Humanity’s ever-increasing hunger for mineral raw materials, caused by a growing global population and ever increasing standards of living, has resulted in economic geology becoming a subject of urgent importance.

This book provides a broad panorama of mineral deposits, covering their origin and geological characteristics, the principles of the search for ores and minerals, and the investigation of newly found deposits. Practical and environmental issues that arise during the life cycle of a mine and after its closure are addressed, with an emphasis on sustainable and “green” mining.

The central scientific theme of the book is to place the extraordinary variability of mineral deposits in the frame of fundamental geological processes.

The book is written for earth science students and practicing geologists worldwide. Professionals in administration, resource development, mining, mine reclamation, metallurgy, and mineral economics will also find the text valuable.

WALTER L. POHL is Emeritus Professor and former Dean of the Faculty of Geosciences at the Technical University of Braunschweig, Germany, and a consulting geologist in economic, engineering and environmental geology. For more information visit: www.walter-pohl.com

A companion website with additional resources is available at: www.wiley.com/go/pohl/geology

Cover image: PHILIPPE PAUL/SPECIFIC PHOTOS LIBRARY. Talc quarry, Tucquebrune, France. The talc quarry is located in the Alps, France. The largest of the four quarries, it produces over 500,000 tonnes of talc per year. The stepped layers show where the quarrying has dug into the ground, leaving behind roads to enable minerals to be brought from the lower levels to the upper levels. Talc (hydrated magnesium silicate) is a very soft mineral that is the main component of talcum powder. After being quarried, the rock is crushed into powder form and is also used in paper, plastics, cosmetics and paints.

Cover design by Design Deluxe
Economic Geology
To the Memory of Walther E. Petrascheck
(1906–1991)

Inspiring Geologist and Academic Teacher

COMPANION WEBSITE
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www.wiley.com/go/pohl/geology
with Figures and Tables from the book for downloading
Economic Geology Principles and Practice

Metals, Minerals, Coal and Hydrocarbons – Introduction to Formation and Sustainable Exploitation of Mineral Deposits

Walter L. Pohl
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This book has a companion website: www.wiley.com/go/pohl/geology
Wisely used, mineral resources create wealth, employment, a vital social and natural environment and peace. If the reverse of these conditions occurs only too often, illustrating the so-called “resource curse”, this should be attributed to the true perpetrators, namely irresponsible, weak or selfish leaders. This book, however, does not intend to provide rules for good governance. I wrote it as a broad overview on geoscientific aspects of mineral deposits, including their origin and geological characteristics, the principles of the search for ores and minerals, and the investigation of newly found deposits. In addition, practical and environmental aspects are addressed that arise during the life-cycle of a mine and after its closure. I am convinced that in our time, economic geology cannot be taught, studied or practised without an understanding of environmental issues. The scientific core of the book is the attempt to present the extraordinary genetic variability of mineral deposits in the frame of fundamental geological process systems. The comprehensive approach – covering materials from metal ores to minerals and hydrocarbons – is both an advantage and a loss. The second concerns the sacrifice of much detail but I chose the first for its benefit of a panoramic view over the whole field of economic geology. Being aware that the specialist level of subjects presented in this book fills whole libraries, I do hope that even experienced practitioners, academic teachers and advanced students of particular subjects will find the synopsis useful.

Over more than 50 years, five editions of this book were published in German. Since the first edition (Wilhelm & Walther E. Petrascheck 1950), the book was intended to provide a concise introduction to the geology of mineral deposits, including its applications to exploration and mining. The target audience has changed, however. Originally, it was written for students of mining engineering. Today, it is mainly directed to aspiring and practising geologists. Each of the seven chapters of the book was developed with my own students as a university course and should be useful to fellow academic teachers. After initially working in industry I never lost contact with applications of economic geology, which is my motive for the constant interweaving of practical aspects in the text and for dedicating one of the chapters to the practice of economic geology. For professional reference purposes, practitioners in geology and mining should appreciate this melange of science and application. Frequent explanations and references to environmental and health aspects of extraction and processing of ores and minerals should assist users involved in environmental work. To those with no background in geology, I recommend they acquire an introductory geoscience text for looking up terms that are employed but cannot be explained in the available space.

Compared with the last German edition (Pohl 2005), this book has been rewritten for an international public. Although it retains a moderate European penchant by referring to examples from this region, important deposits worldwide are preferentially chosen to explain genetic types and practical aspects. I trust that this will be useful to both scholars and practitioners, wherever they work. Generally, it was my ambition to present the state of the art in economic geology, by referring to and citing recent publications as well as earlier fundamental concepts. This should assist and motivate students to pursue topics to greater depth.

Many people have supported me in my life-long pursuit of theory and practice of economic geology, and helped with this book, especially by donating photographs. I cannot name them all but in captions, donors are acknowledged. Here, just let me say thank you.

Walter L. Pohl
Introduction

Human societies need sufficient water, productive soil, energy in different forms, and organic and mineral raw materials as a base for their physical existence. An additional important requirement is a healthy natural and socio-economic environment.

Economic Geology is a subdiscipline of the geosciences. It devotes itself to the scientific study of the Earth’s sources of mineral raw materials and to the practical application of the acquired knowledge. Considering the life-cycle of a mine, economic geology leads in the search for new mineral deposits and in their detailed investigation. It contributes to economic and technical evaluations, which confirm the feasibility of a project and end with the physical establishment of a mine. While mining goes on, economic geology provides many services that assist rational exploitation, foremost by continuously renewing mineable reserves and by limiting effects on the mine’s environment to a minimum. Possible negative impacts of mining include surface subsidence, lowering of the water table, various emissions and mechanically unstable or environmentally doubtful waste rock dumps. In the phase of mine closure, economic geology helps to avoid insufficient or outright wrong measures of physical and chemical stabilization, recultivation and renaturalization.

In recent years, the economic evolution of industrial and of rapidly developing countries caused incisive changes in supply and consumption of mineral raw materials. China, rather than Europe or North America, provides world markets with essential metals and minerals, although at the same time importing large quantities of needed feedstock for its expanding population and industry. The future supply of petroleum appears to be unreliable, but its role as the main source of liquid fuels for transport is hardly dented by biofuels and other developments. Wind and geothermal energy are increasingly contributing to electricity production, yet without coal, nuclear power and natural gas, industrial economies would soon break down and developing nations would be locked in poverty. Ours is a time of transition but we cannot yet discern the outcome. Whatever it will be, metals, minerals and energy raw materials will remain a precondition of human welfare.

WHAT ARE ORE DEPOSITS?

Ore and mineral deposits are natural concentrations of useful metals, minerals or rocks, which can be economically exploited. Concentrations that are too small or too low-grade for mining are called occurrences or mineralizations. It is very important to understand the economic implications of the difference between these terms. Unfortunately, their wrong application is common and leads to fundamentally misleading deductions. Therefore, the denomination
“economic ore deposit” may be used when a clear attribution to this class is to be emphasized. Note that not all ores are strictly natural – it is very common that waste of a former miners’ generation is today’s profitable ore, such as tailings of earlier gold, copper and diamond mining.

Mineral deposits are basically just valuable rocks. Their formation is compared with processes that have produced ordinary rocks and is investigated with petrological methods (Robb 2005). Mineral deposits can also be thought of as a geochemical enrichment of elements or compounds in the Earth’s crust, which is determined by their chemical properties (Railsback 2003; Lehmann et al. 2000b). The ratio between the content of a valued element in an ore deposit and its crustal average (Clarke values, Wedepohl 1995) is called the “concentration factor.” Formation of iron ore, with today’s typical grade of 60% Fe relative to an average crustal iron concentration of ~5%, requires 12-fold concentration. Copper ore that has 1% Cu compared to the crustal average of 0.007% Cu in the crust exhibits a 140-fold enrichment. Gold ore with 10 grams/tonne “distilled” from ordinary rocks with 0.002 g/t Au attests to a 5000-fold concentration.

Manifold are the processes and factors leading to the concentration of elements and minerals, including the formation of mineral deposits (Robb 2005). Final causes are the dynamic interactions between the Earth’s core, mantle and crust, and of the hydro-, bio- and atmosphere. Cooling and devolatilization of the Earth and unmixing of the system in the geological-geochemical cycle and during the transfer of elements have important roles (Lehmann et al. 2000b). With reference to the origin, endogenous and exogenous process systems are distinguished. The first are those resulting from the dynamics of the Earth’s interior that are ultimately driven by the Earth’s heat flow. At present, the total heat flow at the Earth’s surface is 46 ± 3 Terawatts [10^{12} J/s], resulting from heat entering the mantle from the core, of mantle cooling, radiogenic heating of mantle and crust by the decay of radioactive elements and of various minor processes (Lay et al. 2008). Exogenous processes take place at the Earth’s surface and are mainly due to the flow of energy from the sun (~12.10^{18} J/s). In rare cases, extraterrestrial processes have contributed to the formation of mineral deposits by impact of meteorites and asteroids.

The origin of mineral deposits is often due to a complex combination of several processes, boundary conditions and modifying factors, collectively making up the metallogenetic, or minerogenetic system. Evidence for such systems that operated in the geological past is always fragmentary. Some questions can possibly be answered by studying presently active ore-forming systems [e.g. black smokers in the deep oceans], but this method (“actualism”) has limitations. Because of the unknown factors, there is often room for different interpretations [hypotheses] of the scientific facts. Economic geology strives to improve continuously the genetic models of ore formation, i.e. complete schemes of these systems. This effort is assisted by progress in many other sciences [from biology to physics], but the reverse is also true. Economic geology provides a fascinating insight into geological systems that are extremely rare and can only be illuminated by studying mineral deposits. The practical mission of economic geology is the provision of metals and minerals that society requires. Of course, this implies cooperation with other scientific, technical and financial professionals.

**MINING IN THE STRESS FIELD BETWEEN SOCIETY AND ENVIRONMENT**

*Cum semper fuerit inter homines de metallis dissensio, quod alii eis praeconium tribuerent, alii ea graviter vituperarent* (the original text in Latin by Georgius Agricola 1556).

In English: “People were always divided in their opinion about mining, as some praised it highly while others condemned it fiercely.”

Agricola reports that enemies of mining in his time deplored not only harmful effects on the immediate environs but even moral aspects – they accused mining of advancing greed. Today, this remains one motive of opposition to the industry, but fundamental rejection of any extraction of minerals is more common. The main reasons given are
that mining visibly uses the land and often leaves a profound and enduring change.

Certainly there are often sound arguments against mining at a specific location. Compromises should be sought, however, because mineral deposits cannot be installed at arbitrary places. Their locations are predetermined by nature. Examples are sand and gravel deposits in river plains. Today, these raw materials are so scarce in many regions that they have to be protected against other claims (e.g. housing developments). Yet, everyone consumes minerals and mineral-derived products for homes, heating, transport, computers, medicinal use and numerous articles of daily life. Mining provides these minerals. Recycling replaces only part of primary production. As a percentage of total area, land use by mining is very small and only locally visible. Biofuel agriculture, solar and wind energy plants require much more land. Indeed, they create additional demand for minerals (e.g. fertilizer, metals for machines and processing plants, transport). Toxic elements, such as arsenic and cadmium, are essential for sustainable energy production, for example in photovoltaics. In many cases, even low footprint technologies such as geothermal power plants have serious problems with waste, such as brines, salt, toxic and heavy metals (most notably arsenic, mercury and radionuclides). This demonstrates that there are no simple solutions for a sustainable economy without mining. On the contrary, it is undeniable that conservation of our quality of life and development for the major part of humans who still lack the most basic necessities for a life of dignity, require both mineral raw materials and an intact environment.

Mining without an impact on the environment is impossible (Figure 1.1), but the industry strives to minimize negative effects (Figure 1.2) and to improve the welfare of affected communities (“green mining”). Some mining operations create an enriched landscape of constructed ecosystems, which provide humans with a variety of services (e.g. food, flood and erosion control, areas for recreation and aesthetics, and clean water). Examples include lignite and clay pits, which bequeath beautiful new lakes. Hard rock mines and quarries may grow into rare islands of nature in a sea of human occupation. Many of these sites support rare and threatened species from archaea and bacteria to plants and animals, helping to preserve biodiversity (Batty 2005).

Reversing mineral extraction, mines also have an extremely important role as deep disposal sites for the safe storage of society’s unavoidable toxic and radioactive waste. Chemically dangerous waste is usually stored in worked sections of suitable underground mines. For highly toxic and radioactive waste, the construction of dedicated underground disposal mines is the best solution for protecting the biosphere. Underground disposal takes lessons from nature that has preserved high concentrations of hazardous solid and gaseous substances in the form of mineral deposits over many millions of years (e.g. sulphide metal ore, natural gas, uranium and even the remains of natural nuclear reactors).

The World Commission on Environment and Development ("Brundtland-Report", Brundtland 1987) extended the concept of sustainable development to non-renewable resources. Clearly, few mineral resources fit into the concept of sustainability, as it was formulated 300 years ago for the management of forests, “that the amount of wood cut should not exceed the growth rate” (Carlowitz 1713). Such exceptions may be salt, magnesium and potassium harvested from seawater. Most metals and minerals are non-renewable and their use should be managed according to the following rules: i) Consume as little as possible; ii) optimize the recycling rate; and iii) increase the efficiency of using natural resources, especially of energy. The original concept of sustainability considered mainly the interests of later generations. In the Rio Declaration (UN Conference on Environment and Development 1992) the concept of intrageneration fairness was added, to allow for the interests of the living generation of mankind.

In fact, the world population’s rapid growth and demands for a better life enforce a continuing expansion of raw materials production. Yet, every individual extractive operation must have the acceptance of public opinion. To reach that aim, all stakeholders must profit and the mine’s social as well as the natural environment need to
be improved. The radical call that sustainability requires immediate termination of mineral exploitation is, of course, social and economic nonsense (Gilpin 2000). Let us use needed resources in the interest of living humans, and let us trust in technical and economic inventiveness to provide for later generations.

THE MINERAL RESOURCES CONUNDRUM

But is there a sufficient mass of minerals for an ever-increasing consumption? Because of the limited size of our planet it is true that geological resources are principally finite, although very large indeed. The search for most minerals has hardly gone deeper than a few hundred metres below the surface, and only land, shallow seas and the margins of the vast oceans are fully explored for petroleum and gas deposits. Yet, even in the well-known Gulf of Mexico, the new giant Tiber oilfield was recently (2009) discovered. Metal mining on the sea floor has a large future potential. Giant unconventional gas resources promise to fundamentally alter geopolitics of global energy supply. In contrast to resources, reserves that can be exploited at present economic and technological conditions are only a small part of the total geological endowment, because searching and defining reserves is a capital investment that must be paid back with interests. Due to the rules of depreciation of a future income, reserves are typically defined for the next 10 to 30 years. The result is that at any time a division of total reserves by the yearly consumption (the R/C ratio or “life-index”) will predict that in 10 (or 20, or 30) year’s time, “the world will run out of” the respective minerals. This fundamental error was famously made by the Club of Rome when it predicted this dire fate for the years 1990–2000 (Meadows et al. 1974). However, predictions of impending catastrophes are always popular and this gave the Club of Rome’s hypothesis a sweeping impact. Actually, the imminent scarcity of important minerals was announced many times in the past but never arrived. The term “life-index” is misleading, and the figure is rather an indication of specific conditions that dictate financing, production and marketing of individual metals and minerals. With few exceptions, individual R/C ratios change little over time-scales of several decades. In the future, just as in the past, science and technology will continue to provide the mineral raw materials needed by society, both by finding new deposits and by providing natural or synthetic replacement (Wellmer 2008). Temporary scarceness of certain critical raw materials is only possible if political constraints distort markets (European Commission 2010). Furthermore, exploiting lower-grade ores, producing functional replacements for certain minerals and metals, and recycling of materials, all need energy. Accordingly, energy is the most important natural resource of all.

It is undeniable that there are physical limits to the availability of certain quality classes of raw materials. Severe problems arising from this fact are not expected as long as the unlimited resource of human creativity is given the freedom to search for solutions. The continuously expanding reserve base for practically all minerals, roughly in parallel to increasing consumption, is the best proof of this principle in the mining industry.
Economic geology defines ore as a natural material (ore rock) from which metals or minerals can be profitably extracted. Mining professionals use the word in an identical connotation. Note that metals and minerals can also be recovered from quite exotic materials that are not ore *sensu stricto*, for example saline brines (lithium, magnesium), geothermal waters (zinc), metal-accumulating plants (nickel, “phytomining”), acid mine water (copper) and of course, recycled scrap (iron). The term ore is also applied to metalliferous minerals in a rock, for example chromite in dunite, or magnetite in gabbro (“ore minerals”). Ore rock, commonly just called ore, is typically an intergrowth of useless minerals (“gangue”) with ore minerals. Massive ore consists of ore minerals only, with little gangue, for example high-grade haematite iron ore.

Ore deposits form by geological process systems that can be viewed as a large cycle of constructive (e.g. magmatism) and destructive sectors (e.g. weathering, Figure 1.3). Within this cycling of earth materials, individual metals have specific enrichment sites that depend on chemical and physical properties of the metal or its compounds. It is very important to remember that biogeochemical fluxes mediated by life (Falkowski *et al.* 2008) control many ore forming processes.

Part I of this book is divided into two chapters. In Chapter 1, general observations, characteristics and interpretations of ore deposit formation processes, process systems and associated outstanding deposit types are presented. In Chapter 2, the economic geology of metals is systematically presented and illustrated by reference to specific mining districts and deposits.
CHAPTER 1

Geological ore formation process systems (metallogenesis)

Synopsis

Energy flow from the Earth’s interior and from the sun drives geological process systems. The concentration of ore and minerals is part of these systems, which comprise intrusive and extrusive magmatism, weathering, erosion, transport and sedimentation, followed by diagenesis and metamorphism. In this chapter, we aim to acquire an overview of these systems in respect of the principles which govern the generation of ore deposits. Finally, the inspection of the different major systems is brought together in a synthetic view of global dynamics and metallogeny (i.e. the science of ore deposit formation). This chapter lays the ground for the rest of the book.

For a long time in the past, processes associated with differentiation and cooling of magmatic bodies were thought to be the main agents of ore deposit formation. Starting with mafic melt, ore minerals can form upon cooling or metal-rich melts can segregate from the silicate liquid. Because mafic silicate minerals crystallize at higher temperature, intermediate and felsic residual melts are formed with their own suite of ore deposits. Late-stage magmatic fluids collect metals and produce hydrothermal mineralization. Lindgren [1933], Niggli [1948], Schneiderhöhn [1932, 1962], Stanton [1972], Guilbert & Park [1986] and many others developed this concept of igneous ore formation. In addition, the role of weathering, erosion and sedimentation in concentrating metals was recognized. Metamorphic processes were seen to transform previously existing ore but without appreciable mass transfer.

More recently, these earlier views (here very simplified) on ore deposit formation were fundamentally expanded [Robb 2005, Evans 1998]. First, the discovery of plate tectonics caused a revolution in understanding the dynamic interaction of the Earth’s crust and mantle. Plate tectonics determine the origin and distribution of many ore deposits. Present ore-forming processes were investigated. Outstanding impulses brought the exploration of ocean floor hydrothermal venting that produces metal concentrations, which closely resemble long-known ore deposits [e.g. copper on Cyprus Island].

The application of new technologies of the geosciences [e.g. trace element analysis, microprobe, isotope geochemistry, fluid inclusions investigations, mathematical modelling and simulation]
guided by old and new hypotheses, led to changes in metallogenetic thinking and to the recognition of additional ore formation systems. One example is the dehydration of sedimentary basins during diagenesis: Expelled fluids cause appreciable geochemical mass-transport and formation of numerous metallic and mineral concentrations, without involvement of igneous processes. Furthermore, the role of dissolved salt, hydrocarbons, reefs and karst cavities in diagenetic ore formation was illuminated. Long after the first hypothetical considerations, metamorphism was finally proved to cause migration of aqueous fluids that transport and precipitate metals.

The classification of ore deposits by major earth process systems is in principle quite simple. Complications arise mainly because of the extreme variability of individual deposits due to manifold combinations of different processes and factors. Therefore, some authors prefer to arrange deposits into associations and types, which are related by geological setting, paragenesis and form, but not necessarily by the same genetic process [Routhier 1963, Laznicka 1985, 1993]. Other authors dispense with geological environs and concentrate mainly on processes [Robb 2005]. In this book, fundamental geological cycles [Figure 1.3] and ore-forming systems are to guide the reader through metallogeny.

The genetic terms of Table 1.1 provide the basic vocabulary of metallogeny. The non-genetic descriptors stratiform (layer-shaped) and stratabound (restricted to certain strata) only denote shape and position of an orebody in relation to sedimentary features, not its origin. Comprehensive explanations of geological and mining terms can be found in the Dictionary of Mining [AGI 1999] and the Glossary of Geology by Neuendorf et al. [2005]. Geological time nomenclature in this book follows Walker & Geissmann [2009].

1.1 MagmaTic ore formation systems

A very large and diverse group of ore deposits originates by various processes during formation,
evolution, emplacement and crystallization of silicate melts (magmas) in the upper mantle and in the Earth’s crust.

Most post-Archaean magmatic rocks can be classed according to their plate-tectonic environment. Rocks of the ophiolite association (basalt, gabbro, ultramafic rocks) are remnants of former mid-ocean ridges, back arc basins, and of early and primitive parts of immature oceanic island arcs. Mature island arcs and active continental margins are distinguished by profuse amounts of orogenic andesites and equivalent intrusive magmatic

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**Figure 1.2 (Plate 1.2)** Rehabilitated jarrah forest covers former extraction panels of Huntley bauxite mine in front of the lake. Reproduced by permission of Alcoa Inc.

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**Figure 1.3** The origin of gold deposits in relation to major geological process systems within the Earth’s crust, demonstrating the variety of ore-forming systems.
rocks. Continental collision causes melting of sialic crust and voluminous granitic magmatism. Continental rifts are associated with bimodal alkaline volcanism (basalt and rhyolite). Extensional deformation of continents and mantle melting result in emplacement of layered mafic intrusions, flood basalts and alkaline magmatic provinces. Most notable are subvolcanic ring complexes and kimberlite diatremes that transport diamond from 200 km depth to the surface.

The association of certain igneous rocks with specific metal ores was established long ago. Ultramafic rocks host ores of nickel, chromium and platinum, gabbro and norite copper, cobalt, nickel, iron, titanium and vanadium, andesite and intermediate intrusive rocks induce copper and gold ore, and granites are related to beryllium, lithium, tin and tungsten concentrations. Essentially, this distribution was understood as a result of the geochemical fate of different metals during fractional crystallization (solid-liquid fractionation) of silicate melt bodies (Goldschmidt 1958). Meanwhile, magmatic rocks can be further differentiated according to plate-tectonic setting, source rocks, degree of partial melting, role of volatiles and many other genetic variables. Examples are the various basalt types (N- and E-MORB, intraplate, island arc: Pearce et al. 1984, Pearce 1982; Winchester & Floyd 1977), or the S-, I- and A-granitoids. We shall see later in this chapter that some of these rock classes are related to specific ore deposits.

Impact magmas result from heat and high pressure caused by collision of extraterrestrial bodies with the Earth. Melting affects part of the crust and in rare cases even the upper mantle. Impact magmas differ chemically from other melts because whole volumes of crust are liquefied, whereas normally partial melting is the rule. In addition, the impacting body may induce geochemical anomalies, especially regarding siderophile elements [e.g. platinum, iridium, cobalt and nickel]. Post-impact cooling can induce hydrothermal systems that are able to redistribute matter and provoke ore deposit formation.

In conclusion, the geodynamic environment controls the formation of ores from silicate melts in several ways. At the scale of ore-forming processes caused by single magmatic bodies, the following major genetic stages are differentiated:

- Orthomagmatic ore deposits are formed before the melt cools to complete solidification, or in other terms, in the liquid stage before solidus.
- Pegmatitic ore deposits are the result of segregation of small residual melt batches from a large crystallizing magma body approaching the solid state; fertile pegmatite melt is characterized by high amounts of volatiles and of incompatible and rare elements.
- Magmatic-hydrothermal ore deposits are produced by super- or sub-critical fluids, solutions and gases that are segregated by all magmas, which had more dissolved volatiles [H₂O, CO₂, S, B, F, Cl, etc.] than the amount that could be accommodated in silicates during crystallization; because of this connection, the time of fluid phase expulsion is commonly coeval with the formation of solid phases [minerals] from the melt; a significant part of the geochemical signature of magmatic-hydrothermal ore deposits is determined by processes at the magmatic stage (Audétat et al. 2008).

### Table 1.1 Common metallogenetic terms

- **Syngenetic** – denotes ores and minerals that formed at the same time as their host rocks (most often applied to sedimentary rocks and ore)
- **Epigenetic** – ores were emplaced into pre-existing rocks of any origin (e.g. veins, metasomatic ore)
- **Hypogene** – ores that were formed by ascending solutions (e.g. Mississippi Valley type lead-zinc)
- **Supergene** – ore formation by descending solutions (meteoric water interacting with rocks during surficial weathering processes)
- **Lateral secretion** – concentration of metals by abstraction from surrounding rock
- **Endogenetic** – concentration caused by processes in the Earth’s interior (magmatism or metamorphism)
- **Exogenetic** – concentration caused by processes at the Earth’s surface (sedimentation, weathering).
1.1.1 Orthomagmatic ore formation

Oxide (magnetite, ilmenite, chromite), base metal sulphide (Ni, Cu), and ore of precious metals (Pt, Pd, Au) is often found in ultramafic and mafic igneous rocks. More rarely, magnetite occurs in intermediate and felsic silicate melts. Textural and many other observations show that these ores were formed at magmatic temperatures, while the melt was essentially liquid and before total solidification (Naldrett 2004). Therefore, this class of ore deposits is called “orthomagmatic”.

Numerous observations suggest that enrichment processes concentrate (“segregate”) low metal traces from a large mass of silicate melt into small volumes. A common evolution is that the parent melt evolves towards saturation so that either a solid (e.g. chromite) or a liquid (e.g. sulphide melt) accumulates the metal in question. At some stage, residual fluids may intervene. Many parameters influence these processes, including the depth of intrusion, tectonic activities, the temperature gradient in space and time, fractional crystallization, dynamics of the melt body (e.g. convective flow), repeated injection of fresh melt, assimilation of country rocks, sulphur or external fluids, liquid immiscibility of ore and silicate melts and mixing or redissolution (Kerr & Leitch 2005). Because of their higher density compared to silicate liquids, ore melt droplets or solid ore phases typically accumulate above or within floor rocks, which may be cumulates below still liquid magma (gravitational accumulation; Sparks et al. 1993). Consolidation of cumulate minerals can lead to expulsion of intercumulus liquid (“filter pressing”). As the system cools, ore melts themselves may then separate into cumulates (e.g. Fe-sulphides) and residual liquids (Cu-rich sulphide melt).

Various mathematical models have been proposed that describe the orthomagmatic enrichment process. Concentration of metals such as PGM (platinum group metals), Au, Ni and Cu in sulphide melt is controlled by the Nernst partition coefficient (D) between sulphide and silicate liquids, and by kinetic factors. Disequilibrium is exposed by calculating the silicate/sulphide liquid mass ratio (“R-factor”; Robb 2005, Campbell & Naldrett 1979). A zone refining model is appropriate when, for example, sulphide droplets sink through a magma chamber and collect chalcophile metals. Limited base metal content but very high PGM enrichment can be explained by resorption of iron sulphide liquid in undersaturated magma (Kerr & Leitch 2005). In this process, the residual sulphide retains the precious metals, which it may bequeath to a later batch of undersaturated mafic melt.

Most orthomagmatic ore deposits are found in intrusive rocks. Eruptive equivalents are also notable, such as the Ni-Cu-Fe sulphides in komatiitic lava flows of Archaean greenstone belts, or the magnetite and haematite lavas and tuffs in andesitic-rhyolitic volcanoes in Chile, Mexico and Pakistan.

Basic shapes of orthomagmatic orebodies are layers in stratified magmatic rocks (often formed as cumulates), lenses or cross-cutting dykes and veins. This depends on the morphology of the segregation (sedimentation) surface and on dynamic factors. Massive ore is the product of highly efficient unmixing of ore particles or melt droplets and silicates, whereas disseminated mineralization reflects lower efficiency. Highly complex orebody shapes can be found in flow channels and pipes of mafic lavas and intrusions, for example when widening or curvature of flow tubes induce lower flow velocity of silicate melt that carries chromite crystals or sulphide melt droplets (Naldrett 1200, 1199; e.g. Voisey’s Bay, Canada).

Textbook examples of orthomagmatic deposits are sulphide Fe-Ni-(Cu-PGE) ores hosted by Archaean komatiitic lavas of the Yilgarn Craton in Western Australia (Box 1.1; Barnes et al. 2007, Barnes 2004, Hoatson et al. 2006).

Gravitational settling can also explain many features of ore formation in layered mafic intrusions (Naldrett 2004, Cawthorn 1996, Irvine 1982). Other contributing processes include flowage differentiation and convective scavenging (Rice & Von Gruenewaldt 1994), in-situ crystallization on the floor of the melt body, mixing of two different melts, and uptake of material from outside (e.g. by melting siliceous or sulphur-rich host rocks). Often, the formation and segregation of a sulphide melt is the key to enrichment of exploitable metals (Barnes et al. 2009). Layered melt bodies (in respect of composition, temperature and density)
Komatiites are ultramafic volcanic rocks with melting temperatures of ~1700°C containing >18 wt.% MgO (Arndt et al. 2008). Their formation is the consequence of mantle temperatures ~100°C higher than today (Naldrett 2010). Komatiitic melts originated by 30–50% partial melting of mantle. Normally, these melts remained sulphide-undersaturated from extraction through ascent and eruption to emplacement. Liquid komatiite lavas had a very high temperature and very low viscosity (similar to water), resulting in high flow velocities. Komatiite lavas are capable of eroding and melting most volcanic and sedimentary footwall rocks (“ground melting” or “thermochemical erosion”). The flows followed troughs on the seafloor and formed flow tubes similar to submarine basalts. Komatiites were typically charged with suspended olivine crystals. During cooling, cumulates and vesicular textures formed. Because of the extreme temperature difference between ocean water and Mg-rich melts, flow tops are characterized by skeletal growth of olivine and pyroxene (“spinifex textures”; Shore & Fowler 1999).

Elongate massive sulphide bodies, which were clearly formed from liquid sulphide melt, occur at the floor of flow tubes and grade upwards into disseminated (matrix or net-textured) ore (Figure 1.4). Ore textures reflect gravitational settling in the liquid phase. Sulphide melts can only form upon sulphur saturation, implying high sulphur content. The common association of sulphide mineralization with the presence of sulphur-rich interflow sediments and isotopic compositions of sulphur (Bekker et al. 2009) are strong arguments that admixture of crustal sulphur is the main difference between fertile and barren komatiites. The availability of nickel (and elements such as platinum) for partitioning into iron sulphide melt is favoured by low redox conditions. In that case, nickel is dissolved in the silicate liquid as uncharged Ni0 and is not available for incorporation into olivine. Apart from the redox constraints, nickel content of magmatic sulphide liquids is largely controlled by partitioning equilibria and the mass balance between silicate and sulphide melt (the “R-factor”; Campbell & Naldrett 1979), including dynamic factors such as mixing and redissolution. The ore minerals of komatiite nickel deposits comprise pyrrhotite, pentlandite, chalcopyrite and pyrite, with nickel concentrations in ore reaching 20%. Prendergast (2003) describes the nickel-bearing komatiites of Zimbabwe as proximal and basal parts of submarine volcanoes that were quite flat and extended over hundreds of kilometres. The Neoarchaean komatiites of Western Australia (2.7–2.9 Ga) host the majority of the world’s komatiite-associated Ni-Cu-PGE deposits. Palaeoarchaean komatiites are depleted in platinum group elements (PGE) because the metal source of the younger, metalliferous komatiites, i.e. cosmic matter bombarding the Earth during the period from 4.5 to 3.8 Ga, was only gradually mixed into the mantle (Maier et al. 2009). In contrast to Western Australia, the closely comparable Abitibi Greenstone Belt in Canada is richly endowed with volcanogenic massive sulphide deposits (e.g. Kidd Creek, Noranda). Both regions display abundant orogenic gold deposits. It is assumed that the disparity is due to a different lithospheric structure (Barnes et al. 2007).

**Figure 1.4** Massive and disseminated nickeliferous pyrrhotite orebodies (Lunnon shoot, Kambalda, Western Australia) at the base of an Archaean komatiite lava flow (adapted after Groves et al. 1986). By permission from Macmillan Publishers Ltd. Nature © 1986.
BOX 1.2 Orthomagmatic ore formation in the Bushveld Complex

The Bushveld Intrusive Complex comprises the Rustenburg Layered Suite and the Lebowa Granites. The first term designates the layered mafic-ultramafic intrusion, which was formed in the Palaeoproterozoic at ~2054 Ma, and which contains enormous metal resources. The granites have nearly the same age and host less important fluorite and tin deposits. The roof of the Bushveld Complex and the overlying granites consists of thick precursor basaltic andesites to rhyolites (the “Rooiberg Group” volcanics). Rooiberg volcanics and the intruding granites are the products of crustal melting caused by the giant mass of hot mafic melt. Country rocks of the Bushveld intrusion are Palaeoproterozoic sediments and volcanics of the Transvaal Supergroup and Archaean basement. The Rustenburg Layered Suite reaches a thickness of 9000 m. It is strongly layered at all scales. The major units from bottom to top comprise Figure 1.5 and Figure 1.6:

- the Lower Zone with dunite, bronzitite, and harzburgite;
- the conspicuously banded Critical Zone with a lower part of orthopyroxenite, chromitite bands and some harzburgite, and a higher part marked by the first cumulus plagioclase and by cyclic layering of economically significant platiniferous chromitite, harzburgite, bronzitite, norite and anorthosite in this order (cyclic units); its upper boundary is marked by the Merensky Reef (Pt, Ni, Cu);
- the Main Zone with gabbronorite and minor layering;
- the Upper Zone with magnetite (ferro) gabbro and ferrodiorite, which contains numerous magnetite (V-Ti) layers.

**Figure 1.5** Simplified lithostratigraphic column of the mafic Rustenburg Layered Suite in the Eastern Bushveld, South Africa, with major ore horizons.
undergo thermal and chemical diffusion that can concentrate ore metals. Although much less obvious than in many felsic intrusions, mafic melt bodies may also experience unmixing and expulsion of magmatic fluids that can form ore. The largest preserved layered intrusion in the world is the Bushveld Complex of South Africa, hosting an exceptional variety and mass of high-grade metal ores (Box 1.2; Vermaak & Von Gruenewaldt 1986, Eales & Cawthorn 1996).

Layered mafic intrusions occur in several geodynamic settings:

- Archaean greenstone belts;
- intracratonic regions (the Bushveld);
- at passive margins of continents; and
- in active orogenic belts.

Intracratonic regions that experienced tectonic stress can also exhibit unstratified, very complex mafic-ultramafic intrusions with Cu-Ni-PGM ores. The most important district of this kind is Noril’sk-Talnakh in Siberia, which originated at the Permo-Triassic boundary as a feeder to the giant Siberian trap basalt province (Yakubchuk & Nikishin 2004, Li et al. 2009).

Figure 1.6 Bushveld Upper Group (UG1) chromite seam in anorthosite at Dwars River, S.A. Thin bands at the bottom display bifurcation, illustrating the complexity of cumulate ore formation in layered mafic intrusions. Courtesy Bernd Lehmann, Clausthal.