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Cambridge University Press & Assessment
978-1-107-02222-5 — Ore Deposit Geology
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Excerpt
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1 What is an ore deposit?

1.1 Definition and scope of ore deposit geology

We extract many types of commodities from the Earth; minerals and rocks from mines, hydrocarbon liquids and gases and groundwater through pumping or where they rise to the surface under their own pressure, the heat of rocks as geothermal energy. An ore deposit is ‘what is mined’. Precise definitions of the term are based on economics rather than geology, for instance:

> ore is rock that may be, is hoped to be, will be, is or has been mined; and from which something of value may be (or has been) extracted.
>
> (Taylor, 1989, Ore reserves – a general overview. *Mining Industry International*, vol. 990, pp. 5–12.)

Which commodities are included by the definition of ore deposits?

The economic definition of an ore deposit given above would include:

- ores of metals
- ores of gemstones
- ores of minerals used as feedstock for production of industrial chemicals
- ores of minerals used in industrial products
- rock used as aggregate, for building stone
- coal and oil shale

This book does not cover all mined commodities. Traditionally, the study of ore deposit geology has been concerned with mineral resources in which the product of economic interest is one or more mineral, specifically either those minerals from which a metal is extracted or gemstones. A practising ore deposit geologist may be expected to have knowledge of sources of these commodities. The study does not include either the mining of rocks or of coal. Nor does it generally include the mining of minerals that are used exclusively as feedstock in industrial processing or products (**industrial minerals**).

It is, however, not in all cases possible to make a clear-cut distinction between the categories of commodities in the list above: there are some ores from which both a metal and one or more industrial minerals are extracted, for instance products from bauxite are both aluminium metal and feedstocks for Al-bearing abrasives and refractory products, and diamond is both a gemstone and an industrial mineral. Further, not all mineral resources are mined. Some uranium is obtained by *in situ* leach extraction involving pumping solvent through uranium-bearing rocks, specifically sandstones, and some metals are extracted from saline brines pumped from sediments that underlie salars or salt lakes. Despite these caveats, the tradition of ore deposit geology as being concerned with the sources of metals and of gemstones is closely followed in this book, although some industrial minerals are discussed.

What are the important mined commodities?

By tonnage, the major mined commodities are not ores but are coal and construction materials (Table 1.1). The production by tonnage of a number of industrial minerals is also much greater than all metal ores except iron ore. The extraction of a number of metals (e.g. Fe, Al, Cu, Zn, Ni, Au), however, are within the top few commodities in terms of value and each contributes to the order of 0.1% of the dollar value in the world's economy. Metals are low-tonnage–high-value products relative to many larger-tonnage mined commodities (Figure 1.1). Because of this characteristic they are transported and traded worldwide. Other than diamonds, for which industrial uses make up about half the market, gemstones are very minor commodities by both tonnage and value.

What constitutes an ore deposit?

An ore deposit is made up of one or more **ore bodies**. These are the masses of rock that contain ore and from which the commodity of value will be extracted. Not all ore within an ore body will be extracted. Ore bodies are divided into **reserves** and **resources**. These terms have precise legal meanings in many countries, but as a generality the difference is that reserves are ore that is economically feasible to mine and for which there are no legal or engineering impediments to mining, while resources are ores that may potentially be extracted at some time in the future. Engineering constraints on excavation form one set of factors that will influence what ore is economic to mine (Figure 1.2). The mining of an ore body may be from an open pit, an underground mine, or a combination of the two.

1.2 Ore deposit geology and related sciences

The extraction of an economic commodity from ore

Ore contains **ore minerals** intermixed with other minerals (**gangue**) from which they must be separated through milling, to break down ore into constituent minerals, followed, typically, by flotation to separate the minerals of economic interest from the gangue. Most ore minerals of metals are not 'native' metals, but are compounds in which the metals are bonded and from which they must be extracted. Likewise, many industrial minerals need to be refined or processed (**beneficiated**) before sale. Methods of ore processing through flotation, refining and extraction are chosen based on ore mineralogy and on the physical characteristics of the ore. The science of extraction involves aspects of chemistry and engineering and forms a field study called extractive **metallurgy** (Figure 1.3).

The mineralogy of ores

Many ore minerals are relatively rare minerals. Some are widespread as accessory minerals in many types of igneous, metamorphic and sedimentary rock. Others are present

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Table 1.1

Commodity	Energy mineral, Gem, Metal ore, Industrial mineral	Worldwide production, Mt a^{-1}	Per annum increase % (20-year average)	Approx. price per ton, US\$	World value of industry US\$ $\times 10^{6}$/a
Aggregates	**I**	15 000	3	5	**45 000**
Coal	**E**	7000	1	35	**245 000**
Limestone (cement, lime)	**I**	2300	6	6	**13 800**
Pig iron (iron ore)	**M**	2200	7	60	**132 000**
Common clays	I	500	1.5	6	3000
Salt (halite)	**I**	260	3	60	**15 600**
Phosphates	**I**	160	1	127	**20 320**
Gypsum	I	150	5	9	1350
Industrial sand	**I**	112		250	**28 000**
Sulfur	**I**	70	2	260	**18 200**
Aluminium	**M** (I)	37	4	1800	**66 600**
Kaolin	I	30	3	135	4050
Potash	**I**	25	1.5	300	**7500**
Manganese (Fe–Mn)	**M**	23	0	1000	**23 000**
Magnesite	**I**	19	4	400	**7600**
Feldspar	I	18		70	1260
Copper	**M**	15.5	3	7000	**108 500**
Bentonite/ Fullers Earth	I	13.5	2	70	945
Trona/soda ash	I	12	6	140	1680
Zinc	**M**	11	2	1600	**17 600**
Baryte	I	8	4	50	400
Talc	I	7.2	0	110	800
Chromium (Fe–Cr)	**M**	7	4	4000	**28 000**
Borates	**I**	6		1100	**6600**
Titania	I (M)	5.8	3	400	2320
Fluorite	I	5	0	180	900
Lead	M	3.8	0.5	1100	4180
Diatomite	I	2.2	0	250	550
Asbestos	I	2	−3	1100	2200
Nepheline syenite	I	2	−2	100	200

Table 1.1 (*cont.*)

Commodity	Energy mineral, Gem, Metal ore, Industrial mineral	Worldwide production, Mt a^{-1}	Per annum increase % (20-year average)	Approx. price per ton, US$	World value of industry US$ $\times 10^6$/a
Perlite	I	1.7	−1.5	300	510
Nickel	**M**	1.4	3	27 000	**37 800**
Zirconium minerals	I (M)	1.2	2	300	480
Graphite	I	1.1	3	3000	330
Magnesium	M	0.7	5		
Tin	M	0.3	3	13 000	3900
Molybdenum	**M**	0.2	4	44 000	**8800**
Antimony	M	0.19	6	5300	1000
Tungsten	M	0.058	3	30 000	1740
Vanadium (V_2O_5)	M	0.054	3	5500	300
Uranium (U_3O_8)	E	0.051	2	60 000	3060
Silver	**M**	0.021	2	450 000	**9450**
Lithium	M/I	0.015	5	75 000	1100
Gold	**M**	0.0023	−0.5	36 000 000	**82 800**
Mercury	M	0.0013	−8	18 000	25
Platinum-group elements	**M**	0.0005	2	42 000 000	**8400**
Diamonds	**G (I)**	14 t	3	9 × 10^9	**13 000**

Approximate worldwide annual production of major products of the mining industry, rate of increase of production, unit price, and value. Commodities of most value are highlighted in bold. For production less than 1 Mt a^{-1}, only selected important metals and diamond are listed. From Kogel *et al*., 2006, and United States Geological Survey Minerals Yearbooks 2008 and 2009. Prices of many industrial feedstocks and minerals vary greatly with product quality. In these case weighted average prices are given where these are possible to estimate.

only in ores. Important ore minerals include native metals, sulfides, **sulfosalts**, oxides and hydroxides, and specific silicates, carbonates and minerals of other classes (Table 1.2).

Goldschmidt's four-fold geochemical classification of the elements is based on predominant bonding affiliation and was originally formulated to explain the chemical differentiation of the Earth into core, silicate mantle and atmosphere:

- Lithophile – elements that combine with oxygen, dominantly in oxide and silicate minerals;
- Chalcophile – elements that combine with sulfur, dominantly in sulfide minerals;
- Siderophile – elements that occur as native metals or as alloys;
- Atmophile – elements forming elemental gases.

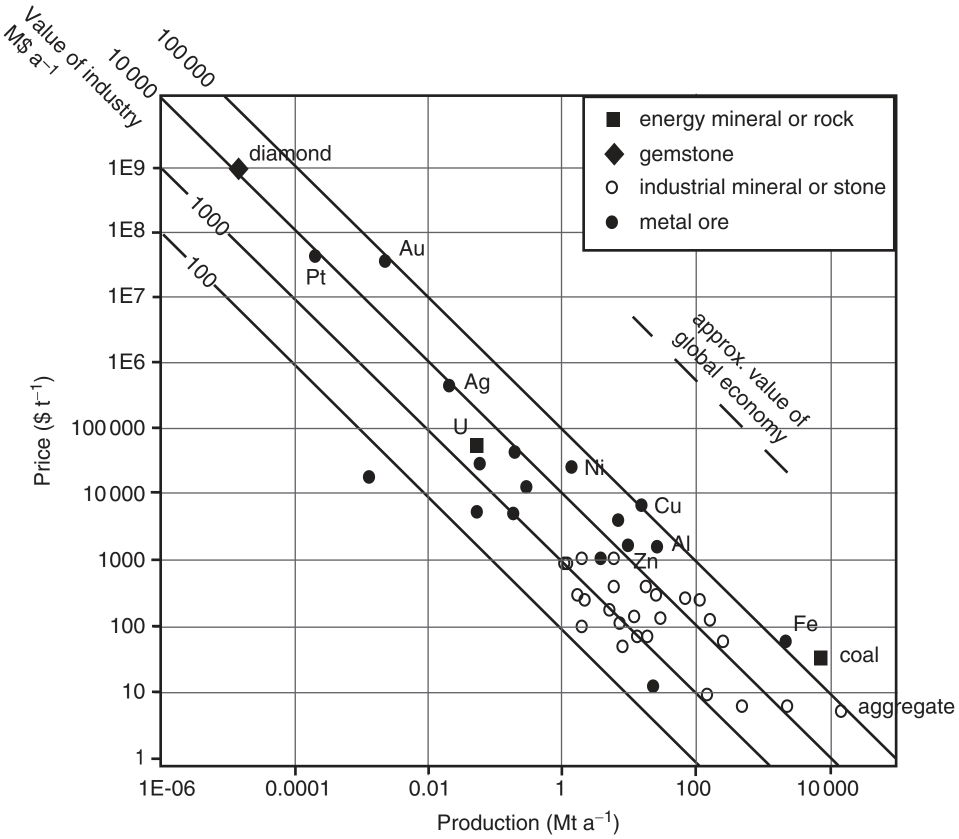

Figure 1.1 World production (Mt a^{-1}) versus price per tonne of mineral and rock commodities (2009 data from USGS Mineral Resources Program publications and various additional sources). Most metals are low-tonnage–high-value commodities. The global value of production of a metal is shown by the diagonal lines and for a number of metals is in the top rank of commodities.

The classification can be modified to reflect chemical behaviour at the Earth's surface, in the crust and in the upper mantle (Figure 1.4), and as such is a guide to the mineral class that each element most commonly occurs in. Each of these groups of elements is systematically positioned within the periodic table (Figure 1.4). Some elements can have two or three bonding affiliations, depending on the geochemical environment, and as indicated by secondary affiliations shown in Figure 1.4. Of particular significance in this respect are high valence states of semi-metals in surface and near-surface geological environments.

Comparison of Figure 1.4 with Table 1.1 shows that many of the economically important metals are chalcophile or siderophile elements (e.g. Ag, Au, Cu, Pb, Pt). Historically, mining of native metals and sulfide minerals dominated the industry because of the relative ease and low costs of extraction. Chemical bonding in sulfide minerals is largely covalent, and is such that the amount of energy required to extract the metal is relatively small. In contrast, chemical bonding in many oxides and in silicate minerals

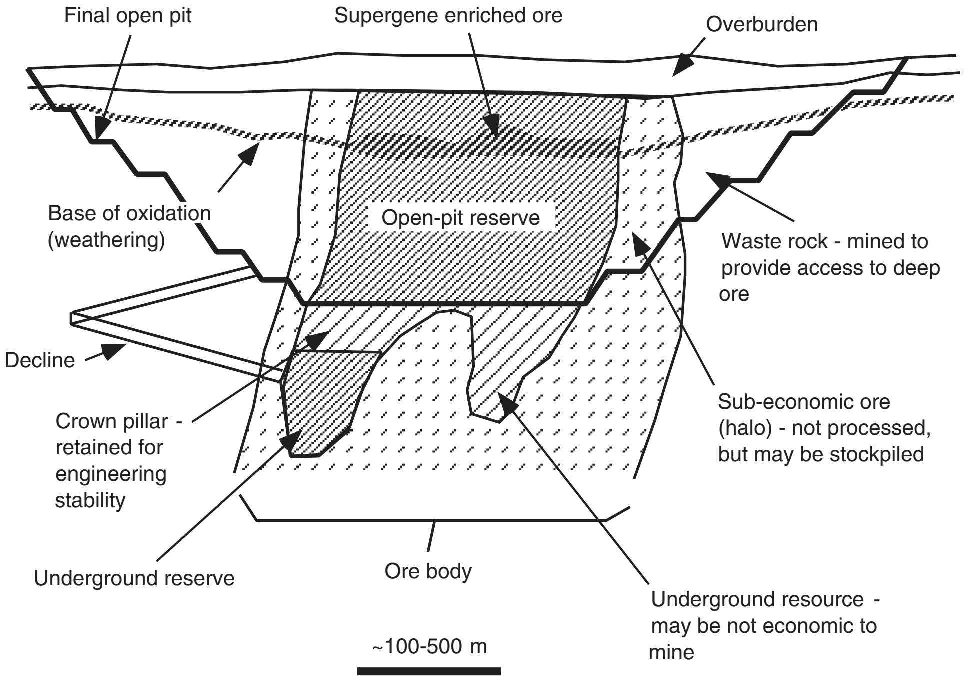

Figure 1.2 Schematic cross section through an open-pit mine, illustrating the geological, economic and engineering definitions of ore, modelled on the case of a porphyry copper deposit. The ore body and the reserves in many deposits have much more irregular shapes than shown here. The scale bar indicates only the order of magnitude scale: a pit could be from hundreds of metres to a couple of kilometres across and would most likely be sub-circular or elliptical in plan view.

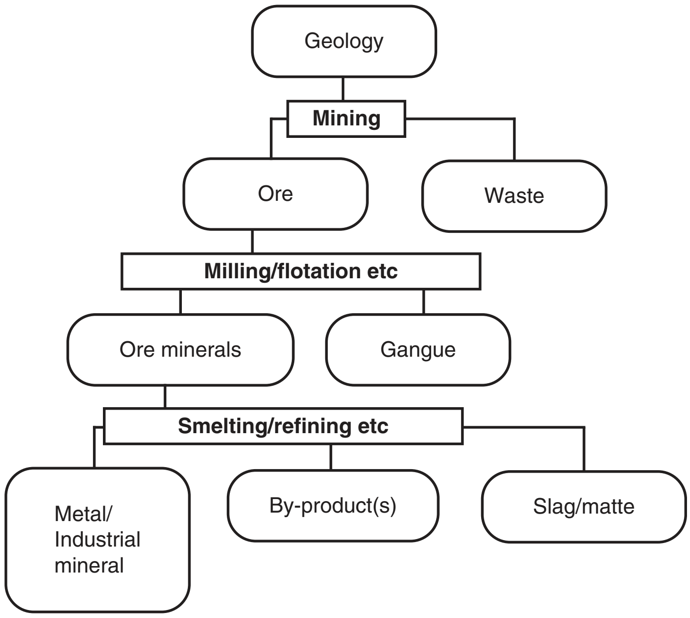

Figure 1.3 The steps and processes involved in extracting a metal from an ore deposit.

Table 1.2

Element	Native metals, alloys		Sulfides, sulfosalts, arsenides, etc.		Oxides, hydroxides		Silicates, tungstates, carbonates, etc.	
Fe			*Pyrite*	FeS_2	Haematite	Fe_2O_3	Siderite	$FeCO_3$
			Pyrrhotite	FeS	*Magnetite*	Fe_3O_4		
					Goethite	$FeO(OH)$		
Mn					Pyrolusite	MnO_2	Rhodochrosite	$MnCO_3$
Al					Gibbsite	$Al(OH)_3$		
					Boehmite	$AlO(OH)$		
Cr					Chromite	$FeCr_2O_4$		
Cu			Chalcopyrite	$CuFeS_2$				
			Bornite	Cu_5FeS_4				
			Chalcocite	Cu_2S				
Zn			Sphalerite	ZnS				
Ti					Ilmenite	$FeTiO_3$		
					Rutile	TiO_2		
Pb			Galena	PbS				
Ni			Pentlandite	$(Ni,Fe)_9S_8$				
Mg							Magnesite	$MgCO_3$
Sn			Stannite	Cu_2FeSn_4	Cassiterite	SnO_2		
Mo			Molybdenite	MoS_2				
U					Uraninite	UO_2	Carnotite	$K(UO_2)(VO_4)\cdot 1.5H_2O$
Ag	Silver	Ag	Argentite	Ag_2S				
Au	Gold	Au						
PGEs	Platinum	Pt	Sperrylite	$PtAs_2$				
			Laurite	RuS_2				

Common ore minerals of economically important metals, classified by mineral class. (Minerals in italics are not currently significant ore minerals.) Some metals are extracted as trace components of ore minerals of more abundant metals, e.g. an important source of silver is as a trace component (solid solution) in galena (100–1000 ppm). PGEs are the platinum-group elements Ru, Rh, Pd, Os, Ir and Pt.

is dominantly ionic, and the technological barriers to the extraction of metals from these minerals were only overcome in the twentieth century.

The geochemistry of ores

In consideration of what is available as Earth resources we are interested in the Earth's crust, and most particularly the continental crust. Any rock in the Earth's crust contains all the 92 naturally occurring elements. The chemical composition of the crust as a whole (known as average crust) has been estimated by averaging chemical analyses of a large number of samples of crustal rock. The concentrations of the elements in the crust vary over many orders of magnitude from major elements present at per cent levels, to trace elements at ppm (parts per million by weight) to ppb (parts per billion) range (Table 1.3),

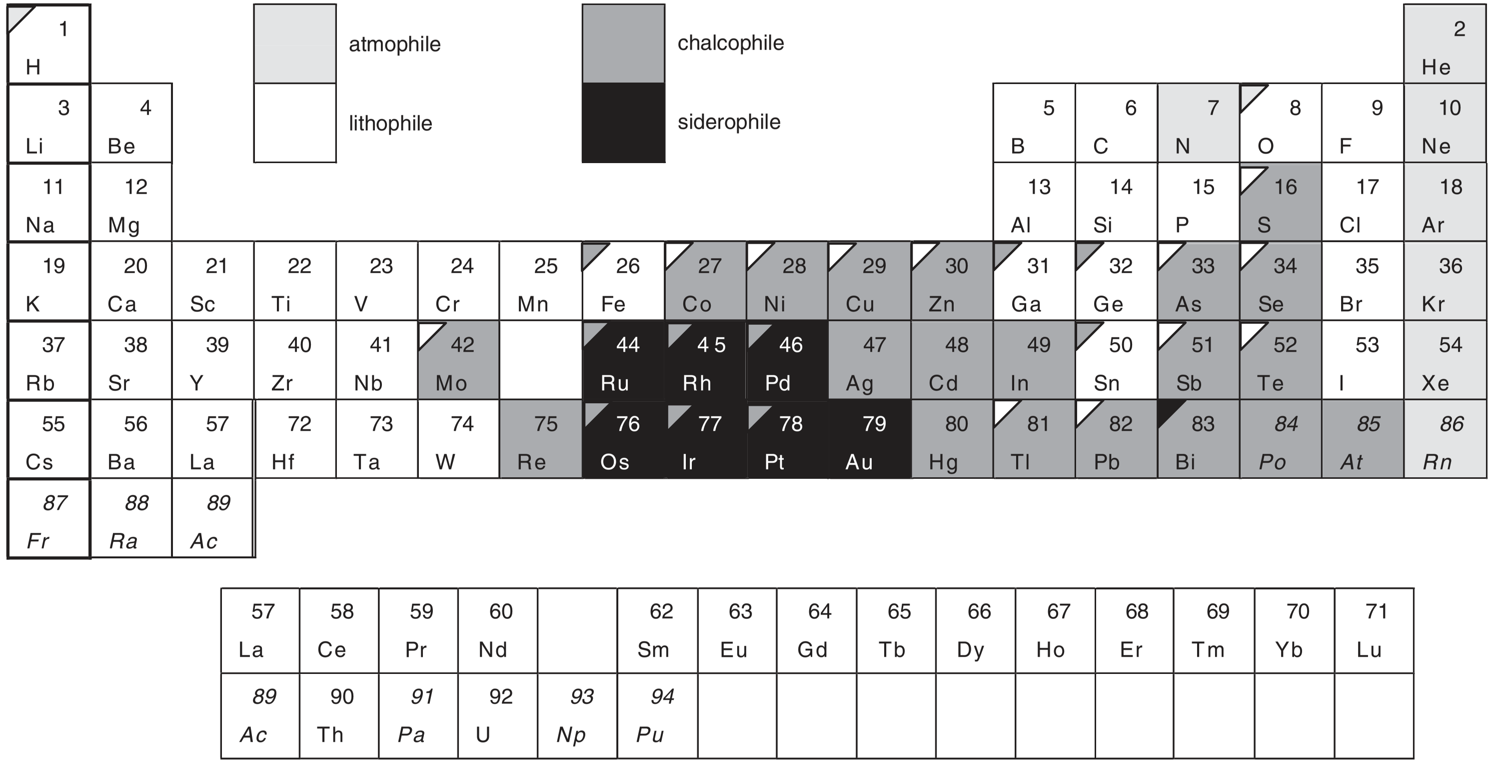

Figure 1.4 Periodic table showing classification of the elements following Goldschmidt, but modified to match the bonding behaviour of the elements in geological environments of the crust and upper mantle. Triangles in the upper left of a cell indicate a secondary affiliation of an element. Short-lived elements of radiogenic decay chains are shown in italics.

Table 1.3 Chemical composition of average crust (approximately equivalent to diorite) in ppm (parts per million = g t^{-1} weight). Economically significant elements are highlighted in bold, see Table 1.1.

Element	ppm	Element	ppm	Element	ppm
O	464 000	La	30	Ge	2
Si	281 500	Nd	28	Ho	1
Al	82 300	Co	25	Eu	1
Fe	56 300	Sc	22	Tb	0.9
Ca	41 500	N	20	Tl	0.5
Na	23 600	Li	20	Lu	0.5
Mg	23 300	Nb	20	I	0.5
K	20 900	Ga	15	Tm	0.5
Ti	5700	**Pb**	13	Sb	0.2
H	1400	B	10	Bi	0.2
P	1050	Th	10	Cd	0.2
Mn	950	Pr	8	In	0.1
F	625	Sm	6	Hg	0.08
Ba	425	Gd	5	**Ag**	0.07
Sr	375	Dy	3	Se	0.05
S	260	Hf	3	Ar	0.04
C	200	Cs	3	Pd	0.01
Zr	165	Yb	3	**Pt**	0.005
V	135	Er	3	**Au**	0.004
Cl	130	Br	3	He	0.003
Cr	100	**U**	3	Te	0.002
Rb	90	Be	3	Rh	0.001
Ni	75	As	2	Re	0.001
Zn	70	Sn	2	Ir	0.001
Ce	60	Ta	2	Os	0.001
Cu	55	W	2	Ru	0.001
Y	33	**Mo**	2		

to short-lived radiogenic decay products, for instance radium, which are present at much less than parts per trillion (ppt).

These patterns of elemental concentration in average crust reflect abundances in the Solar System (cosmic abundances) and chemical partitioning during condensation of the Earth from the cloud of matter from which the Sun formed. In general, element abundances in the Solar System decrease with increasing atomic number Z, most strongly so for atomic numbers greater than Fe ($Z = 26$). There is also a pattern that elements with even atomic number are more abundant than elements of similar mass but odd atomic number (Fe, $Z = 26$, is more abundant than Mn, $Z = 25$, or Co, $Z = 27$). Since condensation of the Earth as a rocky planet, the elements have been internally partitioned on a global scale as a result of two processes. The separation of the metallic core from the silicate component that made up the primitive mantle concentrated siderophile elements

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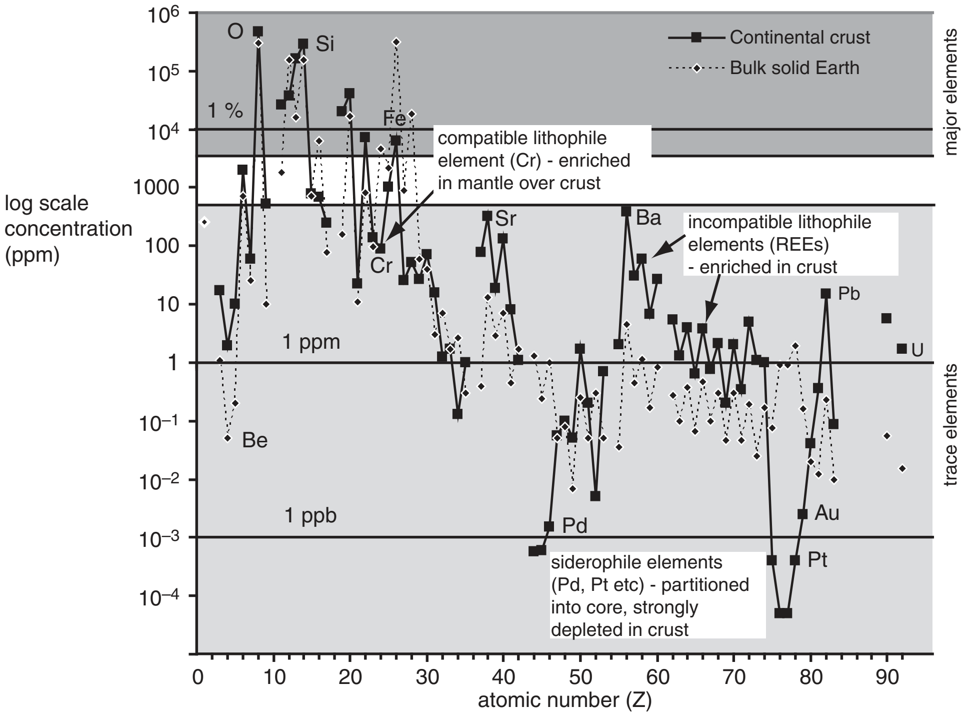

Figure 1.5 Element concentrations by atomic number in bulk solid Earth, as a proxy for its composition at the time of condensation, and in continental crust showing the range of element abundances over about nine orders of magnitude, and examples of relative enrichment and depletion into the crust that result from separation of the core and from formation of the crust through partial melting of mantle. Concentration data from GERM database at http://earthref.org/GERM.

in the core. Melting in the upper mantle progressively through Earth's history has produced a chemically distinct buoyant long-lived crust. Some elements are more abundant in the crust than in the Earth as a whole, while others are less abundant (Figure 1.5).

Except for Fe, Al and Ti, a typical crustal rock contains economically valuable metals in trace concentrations (Table 1.3). These trace elements are present either as minor components in solid solution in silicate and oxide minerals (e.g. Cu in mafic silicates) or as major components in accessory minerals (e.g. Zr in zircon).

1.3 The geology of ore deposits

A geological definition of an ore deposit

As ore is rock from which it is economic to extract a commodity, we need to consider how costs of extraction vary with different rocks and different rock mineralogy. The major costs of the operation of a large open-pit mine are rock haulage (e.g. transport of rock from the mine to the mill, and of waste rock to a dump) and rock crushing. Labour costs normally dominate operational costs of an underground mine, but the underlying cause is