in the case of a porphyry copper deposit is typically comprised of chalcopyrite and pyrite with various silicate phases (e.g., K-feldspar, muscovite, epidote, biotite, and quartz). Above this lies the more-reduced part of the supergene blanket, which may contain secondary sulfide copper minerals such as the more common chalcocite, covellite, and bornite. Above this is the more oxidized supergene assemblage, including copper carbonates and oxides. Above the supergene zone are the leached zones, where sulfide minerals are generally destroyed, and finally, a full profile would be capped by a zone rich in hydrated iron oxides (gossan or iron hat).

The main zone of economic interest is the secondary sulfide zone containing bornite, covellite, and chalcocite. These sulfides are copper-enriched compared to the primary ore, and thus the grades are often significantly higher than the primary ore. In addition, the mineralogy of the ore is more favorable for low-cost solvent-extraction methods of treatment. Gold is generally conserved during the supergene enrichment process, but its fineness and grain size may increase. In lateritic weathering terranes, however, gold grades may be significantly upgraded.

Subtype 10.2.2: Secondary Zinc

- La Calamine, Belgium
1.9 Mt at 40% Zn
- Jabali, Yemen
9.4 Mt at 10.8% Zn, 2.3% Pb, 77 g/t Ag
- Angouran, Iran
3.3 Mt at 38% Zn, 2% Pb
- Jinding, China
50 Mt at 8% Zn, 1% Pb
- Silesia, Poland
17.3 Mt at 17% Zn
- Skorpion, Namibia
24.6 Mt at 10.6% Zn

General Characteristics

Three types of secondary zinc deposits are defined: direct replacement, wall-rock replacement, and residual and karst

fill deposits. Direct replacement deposits are effectively zinc-rich gossans where the sulfide body is weathered. In this case, sphalerite is replaced by smithsonite and hemimorphite. Usually, deposits are complex mixtures of sulfides (galena, pyrite, chalcopyrite, etc.), so the secondary assemblage is usually a more complex mixture of oxides, carbonates, and silicates. Deposits formed from a weathered MVT tend to be the most mineralogically simple, dominated by smithsonite, hemimorphite, and hydrozincite. In more arid weathering profiles, willemite (silicate) is formed.

CLASS 11: PLACER DEPOSITS

Placers have been a source of metals from early times, as they are easily worked by manual methods, processing by washing or winnowing techniques. Most major gold rushes were based on the discoveries of alluvial gold, which may have later led to hard rock discovery. Very significant placer diamond deposits are worked on the west coast of southern Africa. Beach sands are mined in various regions of Australia, eastern Africa, and the Americas.

Deposit types range from various beach sands containing heavy minerals, such as rutile, ilmenite, zircon, and monazite, to deposits of gold, platinum, tin (cassiterite), and diamonds. In all these cases, the mineral of interest becomes concentrated in either river drainages or in active marine environments by the action of moving water. The minerals of interest are generally both obdurate and of higher density than other minerals, so they tend to become concentrated in higher-energy environments in marine or river systems.

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