

Summary of section 1

1. The importance of metals to the industrialised world stems from the vast array of properties that they exhibit, both in their pure form and when used in combined form in alloys, chemical compounds and composite materials. The choice of a metal for a particular use depends on the suitability of its properties, its price and the availability of substitutes.
2. The metal resources industry is a dynamic system. Usefulness and the perceived value create the demand that supports the price of a metal, which may place limits on potential sources. Price also depends on the accessibility of the ore and the cost of processing necessary for the metal to be extracted. Supply is ultimately constrained by the availability of a metal, and the distribution and extent of natural concentrations. Demand can be affected by substitution for or by other materials. Price, supply and demand are all affected by economic, technological and political factors.
3. Metals are derived from ores, defined as rocks containing ore minerals in sufficient quantities to be exploited economically. To be an ore mineral, a mineral must normally contain relatively high concentrations of metals in a form that can be extracted economically. Commonly, ore minerals are oxides and sulphides, from which metals can be extracted by smelting. Ore deposits are economically minable concentrations of ore minerals produced by natural geological processes.
4. Ore minerals are chemical compounds formed naturally under favourable chemical conditions when their major constituents are available. Substitution of major constituents by trace metals may produce impurities in ore minerals. Both impurities and associated minerals on ore deposits can provide valuable metals as by-products, or create costly problems for chemical processing, necessitating the provision of environmental safeguards.
5. The grade of a rock is the concentration of metal that could be extracted. The extent of an ore body is defined by the cut off grade, the minimum grade that can be mined economically. The estimated reserves of a large, low-grade dispersed deposit vary greatly according to the cut-off grade, and therefore on economic circumstances, whereas those of a smaller, high grade, confined deposit are defined primarily by geological constraints on the geometry of a deposit. An extensive dispersed deposit is economic to mine at lower grades than a smaller confined deposit.
6. Many metallic elements are an essential part of the natural environment, both organic and inorganic; but excessive amounts of metals and of waste released

into the environment – by metals extraction and processing industries, for example – may have harmful effects

7. Metals are non renewable resources, but a degree so sustainability may be achieved by continuing current trends towards increased conservation through recycling and substitution as well as improved efficiency in extraction and exploration
8. The earth's crust and mantle are the main sources of metals; they are concentrated by igneous, aqueous and sedimentary fractionation processes to produce ore deposits
9. Agents that transport metals from their source to their site of deposition include: magmas in igneous systems, cool meteoric water and seawater at the Earth's surface; and hot, reactive groundwaters - aqueous solutions better known as hydrothermal fluids – in subsurface environments. Physical transportation involves crystal grains in magmatic systems and sedimentary grains in surface waters. Chemical transportation of metals occurs in magmas, in cool surface waters, and in hydrothermal solutions.
10. Deposition of ore minerals takes place where space is available, on and beneath the Earth's surface, due to changes in the physical or chemical conditions experienced by the transporting agent.
11. Forms of energy involved in concentration processes include radioactive heating within the earth, the Earth's gravitational energy and the Sun's energy at the Earth's surface. They are responsible for mobilizing the agents of transportation and promoting chemical reactions.
12. Concentration processes must operate on a large scale or for a long period of time for ore minerals to be concentrated sufficiently to form an ore deposit. This requires an ample supply of metals, a plentiful and/or long-lived supply of the agent with access to open pathways, a continuing source of energy to maintain the system, and the presence of persistent conditions with open space at the site of deposition

Summary of section 2

1. Igneous processes take place in magmatic systems, and involve crystals, immiscible liquids (magma, sulphide melt, oxide melt, water), and gases (as formed when water boils). Chemical and physical processes associated with the separation of crystals or immiscible liquids from magma, give rise to magmatic fractionation, which can produce a range of igneous rock types and may concentrate metals to form ore deposits
2. Igneous rocks span a range of compositions – from peridotite to gabbro (basalt) to diorite (andesite) to granite (rhyolite) – the formation of which depends on the source of the magma and the extent to which magmatic fractionation has occurred. Different types of ore deposit are associated with particular types of igneous rock: magmatic segregation deposits are associated with peridotites and gabbros, pegmatite ore deposits with granites, and porphyry ore deposits with diorites, granodiorites and granites.
3. Magmatic segregation deposits separate from hot fluid basaltic magmas when either dense early formed crystals, or dense immiscible liquids (sulphide or oxide), sink towards the floor of a magma chamber and form cumulate layers. Settling of crystals may produce chromite and magnetite ore deposits; settling of sulphide rich immiscible liquids may produce ore deposit rich in copper, nickel, gold or platinum; settling of oxide rich immiscible liquids may produce ore deposits rich in iron or iron-titanium oxides. Development of the multiple layering that is typical of many magmatic segregation deposits requires periodic influxes of hot magma into the magma chamber to reinitiate convection
4. Pegmatites form from granitic magma after anhydrous minerals have crystallised from it, so enriching the remaining melt in water and sometimes incompatible elements, and thus making it particularly fluid. Pegmatites are not often mineralise, but when they are, they can be enriched in ore minerals of valuable metals, including beryllium, caesium, lithium, niobium, rare earth elements (such as cerium) tantalum, thorium, tin, tungsten, uranium and zirconium, many of which rarely form mineral deposits in other circumstances
5. Porphyry deposits are formed when metal rich watery fluids boil and are released explosively from a wet granodioritic magma being emplaced at a high level in the crust. The network of fractures produced, provides pathways for distribution of metal-rich fluids that are derived initially from the magma and subsequently, through convection of meteoric water, from surrounding rocks. The fractures also provide sites for the deposition of ore minerals, as fluids cool and react with wall rocks. Porphyry deposits provide much of the world's copper and molybdenum, as well as substantial quantities of tin, silver and gold as by products. They are typically low grade but extremely large deposits.

Summary of section 3

1. Processes at the Earth's surface, in addition to forming deposits of bulk resources – particularly industrial minerals – can also concentrate metals to form ore deposits. Minerals resistant to weathering are concentrated by physical transport and deposition to form placer deposits. Chemical processes concentrate metals through removal of soluble material to leave behind residual deposits, and by precipitation of dissolved material in a variety of different environments, to form bedded sedimentary deposits and encrusted deposits underwater, and secondary enrichment deposits beneath the land surface
2. Chemical transport and precipitation of metals in surface and near surface waters are controlled largely by changes in the pH and/or the oxidising conditions of the environment. These conditions are often influenced by the reducing properties of decaying organic matter. Percolating groundwater starts off as oxidising and slightly acidic due to the dissolved atmospheric gasses in rainwater. With progressive seepage, reactions with rocks and organic matter change the pH and make the groundwater more reducing.
3. Residual deposits are the insoluble residues that result from intense weathering of surface rocks in tropical climates where rainfall is high and intermittent, but drainage is good, erosion is minimal, and soils dry out regularly. Lateritic soils rich in insoluble oxides of iron and aluminium are a common form of residual deposit. Sometimes they contain ore deposits of nickel, cobalt, copper and gold, which are minable to quite low grades because they are easily accessible and poorly consolidated. The most important form of laterite is bauxite, the ore of aluminium, which is composed largely of hydrated aluminium oxides. The best sources of bauxite are rocks accessible to percolating rainwater and low in other metals, such as iron and titanium, which also form insoluble weathering products but are undesirable as impurities in the ore. Under warm, humid climatic conditions, silica produced during chemical weathering is more soluble than alumina in surface waters
4. Weathering of mineral deposits by oxidising rainwater often leads to the formation of secondary enrichment deposits. Metals such as copper and silver may be leached from sulphide minerals under oxidising conditions at and near the Earth's surface, often leaving an oxidized deposit of hydrated iron (III) oxide as a leached capping or gossan. The metal rich solutions migrate downwards to the water table, where they may react with primary ore minerals under reducing conditions to form metal enriched secondary minerals. Secondary enrichment zones are particularly important in dispersed porphyry ore deposits.

5. Chemical (or bio chemical) precipitation in shallow seas was responsible for deposition of Precambrian BIF and more recent Jurassic ironstones, which form extensive iron rich deposits. The ultimate source of iron is not always clear: it is most likely to have been transported as Fe^{2+} ions either in solution or attached to organic colloids. Economic grades currently exceeding 60% iron in many BIF deposits have usually been enhanced by leaching and secondary enrichment processes.

6. Manganese nodules form slowly on the floors of deep oceans by precipitation of hydrated iron (III) and manganese (IV) oxides in layers. They also contain relatively high levels of nickel, copper and cobalt, along with zinc and lead, reaching combined abundance of 3% in some parts of the oceans. Thus, manganese nodules are a potential resource for these metals if problems of extraction, ownership and environmental damage can be resolved; they are currently a conditional resource.

7. Placer deposits are concentrations of hard, dense, chemically stable minerals which are liberated by chemical breakdown and erosion of source rocks. These heavy minerals are physically concentrated through transport in surface waters and subsequent deposition, to form alluvial deposits in rivers and beach deposits along coasts. The main minerals recovered are gold and cassiterite (SnO_2) from alluvial deposits and heavy oxide minerals such as rutile (TiO_2) and ilmenite (FeTiO_3) from beach deposits. Some “fossil” placer deposits of Precambrian age are among the world’s most important gold and uranium deposits. Recent, unconsolidated placer deposits are easy to mine by dredging or with high-pressure water jets.

Summary of section 4

1. Hydrothermal systems involve the *movement* of large volumes of hot, aqueous fluids through pathways in the crust in response to:
 - a. Convection – driven by normal geothermal heating or igneous intrusion; and/or
 - b. Compaction – through burial of wet sediments
2. To form a hydrothermal ore deposit also requires:
 - a. An extensive and fertile source of ore mineral constituents (metals and sulphur especially);
 - b. A fluid of suitable composition to extract and transport those constituents;
 - c. A suitable site where space is available for deposition, to which prolonged fluid flow is focused, and where local conditions favour the precipitation of ore minerals
3. Compositions of hydrothermal fluids, and of the ores they may produce, depend on the source of the water and on the assemblage of the source rocks that they leach. Therefore different types of deposit, in terms of their form and typical ore minerals are associated with different geological environments. However, the *principles* that govern the concentration of metals – involving the leaching of large volumes of rocks, the transportation of soluble components and the localised precipitation of ore minerals- are always the same.
4. Exhalative hydrothermal deposits can be seen forming on the Earth's surface at present day, both on and (associated with hot springs) and on the ocean floor (associated with black smokers) in areas of active volcanism
 - a) Hydrothermal systems associated with hot springs may form high-grade gold-bearing veins and breccias well below ground level, and low-grade disseminated gold in more extensive replacement and alteration zones.
 - b) Hydrothermal systems associated with sea-floor volcanism form submarine massive sulphide deposits, known as Cyprus-type, when formed in oceanic settings, and Kuroko-type, in volcanic arc settings
5. Hydrothermal deposits formed with continental crust are often associated with thick sequences of sediments in which background geothermal heat may be enhanced by the intrusion of large igneous bodies. They commonly occur as vein deposits within fractured rocks.
 - a) Limestones sometimes host low-temperature hydrothermal lead-zinc deposits in veins and in solution cavities. Interaction of hydrothermal

fluid either with limestone or another fluid may cause the deposition of ore minerals; both fluids and metals may be derived from associated shales and evaporites

- b) High temperature hydrothermal tin-tungsten vein deposits are often associated with large granitic intrusions, which provide additional heat as well as metals and fluids; but most of the fluid and the metals for accompanying copper, lead and zinc mineralisation are derived from surrounding, usually mainly sedimentary, rocks.

Summary of section 5

- 1 The concentration of metals to produce ore deposits involves igneous, sedimentary and aqueous fractionation by natural physical and/or chemical processes in magmatic, sedimentary and hydrothermal systems. Most of these processes occur within the rock cycle. Many are driven by plate tectonic activity.
2. Mineral deposits linked to specific tectonic settings are:
 - Podiform chromites, Cyprus- type massive sulphides and metalliferous sediments, which *form* at constructive plate margins but *are preserved* at former destructive plate margins;
 - Porphyry (copper and molybdenum) ore deposits and Kuroko-type massive sulphide deposits, which form at destructive plate margins.
 - Pegmatite and high-temperature hydrothermal vein deposits associated with granites, which form in collision settings at former destructive plate margins.
 - Sedimentary deposits, such as ironstones, and the limestone hosts of hydrothermal Pb-Zn deposits, which form in sedimentary basins at stable continental margins.
 - Banded iron formations and stratiform igneous segregation deposits, which occur in ancient, relatively stable parts of continents, the cratons.
- 3 Many types of mineral deposit are restricted to particular geological settings. Links with particular geographic locations and geological ages are important in mineral exploration