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Nicholas Arndt
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Metals and Society

An Introduction to Economic Geology

Second Edition

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An Introduction to Economic Geology

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Foreword

Throughout history mineral, resources, particularly metals, have been the building blocks of human civilization. This continues to be true today as the amount, diversity, and utility of mineral resources used in every aspect of modern society have never been greater. Advanced technology utilizes almost the entire periodic table as exemplified by the ubiquitous smart phone, which now contains about 75 different and essential elements in its construction. Although mostly taken for granted by the general populace, the availability of mineral resources is a subject for serious study and this book fills a useful role in bringing essential information to a general geological audience.

The average citizen typically is not aware of this enormous dependence on mineral resources and some people are opposed to mineral exploration and production, even though they use the results of that mineral exploration and production in almost every aspect of their daily lives. Sadly, the average undergraduate geology student is no better informed and has little idea on how ore deposits form, nor of the non-geologic factors that influence their viability. If we don't teach geology students about economic geology, how is society at large to learn about the problem?

That is where the new second edition of this textbook comes in. It serves at least two admirable purposes. First, it is a primer on the general characteristics of ore deposits, including their geology and economics, with helpful boxed sidelights that ask the reader to explore important issues of competing societal expectations. Second, it explores more nuanced issues about the adequacy of mineral resources for future generations (the "peak oil" conundrum), the environmental consequences of mining in the context of competing uses for land, the rise of China as the world's largest consumer and producer of many mineral commodities, changing concepts of sustainability, and the important but complex issue of the social license to mine.

The final chapter provides a lively discussion of several topics such as "locavore minerals" that may be new to some readers and raises the question "is it reasonable to shun Kenyan green beans while consuming copper from the Congo?" This is tied into the concept of sustainable mining and the meaning of sustainability. To greatly simplify, does sustainability mean that one is responsible for the entire life-cycle consequences of the resources one consumes? If so, does this make NIMBY (not in my backyard) morally indefensible, since in most cases “offshoring” the consequences of resource development is to shirk the ability to manage and minimize that impact? A more fundamental question is whether our current lifestyle is even possible without mining. If not, then the grand challenge is to improve it and manage it responsibly—not just ignore it and offshore it to distant lands.

This book provides the information that geology students need if they are to help with intelligent discussion of society’s mineral resource challenges. In an uncertain world one thing is certain, the need for mineral resources will not go away. Even if recycling were 100 % efficient (a thermodynamic impossibility), new supplies of mineral resources will be necessary because of world population growth, rising standards of living, and the sequestering of essential metals like copper, iron, and aluminum in cars, buildings, and other infrastructure for decades or even centuries. This book provides the starting point and needed geological background to begin this important discussion.

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Preface to Second Edition

The first edition of this book was reviewed by Stephen Kesler who was generally positive, but suggested that Chaps. 4 and 5 could be expanded to provide more information on deposits of current exploration and research interest. To resolve the problem he was invited to join as a co-author for the new edition. We made minor revisions to Chap. 3 on magmatic deposits and revised thoroughly the chapters that open and close the book. In so doing we were able to take into account recent developments in the world of economic geology. We revisited the question of peak copper—when, or if, we will ever exhaust our reserves of mineral products—and added new sections on the impact of China of the global mineral industry and on the ever more important socio-economic factors that influence the exploitation of ore deposits.

During the writing of the second addition we received help from many friends and colleagues. In addition to those who reviewed chapters in the first edition we particularly thank Steve Barnes, Jean Cline, Richard Goldfarb, Mark Hannington, Jeffrey Hedenquist, Murray Hitzman, Richard Kyle, Kurt Kyser, Eric Marcoux, John Thompson and Olivier Vidal for reading selected chapters and offering comments and advice. The French Centre Nationale de Recherche Scientifique (CNRS), the Université Grenoble Alpes and the Université de Nice—Sophia Antipolis supported us during the preparation of the manuscript.

Preface to First Edition

In the years that preceded the writing of this book, metal prices first soared to record levels, then plummeted to half these values (Fig. 0.1). Accelerating demand from China and other developing countries triggered the rise; collapse of the world economy triggered the fall. When prices were high, mineral exploration companies doubled their efforts to find new resources, and geologists were in great demand; the fall has stifled this demand. When the economy eventually recovers, the demand will renew. Production in existing ore deposits will accelerate and new deposits will be sought, and once again there will be a need for geologists with a sound knowledge of how ore deposits are formed. These geologists will also need to know something about economic geology in general.

We wrote this book to fill a gap in the literature available to students of the earth sciences. Many excellent and modern books describe in detail the characteristics of ore deposits and others discuss how the deposits have formed. Some books deal briefly with the economic issues that govern the exploitation of ore deposits, but usually this treatment is secondary. As we explain in the first chapter, the very definition of an ore and of an ore deposit is grounded in economics (ore is natural material that can be mined at a profit). Any comprehensive treatment of the subject must include discussion of what distinguishes an ore deposit from any other body of rock and to follow such a discussion requires at least a basic knowledge of the commercial aspects of mining operations and of world trade in mineral products. Our aim here is first to provide basic information about the scientific issues related to the nature and origin of ore deposits, to explain how, where and why metals and mineral products are used in our modern society, and to illustrate the extent to which society cannot function without these products.

In the past, and most probably in the future as well, the minerals industry has employed geology students. The activity in this domain is notoriously cyclic and at the time we finished the book the minerals industry was at low ebb. But with improvement of the global economy, demand for metals will inevitably pick up, fuelled by the enormous needs of China and other developing countries. Earth science students in most European and North American universities have a broad geological education that includes high-level courses in the subjects required of an exploration geologist – structural geology, field mapping, remote sensing, geophysics. What is missing is an elementary knowledge of economic geology.

The expansion of exploration and development of ore deposits will coincide with an increasing awareness of the fragility of our planet's environment, particularly the threat posed by global warming. Calls for "sustainable development" will accompany this economic revival, and the mining, transport, refining and consumption of raw materials will be subject to close scrutiny. At present most university students are taught almost nothing of this issue (or if they are taught, in courses on ecology and the environment, the reference to mining is totally and massively negative). The exploitation of ore deposits in the past has caused great damage to small parts of the Earth's surface, and mining with no regard to the environment can no longer be permitted. But if the world requires steel or aluminium – to build wind turbines, for example – or copper and silica to build solar panels, the raw materials must be mined. These and other issues are discussed in our book.

Throughout the book, exercises are provided to illustrate the complexities, contradictions and dilemmas posed by society's needs for natural resources. We discuss the issue of when, or more exactly if ever, our supplies of metals will be exhausted. We consider the notion of sustainable development and the environmental damage done by many mining operations. At present the needs of the industrialized "first-world" countries are met in large part by the importation of ores from lesser-developed countries; we consider the economics and the ethics of this trade. Throughout the book we have not hesitated to express our opinions. To a student who has received all his or her knowledge of mineral economics and global trade from local media and other popular sources of information, many of these views will come as a surprise, even as a shock, but we have not toned down the our treatment to conform to prevailing viewpoints. Instead we have written many relevant sections in a deliberately provocative manner in order to encourage discussion of these important issues.

In the first two chapters and in the last, geological and economical issues receive equal billing. In these chapters we define ores and ore deposits, discuss how they are classified, and explain that the study of ore deposits is intrinsically linked with the global economy. We explain how the viability of an ore deposit depends directly on the metal price, which in turn is linked to the demand from society for the mineral product. The factors that control this demand and the way the demand is satisfied by the discovery of new mineral deposits is a major subject in these chapters. Chapter 2 is an overview of the global distribution of ore deposits – where they are mined, where they are refined, and where the final products are consumed.

The following three chapters are more geological. In them we discuss the nature and origin of three broad groups of ore deposits: those that form through magmatic processes, those that result from the precipitation of minerals from hydrothermal fluids, and those that form in a sedimentary or superficial environment. The emphasis is on the ore-forming process and exhaustive descriptions of the ore deposits themselves are largely missing, but important principles are illustrating by way of discussion of a selection of well-known examples.

In the final chapter, which deals with the future of economic geology, we consider two 'new' types of strategic ores – rare earth elements and lithium – that will become increasingly important for the electronics and transport industries of the 21st century. We chose these examples because they illustrate well the paradoxes and challenges posed by the need to supply society with strategic materials at a time when the global balance of power is rapidly changing.

We thank Chris Arndt, Anne-Marie Boullier, Marie Dubernet, Mélina Ganino, Jon Hronsky, Emilie Janots, Elaine Knuth, John Ludden, Tony Naldrett, Jérôme Nomade, Michel Piboule, Gleb Pokrovski and Chystèle Verati for their carefully reading the first version of this book and for their useful comments and suggestions. We also thank Grant Cawthorn, Axel Hofmann, Kurt Konhauser and Peter Mueller for the photographs they provided. The French Centre Nationale de Recherche Scientifique (CNRS), the Université Joseph Fourier in Grenoble and the Université de Nice – Sophia Antipolis supported us during the preparation of the manuscript.

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Chapter 1
Introduction

1.1 What is Economic Geology?

Our dependence on the minerals that underpin modern life has grown enormously over the last few decades. Figure 1.1 shows the price, the average grade and production of copper ore has changed dramatically from 1900 to the present. At the start of last century the price was 7000 US$ per ton (expressed in 1998 currency) to negate the effects of inflation; by 2002 it had decreased three-fold to about 1800 US $ per ton, then, in the three years to 2010 it rose sharply to about 9000 US$ per ton before declining again in the latest recession. Over the same period, the total amount of copper mined gradually increased, except in the early 20s and 30s when both price and production dropped. How do we explain these changes, and what do they tell us about how the metal is found and mined, and about how it is used by society? Understanding these concepts is the basis of economic geology.

To explain these trends—the broad correlation between price and grade, the anti-correlation between price and production, and the periods that bucked the trend in the 1930s and in the past few years—we first consider the declining prices. Why was the price of copper in the year 2000 only 30 % of the price at the start of the previous century? The more important, and apparently contradictory, elements of an explanation, are:

- *Exhaustion of rich and easily mined deposits*. As these deposits are mined out, we have turned to deposits with lower concentrations of copper. The average grade has decreased from about 1 % at the turn of the 19th century to about 0.7 % at the start of the 21st century. At the same time, deposits close to centres of industry in Europe or America have been exhausted and new mines have opened far from the regions where the metal is used, often in regions with hostile climate or difficult mining conditions. Normally one would think that these trends would be associated with an increasing scarcity of copper—a decrease in supply that should, according to the economic rule of supply and demand, have led to a price increase. Yet, from the start of the century, the

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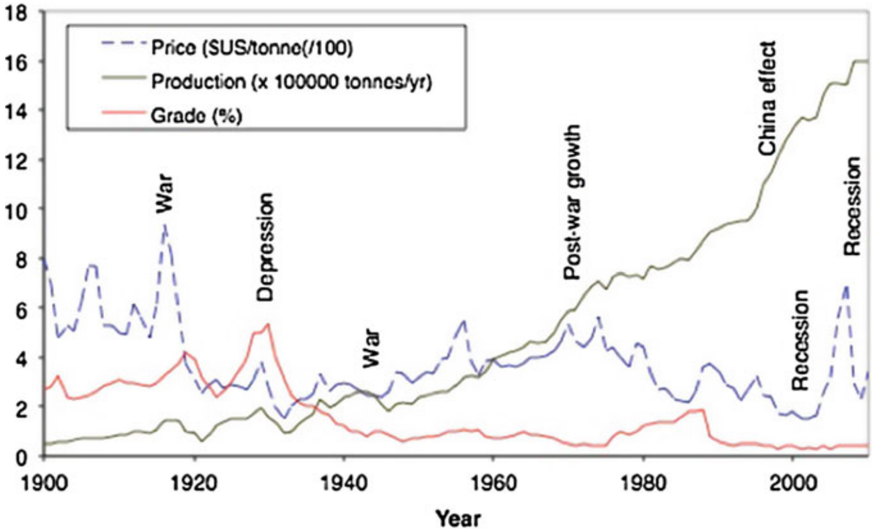


Fig. 1.1 Evolution in the price and production of copper over the past 120 years (statistics from the United States Geological Survey, Mineral Resources Program. http://minerals.usgs.gov/products/index.html)

opposite has happened. Instead of declining, reserves of copper have generally increased (Fig. 1.2). Why?

- *Improvements in technology*. The main reason the price of copper has dropped steadily is the improvements in the efficiency and increase in the scale of the mining and refining industry, a sequence of operations that starts with the search for new deposits, continues through the mining of these deposits and ends with the extraction of the metal from the mined ore. At the turn of the last century it was only possible to mine deposits with high grades that were close to the surface and close to industrial centres. Exceptions were a few unusually large and unusually rich deposits in more remote areas. The improvements in mining and extraction technologies illustrated in Fig. 1.3 have changed all this. Today's copper mines are enormous operations—vast open-pits or large underground mines that extract hundreds of thousands of tons of ore and waste per day. Through the advantages of scale and the utilisation of modern techniques, it is possible now to mine ore with as little as 0.5 % Cu. And with the economy of scale and improvement of technology has come a decrease in the cost of mining, an increase in supply, and a century-long drop in the price of the metal.

Now let us consider in more detail the trends illustrated in Fig. 1.1. The decrease in the price of copper in the 1930s, and the accompanying decrease in production, coincided with the Great Depression. Economies throughout the world collapsed, demand for copper plummeted along with the price. The opposite has happened in the

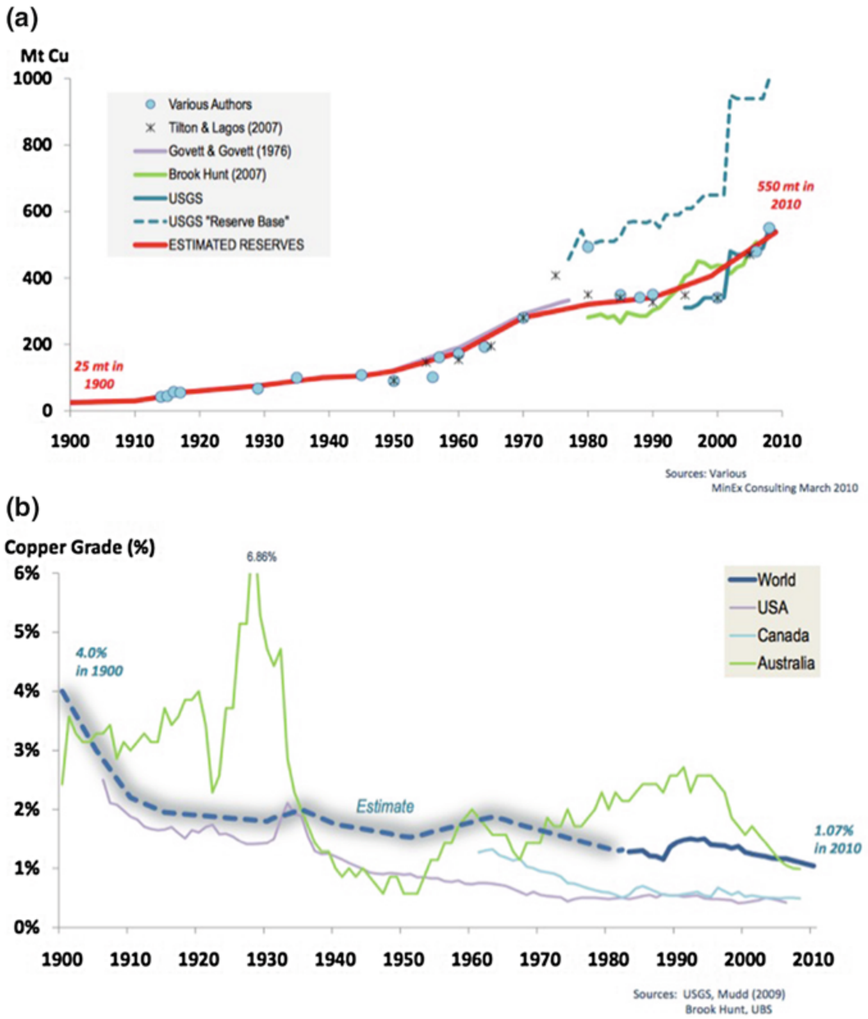
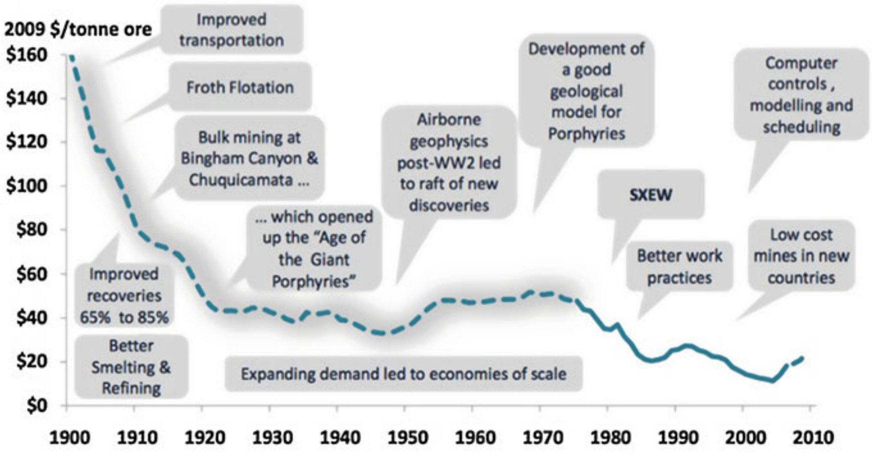


Fig. 1.2 **a** Evolution of copper reserves since the start of last century, which have increased from about 25 million tons in 1900 to 550 million tons in 2010. **b** Evolution of copper grades during the same period (from Schodde 2011; http://www.minexconsulting.com/publications/Growth%20Factors%20for%20Copper%20SME-MEMS%20March%202010.pdf, with permission from the author)

past five years. The economic miracle in China has boosted the industrial and societal demands of 1.2 billion people. To construct the cell phones, cooking pans and power stations that they now expect (so as to live in more or less the same way as people in Europe and America) requires a vast acceleration in the rate at which copper is mined. Demand has exploded and this has triggered an increase in the price of the metal.



Sources: Brook Hunt, CRU, Historical reports
MinEx Consulting estimates (for 1900-1974)

Fig. 1.3 Diagram showing the technological, social and economic factors that contributed to the fall in copper process in the past century (from Schodde 2011; http://www.minexconsulting.com/publications/Growth%20Factors%20for%20Copper%20SME-MEMS%20March%202010.pdf, with permission from the author)

How has this demand been met? New deposits of copper cannot be found overnight. The average time between the inauguration of a new exploration program and the start of mining of a new deposit (if one is found) is 10–15 years. Copper production has increased irregularly but steadily over the past two decades, initially during a period of falling prices, and more recently during a period when the price of copper has tripled. In the first period, exploitation of stockpiles, the introduction of new and improved mining and extraction techniques, and the opening of new large high-production mines, particularly in South America, Asia and Oceania, made this possible. But throughout the 1990s many mines were running at a loss: the cost of production was greater than the value of the metal recovered from the mine. Then, from about 2001 onwards, as the copper price increased, mines that had been loss-making operations suddenly started making money. Improvements in technology, which made it possible to mine and refine the ore more efficiently, aided the return to profitability. Other deposits that had been explored and evaluated by mineral exploration companies but had been put aside because they were not viable at low copper prices suddenly became economically interesting. Nothing had happened to the deposit: it still contained the same concentration of copper and the same total amount of copper, and its location, both geographically and geologically, had also not changed. But a geological deposit that in the year 1998 was of little economic interest had became potentially highly profitable in 2010. Then, in 2013, the economic problems in the USA and Europe combined with a slight drop in the rate of growth of the Chinese economy, led again to a drop in the metal price and a slight decrease in production. Deposits that were viable in 2010 once again became economically marginal. These ideas—particularly the links between the global economy, the metal price and the production of the metal—lead us to examine several definitions and concepts that are fundamental to economic geology.

Exercise 1.1 Consider the Following Statements and Discuss What They Tell Us About Economic Geology and the Mining Industry, As Perceived by the General Public

1. In the 1990s a Japanese scientist developed a new type of catalytic converter in which manganese replaced platinum. Why is this discovery important?
2. Also in the 1990s, English ecologists proposed that a new tax should be applied to "rare" metals such as silver, lead and copper. What do you think of this suggestion?
3. A journalist recently suggested that war might break out over the last drops of petrol (gasoline). Is this suggestion reasonable and realistic?

Response

Consider the first statement. Why would it be important if manganese could be used in the place of platinum in the catalytic converters that are fitted to every new car? The answer lies in the price of the two metals. In February 2008, platinum (Pt) sold for about €100 per gram and manganese (Mn) for 10 cents per gram, a thousand-fold difference in price. If Mn could replace Pt, catalytic converters would be much cheaper. Currently the cost of the metal makes up about half the cost of the converter, so if Mn replaced Pt, the cost would be cut by almost half. (Unfortunately the process does not work and Pt continues to be a highly sought metal.) The following question is raised: why is platinum so much more expensive than manganese?

Consider now the other two statements. Both focus on the idea that resources of natural products such as metals and petroleum will soon be totally mined out or exhausted. "Peak oil", the notion that global production of petroleum has already, or very soon will, pass through a maximum, expresses the same idea. (You may have seen a TV program showing a sad fleet of aircraft stranded at an airport, the last drops of kerosene having been used up.) Is this idea reasonable?

In the following section, and in more detail in Chap. 6, we critically examine the notion that supplies of natural resources may become depleted or exhausted in the near future.

1.2 What is Ore?

According to one commonly accepted definition, an ore is *a naturally occurring solid material containing a useful commodity that can be extracted at a profit*. There are several key phrases in this definition. By “useful commodity” we mean any substance that is useful or essential to society, such as metals, or energy sources, or minerals with distinctive properties.

The uses of copper are well known. Without this metal (or other metals with similar properties) there would be no television sets, power stations and airliners, not to mention brass cooking pots and green-coloured domes on old cathedrals. Other metals such as iron, manganese, titanium and gold find a multitude of applications in the world in which we live and most of these are listed in the excellent web sites of the United States Geological Survey http://minerals.usgs.gov/granted.html and the British Geological Survey http://www.bgs.ac.uk/mineralsuk/statistics/worldStatistics.html. Ores also include some energy sources, specifically coal and uranium. Petroleum is normally excluded from the definition, which is generally restricted to solids, but the bitumen mined in deposits such as the Athabasca tar sands in Canada might be considered an ore. Finally there is a range of products, generally of low cost, that are also mined and also constitute ores: included in this list are building materials such as limestone for cement, gravel for road construction and the building industry, ornamental stones and gems, fertilisers, abrasives, even common salt.

Box 1.1 Critical Metals

In 2008, a committee of geologists and economists from various governmental agencies and universities in the USA published a report evaluating the supply situation of a wide range of metals and mineral products (National Research Council 2008; http://dels.nas.edu/dels/rpt_briefs/critical_minerals_final.pdf). The committee defined the “criticality index” which is the product of the importance of the product in an industrial society (the x-axis) and the degree to which its supply is subject to potential restrictions (the y axis). The importance depends not so much on the amount that is used but more on whether the product is used in critical applications and whether it can be substituted by other materials. The supply risk depends on factors such as whether the product is produced locally or must be imported, the geographic location of sources, and the political stability of the supplying country or region. In Fig. 1.4, taken from a similar evaluation made by the European Commission, we see that nickel is very important to industry but is subject to little supply risk (because the metal is produced in many parts of the world). The rare earths and the other “critical metals” in the orange box, are used in many applications where they are difficult to replace, and are produced in a small number of not necessarily dependable regions, making their criticality

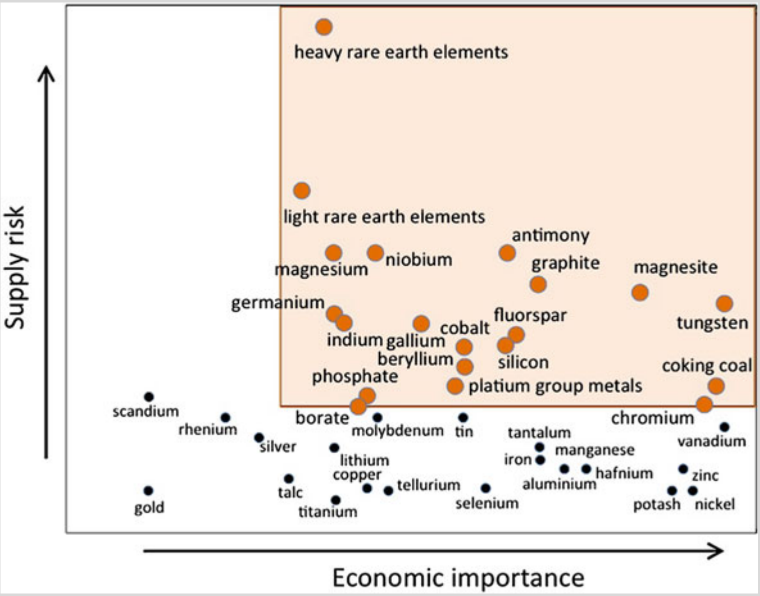


Fig. 1.4 The criticality index for mineral commodities in the European Union, redrawn from http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/crm-report-on-critical-raw-materials_en.pdf (some non-metallic materials are not shown)

index high. The list of critical metals differs from region to region; the lists for Europe and the USA are generally similar but that for China is very different. This issue is discussed in Chap. 6.

1.3 What is an Ore Deposit?

An ore deposit is defined *as an accumulation of a useful commodity that is present in high-enough concentration and in sufficient quantity to be extractable at a profit.* In this definition as well we find the terms "*useful commodity*" and "*profit*": the definition is both geological and economic. To understand these ideas, consider the following exercise.

Exercise 1.2 Selection of a Mining Property
Imagine that you are the director of a mining company and that a prospector comes to you with the following list of properties. You have to decide which is the most attractive target for development in the coming 5–10 years.

1. A deposit of 10 million tons with 0.2 % Cu near Timmins in northern Ontario
2. A deposit of 1 million tons with 1 % Cu near Timmins
3. A deposit of 10 million tons with 2 % Cu at Daneborg on the northeast coast of Greenland*
4. A deposit of 10 millions tons with 5 % Cu in the northeast of Pakistan
5. A deposit of 5 million tons with 1 % Cu near Timmins
6. A deposit of 100 millions tons with 0.7 % Cu near Timmins
7. A deposit of 100 millions tons with 0.7 % Cu on the Larzac plateau, France

Response

You see that the list comprises seven hypothetical copper deposits that are distinguished by their size, their grade, and their location. To make a choice, it is easiest to start by eliminating the properties that are the least attractive, either because of their size or grade, or because they are located in inhospitable regions. To help with the choice, you will recall that in the previous section we said that the average grade of mined copper is about 0.7 % and that a normal deposit contains 100s of millions of tons of ore. With this information we can eliminate deposit number 1, whose grade is too low, and deposit number 2, which is far too small. The deposit at Daneborg, situated on the east coast of Greenland some 500 km north of the Arctic Circle, is unattractive because of its small size and its location far from centres of industry in a region with extreme climate. And given the state of war that exists in the "tribal areas" of northern Pakistan (number 4), no responsible mining company would consider opening a deposit in that region.

This leaves the last three deposits. The Larzac plateau is the home of José Bové, the radical French farmer and professional protestor who rose to fame when he tore the roof off a Macdonald's restaurant. As a fervent anti-capitalist and fierce opponent of the exploration for shale gas, it is most unlikely that he would want a large copper mine to open on the farm where he raises the sheep that produce his Roquefort cheese.

The only two deposits that remain, numbers 5 and 6, are in northern Ontario, a region with a long mining history and a political climate favourable to mining. To distinguish between these two we need only consider the amount of copper in each deposit. Deposit 5 contains 50,000 tons; deposit 6 contains 700,000 tons. The much larger amount of metal in the latter deposit would offset the higher cost of mining its lower grade ore, making deposit 6 the most attractive.

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*Were the deposit much larger and on the more hospitable west coast, it might be viable. The Black Angel Pb–Zn deposit, located on a precipitous cliff on the margin of a fjord near Maamorilik, was mined successfully from 1973 to 1990 and it closed only because of falling metal prices at that time

(Pb and Zn followed a trend similar to that of copper, as shown in Fig. 1.2). In 2006 the retreat of a coastal glacier revealed another very large and rich Zn–Pb–Ag deposit which is currently being mined—a silver lining on the cloud of global warming?

1.4 Factors that Influence whether a Deposit can be Mined

1.4.1 Tenor and Tonnage

Some features of the relationship between grade, tonnage and viability of an ore deposit were explained in Exercise 1.2. For a deposit to be mineable, it must contain more than a certain concentration of the valuable commodity, and more than a certain tonnage of this commodity. As shown very schematically in Fig. 1.5a, deposits tend to be distributed along a trend from an extremely small and rich deposit—a single crystal of copper is the extreme example—to another deposit that is very large but with much lower grade—the entire Earth. Most deposits that are big, close to the surface and/or close to centres of population and/or contain high-grade have been mined out; what remains are rich deposits in more remote regions, more deeply buried settings, or lower-grade deposits.

Figure 1.5b shows in an equally crude way the relationship between grade and metal price (this relationship is explored in more detail in a later section). Some metals are abundant in the Earth's crust and these metals are present in high concentrations in ores. As a consequence of their abundance, their price is relatively low. Other metals are present in far lower concentrations and their price is much higher.

Within many individual deposits the ore type varies, from small packets of rich, high-grade ore to larger volumes with lower grades. The values shown in Fig. 1.5a are the average grades that are mined, a mixture of high and low grade ore. What is

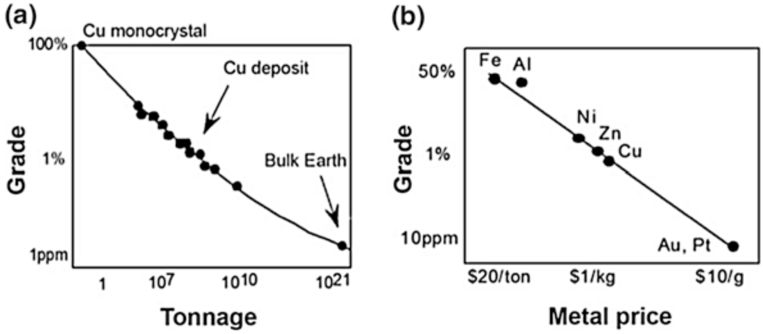

Fig. 1.5 Schematic diagrams showing. **a** Variation in the grade and size of ore deposits, rocks and the Earth. **b** The relationship between grade of ore deposits and price of selected metals

left in the ground after mining is material—geologically very similar to the material that has been mined—but containing a lower concentration of the ore metal, a concentration that is below a certain threshold. This important parameter is called the *cut-off grade*. To include sub-ore in the material being mined would lead to the operation becoming unprofitable: the cost of mining this material would exceed the value of the recovered metal.

But what would happen if the metal price improves? It is evident that if the price *increases*, the cut-off grade *decreases* because lower-grade material can then be mined at a profit. As a consequence, the amount of mineable material in the deposit increases. The example discussed in Exercise 1.3 illustrates how the amount of recoverable metal depends on the price.

Exercise 1.3 Estimation of the Amount of Recoverable Ore As a Function of Price and Cut-Off Grade

Figure 1.6 is a sketch of a hypothetical ore deposit that contains a rich, high-grade core surrounded by a much larger volume of lower grade material. Suppose that the price of copper increases from $4000 to $8000 per ton, as it did during the period 2004–2008, and that the increase led to a drop in the cut-off grade. What is the effect of the increase in metal price?

Response

In the example, the radius of the zone that can be mined increases from 1.6 to 2.7 km as the cut-off grade drops from 1 to 0.5 %. The tonnage of ore that can be mined depends on the square of this distance (assuming that the maximum depth of mining remains fixed at 1 km) and the volume increases from 8.0 km^3 *(*$\sim n \times 1.6^2 \times 1$*) to 32.2 km*^{3} *(*$\sim n \times 3.2^2 \times 1$*). Taking into account the lower grade of the newly recoverable ore (0.5 % instead of 1 %), the tonnage of*

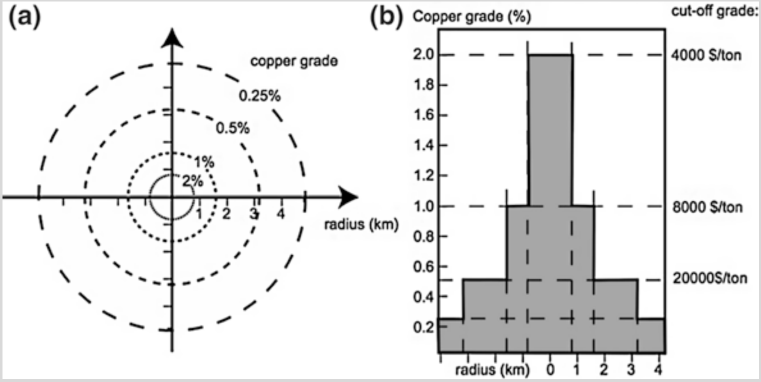

Fig. 1.6 Highly schematic plan of an ore deposit and variations in ore grade, showing how an increase in ore price results in a decrease in the cut-off grade which increases the volume of ore that can be mined and the quantity of metal that can be recovered

mined copper almost doubles, from 232 Mt (8.0 km^3 × 2.9 × 10^9× 1 %) to 583 Mt (8.0 km^3 × 2.9 × 10^9 × 1 %) + (32.2 km^3 – 8.0 km^3) × 2.9 × 10^9 × 0.5 %) tons. The consequence is that a much larger amount of ore can be mined and the amount of copper that can be recovered increases.

This brings us to an important point: if society requires a commodity, and if no substitutes can be found, and if recycling or substitution cannot make up any shortfall, then the price will increase to the extent that low-grade accumulations of the material become ore.

There are, of course, limits and complications, but this type of argument leads to the suggestion that resources of many metals will never be exhausted. This does not mean that industry's demand for all types of metal will always be met. It is possible that other factors such as the environmental impact of mining and society's resistance to this impact or the increasing amounts of energy needed to extract and process low-grade ores might limit or curtail the exploitation of certain types of deposits. In such cases a choice must be made—either the cost of the metal must increase to the extent that the deposit can be mined in an environmentally and energetically sustainable manner, or a substitute for the metal must be found. In recent years the notion of "sustainable mining" has received more and more attention. This term expresses the idea that metals and other raw materials should only be mined at a rate, and in a manner, that exhaust supplies for future generations, and does not cause irreparable or unacceptable harm to the environment.

As illustrated in Fig. 1.2a, reserves of copper have in fact increased over most of the past century, despite the increasing production required to meet the needs of a growing population. This trend was only disrupted in the last decade, due to the extraordinary demand from China. This issue is discussed further in Chap. 6.

1.4.2 Nature of Ore

One factor that strongly influences the viability of a deposit is the nature of the ore. Characteristics to be considered include the type of mineral, its grain size, and how it is intergrown with other minerals, all of which influence the cost of mining the ore and extracting the valuable commodity. The lowest extraction costs are for ores in which the extracted element is only mechanically bound into the waste minerals, which are known as gangue. Examples include native gold or heavy minerals in placer deposits. Higher extraction costs are associated with ores in which the element is chemically bound to sulfur or oxide (the case of most base-metal ores) because it takes more energy to break such chemical bonds than to mechanically liberate a grain of ore mineral. The highest extraction costs are for ores in which the element is chemically bound to silicates because these bonds are much stronger than metal-sulfur or metal-oxide bonds. Consider, for example, the two major types of nickel ore: magmatic and lateritic. In the first, the ore mineral is sulfide (mainly pentlandite, $(Fe,Ni)_9S_8$), whereas in lateritic ore it is garnierite (a clay-like mineral) or goethite (Fe hydroxide). Each type of ore has its advantages and disadvantages. The capital investment and the energy required to extract Ni is much higher for the lateritic ores, a major disadvantage in times of high energy costs; on the other hand, the refinement of sulfide ore produces vast amount of sulfur, only some of which can the sold as a by-product. The development of hydrometallurgical technologies, which allow the extraction of Ni and Co without using high temperatures and pressures, will cut the energy requirements for the treatment of lateritic ores.

The grain size and the hardness of the ore influence the cost of grinding it to the fine powder that is usually required to separate ore minerals from gangue. Three Australian Zn–Pb deposits provide a striking example (Fig. 1.7). All have similar ore grades but the Broken Hill deposit has been metamorphosed to granulite facies and its coarse-grained ore allows easy separation of ore minerals such as galena and sphalerite from gangue minerals such as pyrite or silicates; Mt Isa is less

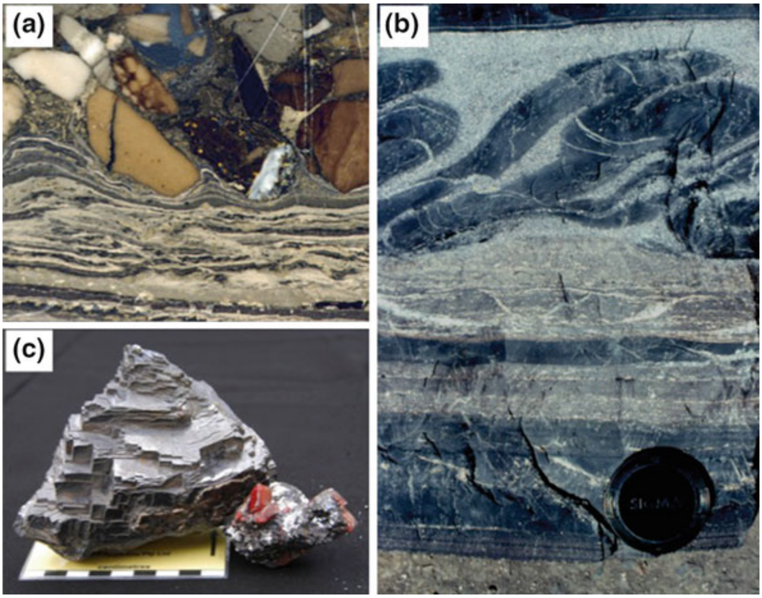

Fig. 1.7 Three types of Pb–Zn sulfide ore, all of similar origin, distinguished by different grain size. **a** Very fine-grained unmetamorphosed ore from the McArthur River deposit (width of the field of view is 1 cm). The pale-yellow layered material is fine-grained Zn–Fe sulfides and clay minerals, the detrital grains of quartz and lithic fragments deform these bands. **b** Fine-grained and deformed, slightly metamorphosed ore from Mt Isa (lens cap gives the scale). **c** Coarse-grained galena (the flat surfaces are cleavage planes within large crystals) and bustamite (Mn–Ca silicate) from Broken Hill where granulite-facies metamorphism has produced large crystals (the cleavage planes in the large fragment shows that it is part of a single crystal) (*Photo a* from Ross Large, *photo b* from Peter Muhling, *photo c* from Chris Arndt)

metamorphosed and its finer-grained ore is less attractive; and in the virtually unmetamorphosed McArthur River deposit, the ore is so fine-grained that the metals could not initially be extracted from waste minerals by simple crushing and flotation. In fact, the mine was not opened until about 40 years after its discovery when new methods for crushing and mineral separation were finally developed.

Minor elements increase or decrease the value of an ore. Many ores contain valuable metals in concentrations well below the normal cut-off grade, but if they are extracted as a by-product during the recovery of the major ore metals, they contribute significantly to the viability of the mining operation. Common examples of such "bonus" metals include gold or silver in copper ores, and platinum metals in nickel ores. Another topical example is the rare earth elements, which were initially recovered as a by-product of mining of an iron deposit (Bayan Obo) in China (see Chap. 6). In contrast, the presence of a small amount of other metals can complicate the extraction process and decrease the value of the ore. Examples of "toxic" or unwanted metals include phosphorous in iron ore and arsenic in base-metal sulfide ores.

1.4.3 Location of the Deposit

Exercise 1.4 also illustrates the influence of the location of a deposit. Its value, and its very viability, decrease if it is far from centres of industry or population, or in a harsh climate, or in a politically unstable region. All these factors increase the cost of mining or transport of metals to market; or they render the operation of a mine too risky. Political instability is a particularly important risk; the Panguna mine on Bouganville Island in Papua New Guinea, once the world's biggest open-pit Cu-Au mine, closed in 1989 because of civil war triggered by the mine's impact on the island's environment and social structure.

Also important is the geological situation. The largest Ni deposit we know of is in the centre of the Earth. The core of our planet contains some 10^{19} tons of Ni metal but it is of course totally inaccessible (except for heroes of Hollywood movies). The depth of a deposit has a major influence on the cost of mining. A shallow deposit can be exploited in an open-pit mine, which is far cheaper than the alternative—an underground mine—which must be developed if the deposit is deeper. Friable and soft sedimentary ores are easier to mine and process than ores in hard igneous rocks. And finally a continuous and compact ore body is easier to mine than one that is disrupted by faulting or other geological factors. Two platinum deposits in southern Africa provide an interesting example. Those in the Bushveld Complex in South Africa are mainly in near-continuous layers that make the mining operation predictable and efficient, but deposits in another intrusion, the Great Dyke in Zimbabwe, although of similar grade to the Bushveld deposits, are so irregular and disrupted by faulting that mining has proved very difficult. And destabilization of that country's economy by the present government has made the operation even more hazardous.

1.4.4 Technical, Economical and Political Factors

As illustrated above, economic and political issues strongly influence the viability of a deposit, in some cases increasing its value, in other cases detracting from it. The role of technology, on the other hand, is generally positive. Only through improvements in the techniques used to mine and process ore have we been able to extract metals from deposits with lower and lower grades.

One example of this tendency is the decrease in the copper grade discussed at the start of the chapter. Another striking example is the reprocessing of gold ores in Western Australia. When the deposits of the Coolgardie-Kalgoorlie region were first discovered in 1893, only alluvial gold was exploited. Underground mining soon followed and in the early part of the 20th century, vast waste dumps surrounded the growing boomtowns. In the following century these dumps have been reprocessed several times and each time gold that had previously been discarded was recovered. The process was driven by increases in the price of gold, notably with the abandonment of the gold standard in 1971 and the more recently with the metals boom and economic uncertainty at the start of this century. But coupled with these economic pressures were technological advances that allowed the recovery of gold that was unattainable using earlier techniques. Recent advances utilize in situ leaching in which fluids containing gold-eating bacteria, are allowed to percolate through the waste dumps. Other advances include the development of more efficient mining methods, as best expressed in the vast open cast mines that exploit large, low-grade, near-surface deposits of copper, gold, iron and other metals.

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Chapter 2
Classification, Distribution and Uses of Ores and Ore Deposits

2.1 Classifications of Ores

The geological literature contains many schemes for classifying ore minerals. Some have an economic basis linked to the end use of the metal or mineral; others depend partly or entirely on geologic factors.

2.1.1 Classifications Based on the Use of the Metal or Ore Mineral

In older books it is common to find minerals classified, as in Table 2.1, according to the use that is made of the metal or mineral extracted from the ore. Table 2.2 contains some of the minerals that are mined for copper. We see that this metal is extracted from various types of sulfides and sulfosalts, as well as from sulfates, carbonates, oxides and in rare cases as a native metal. Copper is one of the "base metals", a term that refers to a group of common metals, dominated by the transition elements, which are widely used in industry. Gold and platinum are classed as "precious metals". Other classes of ores comprise minerals that are used in their natural state, without refinement or extraction of a specific element. Barite, a sulfate of the heavy element barium, is employed to increase the density of the fluids ("muds") used when drilling for oil. Uranium and coal are sources of energy. Various types of hard minerals are used as abrasives; garnet and industrial diamond are two examples, as is feldspar (next time you buy a tube of toothpaste, read the list of ingredients to see if it contains "sodium-aluminium silicate"). This type of table provides a useful link between the various types of ores and the use that society makes of them.

N. Arndt et al., *Metals and Society*, Springer Mineralogy,
DOI 10.1007/978-3-319-17232-3_2

Table 2.1 Metals, useful minerals and their ores

Class	Element	Mineral	Composition*
Ferrous metals	Iron (Fe)	Hematite	Fe_2O_3
		Limonite, goethite	$FeO \cdot OH$
		Magnetite	Fe_3O_4
	Manganese (Mn)	Pyrolusite	MnO_2
	Chromium (Cr)	Chromite	$FeCr_2O_4$
	Nickel (Ni)	Pentlandite	$(Fe, Ni)_9S_8$
		Garnierite	$(Ni, Mg)_3Si_2O_5(OH)_4$
	Molybdenum (Mo)	Molybdenite	MoS_2
	Vanadium (V)	Magnetite	$(Fe, V)_3O_4$
Aluminium	Aluminium (Al)	Gibbsite	$Al(OH)_3$
Base metals	Copper (Cu)	Chalcopyrite	$CuFeS_2$
		Chalcocite	Cu_2S
		Cuprite	Cu_2O
		Tetrahedrite	$(Cu, Ag)_{12}Sb_4S_{13}$
		Malachite	$Cu_2CO_3(OH)_2$
		Azurite	$Cu_3(CO_3)_2(OH)_2$
		Native copper	Cu
	Zinc (Zn)	Sphalerite	(Zn, Fe)S
	Lead (Pb)	Galena	PbS
	Tin (Sn)	Cassiterite	SnO_2
Precious metals	Gold (Au)	Native gold	Au
	Platinum (Pt)	Alloys of platinum group elements (PGE)	Pt, Pd, Os, Ir …
	Silver (Ag)	Native silver Argentite	Ag (Ag_2S)
Energy sources	Uranium (U)	Pitchblende	UO_2
	Coal (C)	Coal	C
High-technology metals	Titanium (Ti)	Ilmenite Rutile	$FeTiO_3$ TiO_2
	Zirconium (Zr)	Zircon	$ZiSiO_4$
	Niobium (Nb), thorium (Th), rare earth elements	Monazite, apatite and rare minerals (bastnäsite, pollusite, etc.)	Nb, Th, La, Ce, Nd …
Other elements	Barium (Ba)	Barite	$BaSO_4$
	Fluorine (F)	Fluorite	CaF_2
	Potassium (K)	Sylvite	KCl

(continued)

Table 2.1 (continued)

Class	Element	Mineral	Composition*
Minerals		Diamond	C
		Corundum	Al_2O_3
		Garnet	Silicate of Al, Mg, Fe
		Talc	$Mg_3Si_4O_8(OH)_2$
		Mica	Phyllosilicate
		Diatomite	Silica
		Andalusite, kyanite	Al_2SiO_5
		Albite	$NaAlSi_3O_8$
		Halite	NaCl
		Calcite	$CaCO_3$

Table 2.2 Classification of ore minerals

Sulfides and sulfosalts
Covellite—CuS
Chalcocite—Cu_2S
Chalcopyrite—$CuFeS_2$
Bornite—$Cu_8 FeS_4$
Tetrahedrite—$(Cu, Ag)_{12}Sb_4 S_{13}$
Galena—PbS
Sphalerite—(Zn, Fe)S
Cinnabar—HgS
Cobaltite—(Co, Fe)AsS
Molybdenite—MoS_2
Pentlandite—$(Fe, Ni)_9S_8$
Millerite—NiS
Realgar—AsS
Stibnite—Sb_2S_3
Sperrylite—$PtAs_2$
Laurite—RuS_2
Oxides and hydroxides
Bauxite
Gibbsite—$Al(OH)_3$
Boehmite—(γ-AlO(OH))
Diaspore—(α-AlO(OH))
Cassiterite—SnO_2
Cuprite—Cu_2O
Chromite—$(Fe, Mg)Cr_2O_4$
Columbite—Tantalite or coltan $(Fe, Mn)(Nb, Ta)_2O_6$
Hematite—Fe_2O_3
Ilmenite—$FeTiO_3$

(continued)

Table 2.2 (continued)

Magnetite—Fe_3O_4
Pyrolusite—MnO_2
Rutile—TiO_2
Uraninite (pitchblende)—UO_2
Oxysalts
Calcite—$CaCO_3$
Rhodochrosite—$MnCO_3$
Smithsonite—$ZnCO_3$
Malachite—$Cu_2CO_3(OH)_2$
Barite—$BaSO_4$
Gypsum—$CaSO_4.2H_2O$
Scheelite—$CaWO_4$
Wolframite—$(Fe, Mn)WO_4$
Apatite—$Ca_8\ (PO_4)_3\ (F,Cl, OH)$
Halides
Halite—$NaCl$
Sylvite—KCl
Fluorite—CaF_2
Metals and native elements
Gold—Au
Silver—Ag
Platinum-group metals—Pt, Pd, Ru
Copper—Cu
Carbon—C (diamond, graphite)
Silicates
Beryl—$Be_3\ Al_2\ (SiO_3)_6$
Garnet—Silicate of Al, Mg, Fe
Garnierite—Mixture of the Ni-Mg-hydrosilicates
Kaolinite—$Al_4\ Si_4\ O_8\ (OH)_8$
Sillimanite—$Al_2\ SiO_8$
Spodumene—$LiAlSi_2\ O_6$
Talc—$Mg_3\ Si_4\ O_8\ (OH)_2$
Zircon—$ZrSiO_4$

2.1.2 Classifications Based on the Type of Mineral

The type of mineral provides the basis of the classification given in Table 2.2. Here we see that many important metals are mined in the form of sulfides (e.g. Cu as chalcopyrite, Pd as galena, Ni as pentlandite). Another important class is the oxides, which are mined for tin as the mineral cassiterite (SnO_2), iron as magnetite (Fe_3O_4) and uranium as pitchblende (UO_2). Other types of metals are found as carbonates or sulfates, usually in alteration zones overlying primary deposits.

Very few metals are mined in their native form, the only common examples being gold and the platinum-group elements. Carbon is also mined as a native element as diamond or graphite, and in an impure form as coal. Although copper does occur as a native metal, its presence in this form is usually more an impediment than an advantage. Although native copper does indeed contain 100 % Cu and its presence boosts the copper grade, the mineral in malleable and tends to gum up the crushing machines which are designed for brittle sulfides and silicates.

Silicates, by far the most important rock-forming mineral, are uncommon in lists of ore minerals. Exceptions are garnierite, a clay-like mineral that is a major ore mineral in Ni laterites; zircon ($ZrSiO_4$), a heavy detrital mineral mined for the high-technology metal zirconium; and garnet, which is used as an abrasive. Quartz is becoming increasing important as a source of the silica that is used in semiconductors and in solar panels.

Box 2.1 Copper, a Highly Versatile Metal

Copper, along with gold, was one the first metals to be used by mankind and it is very widely used today. It is mined in almost all parts of the world, and is used very widely in industry. The major copper producing countries are Chile, USA, Peru and China. Almost every country is a consumer of copper, the level depending on the size of the population and the extent of industrialization.

Common uses of copper are given in Table 2.3. Its high electrical and thermal conductivity, its resistance to corrosion and its attractive colour lead to a wide range of applications. It is used as wire to conduct electricity in electrical appliances and in alloys with zinc (brass) or other metals in utensils and coins. The development of new types of alloys has led to new uses in superconductors and batteries; and copper compounds are used in a wide variety of products such as pesticides (copper sulfate pentahydrate is used to control fungus on grapes and algae in swimming pools) and antibiotics.

In developed countries, the per capita consumption of copper has remained nearly constant for decades. New uses of the metal generally require only relatively small quantities of copper and these additions are countered by abandonment of other industrial applications and by increased recycling. However, increasing demand from developing countries will require that global production be increased significantly; this production can only be met by discovery of new deposits and efficient exploitation of these deposits.

Table 2.3 Uses of copper in modern industry

Electricity, electronics	42 %
Construction	28 %
Transport	12 %
Industrial machinery	9 %
Other (coins, medicines, fungicides)	9 %

Source Standard CIB Global Research www.standardbank.co.za

In addition, with the increasing use of electronics in cars and household or industrial devices, per-capita use of copper in wiring and circuits is expected to increase slightly, even in industrialized countries.

2.2 Classifications of Ore Deposits

There are some parallels between the schemes used to classify ore minerals and those used to classify ore deposits. Again in older texts, deposits are classified according to the type of metal or material they produce; copper deposits, gold deposits, energy sources (uranium and coal), and so on. This type of classification finds some application in a purely economic context but is not employed here.

Through the 20th century many classifications were based on the types of rocks that host the ore deposits or on the geological context—the geometry of the deposit and its relation to its host rocks. An example is given in Table 2.4. Deposits in granites were distinguished from those in sedimentary rocks; vein-like deposits were distinguished from layers conformable with stratification of the host rock; massive ores were distinguished from disseminated ores. A popular classification developed by Lindgren, an American economic geologist who was very influential in the mid 20th century, distinguished deposits that formed at different levels in the

Table 2.4 Lindgren's Classification of Ore Deposits (modified from Lindgren 1933; Evans 1993)

	Depth	Temperature (°C)	Occurrence	Metals
Telethermal	Near surface	±100	In sedimentary rocks or lava flows; open fractures, cavities, joints. No replacement phenomena	Pb, Zn, Cd, Ge
Epithermal	Near surface to 1.5 km	50–200	In sedimentary or igneous rocks; often in fault systems; simple veins or pipes and stockworks; little replacement phenomena	Pb, Zn, Au, Ag, Hg, Sb, Cu, Se, Bi, U
Mesothermal	1.2–4.5 km	200–300	Generally in or near intrusive igneous rocks; associated with regional faults; extensive replacement deposits or fracture fillings; tabular bodies, stockworks, pipes	Au, Ag, Cu, As, Pb, Zn, Ni, Co, W, Mo, U etc.
Hypothermal	3–15 km	300–600	In or near deep-seated felsic plutonic rocks in deeply eroded areas. Fracture-filling and replacement bodies; tabular or irregular shapes	Au, Sn, Mo, W, Cu, Pb, Zn, As

crust (Table 2.4). His terms “epizone”, “mesozone” and “catazone”, for deposits at shallow, intermediate, and deep levels in the crust, are still employed today. A further distinction can be made between “syngenetic” deposits, which formed together with and as part of the host rock, and “epigenetic” deposits, which formed through introduction of ore minerals into already consolidated rocks.

The development in the 20th century of the theory of plate tectonics spawned a swarm of classifications based on tectonic settings. As in Table 2.5, deposits in ocean basins were distinguished from those in convergent margins or intracratonic settings, and so on. This type of classification is still used, particularly when discussing the broad-scale distribution of ore deposits, as we do in the following section. However, newer schemes in which the basic criterion is the *ore-forming process* have largely replaced this type of classification (Table 2.6). Although it might be argued that a rigorous classification should be based on objective parameters that can be measured and quantified, and not on properties that must be inferred, this is the classification we will use in this book.

The scheme we have chosen has some disadvantages and, as will be seen in following chapters, it is often not clear whether a certain deposit should be placed in one box and not another, but it also has the great advantage that it emphasizes that

Table 2.5 Tectonic classification of ore deposits

I. Deposits at oceanic ridges (divergent plate margins)
Volcanogenic massive sulfide deposits (Cu, Zn)
Sedimentary exhalative deposits (Zn, Cu, Pb, Au and Ag). e.g. Red Sea
Mn nodules (Mn, Ni, Cu, Co …)
Cr, PGE, asbestos in ultramafic rocks
II. Deposits at convergent plate margins
Porphyry Cu-Mo deposits
Other base metal deposits (Cu, Pb, Zn, Mo)
Precious metals (Pt, Au, Ag)
Pb–Zn–Ag veins and contact metasomatic deposits
Other metals (Sn, W, Sb, Hg)
III. Deposits in cratonic rift systems
Deposits of Sn, fluorite, barite in granites
Evaporites in rift basins
Carbonatites containing Nb, P, REE, U, Th and other rare elements
IV. Deposits in intracontinental settings
Ni and PGE in layered intrusions
Ti in anorthosites
Iron-oxide Cu-Au deposits
Pb–Zn–Ag deposits in limestones and clastic sediments
Sedimentary Cu deposits
Ni, Al laterites
Diamonds in kimberlites

Table 2.6 Classification of deposits based on the ore-forming process

1. **Magmatic**: ores that form by the accumulation of minerals that crystallize directly from magma
(a) *In mafic and ultramafic rocks*
• Chromite and platinum-group elements (PGE) in large layered intrusions (Bushveld in South Africa, Great Dyke in Zimbabwe)
• Chromite in ophiolites (Turkey)
• Cu-Ni-Fe sulfide in the layered intrusions (Sudbury, Norilsk)
• Sulfide Ni–Cu–Fe in komatiitic lavas (Kambalda)
• Diamonds in kimberlites
(b) *Associated with felsic intrusions*
• Cu ore in carbonatites (Phalabora)
• REE, P, Nb, Li, Be etc. in pegmatites
2. **Deposits associated with hydrothermal fluids**: metals are mobilized within and precipitated from aqueous fluids or various origins—classification based on origin and geologic setting of the aqueous fluid
(a) Meteoric water systems
• Epithermal Au-Ag deposits (United States, Chile, Argentina, Peru)
(b) Seawater systems
• Volcanogenic massive sulfide Cu-Zn-Pb deposits (Canada, Japan)
(c) Magmatic water systems
• Porphyry Cu-Mo-Au deposits (Chile, Peru, United States)
• Skarn Cu-Zn-Pb-Fe-W-Sn-Au-Ag deposits (Indonesia)
(d) Basinal water systems
• Sedimentary exhalative (SEDEX) Pb-Zn deposits (Australia, Canada)
• Mississippi Valley-type (MVT) Pb-Zn-Ba-F deposits (United States, Canada, Australia)
• Sedimentary rock-hosted stratiform Cu-Co-(Ag) deposits (Democratic Republic of Congo, Zambia, Poland, Germany)
• Unconformity and sandstone U deposits (Canada, Australia)
(e) Metamorphic water systems
• Orogenic Au deposits (Canada, Australia)
(f) Systems with transitional characteristics
• Carlin-type Au-As-Sb-Hg deposits (United States, Iran, China)
• Iron-oxide, copper-gold (IOCG) and iron-oxide apatite (IOA) deposits (Australia, Sweden, Chile)
3. **Sedimentary deposits**: concentrations of detrital minerals or precipitates
(a) Placer and paleoplacer deposits
• Modern beach and river Au, Ti-Zr and diamond placers (California, Australia, Brazil, Namibia)
• Ancient Au-U paleoplacer deposits (Witwatersrand, South Africa)
(b) Chemical sedimentary deposits
• Banded (BIF) and granular (GIF) iron formations—Australia, Brazil, United States, South Africa, Canada
• Manganese deposits—South Africa
• Evaporites, including marine (Na-K-Ca-Mg-Br) and non-marine (Li, B)
• Phosphorites
4. **Deposits related to weathering**
(a) Laterite deposits
• Al laterite—bauxite (Jamaica, France, Australia)
• Ni laterite (New Caledonia)
(b) "Supergene" enriched deposits
• Cu, Zn, Au supergene and oxide deposits
5. **Metamorphic deposits**
(a) Deposits in skarn (China, Scandinavia, USA)

ore deposits result from normal geological processes like those that form common igneous or sedimentary rocks. It provides an incentive to move the discipline from "gîtologie"—a French term that can the translated as "depositology", an essentially descriptive catalogue of ore deposits—to a modern interpretative science. Finally, the approach provides a means of applying our knowledge of geological processes and concepts such as the partitioning of major and trace elements between melt and crystal, the sorting of light from heavy minerals during fluvial transport, or the stability of mineral phases in aqueous solutions, to improve our understanding of how an ore deposit forms.

2.2.1 A Classification Based on the Ore-Forming Process

The list of headings in Table 2.6 overlaps the list of geological processes that are found in most introductory geology texts. We see, for example, that magmatic processes form some deposits, and sedimentation or surface weathering form others. What distinguishes the two lists is the minor importance of metamorphism in the list of important ore-forming processes and, in its place, a major class comprising deposits that are linked to hydrothermal fluids. When the functioning of the Earth as a whole is considered, the circulation of hot aqueous fluids through the crust is normally mentioned only as an agent that alters the composition or texture of primary magmatic or sedimentary rocks; the same process, however, is responsible for forming a vast range of important ore deposits and has created well over half of all ore bodies that are known to exist.

Consider now the first category in Table 2.6, magmatic deposits. We note that many examples of large and important magmatic deposits are found in mafic-ultramafic rocks and only a few less important types in evolved, felsic or silicic, rocks. Many ore deposits are indeed hosted by granites, but according to modern ideas of ore genesis, such deposits generally result from the precipitation of ore minerals from aqueous fluids and not from the granitic magma itself. The type of ore mineral in the deposit is directly linked to the composition of the host rock. For example, in mafic-ultramafic rocks we find deposits of Ni, Cr and platinum-group elements, all of which partition strongly into minerals that crystallize early during normal magmatic differentiation. Magmatic ores in felsic rocks, by contrast, are confined to metals that concentrate in the evolved siliceous magmatic liquid. Some of these form late-crystallizing phases such as the mineral ilmenite, which contains Ti, and cassiterite, the ore of Sn. Other ore metals become concentrated in the water-rich fluid that separates from the silicate liquid, to be redeposited in pegmatites or in hydrothermal ore bodies. Pegmatites and carbonatites are important sources of rare but increasingly important metals such as Li, Be and the rare earth elements.

Some metals are restricted to a single type of ore-forming process, the best example being Cr, which, with virtually no exceptions, is mined as chromite, a magmatic oxide that accumulates during the crystallization of mafic or ultramafic magmas. Some very minor placer (sedimentary) chromite deposits have been mined, but hydrothermal deposits are unknown. More than 98 % of Al is mined as bauxite, a lateritic soil that forms in hot and humid climates, but the same metal is also extracted from feldspar in a Russian mine. The host rock is nepheline syenite, a magmatic rock.

Most metals, however, occur in deposits of diverse origins. Alloys of the platinum-group elements and cassiterite, an oxide of Sn, are cited as type examples of magmatic ores, but when the magmatic host rocks are exposed to erosion at the surface, the same minerals may become re-concentrated by fluvial processes to form sedimentary placer deposits. Metals such as copper and gold are present in almost every class of deposit in the list. The distribution of ore metals and the processes that create their deposits are discussed in more detail in following chapters.

2.3 Global Distribution of Ore Deposits

Ore deposits are not distributed uniformly across the globe. Vast tracts of land are devoid of viable deposits while others constitute what are known as 'metallogenic provinces'—regions containing an unusually high concentration of deposits of one or several types. Notable examples include the numerous copper deposits in the southwestern United States, the clusters of lead-zinc deposits in northeastern Australia, and the tin deposits of SE Asia. For both geological and economic reasons, it is important to have some knowledge of this distribution. From a geological point of view, the distribution provides important clues to the ore-forming process; from an economic point of view, the irregular distribution strongly influences metal prices and global trade, and is a factor that influences many of the alliances and conflicts that govern relationships between countries around the world.

In plate tectonic classifications of ore deposits, the emphasis is quite naturally on the tectonic setting in which the deposit occurs. But many deposits develop in sedimentary settings or as a result of superficial weathering; in such cases geomorphology, surface relief, and modern or past climate exert an additional important influence of the localization of the deposits. All these factors are discussed briefly in the following section and are then elaborated upon in subsequent chapters.

2.3.1 Geological Factors

Figure 2.1 illustrates the global distribution of selected types of ore deposits in the series of maps giving the locations of major examples. We have selected only a few major commodities that serve to illustrate the basic principles that govern the distribution of ores; more detailed and exhaustive information is found in standard texts and on the internet, as listed at the end of the chapter.

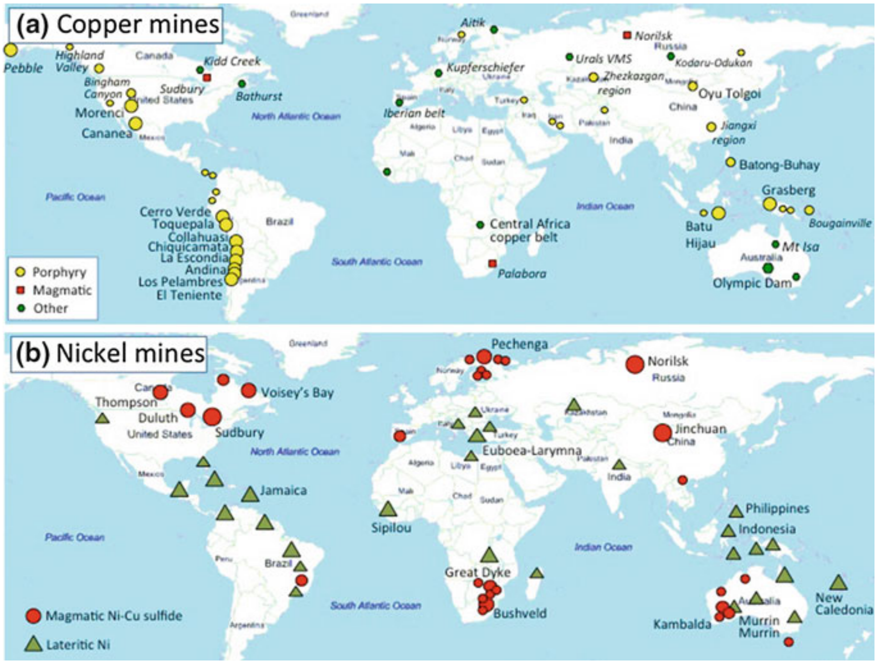


Fig. 2.1 Global distribution of ore deposits (from numerous sources)

We will start with copper, an industrial metal that is used in every country and is mined in all parts of the world (Fig. 2.1a). A large proportion of the resources of this metal are tied up in a single type of deposit, the so-called "porphyry copper" or simply "porphyry" deposits (Chap. 4). These deposits are directly associated with subduction and thus are found in island arcs and convergent margins. This is the origin of the string of deposits that extends along the entire western margin of North and South America (Fig. 2.1a) and throughout the islands of the southwest Pacific (Indonesia, Philippines, etc.). Large deposits of the same type are also found in accreted island arcs that have been incorporated into continental collision zones, as in the Alpine-Carpathian-Himalayan belt. Another major class of copper deposits formed in mature sedimentary rocks in intracratonic basins, as in the deposits of the central African "copper belt". Copper is also found in deposits associated with volcanic rocks, as in the volcanogenic massive sulphide (VMS) deposits such as Kidd Creek and Bathurst in Canada, and those of the Iberian belt and the Urals, and in deposits associated with shales, such as Mt Isa in Australia (Fig. 2.1a). It is also mined from deposits in magmatic intrusions, most of which form in intracratonic settings. Two important examples formed in very different ways. The Norilsk deposits in northern Siberia are associated with a large igneous province and those of the Sudbury area in Canada formed during crystallization of a melt sheet created by the impact of a large meteorite. Another unusual example of a copper ore body is the Phalabora intrusion, a carbonatite emplaced in the Archean Kaapvaal craton.

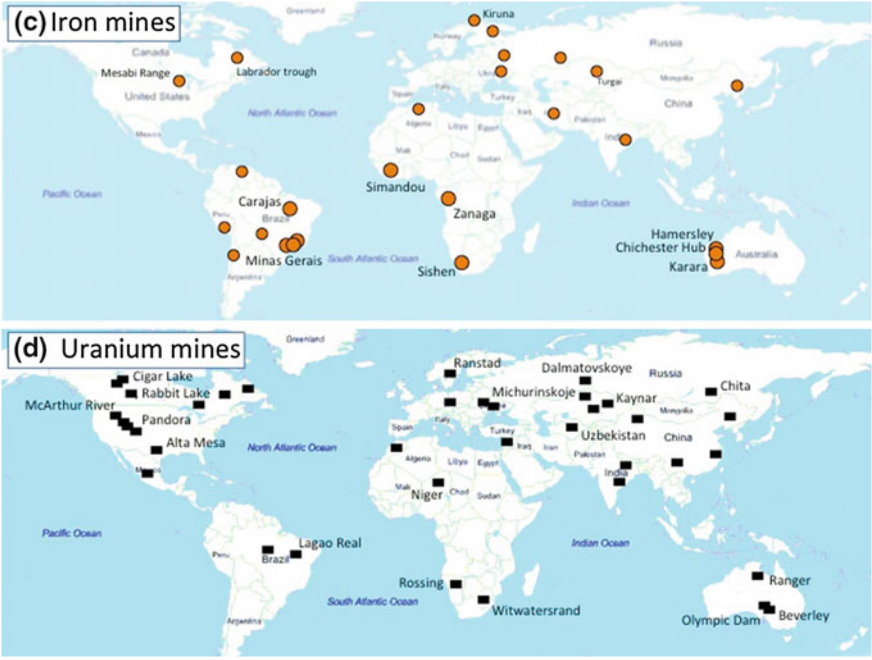


Fig. 2.1 (continued)

In many magmatic deposits, copper occurs together with nickel (Fig. 2.1b). This is the case for most major magmatic deposits, not only Sudbury but also Norilsk in Russia, Voisey's Bay in Canada and Jinchuan in China. Another class of nickel deposit is hosted by komatiite, a type of ultramafic lava that erupted only in the Archean and early Proterozoic. Komatite-hosted Ni-Cu deposits are therefore restricted to the oldest parts of the earth's crust, in the greenstone belts of Australia (Kambalda), Canada (Thompson) and Zimbabwe. But not all nickel deposits are magmatic; another major type is nickel laterite and for these the distribution is quite different. Whereas crustal structure and tectonic setting influence the location of the magmatic variety, laterite is a type of soil that develops at the surface of the Earth in hot, humid climates. All deposits of this type are located in regions that are relatively close to the equator, or were close to the equator when the deposits formed. Major lateritic Ni deposits are located in New Caledonia, Indonesia, Cuba, Brazil and Australia (Fig. 2.1b).

Most major iron deposits (Fig. 2.1c) formed in a very specific geological setting during a unique period of Earth history. About 90 % of iron ore is mined from "banded iron formations", a type of chemical sediment that precipitated from seawater on shallow continental platforms during the early Proterozoic. As explained in Chap. 5, this period in Earth history coincided with a marked increase in the oxygen content of the atmosphere and oceans. Most of the world's great iron deposits are therefore found in sedimentary sequences overlying Archean cratons;

in Brazil (Carajas, Minas Gerais), Australia (Hamersley), South Africa (Sishen) and Canada (Labrador Trough), as well as in newly discovered deposits in Guinea (Simandou), and Zanaga (Republic of Congo). An exception is the Kiruna deposit in Sweden, an enormous magnetite deposit of magmatic or hydrothermal origin.

The final mineral in our short selection of commodities is uranium (Fig. 2.1d). An important class of deposits are localized at unconformities at the base of Proterozoic sedimentary basins that overlie Archean cratons in northern Canada (Cigar Lake, Rabbit Lake) and northern Australia (Ranger). Hydrothermal deposits in the USA (McArthur River, Pandora, Alta Mesa) and through central Asia occur in younger sedimentary basins. Two notable examples where uranium is produced in multi-element deposits are Olympic Dam in Australia and the Witwatersrand conglomerates of South Africa (Fig. 2.1d). The Rössing deposit in Namibia is magmatic, Randstad in Sweden occurs in black shales, and the Yeelirrie deposit of Australia is hosted by surficial sediments (calcretes).

Gold deposits form in a wide range of tectonic settings. Some of the largest are orogenic gold deposits, which form in the active margins of the continents, such as the Cordillera of North America or the Alpine-Himalaya belt, and in island arcs. Older examples formed in their Precambrian equivalents, the Archean greenstone belts of Canada and Australia. Other gold deposits known as epithermal type form by hydrothermal activity in subaerial volcanic terranes, usually at convergent margins. Because gold follows copper in many hydrothermal processes, some of the largest gold deposits are actually copper mines with by-product gold, such as Grasberg in Indonesia. A quite different form of gold deposit are the placers (accumulations of heavy minerals in fluvial settings), which include the enormous, Archean-age Witwatersrand paleoplacers in South Africa and the more modern placers of California, the Klondike and Yukon in Canada and Victoria in Australia.

Titanium is mined in two very different types of deposits. The most common ore is ilmenite, a mineral that occurs in low concentrations as an accessory phase in a wide variety of igneous and metamorphic rocks but also in much higher abundances in a specific type of rock called anorthosite. This rock consists essentially of calcic plagioclase with a few percent of ferromagnesian minerals and a variable amount of Fe–Ti oxide. A specific type called "massif anorthosite" was emplaced in continental crust during the middle Proterozoic and this type commonly contains mineable concentrations of ilmenite. Large deposits of this type are found in a belt that extends from Quebec in Canada through to Norway.

When igneous or metamorphic rocks are subject to chemical weathering and erosion, ilmenite is released, transported in rivers and redeposited at the coastline. When the continental crust is stable and subject to protracted periods of weathering, and when the coastline is a stable passive margin, large accumulations of dense stable minerals may build up in beach sands. Major deposits of ilmenite, together with associated heavy minerals such as rutile (another Ti mineral), zircon (a source of Zr) and monazite (a source of Th and the rare earth elements) occur in sands along the coasts of Australia, India and South Africa.

Diamond also in mined in two types of deposits. The major and primary source is kimberlite, a rare type of ultramafic rock that is emplaced as pipe and dike-like intrusions at or near the margins of Archean cratons. The other type forms when kimberlite is eroded and the diamonds are released and accumulate in alluvial deposits in rivers or coastal sands and gravels. In historical times most diamonds were found in alluvial deposits in India (from a source whose location that remains unknown). Then the major deposits of South Africa, both kimberlitic and alluvial, were discovered and these provided the bulk of mined diamond for most of the 20th century. In the last decade, new deposits have been located in almost every country with a stable Archean craton; in Russia, Australia, Canada, Brazil, Greenland and Finland.

2.4 Global Production and Consumption of Mineral Resources

Figures 2.1, 2.2, 2.3 and the lists in Tables 2.7 and 2.8 indicate where metals and ore minerals are mined and consumed. Table 2.8 ranks countries in terms of their production of a small selection of commodities; the second the amount of the commodity they consume. Note that petroleum is not included in the selection of commodities. Although many of the largest countries figure near the top of both lists, as is to be expected, a number of anomalies provide useful information about how the global minerals industry functions.

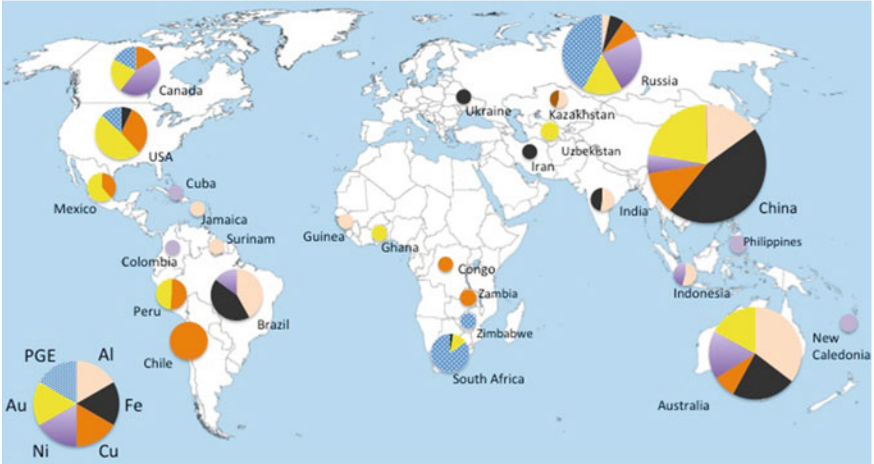


Fig. 2.2 Map showing the major producers of a selection of metals (from British Geological Survey, World Mineral Production 2005–2009, http://www.bgs.ac.uk/mineralsuk/statistics/worldStatistics.html)

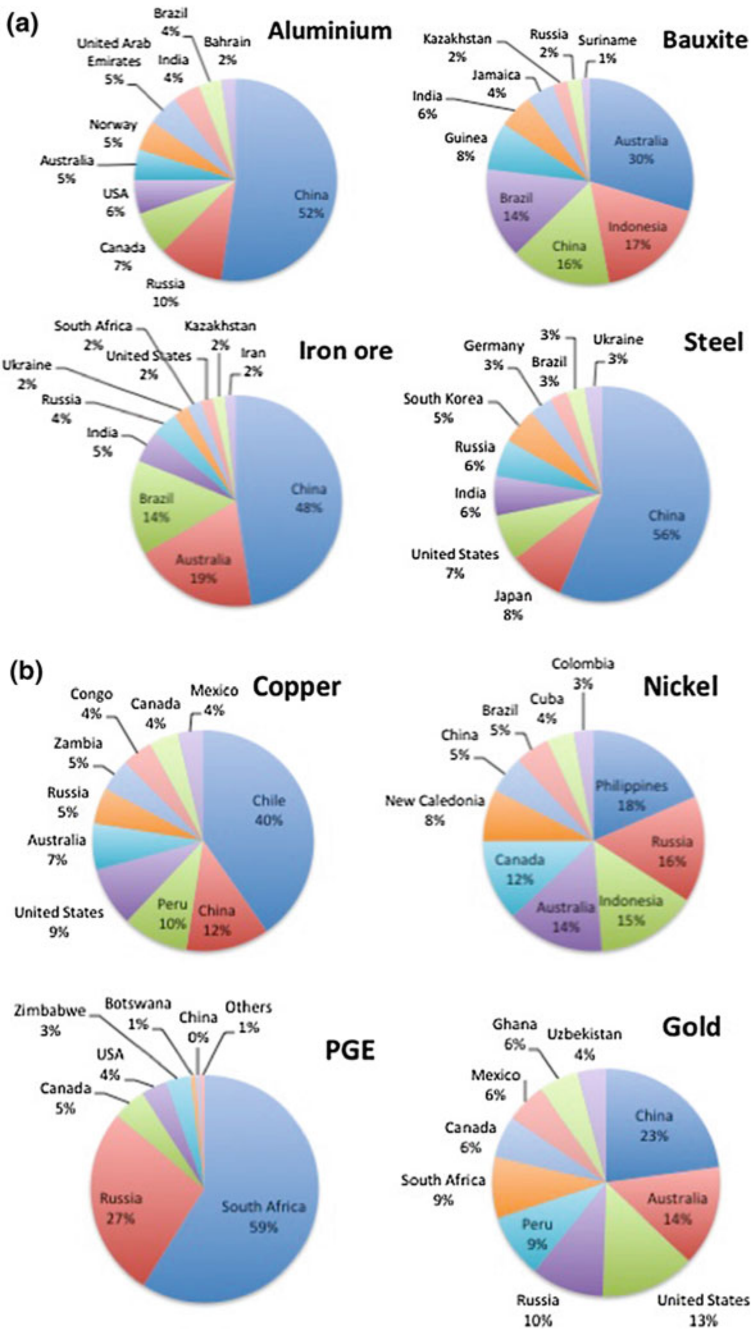


Fig. 2.3 The major producers of a selection of metals (from British Geological Survey, World Mineral Production 2005–2009, http://www.bgs.ac.uk/mineralsuk/statistics/worldStatistics.html)

Table 2.7 Major ore-importing and ore-exporting countries (2010)

	Country	Value ($US)
(a) *Importers*		
1	China	85,280,550
2	Japan	28,365,440
3	Germany	9,307,674
4	Korea	6,623,871
5	India	5,250,223
6	United Kingdom	4,679,500
7	USA	4,487,631
8	Belgium	3,183,008
9	Netherlands	3,081,213
10	Italy	2,912,043
11	Finland	2,896,519
12	Canada	2,775,180
13	France	2,630,696
14	Russia	2,307,253
15	Spain	2,217,288
(b) *Exporters*		
1	Australia	34,546,550
2	Brazil	18,726,620
3	Chile	14,888,160
4	Peru	7,273,738
5	South Africa	7,268,294
6	India	6,519,472
7	USA	6,487,638
8	Canada	6,053,128
9	Indonesia	4,295,629
10	Sweden	2,628,527
11	Kazakhstan	2,412,308
12	Russia	2,374,813
13	Ukraine	2,153,611
14	Iran	1,579,345
15	Congo	1,555,942

From http://www.trademap.org/

In each list we see three different categories of countries: (1) large industrialized countries that have large domestic mineral resources; (2) countries with few or no mineral resources; and (3) countries with large resources but relatively small populations and/or a poorly developed industrial base. The first type of country, for which we could cite as examples China, USA and Russia, is near the top of the lists of both producers and consumers (Tables 2.7 and 2.8; Figs. 2.2 and 2.3); their own domestic sources are large enough to provide a major proportion of the metals that they consume.

Table 2.8 Global production of selected metals and ores (from British Geological Survey 2012. World mineral production 2008–2012)

	Aluminium	Tonnes × 1000	Bauxite	Tonnes × 1000	Steel	Tonnes × 10^6	Iron Ore	Tonnes × 10^6
1	China	20.3	Australia	70.2	China	716	China	1309
2	Russia	4	Indonesia	41.0	Japan	107	Australia	519
3	Canada	2.7	China	37.1	United States	88	Brazil	400
4	USA	2.1	Brazil	33.6	India	76	India	136
5	Australia	1.9	Guinea	17.6	Russia	70	Russia	104
6	Norway	1.9	India	12.9	South Korea	69	Ukraine	67
7	United Arab Emirates	1.9	Jamaica	10.1	Germany	42	South Africa	55
8	India	1.7	Kazakhstan	5.5	Brazil	34	United States	53
9	Brazil	1.4	Russia	5.3	Turkey	35	Kazakhstan	52
10	Bahrain	0.9	Suriname	3.2	Ukraine	33	Iran	48
	Copper	Tonnes × 1000	Nickel	Tonnes × 1000	Gold	Tonnes	Platinum Group Elements	Tonnes
1	Chile	5433	Philippines	317	China	403	South Africa	254
2	China	1642	Russia	268	Australia	253	Russia	117
3	Peru	1298	Indonesia	253	United States	235	Canada	20
4	United States	1170	Australia	244	Russia	182	USA	16
5	Australia	914	Canada	204	Peru	161	Zimbabwe	15
6	Russia	720	New Caledonia	131	South Africa	154	Botswana	3.4
7	Zambia	629	China	93	Canada	104	China	2.1
8	Congo	608	Brazil	87	Mexico	102	Others	3
9	Canada	578	Cuba	68	Ghana	98		
10	Mexico	500	Colombia	51	Uzbekistan	73		

Exercise 2.1 Development of a Platinum Deposit in Greenland

The retreat of inland ice in many parts of Greenland has allowed mineral exploration companies to search for new deposits in areas that previously were covered by ice. One of the major targets is deposits of the platinum-group elements. As will be discussed in the following chapter, these deposits are found in layered mafic-ultramafic intrusions, particularly, but not uniquely, those in Precambrian areas.

In this exercise, we ask you to:

(a) Use your knowledge of the geological and tectonic make-up of Greenland to suggest likely areas where exploration could be carried out. (Geological maps and other information is readily available on the internet; e.g. http://www.geus.dk/program-areas/raw-materials-greenl-map/greenland/gr-map/kost_1-uk.htm).

(b) Discuss the economic, political and environmental aspects of the development of a large platinum deposit in the region. In this discussion you should take into account the geographical position of possible deposits, climate and other factors that will influence the development of a mine; distance to likely markets and global trade in the metals; present and future uses of the metals; and finally the political issues—is Greenland a potentially stable supplier of mineral products and how does it compare with other sources?

Elements of a response:

(a) Inspection of the legend of the geological map reveals the presence of mafic intrusions of various ages. Notable examples include those intruded at about 2.7 Ga—that of Ni–Cu–PGE deposits in Australia; at 2.1 Ga—that of the Bushveld intrusion; and in the Tertiary—those that form part of the North Atlantic Igneous Province which resembles the setting of the Norilsk deposits in Russia. Descriptions of all these deposits are given in Chap. 3. An exploration geologist would use the map of Greenland to find areas where such deposits have been located or where new deposits might be found.

(b) For possible mining of a deposit, factors to take into account include climate (more extreme in the north and on the east coast); the distance from the coast and means of transporting ore to a site where it could be shipped to future customers; the site of a refinery and possibly a smelter (in Greenland or elsewhere—Outukumpu in Finland is a possibility); measures to be taken to assure that any future mining is conducted in an environmentally correct manner;

(c) Political issues must also be considered. Government agencies will need to issue the authorisation to explore and eventually to mine a deposit, there are royalties to be paid, local workers to be hired and so on.

Potentially more serious are the particular sensibilities of the Greenland government. For many years there was a blanket ban on mining of ores containing radioactive elements. This hampered plans to exploit REE deposits (see Chap. 6) but should not influence the mining of platinum ores, which contain low concentrations of these elements.

In the second category we find countries like Japan and Germany, which contain very few domestic ore deposits but have an abundant and active industrial sector that consumes large amounts of raw materials. These countries are major importers of ores and/or refined metals. Finally, the countries in the last category—those countries with large resources but small populations or underdeveloped industry—are the major exporters of minerals (Table 2.8). Examples include Australia, South Africa, Chile, Brazil and Jamaica. There are, of course, many exceptions to these general observations. The USA, for example, contains very few large deposits of Ni and Cr, and domestic resources of these metals, which are essential for steel production, are totally inadequate for its needs. The USA is therefore a major importer of these metals. However, it produces large amounts of coal, trona (sodium carbonate) and other minerals that it exports widely. The incredible industrial expansion in China has multiplied its need for a wide range of metals and even its large domestic resources cannot meet these requirements. China is therefore a major importer of a wide range of minerals. On the other hand, China contains large deposits of tungsten and produces more than it needs; it is therefore an exporter of this metal. Australia, a country with abundant resources of almost all types of minerals, and a leading exporter of all these minerals, lacks major deposits of Cr and is an importer of this metal.

Box 2.2 The Mining and Refining of Nickel Ores

Mining

Nickel is found in two different types of ore, magmatic sulfide and laterite. The former are usually mined by underground techniques or in large and deep open pits for some new deposits; the latter are mined in shallow pits using heavy earth-moving equipment such as shovels, draglines, and front-end loaders.

Treating Sulfide Ores

Beneficiation—Benficiation is the next step. It converts the ore into a form that can be smelted to separate the metal. The goal of the process is to make a smaller volume that will require less heat and chemicals to separate the metal.

Sulfide ore is first ground in large mills to powder that is fine enough that the particle size is less than that of individual grains of the ore minerals. The nickel-bearing minerals are then separated from the gangue by the flotation process. The ground ore is mixed in large vats with water and chemicals such as fatty acids and oils that increase the hydrophobicity of the nickel-bearing minerals. Mechanical and pneumatic devices stir the mixture and produce air bubbles, which are injected at the base of the vats. Nickel-bearing minerals adhere to the bubbles and float to the surface where they are recovered by scraping away the froth. The magnetic properties of Fe-Ni sulfides are used to aid their extraction. The waste from this process contains all of the other minerals and is known as tailings.

Smelting and Refining—The nickel concentrates from the sulfide ores are then dried, mixed with flux, and heated to about 1350 °C in an oxidizing environment in smelters. The reaction of oxygen with iron and sulfur in sulfide ore supplies some of the heat required for smelting. The product is an artificial nickel-iron sulfide known as matte, which contains 25 to 45 % nickel. The iron is then converted to an oxide, which combines with silica flux to form a slag. When the slag is drawn off, the matte contains 70 to 75 % nickel.

The nickel matte is either leached at high pressure with ammonia and the metal is recovered from solution, or the matte is roasted to produce high-grade nickel oxide. The final stage is electrorefining: the nickel oxide is dissolved in sulfate or chloride solutions in electrolytic cells and pure nickel metal is deposited on the cathode. Sulfur is released in large quantities at several stages of the process. Some is recovered to be used in industry as a fertilizer, but a large fraction is lost in smelter fumes and constitutes a serious pollutant (Fig. 2.4).

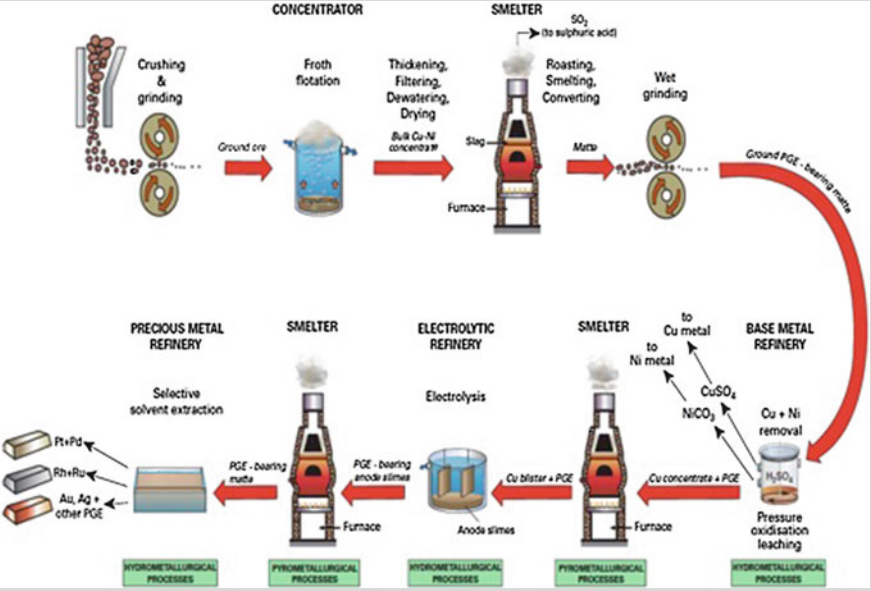


Fig. 2.4 Flowsheet for processing of Ni–Cu–PGE sulfide ores (from British Geological Survey, Platinum commodity profile, 2009; www.MineralsUK.com)

Treating Laterite Ores

Laterite nickel ores do not contain sulfur and do not cause SO_2 pollution, but separating nickel from the ore requires much higher energy input. The ore minerals are oxide or silicates that are not amenable to flotation and other conventional processes. Thus, large tonnages of untreated ore must be smelted. In addition, the reactions of oxide ores during smelting are not exothermic, which increases the amount of energy required by the smelter. The first step is removal of water from hydrous ore and gangue minerals, which is usually done by roasting in large high-temperature kilns. The nickel oxide is then smelted in furnaces that run at 1360 to 1610 °C, the high temperatures being required to accommodate the high magnesium content. Most laterite smelters produce a ferronickel alloy that is sold directly to steel manufacturers.

More recently, lateritic ores are processed using hydrometallurgy. In this method, nickel ± cobalt, is extracted from silicate or oxide ores via leaching at high pressure in concentrated acid or alternatively in ammonia. Following extraction the metals are purified by smelting and electrolytic processes.

Further complications arise when one distinguishes production of refined metals from unrefined ores. In some cases, ore is exported in its unprocessed form, more or less as it is mined; this is called “direct-shipping ore”. This is the case for some iron ores that are shipped directly from mines in Australia or Brazil to steel-making plants in Japan or China. At the other extreme we have gold or diamond, which almost always are separated from the gangue and refined at the sites where they are mined, leaving only the pure metal or uncut gemstone to be transported to market. In most other cases, ores or refined products with variable degrees of purity are exported. Consider, for example, the several major steps in the processing of Ni-Cu ore: during mining, the first step, an effort is made to extract only the material rich in the ore mineral (mainly pentlandite $(Fe, Ni)_9S_8$ and chalcopyrite ($CuFeS_2$); in the second step, the pentlandite and chalcopyrite are separated from the gangue minerals in a beneficiation plant that makes a sulphide concentrate; in the third, Ni and Cu are extracted from the sulphide concentrate in a smelter; and in the fourth the precious platinum-group elements are separated from the Ni and Cu metal. At each step the value of the product increases. Viewed in this way, it would seem obvious that mineral-producing countries should build beneficiation plants and smelters so that they can export the more valuable end products rather than the raw ore; but, as is illustrated in the following exercise, the situation is not that straightforward.

Box 2.3 Debate About the Politics of Exportation—Raw Materials or Finished Products?

A major dilemma confronts all producers of mineral products. Should they export unrefined ore or the refined, pure metal or mineral? The value of the refined product is many times that of the raw ore, and by exporting the refined product, the company or the country will earn far more. In addition, the construction and operation of beneficiation plants and smelters generates employment, industrial infrastructure and domestic expertise that are of great benefit to the exporting country. Indonesia, in 2014, began to restrict exportation of raw ores in an attempt to encourage mining companies to set up processing facilities, thereby promoting industrial development in the country and increasing revenues to the country.

The counter arguments come from the cost of constructing and operating the processing facilities. In order for these plants to function economically, the operation must be of a certain size; if the ore deposit is small, construction of even a beneficiation plant, not to mention a smelter, might not be viable. In addition, a large investment is needed to develop the infrastructure to supply electric power and roads to move products. Many countries do not have required funds, which have to be borrowed and interest has to be paid.

Consider the following example. A deposit of nickel containing 10 mt of ore with 2 % Ni is found in Zimberia, a small country in central Africa. The deposit contains 200 000 tonnes of Ni of which about 70 % can be extracted, given a total of 140,000 t. If sold as refined metal, the nickel is worth a total of about 2 billion euros at current nickel prices of about 15,000 euro per tonne. In the future the nickel price might increase or it might decrease. The raw ore is sold for about 70 euros per tonne, giving a total value of the unrefined ore of only 140 million euros, about 7 % of the value of the refined metal. The expected lifetime of the deposit (i.e. the time before it is completely mined out) is 20 years. Additional deposits may, however, be found in the region in the future, to increase the life of the operation.

The total cost of building the refinery and smelter needed to purify the metal is about 3 billion euros. Zimberia does not have the funds and would have to borrow on the international market. The total cost of borrowing this money for a period of 20 years is about the same as the capital amount or about 3 billion euros.

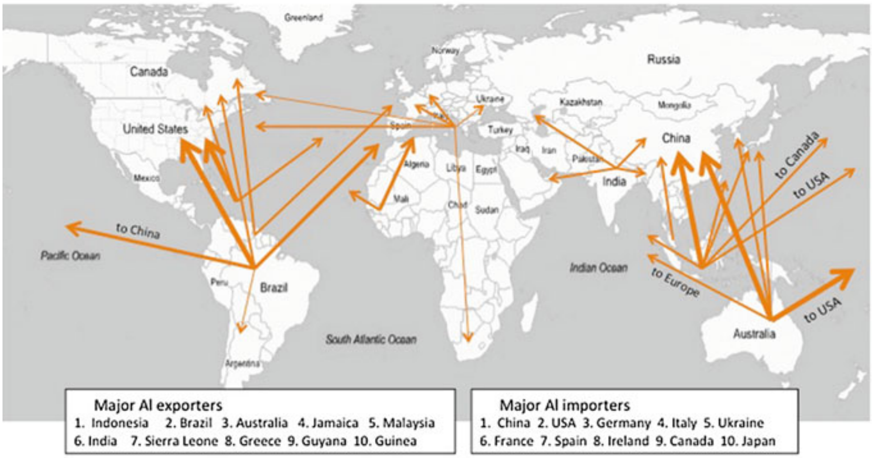
Discuss whether it is worthwhile for Zimberia to construct a Ni refinery so that the country can export refined metal and not the raw ore. Be sure to consider external factors such as competitive mines that are open or might open and the outlook for future nickel demand.

In the exercise outlined in Box 2.3, we see that the viability of a Ni smelter depends on a variety of factors, not least future metal prices, which are very difficult to predict. Also important in world trade are elements such as the cost of the energy needed to refine the ore. In Chap. 5 we discuss a curious situation. Because of the large amounts of energy needed to refine aluminium, it is worthwhile to ship bauxite from countries like Jamaica or Guinea, where it is mined, across the Atlantic Ocean to Iceland, where it is refined. This exercise, which no doubt causes nightmares for ecologists worried about shipping tomatoes from Morocco to Germany, is made possible because of the availability of abundant, cheap, greenhouse-gas-free sources of hydro and geothermal energy in that small island in the middle of the North Atlantic ocean.

Discussed in Chap. 6 are the problems associated with the production of ore in some third-world countries. A case in point is the large and rich copper deposits of central Africa, which should have provided wealth for the extremely poor countries of the region but never have because of exploitation by colonising countries at first, and the corruption and inefficiency of the governments of newly independent countries thereafter.

2.5 Global Trade of Mineral Resources

Patterns of world trade in metals and mineral products are summarized in Fig. 2.5. The arrows, which show the direction of trade, link metal-producing countries like Chile or Australia to large industrialized countries or regions like the USA, Japan, China and Europe. The geographic position of producer and consumer influences the direction of trade: most Chilean copper is shipped across the Pacific to USA, Japan and China and not around Cape Horn to Europe (large ore carriers cannot pass through the Panama Canal). But other factors enter into the equation. Australia has a distinct geographical advantage when selling iron ore to China and Japan, and would be capable of supplying almost all the needs of these countries, but these countries also import ore from Brazil. Brazilian ore must be shipped around Cape Horn, but the consuming countries are willing to pay the extra transport costs in order to give them some leverage when negotiating the price they pay for ore from both sources. If Australian producers had a monopoly on the market, they could charge higher prices.


(a) Trade in Bauxite and Alumina

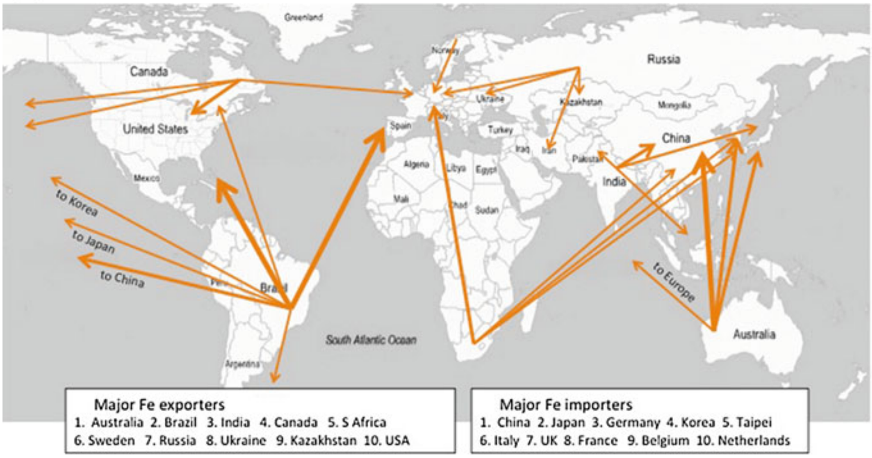
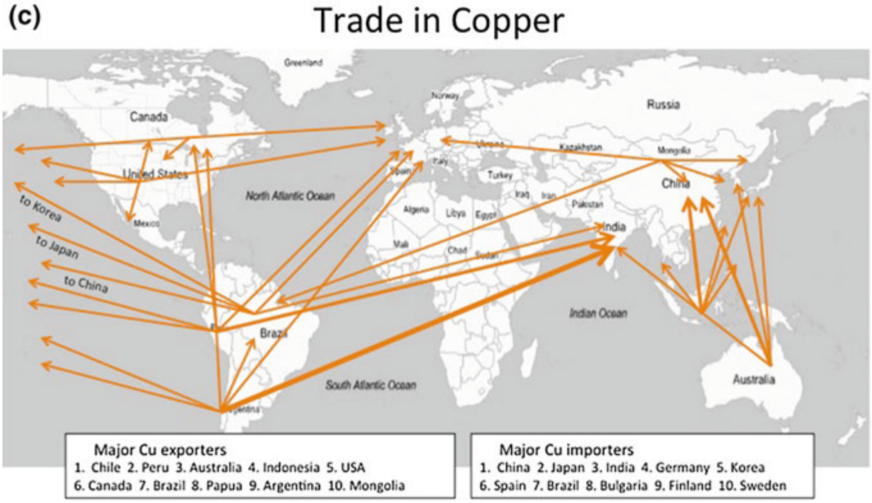

(b) Trade in Iron Ore

Fig. 2.5 Global trade in minerals (compiled from http://minerals.usgs.gov/minerals/pubs/commodity/myb/)

Box 2.4 Iron Ore Shipment from Brazil to China

To allow efficient shipment of bulk ore, and to enable Brazil to compete with Australia as a supplier of iron ore, a new class of ship has been developed. These are called "Valemax" ships after Vale, the Brazilian iron ore company. They are the largest bulk carriers ever built, each capable of transporting up to 400,000 tons of ore efficiently from Brazil to China around the Cape of Good Hope, a distance of almost 20,000 km (Fig. 2.6).



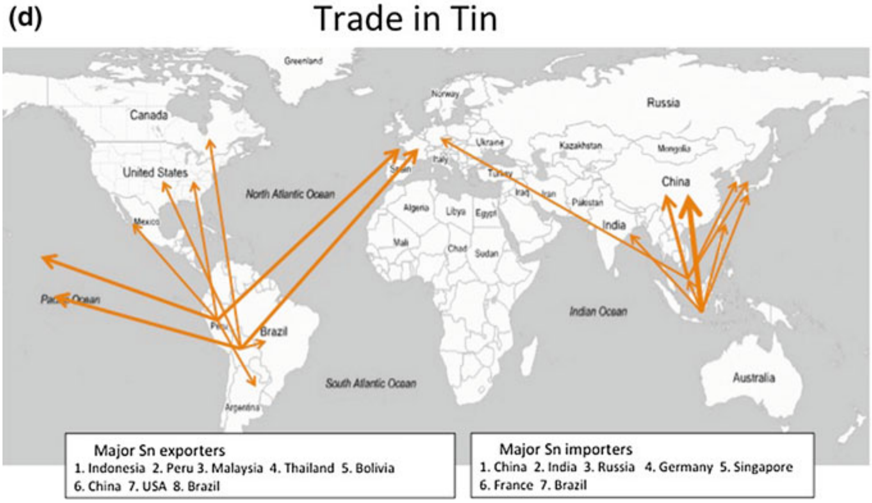


Fig. 2.5 (continued)

Also seen in these maps are the precarious sources of some commodities. Sources of the platinum group metals that are essential in modern industry for the fabrication of catalytic converters in cars, and in the future for the construction of fuel cells, are located in only a few countries. A small amount is produced in Canada and Australia, which will probably remain stable and reliable suppliers for the foreseeable future. Another supplier is Russia, a country whose reputation has been compromised in the past decade by its manipulation of gas supplies to Europe. The third, and by far the major supplier, is South Africa, thanks to the enormous

Fig. 2.6 A Valemax bulk ore carrier

resources in the Bushveld Complex (Chap. 3). If South Africa continues its tradition of democratically elected and relatively stable governments, and if it continues its market-oriented policies, the country might remain a reliable supplier of the platinum-group metals. But if government policies change, or if social peace is compromised, there might be a global crisis in supplies of these metals. The increase in the global price of platinum caused by the 2012 strikes at the Marikana platinum mine is a case in point. What would be the consequences a global crisis? In the short term, the metal price would skyrocket and the cost of producing cars and other products that use the metals would increase; in some cases production might stop if replacement supplies could not be found. In the longer term, however, the higher metal price would encourage companies to open mines in hitherto marginal deposits. These issues are revisited in Chap. 6.

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Trade Map—Trade statistics for international mineral trade. http://www.trademap.org/Country_SelProduct_Map.aspx

Chapter 3
Magmatic Ore Deposits

3.1 Introduction

A magmatic ore deposit is an accumulation of magmatic minerals. Some of these minerals are extremely rare and almost never encountered in common rocks, an example being alloys of the platinum metals; other minerals, such as magnetite, are common and can be seen in most thin sections. They form an ore deposit when they are present in large amounts and at unusually high concentrations. The question is how these concentrations come about.

3.2 Chromite Deposits of the Bushveld Complex

To illustrate the ore-forming process, we will take as our first example the deposits of chromite, the Cr-Fe oxide that is the ore of the metal chromium, in the Bushveld Complex of South Africa. A brief description of the complex, emphasizing its economic importance, is given in Box 3.1. Bushveld contains the type examples of ore deposits in a large layered intrusion, but this is not the sole type of chromite deposit; others are found in ophiolites, particularly in the Urals, Turkey, Greece and India. In addition to their great economic value, the deposits of the Bushveld were chosen because they illustrate several fundamental processes governing ore formation in a magmatic setting.

Figure 3.1, a photo of chromite seams or veins from the Dwars River location in the eastern side of the complex, clearly shows some important features of a chromite deposit. The mineral occurs in layers reaching a metre or more in thickness that alternate with layers composed of other magmatic minerals. The rock is a cumulate, having formed by the transport of magmatic minerals on the floor of the Bushveld magma chamber. The Bushveld Complex itself (Fig. 3.2) is a vast, roughly funnel-shaped differentiated intrusion composed mainly of cumulates of

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Fig. 3.1 Chromite seams at Dwars River, Bushveld Complex (photo with permission from Cawthorn)

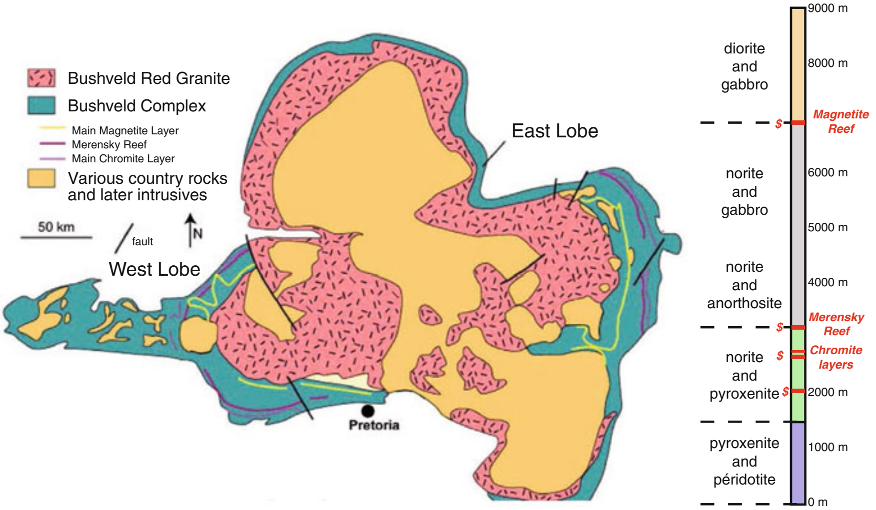


Fig. 3.2 The best examples of magmatic ore deposits: chromite and platinum group elements in the Bushveld Complex, South Africa

mafic minerals and plagioclase. In the ultramafic Lower Zone, the cumulus minerals are olivine and orthopyroxene, joined by cumulus plagioclase in the Main Zone. The Upper Zone consists of diorite or gabbro. Intervening between Lower and Main Zone is the Critical Zone, which contains the chromite and PGE deposits. More detailed descriptions of the complex and its ores are found in Cawthorn (1996) and Cawthorn et al. (2005).

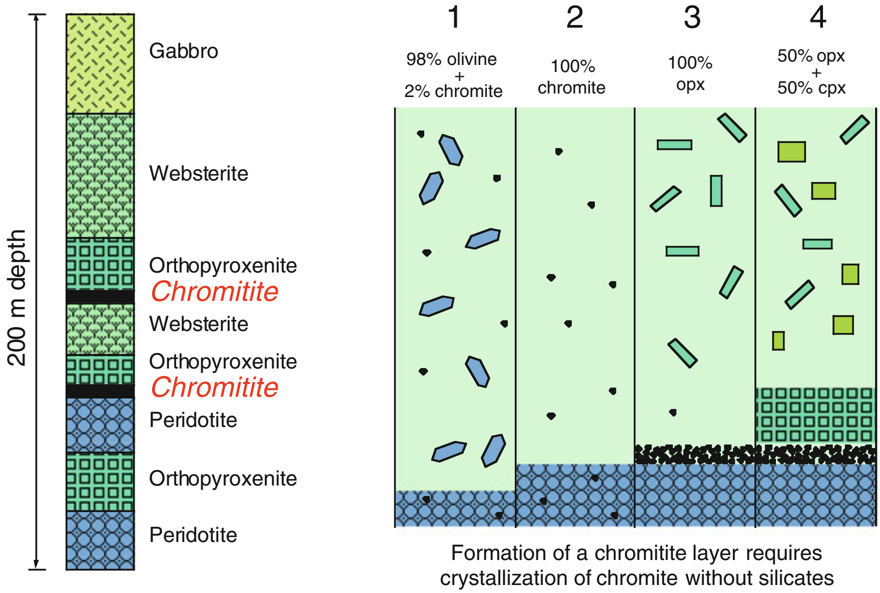
Chromite, the ore mineral, is present throughout the lower ultramafic part of the intrusion, but normally its concentration is limited to less than 1–2 %. At these levels the rock is not ore. Only at specific levels in the Complex, in olivine ± orthopyroxene cumulates in the upper part of the Critical Zone (Fig. 3.2) is chromite present in sufficient quantities and at sufficient concentrations to constitute an ore deposit. The chromite cumulate layers consist of close to 100 % of the ore mineral, and typical ore grades are around 25–35 % Cr. The concentration of the same element in the continental crust is only a few 10's of ppm, but this figure is not relevant because chrome deposits are found in ultramafic rocks in which the concentration is much higher. But even taking a typical level for ultramafic intrusions of 1000 ppm means that the enrichment factor; i.e. the ratio of the ore grade over the background level, is 250–350. In other words, to form the ore deposit, the concentration of Cr had to be increased by several hundred percent. What geological process could have produced this degree of enrichment?

Box 3.1 Deposits of the Bushveld Complex

The Bushveld complex in South Africa (Fig. 3.2) is the world's largest mafic-ultramafic intrusion. As shown in the figure, it has a complex form in plan view consisting of a collection of intrusions that are roughly circular in plan in plan view; in section it probably comprises a series of funnel-shaped (lopolithic) magmatic bodies. The dip is persistently towards the interior and thus the base of the intrusion is exposed along the margin. The stratigraphic section shows that the rock-types change from ultramafic at the base to intermediate at the top. The lowermost rocks are olivine and pyroxene cumulates; these pass upwards through pyroxene plagioclase cumulate to the diorites that occupy the upper third of the complex.

Three types of ore deposit are found in the complex. (1) Chromite deposits, such as the layers illustrated in the photo, are located in the ultramafic cumulates. These deposits are mined for chrome and in some cases for platinum group elements as well. (2) Platinum group elements are also mined in the famous Merensky Reef, which is located at the top of the Critical Zone, where the rocks change from ultramafic to mafic in composition. (3) Finally, magnetite veins, which are mined for the vanadium, are hosted in the mafic rocks in the upper part of the complex.

These deposits supply a very large proportion of the global demand for these metals. The chrome production is about 50 % of the global total and platinum and palladium production from the complex represents 72 and 34 %, respectively, of annual global production.

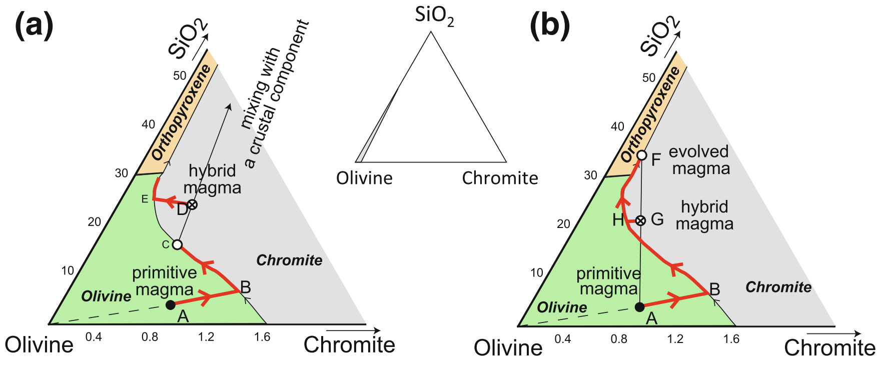


from Irvine (1978)

Fig. 3.3 Formation of chromite veins in the Muskox Intrusion, Canada

Neil Irvine, in papers published in the 1970s (Irvine 1975, 1977), developed an interesting and important model for the origin of chromite deposits in the Bushveld Complex and in other layered intrusions (Fig. 3.2). His phase diagram, modified as Fig. 3.3, shows that under normal conditions 1–2 % chromite crystallizes together with olivine. Mafic-ultramafic liquids, such as the parental magma of the Bushveld Complex, plot in the field of olivine. Such a liquid initially crystallizes olivine, whose removal drives the residual liquid composition to the cotectic, at which point chromite starts to crystallize. Chromite and olivine crystallize together, in the proportion given by the intersection of a tangent to the cotectic and the olivine-chromite edge of the diagram. The proportion of chromite ranges from 1.8 to 1.4 %, the amount observed in normal olivine cumulates of the complex. To produce a layer of almost pure chromite requires suppression of the accumulation of olivine and other silicate minerals (Fig. 3.2). Irvine suggested two ways this might happen, both illustrated in the phase diagrams of Fig. 3.4.

In this simple diagram, a strongly curved cotectic separates the primary phase fields of olivine and chromite. For chromite to crystallize alone, the composition of the liquid must be driven off the cotectic and into the chromite field. Irvine (1975) proposed that one way that this might happen is when the magma becomes contaminated with granitoid country rock (which plots at the SiO_2 apex in this diagram), such as that which makes up most of the Archean continental crust into



Contamination from wall-rock

Mixing of the evolved magma with a primitive magma

Fig. 3.4 Irvine's mechanisms explaining how chromite can crystallize alone. **a** Contamination model. **b** Magma mixing model

which the Bushveld magma intruded. A hybrid, contaminated magma plots on a line between the magma composition and the apex, at the point labelled D, and in the chromite field. This magma crystallizes chromite until its composition regains the cotectic. The interval in which chromite crystallizes alone seems small, but in a large intrusion like the Bushveld, the chromite that crystallizes during the interval is enough to form a layer of appreciable thickness.

The second process depends on the strongly curved shape of the cotectic. Irvine (1977) argued that because of this shape, when an evolved liquid residing in the chamber mixes with a more primitive liquid that enters the chamber, the hybrid liquids plot within the chromite field. Like the contaminated liquid, the hybrid liquid as well crystallizes chromite alone. Most probably both processes—contamination and magma mixing—operate together to produce the chromite deposits of the Bushveld Complex. Obviously the process is not that simple; in particular, it is very difficult to understand how the chromite crystals accumulated and how they were extracted from the enormous volume of magma needed to yield metre-thick layers of chromite. Cawthorn et al. (2005) give a clear account of these difficulties.

Nonetheless, the formation of chromite deposits illustrates an important principle: the ore mineral, in this case chromite, is a normal constituent of many ultramafic intrusions and it forms through normal magmatic processes. Under ordinary circumstances it is present in low concentrations and normal rocks are not ores. For a deposit to form, the normal process must be perturbed so that the ore mineral accumulates in far higher concentrations. In the case of the chromite deposits, contamination or magma mixing are among the perturbing processes; and, as we will see in subsequent chapters, a large range of special circumstances will modify other geological processes such as sedimentation or the circulation of hydrothermal fluids so as to create the unusual concentrations of minerals that constitute an ore.

3.3 Magnetite and Platinum Group Element Deposits of the Bushveld Complex

The Bushveld Complex contains two other important types of deposit. Layers of magnetite, mined for their vanadium contents, occur in the upper part of the intrusion. These magmatic deposits probably formed in a manner similar to the chromite deposits. The other type, economically far more important, are deposits of the platinum group elements (PGE). The Bushveld Complex contains about 60 % of global reserves of these increasing valuable metals, which have been mined for close to a century in two specific horizons in the lower part of the intrusion. The upper layer is the famous Merensky Reef, a thin (1–10 m) layer of pegmatoid pyroxenite located at the top of the Critical Zone (Fig. 3.2). Seemingly low, but economically viable, concentrations of PGE (5–500 ppm) are associated with minor sulfides mainly towards the base of the Reef. Because of the high cost of the platinum group elements, even these low concentrations of metals can be exploited at a profit. The second major mineralized layer is called UG2, a series of thick chromite reefs that, in addition to high PGE content, are also exploited for their Cr contents. In the past decade, the centre of mining has shifted to the Platreef in the northern limb of the complex.

Various hypotheses have been advanced to explain the deposits. The main problem is to explain how the PGE, which are present in low concentration in mafic magmas, were extracted and concentrated in the ore horizons. Campbell et al. (1983) proposed that a plume of primitive magmatic liquid was injected in from the base of the chamber and then mixed with evolved liquid to produce a hybrid magma that became saturated in sulfide. Small droplets of magmatic sulfide segregated from the silicate liquid and these attracted the chalcophile (S-loving) PGE. The droplets of PGE-enriched sulfide then settled to the floor of the intrusion to slowly build up the ore-bearing horizon.

Platinum-group elements are recovered from other large layered mafic-ultramafic intrusions like the Stillwater in the USA and the Great Dyke in Zimbabwe, and these constitute the major source of these metals. The same metals are also recovered, though in differing proportions, as a valuable by-product of mining magmatic sulfide deposits, our third example of a magmatic ore deposit, and in placer deposits, which are discussed briefly in Chap. 5.

3.4 Magmatic Sulfide Deposits

As a mafic liquid cools, it crystallizes. A series of solid phases appear, typically olivine, pyroxene, feldspar and oxides, which become the common constituents of mafic and ultramafic magmatic rocks. But under some circumstances, a second liquid separates: in rare cases an immiscible silicate liquid, which is immiscible with the first silicate liquid, or, if the sulfur content of the liquid is high, an immiscible sulfide liquid. In the remarkable example shown in Fig. 3.5, droplets of

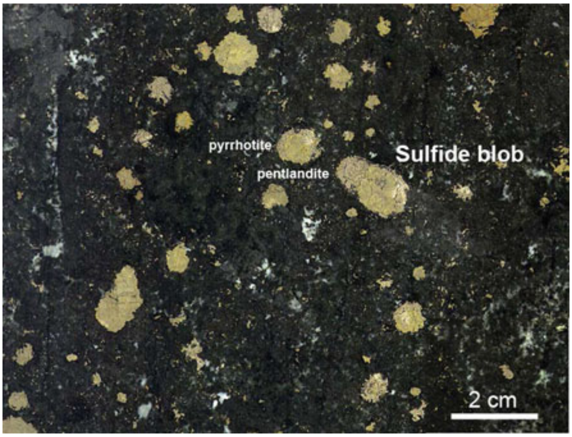


Fig. 3.5 Blobs of magmatic sulfide from the Norilsk-Talnakh Ni-Cu sulfide deposit (photo from N. Arndt)

sulfide liquid have been frozen in place, suspended in the surrounding mafic magma which has solidified to gabbro. The droplets of sulfide liquid contain elevated concentrations of elements such as Ni, Cu and the PGE, which are "chalcophile" or sulfide-loving. Because the sulfide liquid is denser than the silicate liquid, it tends to settle to the base of the magma body. If enough of it segregates, and if the concentrations of metals are high enough, it becomes an ore deposit.

This process seems straightforward, yet once again we are faced with a problem: mafic-ultramafic intrusions are known throughout the world, and from petrological and geochemical data we can infer that their parental magmas contained high concentrations of Ni, Cu and the PGE. Inspection of polished thin sections shows that these rocks do indeed contain sulfides that separated as an immiscible liquid, but in most cases this phase appears only at a very late stage in the crystallization sequence and only in very low quantities. What was the particularity of certain magmas that led them to segregate copious amounts of metal-rich sulfide? Or to put it another way, how was the normal magmatic differentiation sequence perturbed so as to form an ore deposit?

To answer these questions we will first discuss the processes that govern whether or not a sulfide liquid separates from a mafic or ultramafic magma, and, equally important, produces high concentrations of ore metals in this liquid. Then we consider how the sulfide segregates to form an ore body, taking as our example the deposits of the Kambalda region in Western Australia.

3.4.1 Controls on the Formation of Magmatic Sulfide Liquid

Mafic and ultramafic magmas form by partial melting a great depth, from about 30–300 km, in the mantle. Most of the magmas that yield magmatic ore deposit result from melting in mantle plumes, which are rising cylinders or more irregular

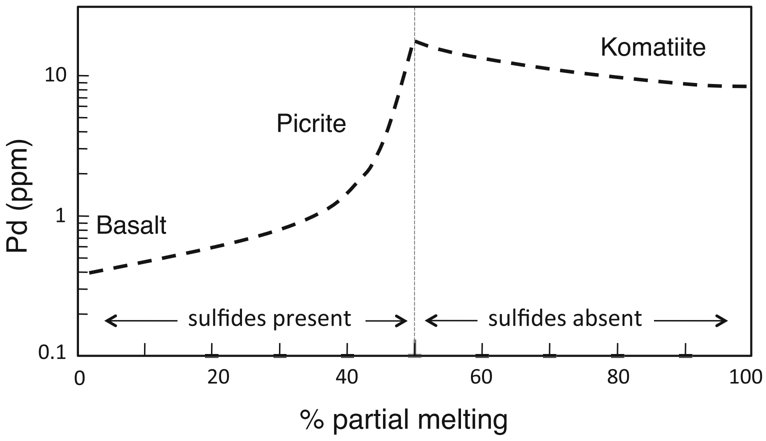


Fig. 3.6 Controls on the chalcophile element contents of mantle-derived melts

masses of solid mantle that are hotter than the surrounding ambient mantle. Only part of the mantle peridotite melts, between 5–20 % for basalts, 20–30 % for picrites and up to 60 % for komatiites, and the composition of the magma depends strongly on the types of minerals that remain in the residue. The overall character of the melt is controlled by the silicate phases of the residue while the contents of ore metals like Ni, Cu and the PGE depend on the sulfide. Sulfur in normal mantle is present as sulfide, which enters to liquid preferentially and is normally exhausted when the degree of melting exceeds 20–30 %. As shown in Fig. 3.6, sulfide is retained in the residue during the formation of low-degree melt like basalt but is exhausted in high-degree melt like komatiite. Nickel, Cu and the PGE are all strongly chalcophile, which means that when sulfide is retained in the residue, it holds back these elements: the resultant magmas contain only low concentrations. High-degree melts, on the other hand acquire their full component of these metals, and partly for this reason are the most prone to form ore deposits.

In order for a sulfide liquid to separate from the silicate liquid, the concentration of sulfur must exceed the sulfide solubility. The situation can be compared with crystallization of salt from brine. Only if concentration of salt is high enough will the brine become saturated and salt crystallize. But saturation can also be reached if the brine evaporates, which decreases the amount of water and increases the salt concentration in the remaining brine; or by decreasing the solubility of salt by reducing the temperature; or simply by adding salt to the solution. The same principles apply to the separation of a sulfide liquid from a silicate liquid. Experimental studies have shown that the solubility of sulfide depends on external parameters such as temperature and pressure, and on the composition of the melt. Table 3.1 summarizes the situation.

During fractional crystallization the temperature drops, the Fe content usually varies little and the Si content increases. The process will therefore lead eventually to sulfide saturation and the separation of sulfide liquid. The process can be

Table 3.1 Controls on the solubility of sulfide in silicate melts

Factors that increase sulfide solubility
–Increasing temperature
–Increasing Fe content
Factors that decrease sulfide solubility
–Increasing pressure
–Increasing Si content

accelerated in the magma is contaminated with granitoid country rock, which increases Si and decreases Fe; or it can be triggered by the assimilation of sulfide- or sulphate-bearing sediments, which directly increases the S content of the melt.

Mavrogenes and O'Neill (1999) showed that sulfide solubility varies inversely with pressure. This means that magma that formed deep in the mantle, at high pressure, is capable of dissolving less sulfide than the same magma at crustal depths and lower pressure. The consequence is that most magmas from deep in the mantle are moderately to highly undersaturated in sulfide when they intrude into the crust. To segregate sulfide liquid, either they must undergo advanced fractional crystallization (in which case the sulfide will be trapped between abundant crystal and cannot accumulate to form an ore deposit) or the system must be perturbed so that the sulfide segregates sooner.

3.4.2 Controls on the Segregation and the Tenor of Magmatic Sulfide Liquid

The value of an ore deposit can vary considerably, depending on the concentrations of ore metals in the sulfide. Some large accumulations of sulfide contain very low concentrations of Ni, Cu and PGE (they consist essentially of pyrrhotite, $FeS_{(1\text{-}x)}$ and pyrite, FeS_2) and they do not constitute an ore deposit. Other deposits contain a high proportion of Ni-rich sulfides like pentlandite $(Ni, Fe)_9S_8$ or better still millerite or nicolite and they form an ore body even if the amount of sulfide is low.

The ore metals Ni, Cu and the PGE are all chalcophile and have a tendency to partition more or less strongly into the sulfide. Nickel is lithophile as well as chalcophile and in normal ultramafic rocks it is distributed between olivine and sulfide. Copper is highly chalcophile ($KD^{\text{sulf}-\text{silicate liquid}} \approx 1000$), but the PGE are enormously chalcophile, having KD on the order of close to one million. This means that any sulfide present in a silicate liquid will extract most of the Cu and Ni and effectively all of the PGE from the surrounding silicate liquid. If the sulfide can strip these elements from the silicate liquid, then be concentrated efficiently, usually by gravitative settling, then an ore deposit can form.

In practice, other processes intervene. The metal contents of the magma influence the composition of the ore—magma with little to no Ni cannot produce a nickel deposit. Ultramafic magma has high Ni but low Cu contents and sulfide ores in ultramafic rocks have high Ni/Cu. More important, however, is the relative proportion of sulfide to silicate liquid which influences the amount of the chalcophile elements that can be concentrated in the sulfide. The situation is best illustrated by the extremely chalcophile PGE, which, at equilibrium, will be almost entirely contained in the sulfide phase. However, in a static system, the PGE will migrate into the sulfide by diffusion, which is inefficient. In the absence of mechanical mixing of the two phases, each sulfide droplet will be surrounded by a zone of silicate liquid that is effectively stripped of PGE. Only if the sulfide is mixed with a large volume of silicate liquid can it realize the high PGE content promised by the high partition coefficients. To describe this process, Campbell and Naldrett (1979) introduced the R-factor, which is essentially the relative proportion of silicate liquid that interacted with sulfide liquid. If the R-factor is low; i.e. the a small volume of silicate liquid mixed with a large volume of sulfide, the content of PGE and other chalcophile elements of the sulfide is low. This is the case for ore deposits in small intrusions or lava flows, like the Kambalda example discussed below. If, however, a small volume of sulfide can mix with a large volume of silicate liquid, the chalcophile element content is high. This is the case for the sulfide of the Merensky Reef, as discussed in the previous section (Campbell et al. 1983).

3.4.3 Kambalda Nickel Sulfide Deposits

We chose not to consider the very largest and richest Ni-Cu sulfide deposits, which are found in intrusive rocks of various types and origin, but will start by investigating the characteristics of the Kambalda deposits, one of very few magmatic deposits that occur a volcanic setting. The deposit was discovered in 1967 and since then the deposits have almost been mined out, but similar deposits have since been found in other regions (e.g. the Mt Keith and Perseverance deposits in Australia and Raglan in Canada). Kambalda is located in hot, dry savannah of the Western Australian outback, in the Archean (2.7 Ga) Yilgarn Craton. The geological make-up of this region, summarized from Marston et al. (1981), Lesher (1989) and Lesher and Keays (2002), is shown in Fig. 3.7: a series of ultramafic lava flows (komatiites), is underlain by tholeiitic basalts and overlain by magnesian basalts. The complete sequence is exposed in a small structural dome. Figure 3.8 is a schematic cross section through the lava pile. The ore deposits are mainly restricted to the lowermost komatiite flow and they are localized at the base of this flow, within a trough in the underlying basaltic sequence. Away from the ore deposit, thin bands of sulfide-rich cherty sediment intervene between basalt and komatiite but in the troughs that contain the ore, these sediments are missing.

The ores themselves have features that need to be catalogued because they provide important clues as to the ore-forming process. Strictly speaking, the ore minerals should be described as Fe-Ni-Cu-PGE sulfides because they contain all these metals. The main ore minerals are pentlandite $(Fe, Ni)_9S_8$ and chalcopyrite $CuFeS_4$ which coexist with the barren Fe sulfide pyrrhotite $(Fe_{(1-x)}S)$. In many ore

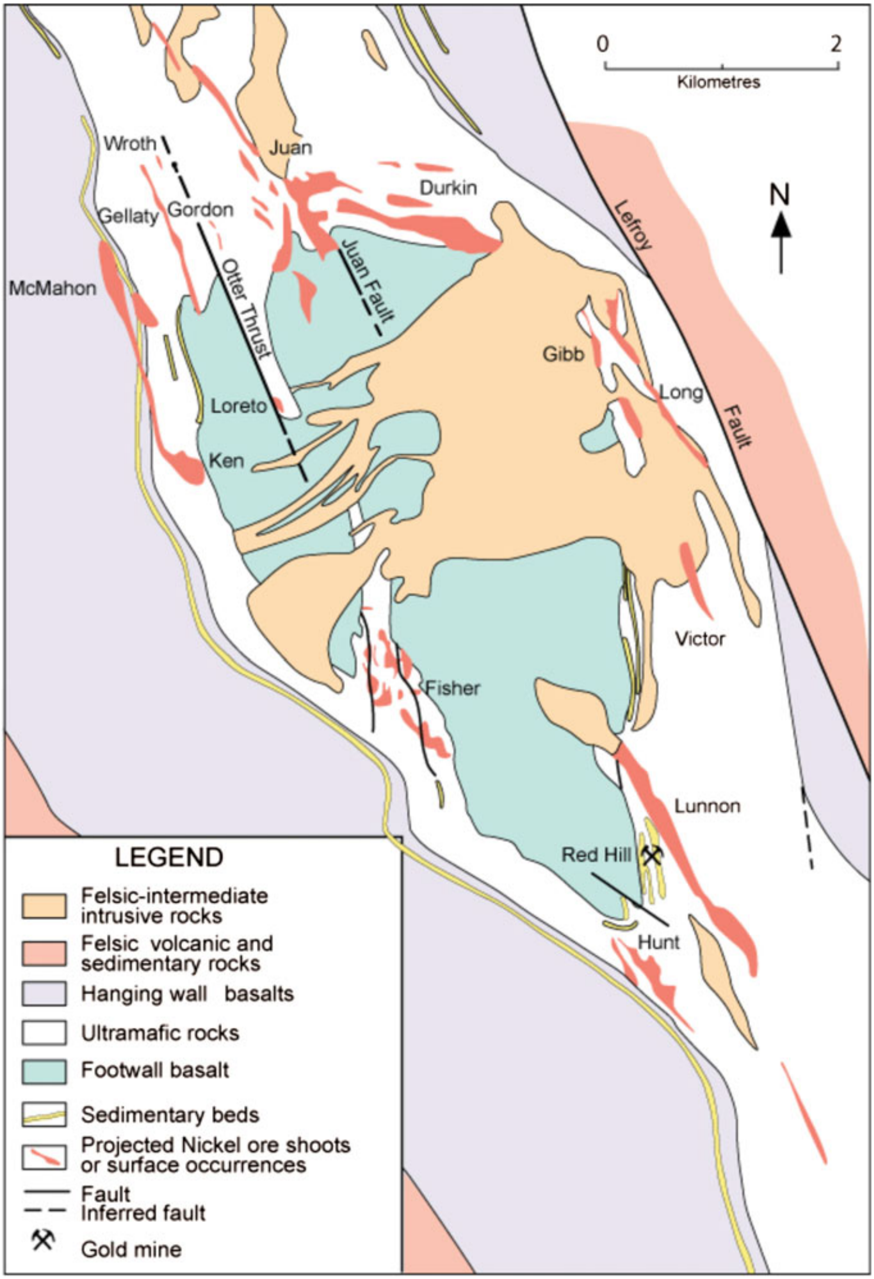


Fig. 3.7 Geological map of the Kambalda region, Australia (permission from Barnes)

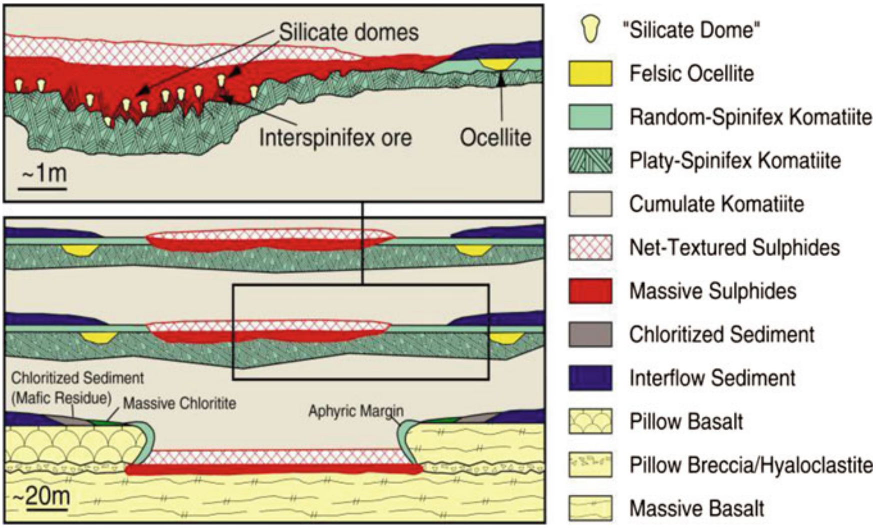


Fig. 3.8 Schematic cross-section through a typical Kambalda ore shoot, showing distributions of volcanic and sedimentary rocks and the ores themselves (after Groves et al. 1986)

sections, a layer of massive 100 % sulfide lines the base of the komatiite flow and is overlain by "net-textured" ore, in which serpentinized olivine grains are enclosed in a sulfide matrix, and in turn by (serpentinized) olivine cumulate containing disseminated sulfides. Veins and lenses of Cu-rich sulfides penetrate into the floor rock and in places up into the upper part of the komatiite flow. The composition of the disseminated sulfide corresponds to the immiscible liquid that separates from the silicate liquid. The massive sulfide liquid fractionally crystallizes, just like a silicate liquid. The first phase to appear is "monosulfide solid solution", a sulfide with relatively rich in Ni and Fe. This material remains as a "cumulate" layer at the base of the flow while the late-solidifying Cu- and PGE-rich sulfide liquid may leak out to form veins in surrounding rocks.

Komatiite lava flows occur throughout the 700 km long Yilgarn Craton, but ore deposits are known in only some of them. And komatiites are common in the much larger Abitibi belt in Canada, but there the ore deposits are small and rare. With this background we are in the position to ask a number of questions:

- Why do the sulfide deposits occur preferentially in the lower part of the lowermost komatiite flow?
- Why are sedimentary rocks present between the komatiite flows, except in the troughs that contain the ore deposits?
- Why do Ni deposits form in komatiites and not in basaltic lava flows?
- Why are Ni sulfide deposits more common in the Yilgarn than in the Abitibi belt?
- What distinguishes the ore-bearing Kambalda komatiites from barren komatiites?

Table 3.2 Physical properties of basalts and komatiites

	Komatiite	Basalt
MgO (wt%)	30	8
Temperature (°C)	1600	1200
Viscosity (poises)	5	100
Reynold's number	500	10^4–10^5

Table 3.2 compares the chemical and physical properties of komatiitic and basaltic magmas. The ultramafic magma has much higher MgO and lower SiO_2 than the basaltic magma, which means that it erupts at much higher temperature (up to 1600 °C) and has a much lower viscosity than the basalt. The Reynolds Number, a fluid-dynamic parameter that describes whether the flowage within a liquid is linear or turbulent, is around 10^5 for a 10 m thick komatiite flow, well above the threshold of 500 that separates the two flow regimes. Komatiite lava therefore flows turbulently and as a consequence the heat from this ultra high-temperature lava is transferred directly to the floor rocks (Fig. 3.9). The

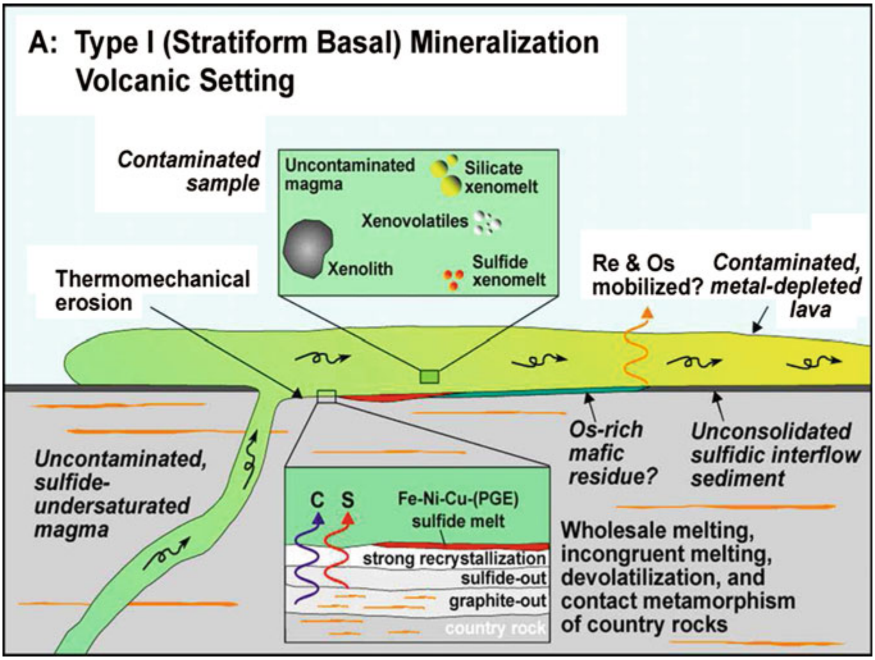


Fig. 3.9 The ore-forming process at Kambalda illustrating how the komatiite erodes its wall rocks a process that transfers sulfide from sedimentary floor rocks to the lava. The sulfide then takes up Ni, Cu and PGE from the lava (from Lesher et al. 2001)

consequence is that the floor rocks melt and are assimilated into the komatiite lava. At Kambalda, the floor rocks comprise sulfide (pyrite)-rich cherty sediments and as they are assimilated, they change the composition of the magma. This contamination can boost the S content and decrease sulfide solubility, which leads to the segregation of immiscible sulfide liquid. Or the sulfide-rich sediment may just be physically entrained into the komatiite lava. Because the komatiite contains a high Ni content, and because Ni is a chalcophile element, the sulfide becomes rich in Ni (and other chalcophile elements like Cu and the PGE); because the sulfide is denser than the silicate liquid, it settles to the base of the flow to form the ore deposit. The process is illustrated in Fig. 3.9.

Basaltic liquids are cooler and more viscous than komatiites and their low Reynold's number means that their flowage was laminar. For this reason they are rarely capable of assimilating their floor rocks. Extra sulfur cannot readily be incorporated from external sources and a separate sulfide liquid forms only at late stage of crystallization when abundant crystals prevent its segregation. In addition, because the basalt is relatively poor in nickel and PGE (because sulfide is retained in the mantle source), the sulfide contains only low tenors of these elements. These are the main reasons why deposits of this type are found in komatiitic and not basaltic flows.

Why are the deposits particularly common in the Kambalda region? There are two contributing factors. The first is the presence of the sulfur-rich sediments which provide the sulfur; the second is the nature of the komatiites themselves. The lava flows that host the ore deposits of the Kambalda dome are unusually thick (up to 100 m) and they consist mainly of cumulates of Fo-rich olivine. These characteristics correspond to those of rocks precipitated from a relatively primitive komatiite liquid, one that was particularly hot, particularly fluid and particularly capable of assimilating its wall rocks. The magma also contains a full complement of Ni, and to a lesser extent the PGE, because these metals are removed during the fractional crystallization that has affected the more evolved komatiitic magmas such as those that erupted in the other areas. The larger and richer deposits of Perseverence and Mt Keith are also hosted by thick, highly magnesian komatiitic units but these are subject to major discussion as to whether they are lava flows or shallow-level sills (e.g. Gole et al. 2013).

3.4.4 Norilsk-Talnakh Nickel Sulfide Deposits

These remarkably large and rich deposits are located in northern Russia (Fig. 3.10a) in a tectonic setting that is very different from Kambalda. The deposits are hosted by small, shallow-level intrusions that form part of the enormous Permo-Triassic (250 Ma) Siberian magmatic province. It is not entirely coincidental that one of the largest continental flood basslt province hosts one to the largest ore deposits; but, as we shall see, this is not the whole story.

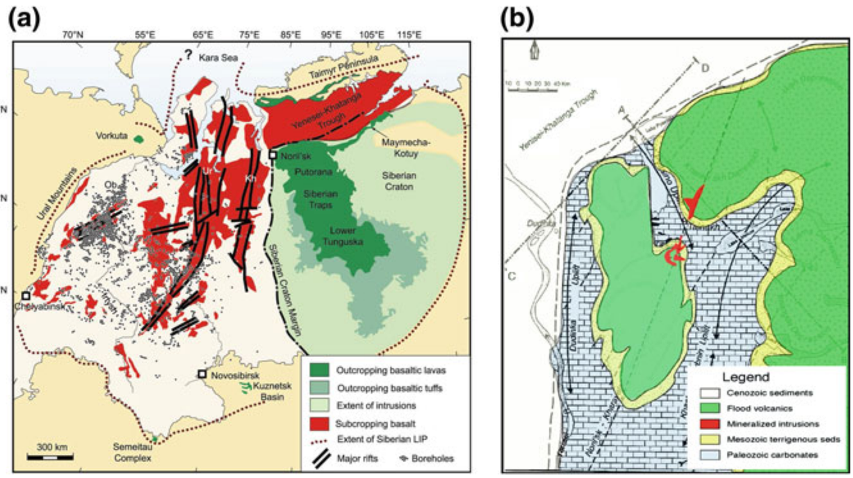


Fig. 3.10 **a** Map of the Siberian flood volcanic province (from Saunders et al. 2009). **b** Geological map of the Norilsk-Talnakh region (modified from Czamanske et al. 1995)

Box 3.2 Mining the Ni-Cu Sulfide Deposits of the Norilsk-Talnakh Region

The town of Norilsk is situated at 56°N, in the far north of Siberia, very close to the Arctic circle. The deposits are fabulously rich, some comprising lenses of massive sulfide that are 10's of metres thick and contain high concentrations of Ni, Cu and platinum-group metals. In terms of the total value of contained metals, the deposits are among the richest in the world.

The deposits at Norilsk were first found in the 1950s and were mined by prisoners of the Soviet Gulag. A series of smelters were set up to refine the ores and for several decades their S-laden fumes devastated the surrounding countryside and damaged the health of everyone in the region. The town of Norilsk has been listed as one of the ten most polluted sites in the world, a description that was certainly merited in the past. It remains to be seen whether recent moves to clean up the operation will have any significant effect. The photos below show some scenes from the town—the damage to the buildings is due to only partly to the smelter fumes, being compounded by shoddy construction and the effects of the extremely harsh climate of northern Siberia.

Figure 3.10b, a geological map of the region, shows the vast extent of the flood volcanic province—it covers an area similar to that of Western Europe. The deposits are located in the northern part of the province, in a region where later deformation has brought to the surface the base of the lava pile and the sedimentary rocks onto which they erupted. Without this deformation the deposits would have remained several kilometres below the surface, hidden from prospectors and probably unmineable. The sedimentary sequence is invaded by a vast and complex series of sills, as shown in Fig. 3.11, and these sills host the ore deposits.

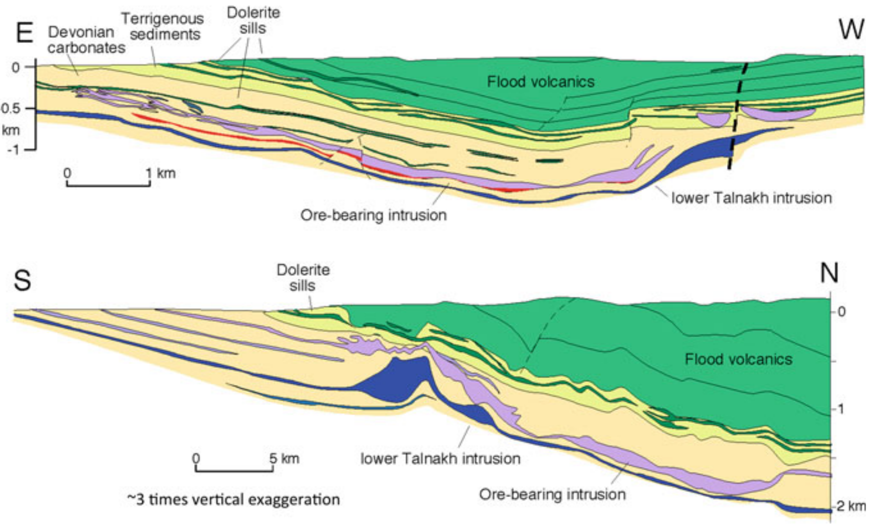


Fig. 3.11 Cross-section of the Norilsk-Talnakh region showing the sedimentary basin intruded by mafic sills and overlain by flood volcanics (modified from Arndt et al. 2003)

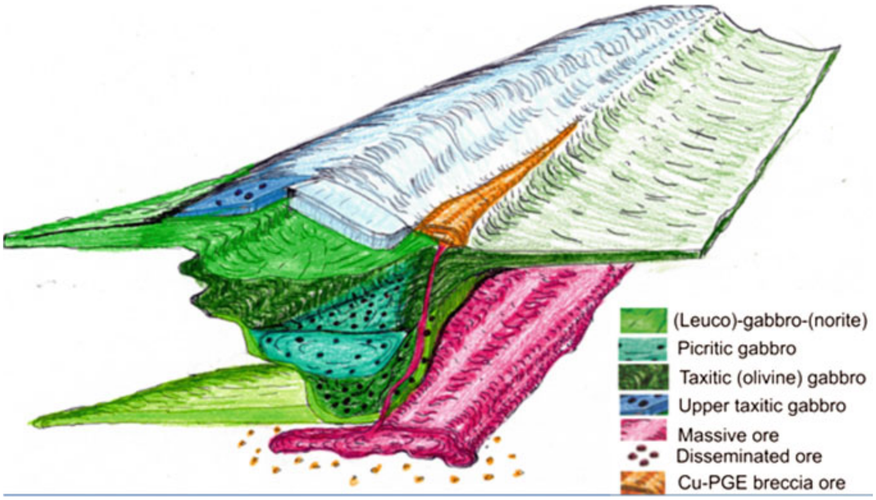


Fig. 3.12 3D perspective of an ore-bearing sill of the Norilsk-Talnakh region (from S. Dowling, 2014, unpublished, modified from Naldrett 2004)

More detailed descriptions of the geology of the Norilsk regions and its ore deposits are provided by Naldrett (2004) and Czamanske et al. (1995).

A schematic section through an ore-bearing sill (Fig. 3.12) illustrates its complex geometry and lithology. The ore deposits are found in thicker-than-normal parts of the sill, and these segments are crudely differentiated, from olivine-enriched "picritic" lower portions to gabbroic upper portions. The ore occurs as remarkable, metre-thick layers of massive sulfide at the base of the intrusion, as disseminated sulfide in the interior, and as veins and lenses throughout the intrusion and penetrating into the wall rocks.

The mineralogy of the ores is similar to that at Kambalda, but they have higher Cu contents. This is related to the compositions of the magmas from which they form; the Ni-rich, Cu-poor ultramafic magmas from Kambalda produced ores with Ni/Cu ratios of about 10 whereas the basaltic magmas at Norilsk, which have lower Ni and higher Cu, produced ores with ratios closer to 2.

In a broad sense the origin of the ores is comparable to that at Kambalda. An immiscible sulfide liquid segregated from the silicate liquid and the dense droplets settled to the base of the intrusions. But what caused the sulfide to segregate from magma of basaltic composition? In addition, the Siberian large igneous province is only one of many such provinces, and despite the best efforts of mineral exploration

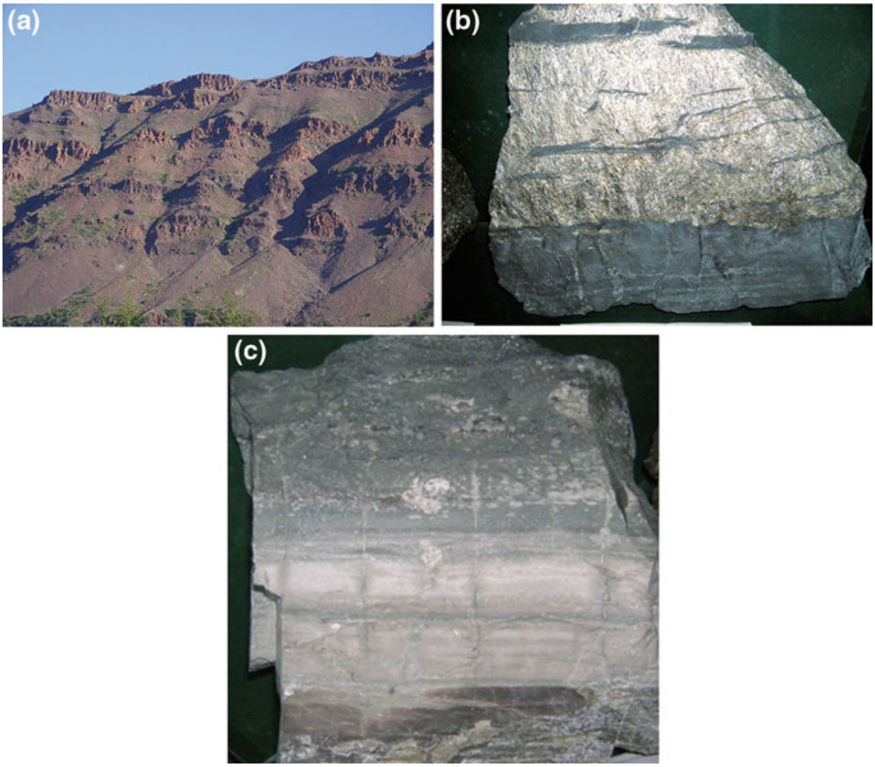


Fig. 3.13 **a** Photo of the Siberian flood volcanics (photo from H. Svensen). **b** A sample of rich Ni-Cu-PGE sulfide ore from the Norilsk-Talnakh deposits (photo from N. Arndt). **c** Evaporitic sedimentary rock from the sequence hosting the deposits (photo from N. Arndt)

companies who have actively explored the others, it is the only one known to contain a large magmatic ore deposit. Why is this?

Part of the explanation lies in the enormous volume of erupted lava, and the high magma fluxes involved in their emplacement. Recent age dating has shown that the vast majority of the lava pile was emplaced in a geologically short time period, most probably less than 1 million years, with the implication that an enormous volume of hot mantle melted rapidly, and that large amounts of hot magma flowed rapidly through the crust to the surface. Under such circumstances crustal interaction is promoted, and indeed abundant geochemical data provide convincing evidence that many of the Siberian flood basalts have assimilated large amounts of continental crust. Yet close inspection of the data shows that the key to the ore forming process is not the assimilation of normal granitoid crust but a subsequent process that took place at shallower levels. The critical evidence is provided in Figs. 3.11, 3.12, 3.13, 3.14 and 3.15.

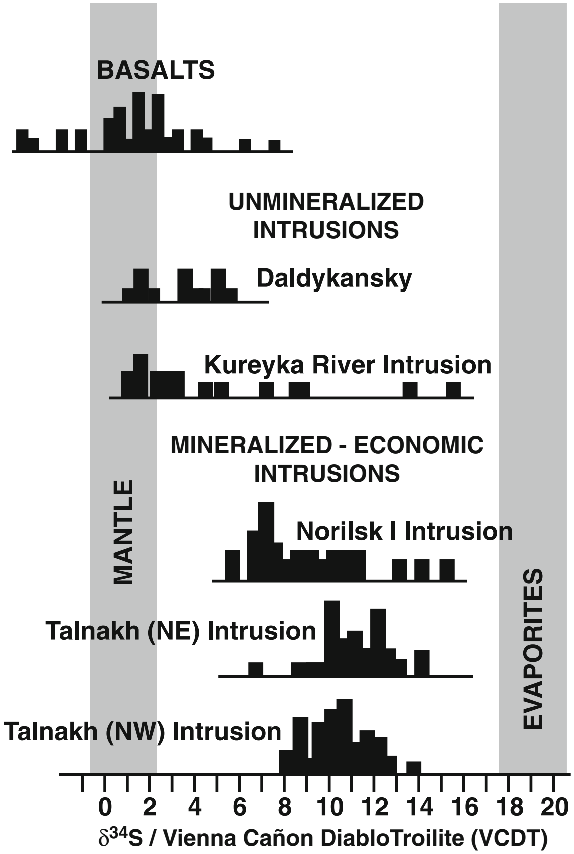


Fig. 3.14 Comparison of the sulfur isotope compositions of Norilsk-Talnakh ores with mantle-derived magma and evaporitic sediments (from Ripley et al. 2003)

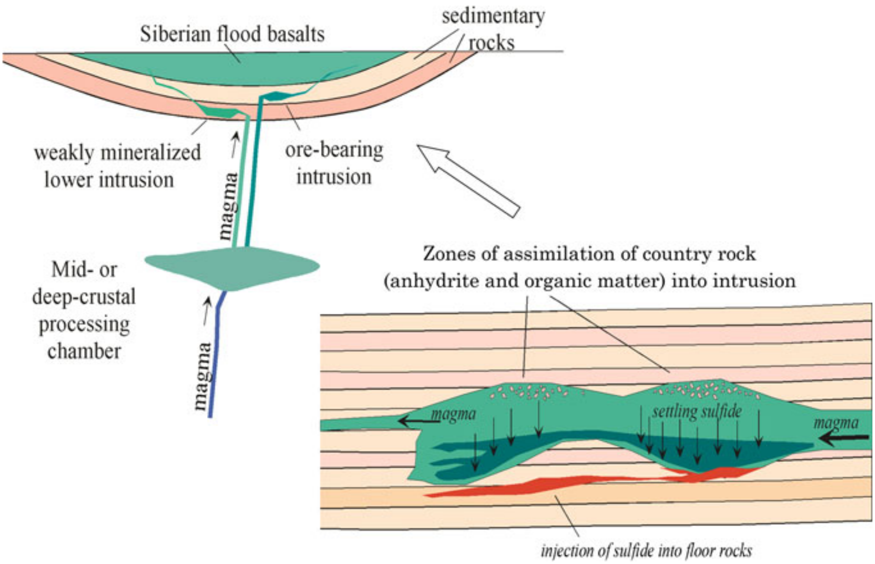


Fig. 3.15 The ore-forming process at Norilsk-Talnakh (modified from Naldrett 2004). In the first stage magma from the mantle assimilates granitic rock in a mid-crustal magma chamber; in the second stage the evolved magma assimilates evaporitic sediment and organic matter in a shallower magma chamber. The evaporate provides the sulphur, the organic matter reduces sulphate to sulfide. The sulfide liquid takes in Ni and Cu from the magma to form the ore

The first diagram shows the sedimentary sequence that underlies the flood basalts and is invaded by the ore-bearing intrusions. The uppermost formation consists of Permian terrigenous sediments, the lower formations of Silurian to Devonian carbonates, marls, and evaporates (Fig. 3.14). It is commonly believed (e.g. Arndt et al. 2003; Li et al. 2009; Naldrett 1992) that these rocks played a crucial role in ore formation. The evaporites are made up of anhydrite ($CaSO_4$) a potential source of sulfur.

The second diagram (Fig. 3.15) compares the sulfur isotopic compositions of the Norilsk-Talnakh ores with those of uncontaminated mantle magmas and with the likely composition of the sedimentary wall rocks. In the ores the sulfur is isotopically heavy, like that of the evaporates, and very different from that of normal mantle magmas. In the opinion of many geologists, this sulfur has been assimilated into the magma where it triggered the segregation of the sulfide ores.

The assimilation of sedimentary countries is believed to have taken place as magma flowed through conduits in the sedimentary pile, as illustrated in Fig. 3.15. To complete the picture it must be noted that the sedimentary S is assimilated in the form of sulfate. To convert it to sulfide requires the addition of a reductant, which, in the case of Norilsk was either coal of the upper sedimentary unit or hydrocarbons in the carbonates.

3.4.5 Other Ni Sulfide Deposits

Of equivalent size to the Norilsk-Talnakh deposits are those of Sudbury in Canada. For many decades following its discovery at the end of the 19th century (see the account in Naldrett 2004), Sudbury was the only known major Ni deposit and it served as a model for the exploration of other deposits. This turned out to be a red herring because the deposit is truly unique, being the only one associated with meteorite impact. Most ores occur as massive layers and pods in depressions in the lower contact of the Sudbury Irruptive Complex, a Paleoproterozoic (1.8 Ga) differentiated intrusion interpreted as the sheet of molten crustal rock that formed by total melting of the rocks at the site of impact (Fig. 3.16). Other deposits occur in "offsets" the name given to vein-like intrusions extending outwards from the margin of the irruptive.

The impact that generated the Sudbury irruptive and its ore deposits was located at the contact between two crustal provinces, one an Archean granite-greenstone terrain, the other consisting mainly of sedimentary rocks. The melt sheet incorporated material from both, including a small fraction of sulfide from mafic intrusions that are inferred to have been present at the site of impact. The molten mafic material, being dense, accumulated in the lower part of the melt sheet, beneath an upper layer of molten felsic layer. The entire melt sheet was extremely hot (it was probably several hundred degrees above its liquidus) and had particularly low viscosity. Sulfide droplets that segregated from the sheet were therefore able to settle efficiently to the base of the intrusion or were injected along fractures into the enclosing rocks. A more complete description of the Sudbury deposits is found in Naldrett (2004, Chap. 8) and Eckstrand and Hubert (2007).

Two other Ni-Cu sulfide deposits that deserve mention are Voisey's Bay in Newfoundland and Jinchuan in China. The Voisey's Bay deposit is unusual in that it is hosted in Mesoproterozoic (1.3 Ga) mafic intrusions that form part of an anorogenic suite that includes troctolites and anorthosites (Li et al. 2000), but the ore formed in a manner broadly similar to that at Norilsk-Talnakh. As the magma flowed up through a complex series of intrusions, it interacted with its wall rocks, perhaps picking up sulfur from sulfide-rich metasediments, and this led to the deposition of Ni-bearing sulfides higher in the magma conduit. The intrusion that hosts the largest ore body is relatively small and it is clear that the sulfides could not have been derived from the small amount of magma represented by the intrusion. Evidently the sulfides were transported from elsewhere, probably from a deeper magma chamber, and were subsequently trapped in the narrow conduit where they are now found.

Jinchuan is the third largest Ni-Cu sulfide deposit (after Norilsk and Sudbury). Unlike the others that we have described in this chapter, which all formed at or near the surface, the Neoproterozoic (800 Ma) Jinchuan deposit is located at a mid-crustal level in a series of strongly metamorphosed and highly deformed gneisses and marbles. The host intrusion is once again small (only about 6 km long and a few hundred metres wide) and it is composed almost entirely of olivine-rich ultramafic rocks. A conspicuous feature of the geological setting is the virtual absence of S-bearing country rocks, which seems to rule out assimilation of external sulfur as the ore-forming process. Tang (1993)

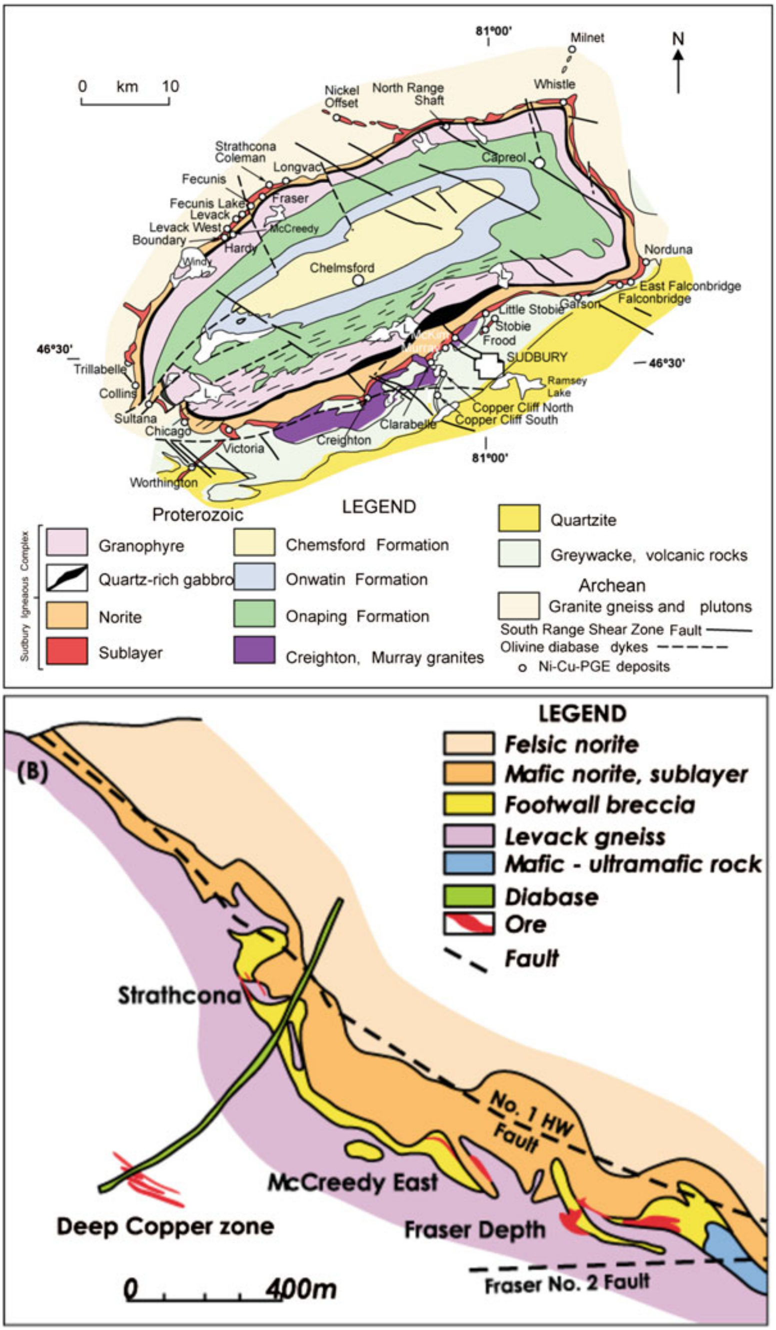


Fig. 3.16 The Sudbury irruptive complex **a** map, **b** section (from Eckstrand and Hulbert (2007) http://www.d.umn.edu/~pmorton/geol5350/2009/deposit_synthesis.ni_cu_pge.eckstrand_hulbert.pdf)

and Lehmann et al. (2007) have suggested that the first stage of ore formation involved the contamination of komatiitic magma in a deeper staging chamber. Then a mush composed of olivine crystals and sulfide droplets in a silicate liquid was injected into the present Jinchuan intrusion. Sulfide segregation or transport may have been aided by interaction of the magma with wall-rock marbles.

3.5 Other Magmatic Deposits

Table 3.3 lists several other types of deposits that are found in igneous rocks and thought to form mainly by magmatic processes. In fact it is not always straightforward to decide whether a deposit should be classed as magmatic or hydrothermal. Porphyry deposits are the most important source of copper, and these deposits are indeed located within or adjacent to granitic rocks. However, as will be shown in the following chapter, they form through the precipitation of ore minerals from

Table 3.3 Other types of magmatic ore deposits

Commodity	Rock type	Geological setting	Examples
Tin	Granite	As a magmatic mineral (cassiterite) within granitic plutons and along margins where late magmatic fluids have interacted with country rocks (greissen)	Tin granites of Malaysia, Australia, Brazil
Iron, titanium, vanadium	Gabbroic and anorthositic intrusions	Ti-V-bearing magnetite occurs as a cumulus phase in gabbroic intrusions; large ilmenite deposits occur in Proterozoic anorthosite massifs	Fe-Ti-V: Bushveld, South Africa; Panzhihua, China Ilmenite: Tellnes, Norway; Allard Lake, Canada
Uranium	Leucogranite	Disseminated uraninite in leucogranite dykes	Rössing, Namibia
Lithium, beryllium, tin, tantalum, niobium etc.	Pegmatite	Magmatic minerals in aqueous fluids released at the end stage of crystallization of granitic magma	Wodgina and Greenbushes, Australia: Bernic Lake, Canada; Marropino, Mozambique
Cu Zr, Ti, U, magnetite, vermiculite	Carbonatite	A carbonatite pipe in a alkaline pyroxentitic intrusion	Phalabora, South Africa
Rare earth elements, Nb, Ta	Carbonatite	The REE occur in bastnäsite, (Ce, La, Nd, …)CO_3F, in carbonatite intrusions	Mountain Pass, USA; Bayan Obo, China
Diamond	Kimberlite, lamproite	Diatremes in Precambrian cratons	Numerous deposits in Botswana, Russia, Congo, South Africa, Canada, Australia

aqueous fluids and thus fit our definition of a hydrothermal deposit. In the case of tin deposits in granites (Table 3.3) similar ambiguity exists because many of these ore bodies are located at the marginal zones of granitic plutons where late-magmatic fluids have interacted with country rocks to produce a type of alteration, called greissen, which produces rock enriched in tin as well as other metals such as Sb, Cu, Pb, Zn. This type of deposit also lies at the limit between magmatic and hydrothermal. The most important magmatic tin deposits are located in the Malaysia, Indonesia, China, Australia and Brazil. The South American countries Peru and Bolivia also produce large amounts of tin as a by-product of mining of polymetallic (Ag-Pb-Zn-Sn) hydrothermal deposits. Historically important deposits in Cornwall provided the metals that helped fuel Britain's industrial revolution.

Less ambiguity surrounds the classification of deposits of Fe-Ti-V oxides in gabbroic or anorthositic intrusions. The example of the V-rich magnetite ores in the upper zone of the Bushveld Complex, which clearly formed through the accumulation of magmatic minerals in the upper part of the Complex, has already been discussed. Other examples, like the Fe-Ti-V oxides in gabbros of the Panxi region in China, form from Fe-rich magmas that are believed to be part of the Permian Emeishan large igneous province.

An important class of ilmenite (Fe-Ti oxide) deposits occurs in anorthosite massifs in Canada and Norway. Anorthosite is a rock consisting almost entirely of calcic plagioclase; anorthosite massifs were emplaced in a restricted time interval in the Mesoproterozoic. Together with heavy mineral deposits in beach sands (Chap. 5), the deposits in these massifs are the dominant source of the high-technology metal titanium. The origin of these deposits is poorly understood—it is not clear how such large amounts of ilmenite, which normally is a late-crystallizing mineral, could have accumulated—but this lack of understanding is perhaps not so surprising because we have no entirely convincing model to explain the anorthosite massifs themselves.

Box 3.3 The Tin Fiasco of the 1980s

For much of the last century Malaysia was the world's major tin producer. In the 1980s it formed a cartel with other tin-producing countries to try to protect tin prices. Substitutes had emerged for traditional tin applications, particularly the use of protective plastic coatings inside what were once called "tin cans". This, together with increased recycling, had stifled demand for the metal. In 1981, the Malaysian government helped set up the International Tin Council, which bought up surplus tin stocks to maintain the price of tin and in so doing to "protect the national interest" of Malaysia. This operation did indeed lead to a rapid price rise, from less than 7000 to 9000 £/ton in eight months. The Council then went further, by buying tin for cash in an attempt to control the global tin market. The purchases were supported by loans from banks linked to the Malaysian government. Crisis loomed when the cost of holding the tin became unsustainable, and this pressure, together with the actions of market speculators, precipitating a massive collapse of tin prices. The new low tin prices rendered unviable tin mining operations throughout the world.

Thousands of mine workers in Malaysia and elsewhere lost their jobs and the last tin mines in Britain were closed. The "good intentions" of the Malaysian government had backfired cruelly, and after the mid-1980s, tin was no longer the country's major export.

http://stocktaleslot.blogspot.com/2008/07/1981-2-malaysian-tin-market-fiasco.html.

This story, together with other tales of misdirected government intervention, illustrates the perils of trying to manipulate world markets. OPEC, the petroleum cartel, was able to operate more or less successfully for several decades, largely because of the capacity of Saudi Arabia to increase or decrease production when the situation demands, so as to maintain the oil price at a level that finds a balance between the need to assure strong returns for producing countries and avoid stifling the world economy. The same does not apply to a commodity with only a small market like tin.

Yet another type of magmatic ore deposit is found in pegmatites and carbonatites, from which metals like Li Be, B, Sn, Nb, Ta and the rare earth elements are mined. In this type of geological setting, little question surrounds the geochemical grounding for the association between metal and host rock. The metals in question are highly incompatible (i.e. they cannot be accommodated in the crystal lattices of common silicate minerals) and for this reason they become concentrated in highly evolved aqueous silicate melts (e.g. pegmatite) or in the products of low-degree melting of the mantle (carbonatite). Deposits in pegmatites and carbonatites are generally small, but with accelerating industrial demand for high-technology metals such as Li and the rare earth elements, which are used in batteries or find multiple applications in the electronics industry, they are increasing sought after by mineral exploration companies and governmental agencies (see Chap. 6).

A notable exception to the small size of such deposits is the enormous Phalabora deposit in South Africa, which is the country's largest copper deposit and a source of numerous other commodities, including Zr, Ti. U, apatite (fertilizer), vermiculite (a clay mineral used as an insulator or a growing medium in agriculture—those fluffy shiny grains you buy from your local garden store) and magnetite. The Phalabora deposit is hosted by a carbonatite pipe within an alkaline pyroxenitic intrusion. The open-cast mine that was excavated in the carbonatite is said to be the largest man-man hole in Africa, if not in the world (see Fig. 3.17).

3.5.1 *Diamond*

Diamond in kimberlite is perhaps the best-known type of magmatic deposit. Kimberlite is a special type of ultramafic magma, one that is charged with volatiles such as water and CO_2. The magma is rich in potassium and incompatible trace

Fig. 3.17 Two views of the Phalabora open pit—a major Cu-rich multi-element deposit hosted in an alkalic intrusion in South Africa. The pit measures approximately 2 km in longest dimension and is about 750 m deep. The top image shows the pit wall failure that took place in 2004 along the north side of the pit

elements, and is probably produced by low-degree partial melting of a volatile-rich, geochemically enriched source deep in the mantle. Controversy exists as to whether this source is located in the basal continental lithosphere or at greater depths in the asthenosphere. Lamproite, a rock type similar to kimberlite, also can contain commercial diamond deposits. Kimberlites and lamproites are emplaced during highly explosive volcanic eruptions and form small, circular, funnel-shaped craters called maars. The giant Argyle mine in Western Australia is the greatest producer of diamonds, in terms of quantity but not value because the quality of the diamonds generally is poor. Unlike most other deposits, the Argyle mine is hosted by lamproite, another type of ultramafic ultrapotassic rock, not kimberlite.

Several decades ago almost all diamond mines were located in southern Africa but more recently many large and important deposits have been found in Russia, Australia, Canada and many other countries. The small African country Botswana is now the world's second largest diamond producer (after Russia, measured by the values of the gems), followed by Canada. This is a remarkable turnaround because diamond deposits were quite unknown in Canada in 1990. Since then the discovery and development of two major deposits, Ekati and Diavik, both of which produce a large proportion of high-quality gems, has made the country a major force on the global diamond market.

Strictly speaking diamonds in kimberlites are not truly magmatic. They are thought to be xenocrysts that were plucked from the sub-continental lithospheric mantle as the kimberlite magma ascended from its deep source to the surface. Diamond is the stable form of carbon at the pressures and temperatures that reign in the lower part the lithosphere. Given that carbon is relatively abundant in mantle rocks, it is probable that this part of the mantle contains a vast reservoir of the gemstone. Kimberlite magma is merely a vehicle that transports the diamonds rapidly to the surface under conditions that prevent them from reverting to graphite, their unattractive low-pressure polymorph.

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Chapter 4
Hydrothermal Deposits

4.1 Introduction

This important class of ore deposits is the source of most of the world's metals. Hydrothermal deposits are mined for almost 100 % of our Pb, Zn, Mo and Ag, 60–90 % of our Cu, Au and U, as well as gemstones and industrial materials such as clay minerals and quartz. Because they are mined in such large volumes, they also supply numerous by-product elements including REE, Se, Te, In and Pd. Hydrothermal deposits are diverse, being present in a wide range of geological settings and tectonic environments including intrusive or metamorphic terranes, subaerial and submarine volcanic provinces and sedimentary basins. What all the deposits have in common is their origin via the precipitation of metals or ore minerals from hot aqueous fluids. In view of the importance of water in the formation of all of these deposits, we have grouped them according to the nature and source of their hydrothermal solutions, which is a direct reflection of the geologic environments in which they form.

4.2 Key Factors in the Formation of a Hydrothermal Ore Deposit

To form a hydrothermal deposit requires: (1) a source of fluid, (2) metals that are dissolved in the fluid, (3) a trigger that causes the fluid to migrate through the crust, and (4) a mechanism that precipitates the metals or minerals (Fig. 4.1). We will discuss each of these factors in turn before describing individual deposit types and discussing how they form.

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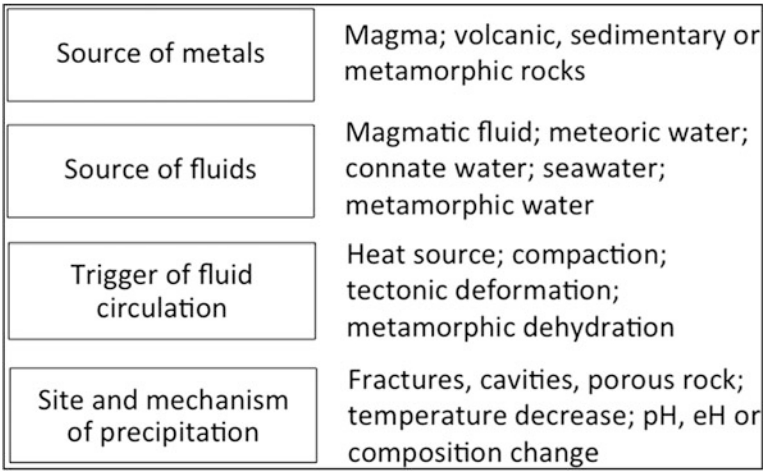


Source of metals	Magma; volcanic, sedimentary or metamorphic rocks
Source of fluids	Magmatic fluid; meteoric water; connate water; seawater; metamorphic water
Trigger of fluid circulation	Heat source; compaction; tectonic deformation; metamorphic dehydration
Site and mechanism of precipitation	Fractures, cavities, porous rock; temperature decrease; pH, eH or composition change

Fig. 4.1 Key factors in the formation of a hydrothermal ore deposit

4.2.1 Source of Fluid

Water is by far the most important requirement for making hydrothermal ore deposits. Without water, nothing happens. It turns out that water in the crust forms in or comes from several very different geologic environments and that these different types of water have different compositions and form different types of ore deposits (Ingebritsen and Appold 2012). For that reason, we have to start by talking about different types of water and the hydrothermal systems in which they are found. In this discussion, we will rely in part on isotopic measurements, which are discussed in Box 4.1 and depicted in Fig. 4.2.

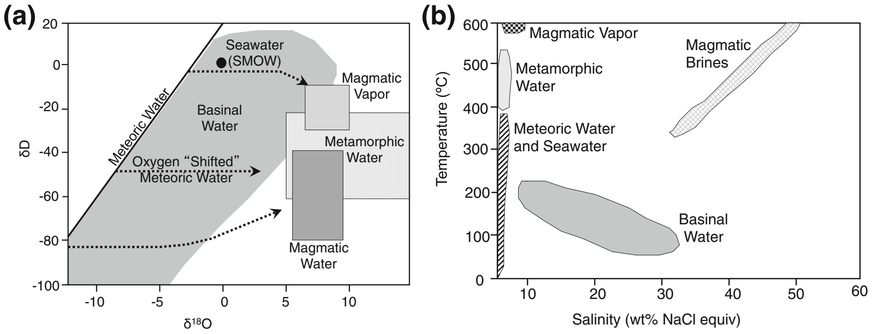


Fig. 4.2 Summary diagram showing: **a** Oxygen and hydrogen isotope compositions of the five main types of hydrothermal solutions as well as the shift in oxygen isotope composition that affects meteoric water as it circulates through the crust and reacts with rock. **b** Generalized temperatures and salinities of the types of hydrothermal solutions

Box 4.1 Stable Isotopes and Isotopic Compositions

The relative abundances of O, H and S isotopes in water and minerals provide information on the source of these elements as well as the temperatures under which their host minerals formed. The ratio of abundances for two isotopes for an element is determined for the sample and for a standard material, and the result is reported as the difference between these two ratios divided by the ratio for the standard, and expressed as permil (‰). For oxygen, the isotopic composition is reported as:

$$\delta^{18}\mathrm{O} = \left\{\left[\left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{sample}} - \left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{SMOW}}\right] \Big/ \left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{SMOW}}\right\} \times 10^{3}$$

where SMOW is the standard material for O known as Standard Mean Ocean Water. Isotope analyses for H and S are reported in the same way, and denoted as δD and δ^{34}S, respectively.

Almost all of differences in isotopic compositions that we observe in natural materials on Earth result from mass-dependent fractionation, which occurs because isotopes with lighter mass react more rapidly. Mass-independent fractionation (MIF) is also possible. MIF was first observed in O from meteorites, but the real surprise was to find it in terrestrial S and Hg (Farquhar et al. 2010). Hg exhibiting MIF has been confirmed so far only in modern organisms and their decay products. S that exhibits MIF is found in S-bearing minerals, but only in sediments that formed before about 2.4 Ga. S isotope MIF is thought to be caused by photochemical reactions in the atmosphere that are impeded by the presence of O_2. This has made MIF in S a key indicator for the increase in O_2 in Earth's atmosphere during the Great Oxidation Event, which is discussed in Chap. 5.

Meteoric water hydrothermal systems consist largely of precipitation (rain or snow) that has percolated downward into the crust. Although meteoric water was long suspected to make up most hot spring waters, it took oxygen and hydrogen isotope measurements to confirm this. In one of the earliest breakthroughs in isotope geochemistry, Harmon Craig, one of the pioneers of the discipline, showed that the oxygen and hydrogen isotopic composition of precipitation falls along a line with lightest oxygen and hydrogen isotopic ratios from areas with highest elevations and/or lowest temperatures (Craig 1961), and that water from hot springs falls along flat arrays extending to the right of this line with greatly changed oxygen isotope compositions and essentially unchanged hydrogen isotope compositions (Fig. 4.2). Circulation through rocks, which contain lots of oxygen but little hydrogen, changed the isotopic composition of meteoric water at the right end of the arrays. Most meteoric water hydrothermal solutions have low dissolved gas and

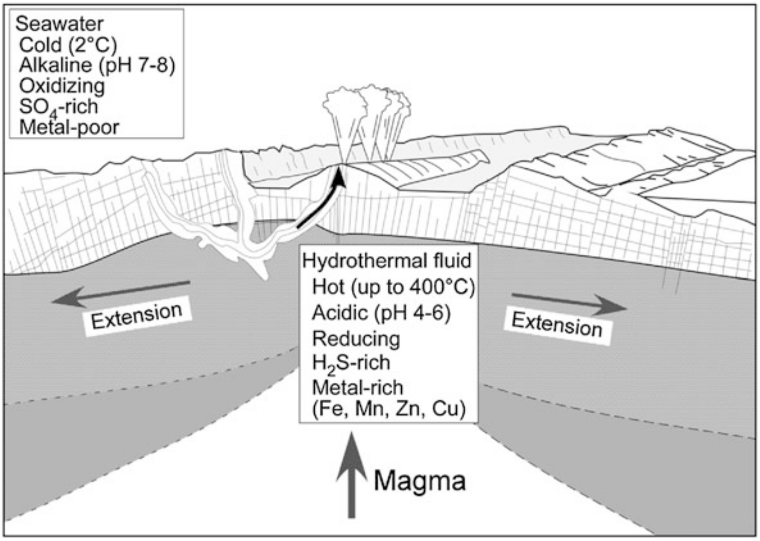


Fig. 4.3 Characteristics and general pattern of circulation of fluids at mid-ocean ridges. These fluids are responsible for the construction of black smokers and lead to the accumulation of sulfides on the seafloor (modified from Robb 2005)

solid contents (Table 4.1), but can contain important amounts of metals, and are they primarily responsible for the formation of some types of epithermal precious metal and U deposits.

Seawater hydrothermal systems consist of seawater that has circulated to depth in the ocean crust. Active examples of these systems have been studied extensively where they form along the mid-ocean ridges. Here, hot rocks and shallowly emplaced basalt magmas heat downward-moving seawater causing it to rise. The 1977 discovery of "black smokers" along the mid-ocean ridges by scientists from Woods Hole Oceanographic Institution in the submersible *Alvin* showed that these fluids returned to the surface as very hot, metal-bearing solutions (Fig. 4.3). Along with some deep waters from geothermal systems, these are the only actual mineralizing hydrothermal solutions that we have been able to study directly. All others are seen only in fluid inclusions or inferred from the compositions of altered rocks. O and H isotope compositions of black smoker fluid are somewhat different from seawater because of exchange reactions with ocean crust (Fig. 4.2). Dissolved solid contents, including metals, of fluids from seawater hydrothermal systems are much higher than those in meteoric water systems (Table 4.1), and they are responsible for formation of volcanogenic massive sulfide (VMS) deposits.

Magmatic water hydrothermal systems consist of water-rich volatile fluids that are derived from magma. Magmas contain a surprising amount of water. For instance, the dacite magma that caused the large 1980 eruption at Mt. St. Helen in the United States contained almost 5 wt% H_2O. At this concentration, only about 630 km^3 of magma could supply water for the entire Caspian Sea. In general, felsic

Table 4.1 Compositions of fluids in selected hydrothermal systems

(a) Continental	T(° C)	pH	Na + K (ppm)	Ca (ppm)	Cl (ppm)	SO_4 (ppm)	SiO_2 (ppm)	CO_3 (ppm)	H_2S (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)
Broadlands-Ohaaki, New Zealand (Simmons and Browne, 2000)	260	6.3	541	7	25	19	170	1144				
Waiotapu, New Zealand (Hedenquist and Henley, 1985)	220	5.9	809	10	732	102	353	1074	86			
Rotokawa, New Zealand (Krupp and Seward, 1987)	329	6.7	355	1.1	515	11	579	4575	106	25	175	125
Rehai (Tengchong), China (Guo et al., 2014)	88	2.6	172	30	5.9	507	317					
Matsao, Taiwan (Ellis, 1979)	245	2.4	6390	1470	13400	350	369	2			1	13
Salton Sea, California (Ellis, 1979)	340	5.5	77800	40000	184000	10				8	102	540
(b) Oceanic	T(° C)	pH	Na + K (ppm)	Ca (ppm)	Cl (ppm)	SO_4 (ppm)	SiO_2 (ppm)	CO_3 (ppm)	H_2S (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)
East Pacific Ridge 21°N, NGS and HG (von Damm, 1990)	273	3.8	12736	832	20555		975		224	1.3	37.8	2600
East Pacific Ridge 13°N and 11°N (von Damm, 1990)	354	3.1	13745	2148	25276		966		279		5.6	325
Mid-Atlantic Ridge TAG and MARK-1 (von Damm, 1990)	350	3.9	12650	396	19844		910		201	1088	10.3	3250
Mid-Atlantic Ridge, Rainbow 36°N (Seyfried et al., 2011)	359	3.4	36134	2680	26944.5	116	900	1740	75			
Juan de Fuca Ridge, Axial Volcano Inferno (von Damm, 1990)	328	3.5	12570	1872	22187		755		238	768	23.4	7435
Juan de Fuca Ridge, Vent-1 (von Damm, 1990)	285	3.2	16658	3388	31808		1140		192	128		39000
Gulf of California, Guaymas 4 and 5 (von Damm, 1990)	315	5.9	12719	1360	21264		690		163	70	47.6	1235

and silicic magmas dissolve more water than mafic magmas and this accounts for their more common association with hydrothermal ore deposits. The oxygen and hydrogen isotopic composition of magmatic water has been estimated from analysis of hydrous minerals in unaltered igneous rocks (Fig. 4.2). Magmatic vapors from fumaroles have isotopic compositions that fall at slightly higher δD compositions. Magmatic waters have not been sampled directly, but fluid inclusions show that they can range from vapors to very concentrated solutions with more than 50 % salt (Table 4.1). These fluids are mainly responsible for formation of porphyry and skarn deposits.

Basinal hydrothermal systems consist of waters that fill pores in sedimentary basins. These waters are sometimes referred to as connate water, which is water that was trapped by enclosing sediments when they were deposited. Connate water can be either fresh or seawater, with salinities reaching a maximum of about 3 %. However, many sedimentary basins contain brines with total dissolved solid contents of more than 10 %. The most abundant dissolved salt in these brines is NaCl, although other elements, including K, Mg, Br, I and S (usually in the form of sulfate) are also present. Some sedimentary brines have distinctive oxygen and hydrogen isotopic compositions, consisting of sloped arrays that extend upward from the meteoric water line from points near the composition of local meteoric water (Fig. 4.2), suggesting that they consist partly of meteoric water that invaded the basins. If so, they probably gained salt by dissolving evaporites. Others do not show this simple relation and have Cl–Br relations supporting an origin from recharge of seawater that evaporated in sabkhas (salt flats) or other saline recharge areas (Yardley and Graham 2002). Basins also contain natural gas and petroleum, both of which might be involved in ore formation, as discussed below. Basinal fluids are responsible for a wide range of ore deposits, including Mississippi Valley-type (MVT), sedimentary exhalative (SEDEX) Pb–Zn and sediment-hosted Cu deposits.

Metamorphic hydrothermal systems contain fluid that is released by prograde metamorphic reactions. H_2O is released from hydrous minerals, CO_2 from carbonate minerals, CH_4 and other hydrocarbons from organic matter and S from sulfides. For instance, the transition from greenschist (chlorite–albite–carbonate) to amphibolite (amphibole-plagioclase) facies assemblages releases a ~400 °C, low-salinity, H_2O–CO_2 fluid containing H_2S. These fluids are released when fluid pressure in the metamorphic rocks exceeds lithostatic pressure, and they can be focused into small areas by fracture systems. Because metamorphic fluids are generated at relatively high temperatures and pass through large volumes of rock after release, they have oxygen and hydrogen isotope compositions that are similar to those of average igneous and metamorphic rocks. The lack of distinctive isotopic compositions makes it hard to identify metamorphic fluids in ore deposits, although they are generally thought to play a role in orogenic Au deposits.

4.2.2 Source of Metals

Although lots of water moves through the crust, not all of it forms ore deposits; probably the most important reason is a lack of dissolved metals. There are actually two issues here, where do the metals come from and how are they dissolved in the water? The source of metals in hydrothermal fluid is one of the big unresolved questions in ore geology. In a few situations, notably porphyry Cu and Mo deposits, the deposits are so closely associated with an intrusive rock that part or all of the metal must have been released from the magma as it cooled. We have just finished a chapter in which metals remained in the magma and formed immiscible sulfide melts. So, you could ask, why do we now talk about metals leaving the magma. The answer is that porphyry deposits form from felsic, granitoid magmas that contain much less S and the S is usually in an oxidized form that does not combine with the metals to retain them in the magma. In addition, they contain much more water, which aids the formation and escape of a hydrothermal fluid.

In most other types of hydrothermal systems, the geologic setting does not point to an obvious source for the metals and we are left with two possibilities. One is that the metals came from a magma that is too far below the deposit to be identified. This is suggested for some epithermal precious metal deposits and for black smoker systems, many of which form in volcanic terrains where an underlying intrusion is likely. Where a magmatic source for metals is out of the question, the other likely possibility is that the metals were released from the rocks through which the fluid flowed. We know that all rocks contain small amounts of metals and some, particularly black shales, are enriched in specific metals. And, we know that reaction with passing fluids can break down minerals containing these metals, possibly releasing them to solution. But there are only a few situations in which a clear link can be identified between a metal source and an ore deposit.

The best way to identify the source of metals in ore deposits is through use of isotopic tracers. Pb isotope analyses have been most useful because they have a wide range of compositions, caused largely by contributions of Pb isotopes from radioactive decay of U and thorium. Some of the most successful Pb isotope results involve recognition of highly radiogenic Pb in galenas from some Mississippi Valley-type deposits, which point to a source of Pb from sedimentary rocks containing Precambrian detritus. Sr isotopes have been used to trace the source of Sr-bearing minerals such as celestite and feldspar. S isotopes are also very useful; a general rule of thumb is that strongly positive $\delta^{34}S$ isotopic ratios reflect an evaporite source, values near zero come from magmas and those with strongly negative values have S of organic origin. More recently, studies involving the heavy stable isotopes of Cu, Zn, Hg and other elements have provided new insights into their sources. In the case of fluid derived from magmas, additional insights have been provided by experimental studies of metal partitioning among magma and coexisting hydrothermal solutions. Despite all of this work, however, the exact source of metals in ore deposits, and in particular whether the sources are enriched in the metals of interest, remains one of the least understood aspects hydrothermal ore deposits.

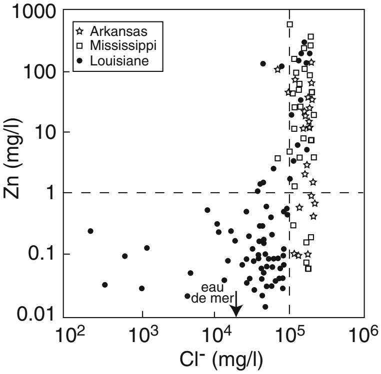


Fig. 4.4 This diagram shows the solubility of zinc as a function of chlorine in the hydrothermal fluid. Note that the solubility increases dramatically through the formation of chlorine complexes as the Cl content increases from low values typical of rain or seawater to high values found in saline brines. If the Cl content decreases, for example when the fluid is diluted, Zn precipitates and can form deposits (modified after Hanor 1996; Cathles and Adams 2005)

The other question about metals in ore deposits is how the metals are dissolved in hydrothermal fluids. The solubility of metals in pure water is very low, even at moderate to high temperature, and for many years it was very unclear how elements such as Pb or Au could be transported in hydrothermal fluids. Early experiments yielded solubilities well below those required to form even modest-sized ore bodies. For example, the solubility of Zn in a slightly acid solution at 100 °C is about 10^{-5} g/l. If such a fluid were to form an ore deposit, the amount of fluid that must pass through the deposit is greater than that of the Caspian Sea, a highly unlikely amount as we saw earlier! More recent work has shown that the formation of metal complexes greatly increases the solubility of ore metals in saline solutions. The major natural ligands are OH^-, Cl^-, HS^-, H_2S, $HCO_3{}^-$, $CO_3^=$ and F^- (Williams-Jones and Migdisov 2014). Figure 4.4 shows how the concentration of Zn increases by more than 5 orders of magnitude as the Cl content increases from the low values present in rain or sea water to the higher values present in saline fluids. In this case the high solubility results from the formation of high-order chloride complexes. The nature of metal complexes depends on the chemical affinities of the metal-ligand: so-called “hard metals” like Al, REE, Zr, U, will form complexes preferentially with ligands like OH^-, F^- and $CO_3^=$, whereas “soft metals” like Au, Pt strongly prefer HS^- or H_2S. Most base metals will be complexed largely with Cl.

4.2.3 Trigger of Fluid Circulation

Even when it contains a relatively high metal concentration, there is still a need for a large volume of hydrothermal solution. For instance, if the hydrothermal solutions that formed the Bingham porphyry Cu deposit in Utah contained about 900 ppm

Cu, as has been estimated recently, about 62 Gt of hydrothermal solution would have been required to deposit the 31.5 Mt of Cu in the ore and lower-grade material in and around the deposit. Regardless of the exact density of this fluid, it would have had a huge volume, much greater than the volume of the deposit itself. This means that a large circulation system must have operated to move the metal-bearing hydrothermal solution through the region of the ore deposit and then out again after it deposited its dissolved metal (Cathles and Adams 2005; Cox 2005).

The cause of fluid circulation differs for different geologic and hydrothermal environments. Perhaps the simplest is convection in meteoric water systems that arises when groundwater percolates to depth where it is heated and becomes buoyant enough to rise. Similarly, in seawater systems, downward-moving seawater is heated, loses density and convects upward. In both cases, cold recharge fluid from the surface takes the place of upward moving fluid leaving the system. In sedimentary basins, flow might also be driven by convection in which cool fluids from elevated parts of the basin flow downward and displace warmer fluids in the deeper parts of the basin, or by recharge from highly-saline fluids with a much greater density than meteoric water. Other possible driving mechanisms include tectonic activity that might tilt the basin causing fluids to flow out the lower side or deform the sediments pushing fluids out by closing porosity or increasing the flow of meteoric water from elevated parts of a thrust belt.

Magmatic and metamorphic fluid systems are driven in part by release and expansion of fluid into confined environments. Both take advantage of the increase in volume of fluid when it is released from the rock, and the fact that the magma or metamorphic source is separated from overlying rock by a plastic, ductile seal (Fournier 1999; Sibson 1988). In the case of magmatic systems, the release of water from the magma is an expansive process; the volume of residual magma and released vapor is larger than the volume of original magma and dissolved water, especially if the released fluid is a low density vapor. Released fluid is injected into surrounding rock, fracturing it, and moving outward. Surrounding rock is heated, and fluid in that rock, usually meteoric water, commonly forms a secondary circulation system. Metamorphic systems probably act in a similar way. As we saw above, prograde metamorphic reactions, such as those accompanying the transition from greenschist to amphibolite facies, can release H_2O, CO_2, H_2S and other gases. This fluid is stored in the rock until fluid pressure breaks the ductile seal enclosing the rocks, and the fluid can then migrate upward through fractures. The Alpine Fault in New Zealand is thought to be undergoing fluid release of this type today and studies of metal-bearing minerals in rocks around the fault show that these reactions also release Hg, As and Au.

A curious feature of most hydrothermal systems is their episodic flow. The simplest examples are epithermal veins, which have numerous layers of fill that are thought to reflect episodic injection of fluid (Fig. 4.5). In basin-related Mississippi Valley-type deposits, gangue dolomite and ore sulfides show a stratigraphy that can be traced for kilometers and that probably represents episodic introduction of fluid.

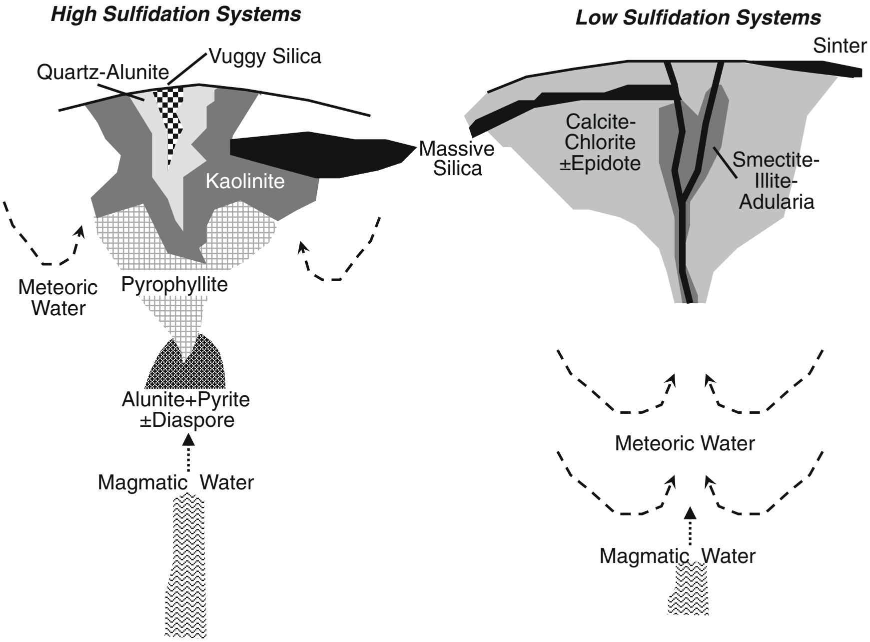


Fig. 4.5 Schematic diagram showing general configuration and alteration zoning in HS and LS epithermal deposits. Proximal alteration in LS systems is commonly zoned outward from assemblages containing adularia, sericite and illite; deeper alteration zoning in HS systems remains poorly defined (greatly modified from Hedenquist et al. 2000; Simmons et al. 2005)

Porphyry Cu deposits consist of numerous intersecting fractures and veinlets that reflect episodic fracturing. In porphyry Cu deposits, this might result from episodic release of magmatic fluids, but in other environments, it probably represents ponding of the fluid behind some sort of valve that is tripped periodically, possibly by overpressuring in the source region, by movement along fault-controlled release zones (earthquakes) or by variations in recharge of fluids that drive the system.

4.2.4 *Site and Mechanism of Precipitation*

For any flow system to form an ore deposit, the metals must remain in solution until the fluid reaches a relatively small zone of precipitation. If deposition takes place over too large a zone, the resulting concentrations of metals in the rock will be too low to attain an economically mineable grade. The most common cause of precipitation is cooling of the hydrothermal solution, which decreases the solubility of the metals (Fig. 4.4). Cooling can take place when hot magmatic fluids enter cooler wall rocks or when two fluids mix, as happens when hot “black smoker” fluid emerges onto the seafloor. Deposition can also be caused by any reaction that changes the composition of the hydrothermal solutions. Dilution of the hydrothermal solution, as happens when two fluids mix, is the simplest case; it decreases the concentration of the complex-forming anions, which destabilizes the dissolved complex causing it to precipitate the metal. Reactions can also take place if two fluids with different compositions mix or simply if their flow paths are juxtaposed. An oft-cited example is that of an oxidized fluid containing dissolved metals that contacts a reduced fluid containing dissolved sulfide. Similar reactions can take place between hydrothermal solutions and wallrock; a solution containing dissolved sulfide might contact a rock containing magnetite, to convert the magnetite to pyrite by a process called sulfidation. Or, a solution containing Cu might react with a rock containing pyrite to form Cu sulfides and expel iron. Redox reactions involving elements that can exist in more than one oxidation state are particularly important as depositional mechanisms. For instance, dissolved sulfate can be reduced to sulfide by reacting with reduced materials such as hydrocarbons or organic-rich shales. This process plays a role in the formation of most U deposits and many base-metal deposits in sedimentary basins.

When ore minerals are deposited, they can either fill open spaces or replace preexisting rock. Many hydrothermal deposits form at shallow levels in the crust where fractures remain open and precipitated ore minerals fill them. Ore bodies formed this way consist of veins, veinlets, complex networks of fractures called stockworks, or breccias. Numerous processes can form this type of porosity, including faulting, partial dissolution of the rock, and expansive release of fluid as discussed above. Cavities and caves in limestone reefs and karst facies, and interstitial space in breccias, are important sites for this type of ore deposition. When hydrothermal solutions in hot springs flow onto the seafloor or subaerial surface they may precipitate ore minerals, usually as layered deposits. Replacement of wallrock takes place when hydrothermal fluids are chemically aggressive and capable of reacting with enclosing rock. This is most common in skarn deposits with carbonate wallrock, although it can also take place in silicate wallrock. Hydrothermal alteration zones result from these reactions and sometimes contain large amounts of ore minerals. In some cases the minerals are disseminated or restricted to zones adjacent to veins; in other cases the original rock is completely replaced by new ore minerals. One such rock, jasperoid, is pure silica that formed by replacement of limestone.

4.3 Examples of Hydrothermal Deposits and Ore-Forming Processes

With all this variation in the composition and physical characteristics of fluids, it is no surprise that there are a lot of different types of hydrothermal ore deposits. In the following discussion, we have divided deposits into groups based on the type of hydrothermal system in which they form. It is impossible to describe all types of deposits, so we have selected the most important types. Our selection has been guided by two factors. First, we have included at least one good representative of each type of hydrothermal system. Second, we have included deposit types that are the most important sources of metals and targets of mineral exploration. As might be expected, some deposits do not fit neatly into the different hydrothermal system divisions—a useful lesson about classifications as well as about ore deposits themselves. For this reason, we have included a final section on two important deposit types with transitional characteristics.

4.3.1 Meteoric Hydrothermal Systems—Epithermal Deposits

Introduction: The term "epithermal" was applied by Waldemar Lindgren in 1911 to precious metal deposits in veins and breccias that formed from relatively low-temperature hydrothermal solutions (<300 °C) in or near volcanic or intrusive rocks. Low-temperature fluids of this type can transport quite a few metals, including Hg, Sb, As, U, V, Ag and Au, and deposits of all of these metals fall into the broad epithermal category. By far the most important are Au–Ag deposits and the term has gradually evolved to refer exclusively to these deposits (Hedenquist et al. 2000; Simmons et al. 2005).

Epithermal Au–Ag deposits have contributed about 8 % of global Au production so far in history, and are estimated to host 14–24 % of remaining resources. Their contribution to global Ag is smaller, but has been very important at special times in history (Box 4.1). The largest epithermal Au deposits include Yanacocha (40 Million ounces (Moz) Au) in Peru, Pueblo Viejo (38 Moz Au) in the Dominican Republic, Ladolam (Lihir) (37 Moz Au) in Papua New Guinea, Cripple Creek (18 Moz Au) in the United States and Pascua-Lama (17 Moz Au) on the Chile-Argentina border (Table 4.1). Other important deposits are Beregove (14 Moz Au) in Ukraine, Martha (Waihi) (8 Moz Au) in New Zealand, Hishikari (8 Moz Au) in Japan, and Comstock (9 Moz Au) in the United States. [Note: Deposit sizes are given here in terms of troy ounces, the unit in which precious metal prices are commonly quoted (a deposit with 1 billion ounces is shown as 1 Boz). Deposit sizes can also be quoted in tons (1 metric ton = 32,150.7466 troy ounces). Although ore grades were originally quoted in ounces per ton, they are now quoted widely in grams per ton, which we use (1 troy ounce = 31.1034768 g)]. The largest Ag deposits include Potosi (2.7 Boz Ag) in Bolivia, Pachuca (1.3 Boz Ag) and Guanajuato (1.1 Boz Ag), both in Mexico. Some epithermal deposits also contain Cu, Pb and Zn, although other deposits discussed below are more important sources of these metals.

Box 4.2 Au and Ag in History

Ag was the first precious metal to be used in commerce, by the Greeks as early as 2000 BCE and by the Chinese and Romans in about 200 BCE. After that, it was used widely in many countries for the next 1500 years, including England with its pound sterling. Au ornaments have been found in burial sites from about 4000 BCE, but it was slower to become a monetary metal. Earliest Au coins date from about 600 BCE in Asia Minor, and it was used widely in coinage by the late Middle Ages. Au coins gradually gave way to paper currency backed by Au in central banks (the Au standard) and finally to today's currency that is not linked directly to the metal.

The relative values of Au and Ag reflect their geological abundances. Ag/Au ratios in epithermal deposits range from 1 to about 400 and average about 35, not greatly different from the ratio of their crustal abundances. Since the late 1600 s, the ratio of the price of Au to the price of Ag has ranged from about 14–100 and averaged about 27, also similar to the average of crustal abundances.

Epithermal deposits with Ag/Au ratios greater than 100 are actually Ag deposits with by-product Au. That was definitely the case for the enormous Pachuca and Guanajuato deposits in Mexico, with Ag/Au ratios of 209 and 220, respectively, and Cerro Rico in Bolivia, with an even higher Ag/Au ratio. Each of these deposits yielded more than 1 billion ounces of Ag during colonial mining, and they were the foundation for the Galleon Trade, which extended from 1565 to 1815. During the Galleon Trade, ships from Acapulco in Mexico carried Ag to the Philippines where it was exchanged for porcelain, silk, ivory, spices and other goods from China, which were shipped back via Mexico to Europe. China had already based its commerce on Ag and the arrival of such large amounts of Ag had a major impact on the Chinese economy.

Underground mines in epithermal deposits that operated in the mid-1900s required grades of at least 15 grams per ton (gpt) Au, whereas mines today can operate with lower grades approaching 3 gpt Au. Open pit mines generally operate at lower grades than underground mines. For many deposits, these grades mask high variability, including the presence of exceptionally high-grade pods or zones (where visible Au is widespread, security becomes an issue in the operation). A big breakthrough in mining epithermal and, for that matter, most other Au deposits, was the development of heap leach methods in which ore was mined and crushed and then put in a pile on which cyanide solution was sprayed, recovered and then treated to remove the Au. This low cost method allowed mines to operate economically on deposits with grades of 1 gpt or less, as long as the ore was oxidized and lacked other metals like Cu that might contaminate the process. Even in oxidized deposits, fine grain size and silica intergrowths can limit access of cyanide, causing poor recoveries of metal. A recent standout in this regard is the Veladero deposit in Chile, with 180 million ounces of Ag that could not be recovered by conventional methods.

Although it has contributed greatly to increased precious metal production, the use of cyanide is controversial, and has been banned in some areas despite its good safety record. A case in point is the Rosia Montana deposit in Romania, which was to become one of Europe's largest mines. The use of cyanide was one of the arguments used by opponents of the mine to convince the Romania government to reverse an earlier decision to allow the mining operation to go ahead. Where cyanide is not used, the alternatives include gravity separation or the amalgam process in which ore is mixed with Hg to form a liquid that is heated to drive off Hg leaving Au. This method is still used in countries with significant artisanal mining and is a major source of Hg pollution.

Description: Most epithermal deposits are associated with felsic, subaerial volcanism. By far the majority of deposits are in zones of relatively recent convergent margin volcanism, especially around the Pacific margin. Other rarer deposits are associated with rift- or plume-related volcanism; one example is Cerro Vanguardia in the Deseado Massif of Argentina, which is associated with volcanic rocks of the Mesozoic-age Patagonian Large Igneous Province that formed during break-up of Gondwana. Epithermal deposits form at relatively shallow depths, usually less than 1 km, and are removed rapidly by erosion. Most deposits are younger than about 10 Ma, and deposits more than about 25 Ma in age remain only because of special geologic preservation. For instance, Cerro Vanguardia was preserved beneath younger Cretaceous-age sedimentary rocks and Tertiary to Quaternary-age back-arc volcanic rocks that have only recently begun to erode.

Even as the first epithermal deposits were being discovered, it was apparent that there were two different types. At Comstock in Nevada, ore consisted of electrum, Au-Ag telluride and Ag sulfides, sulfosalts and selenides. These minerals were associated with quartz or chalcedony and surrounded by rock that was altered to various combinations of calcite, adularia, illite/sericite and pyrite. In contrast, at nearby Goldfield, ore consisted of native Au and electrum with locally important Cu sulfides or sulfosalts and was surrounded by rock that was altered to various combinations of quartz, alunite, pyrophyllite, dickite, kaolinite and pyrite. These two contrasting mineral assemblages form from very different fluids, the first near-neutral and the second quite acid. Two terms are widely used today to distinguish these two types of epithermal deposits (Fig. 4.5); low-sulfidation (LS) for the Comstock type and high-sulfidation (HS) for the Goldfield type, although the older terms adularia-sericite and acid-sulfate, respectively, do a better job of highlighting the differences between their alteration minerals and fluid characteristics.

Most large LS epithermal deposits consist of numerous separate, largely vertical veins that form a conjugate set, sometimes reflecting regional tectonic stress. Individual veins can be up to several meters wide and extend to depths of several hundred meters. Within veins, ore grades are highest in "ore shoots" (zones enriched in Au or Ag), which have vertical extents of a few tens to hundreds of meters. Vein fill has a colloform or crustiform texture (Fig. 4.6) consisting of numerous layers of quartz and/or adularia that appear to record successive episodes of fluid injection; only some of these layers contain Au or Ag minerals. At Pachuca-Real del Monte and many other deposits, ore shoots form a horizontal zone that roughly parallels surface topography. Veins in LS deposits are surrounded by quartz-adularia-illite-pyrite alteration that grades outward to regional smectite-bearing and propylitic assemblages (Fig. 4.5). The uppermost parts of some vein systems contain alteration zones with clays, carbonates and locally alunite. In some deposits that have not undergone significant erosion, such as Buckskin in Nevada, an overlying sinter is preserved, indicating that the fluid emerged at the surface to form a hot spring.

Box 4.3 The Importance of Sinter

Sinter deposits consist of opaline and chalcedonic silica that forms when hydrothermal solutions discharge onto the subaerial surface. They are often found at the surface above geothermal systems and epithermal Au–Ag deposits. Sinters provide a clue to the location of underlying active or fossil hydrothermal systems and their textures, which are shown here, provide information on temperatures of the discharged water. Some sinters are enriched in metals, particularly Hg and Sb. A few sinters are enriched in Au and have been mined, especially Crofoot–Lewis in Nevada. In most cases, the metals were deposited after the sinter by a second, resurgent stage of hydrothermal activity.

Examples of sinter. (Upper Left) Columnar sinter (seen from above), also known as geyserite, from the active Wairaki system in New Zealand, consists of columns of stacked, convex laminations that form in hot systems (<90 °C) that alternate between wet and dry conditions. (Upper Right) Streamer textured sinter from the 0.75 m.y. old McLaughlin Au deposit, California, USA preserves fossils of filamentous algea, which usually forms in lower temperature (<35 °C) systems. (Lower Left) Micro-scale terraces in sinter from the McLaughlin deposit; larger scale terraces of this type are common at most sinter deposits. (Lower Right) Silica coatings on grass formed by spray from the active hot spring field at Beowawe, Nevada.

HS epithermal deposits are generally similar in size to LS systems, but are not as numerous and only a few deposits, such as El Indio, contain well-developed veins. In most others, including the two largest deposits at Yanacocha and Pueblo Viejo, veins are not well developed, and ore and alteration are more pervasively disseminated through the host rock. At the Pueblo Viejo deposit, miners in the 1500s and 1600s followed veins as thin as a few centimeters leaving a larger volume of largely disseminated Au that was recovered by modern mining. Ore-alteration zoning in most HS deposits resulted from several episodes of fluid injection. In some deposits, a relatively simple zonation can be recognized consisting of an innermost zone of vuggy to massive quartz (Fig. 4.6) with encrustations of Au, pyrite, enargite and other sulfosalts surrounded by pyrophyllite and/or kaolinite (dickite) alteration. In the very large systems at Pueblo Viejo and Yanacocha, vuggy silica zones are not as well developed and alteration grades outward from a central quartz-alunite-pyrite assemblage that reflects acid conditions into pyrophyllite or kaolinite-bearing assemblages that also reflect the absence of cations other than H^+, silicon and aluminium. These are overlain by zones of massive silicification that probably reflect the paleo-water table (Fig. 4.5). This alteration is underlain and transgressed locally by altered rock containing diaspore, a mineral that cannot form in the presence of silica and therefore reflects conditions so acid that silica is also mobilized (and helping account for the vuggy silica and the overlying zones of silicification).

O*rigin*: The very different nature of LS and HS epithermal deposits records the presence of two different fluids that indicate different origins. For LS systems, a simple meteoric hydrothermal system appears to have dominated. Fluid inclusion studies show that most LS veins formed from low-salinity fluids, usually less than 1 % NaCl equivalent with some CO_2 and H_2S, although fluids in deposits with relatively large amounts of base metals, such as Fresnillo in Mexico, have considerably higher salinities. In many deposits, coexisting liquid and vapor inclusions show that the fluid boiled. At Buckskin (Nevada) and McLaughlin (California) in the US, where paleodepths can be determined from the preserved sinter,

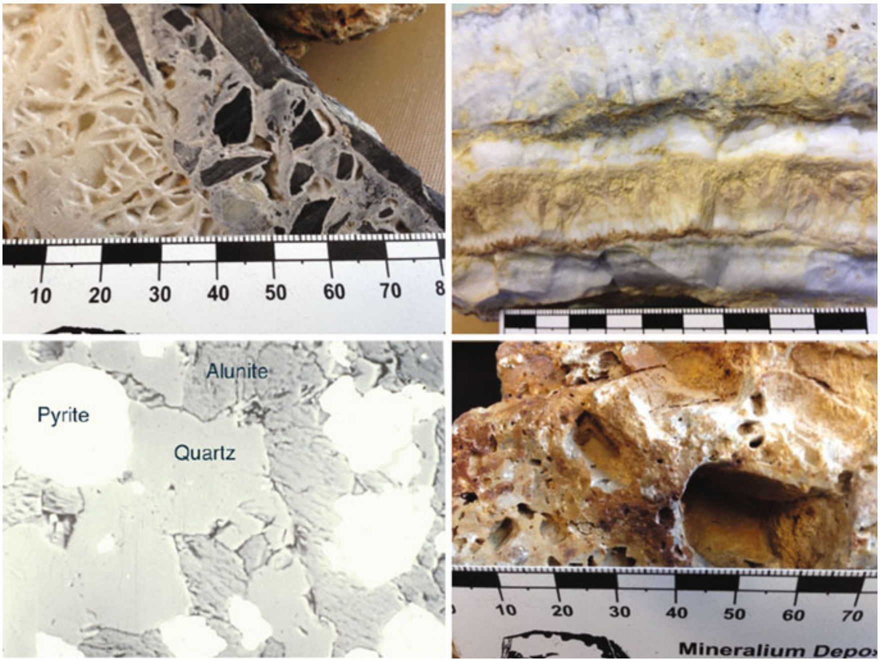


Fig. 4.6 Epithermal ore and alteration. *Top left* LS vein at the Ivanhoe deposit, Nevada, USA, showing blades of silica that replaced calcite (bladed calcite texture indicating boiling fluid) and incorporated wallrock fragments. Wall of vein is on immediate upper right of sample. *Top right* Vein material from the Waihi LS deposit, New Zealand, showing layers of quartz and adularia. Darker layers contain electrum and other gold minerals. *Bottom left* Scanning electron microscope, back scattered electron image of quartz-alunite-pyrite assemblage from the Pueblo Viejo HS deposit, Dominican Republic. *Bottom right* Vuggy silica texture from the Summitville HS deposit, Colorado, USA. Large rectangular opening is feldspar phenocryst that was leached from original volcanic rock. Scale is in centimeters. (photos taken by S. Kesler, SEM image taken by J.L. Muntean; Summitville sample from A. Arribas)

temperatures of the fluid inclusions in the ore zones fall along the boiling curve for water with small amounts of NaCl. Au is thought to be dissolved largely as a bisulfide complex ($Au(HS)_2$) in most LS hydrothermal solutions and the boiling is thought to have deposited Au by releasing H_2S into the vapor, which destabilized the Au–bisulfide complexes. In addition to depositing the Au, boiling of a fluid rising along an open fracture can also account for the location of ore shoots that mimic the topography of the overlying surface and for the presence of alteration chimneys above ore shoots that could be formed by CO_2–H_2S-bearing vapors rising from the boiling fluid. Oxygen and hydrogen isotope analyses of LS epithermal inclusion fluids from most deposits show flat arrays similar to those seen in hot springs (Fig. 4.2). In some deposits the high $\delta^{18}O$ end of the array trends toward the composition of magmatic water, providing support for those who suggest that injections of magmatic fluid provide metals to at least some LS epithermal systems.

There is less good fluid inclusion evidence for the salinity and composition of ore-forming fluids in HS epithermal systems, although what information we have suggests temperatures within the epithermal range for most deposits. The best information comes from mineral assemblages and S and oxygen–hydrogen isotope analyses. The presence of diaspore in deep alteration indicates that fluids were undersaturated with respect to silica, at least when they entered the systems. Furthermore, the coexistence deep in the systems of pyrite and alunite (Fig. 4.6) indicates that the fluid contained both sulfate and sulfide S. S isotope analyses show that the S was probably magmatic in origin and hydrogen–oxygen isotope analyses indicate that the ore fluid ranged from pure magmatic vapor in deposits such as Pueblo Viejo to meteoric with added magmatic at Summitville and elsewhere. This has led to a general genetic model in which HS epithermal deposits form when vapor plumes from underlying magmas enter overlying meteoric or possibly even seawater systems. In most cases, the vapor mixed with the resident water, although in some cases it displaced it entirely. In a few cases, such as Lepanto-Far Southeast, an underlying porphyry Cu deposit probably drove the system (Fig. 4.7). Au might be transported as a chloride complex in the vapor, but it changes to a bisulfide complex as temperature decreases, and deposition probably takes place through boiling and sulfidation.

It should be apparent from this discussion that epithermal Au–Ag deposits are not really simple meteoric water systems. HS systems almost certainly owe their metal content to magmatic input, and many people continue to think that LS systems have a cryptic but pivotal magmatic input as well. As we will see later when we discuss Transitional Hydrothermal Systems, the spectrum gets even more complex and crypto-magmatic when we get to Carlin-type deposits.

Analysis: Epithermal Au–Ag deposits

Source of metals—magmatic vapor for HS deposits and possibly for LS deposits; otherwise alteration and leaching of surrounding volcanic rocks
Source of S—S not an important component of the ore; in HS deposits source is magmatic; in LS deposits it could be leached from surrounding rocks or from magma
Source of fluid—meteoric water with or without magmatic water injection (in a few submarine settings, possible magmatic injection into seawater)
Cause of fluid circulation—convection, commonly related to underlying intrusive rocks
Precipitation process—boiling and dilution as magmatic fluid reacts with meteoric water; sulfidation if wallrock alteration is extensive and mafic minerals are present

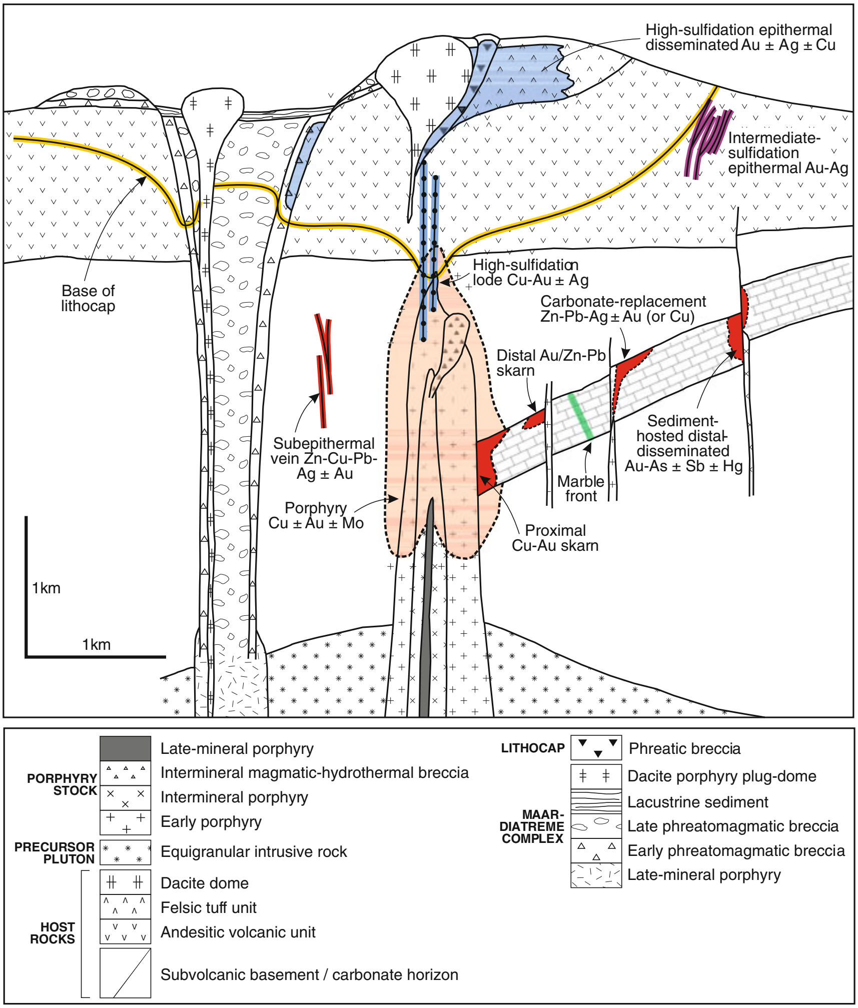


Fig. 4.7 Diagram of the upper part of a granitic pluton in a volcanic-sedimentary edifice, showing the relation of porphyry copper and skarn deposits to intrusive rocks, and the possible magmatic affiliation of HS epithermal and Carlin-type deposits (modified from Sillitoe 2010)

4.3.2 Seawater Hydrothermal Systems—Volcanogenic Massive Sulfide (VMS) Deposits

Introduction: Other than placer Au deposits, VMS deposits were among the first to be mined on a large scale. Deposits in the Troodos massif in Cyprus and the Rio Tinto belt in Spain were exploited over two thousand years ago and provided much of the Cu used in the bronze weapons of Roman centurions. Although Cu was the main element of interest in early mining, VMS deposits are also enriched in Zn and Pb, as well as trace but important amounts of Au, Ag and even Sn. In a recent global estimate, VMS deposits accounted for about 10 % of Cu, 25 % of Zn and 10 % of Pb in global reserves of known deposits. These deposits are particularly attractive because of their relatively high grades, which result from the fact that they form largely as chemical sediments on the seafloor with no wallrock to dilute their metal content. Of course, pyrite and pyrrhotite are common in these deposits and can dilute the grade of other metals; in fact, some VMS deposits such as those at Rio Tinto in Spain, consist almost entirely of Fe sulfide with very minor base metals. Before sulfuric acid became a by-product of coal burning electric power generation and sulfide smelting, VMS Fe sulfide deposits such as these were mined for their S.

Most VMS deposits are relatively small, usually containing only a few million tons of ore, but there are some very imortant exceptions that keep these deposits at the top of every exploration geologist's wish list. In terms of combined Cu + Zn + Pb content, the largest deposit is Brunswick No. 12 in Canada with slightly more than 14 million tons of metal, largely Pb and Zn. Other large deposits, in terms of Cu + Zn + Pb content, include Gaiskoe (9.6 Mt) in Russia, Kidd Creek (12.3 Mt) in Canada and Neves Corvo (7.4 Mt) in Portugal. Cu is usually the most economically important product in these deposits and from that perspective, the largest deposits include Neves Corvo with 3.2 Mt Cu, Kidd Creek (3.1 Mt) and Mt. Lyell (3.1 Mt) in Australia. Base metal ratios vary greatly in the deposits, with Cu/Pb + Zn ratios ranging from lows of about 0.03 at Brunswick No. 12–25 at Jerome in the United States. [Metal ratios provide information about the value of deposits (Cu usually costs 3–4 times more than Pb and Zn) as well as about conditions under which they formed (Cu usually required hotter fluids).] Grades for VMS deposits range from lows around 1 % combined Cu + Zn + Pb for deposits such as Rio Tinto, to highs of 10 % for the richest deposits such as Kidd Creek in Ontario, Canada. Lower grades commonly reflect either the presence of large amounts of Fe sulfide in the massive ore or inclusion of large volumes of feeder zone or distal exhalite (as discussed below) in the material that was mined (Franklin et al. 2005; Herrington et al. 2005; Huston et al. 2010; Tornos et al. 2015).

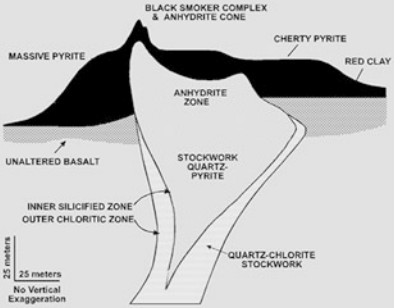
Because of their relatively compact nature and high grades, VMS deposits are often mined by underground methods, although open pits will always be used if the deposits are close enough to the surface. Many deposits are found in deformed rocks and follow steep layering in their host rocks. Kidd Creek, for instance, is essentially a vertical zone that was first mined by open pit and has since been followed to depths of more than 2 km by underground mining. Their high grades and relatively small size (requiring less massive mining) make VMS deposits attractive exploration targets for small or junior mining companies. Even large VMS deposits, however, do not match porphyry Cu deposits for total Cu content or SEDEX deposits for total Zn + Pb content.

Table 4.2 Different types of VMS deposits

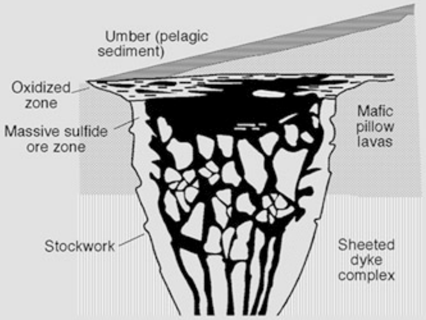
Type	Lithological association	Tectonic setting	Metals	Examples
Bimodal-mafic	Mafic volcanic with up to 25 % felsic volcanic	Volcanic arcs (rifted) above intra-oceanic subduction zones	Cu-Zn	Noranda, Flin-Flon (Canada): Urals (Russia)
Mafic	Ophiolite sequences	Mature intra-oceanic back-arcs	Cu-(Zn)	Urals (Russia), Newfoundland (Canada), Troodos (Cyprus)
Pelitic-mafic	Basalt lavas and sills with associated pelitic sediments	Mature, juvenile and accreted back-arc	Cu-Zn-Pb	Outokumpo (Finland), Windy Craggy (Canada), Besshi (Japan)
Bimodal-felsic	Felsic volcanic and terrigenous sedimentary rocks	Continental margin arcs and related back arcs	Cu-Zn-Pb	Bergslagen (Sweden), Tasman orogeny (Australia)
Siliciclastic-felsic	Felsic volcaniclastic rocks and high-level intrusions	Mature, epicontinental back arcs	Cu-Zn-Pb	Golden Grove (Australia), Iberian pyrite belt (Spain-Protugal); Bathurst (Canada)

Description: VMS deposits are hosted by submarine volcanic rocks that range from mafic (basaltic) to felsic and form in a wide variety of tectonic environments. Although the modern black smokers that provided the clues to their origin are best known along mid-ocean ridges, many deposits formed in convergent margin settings. Sedimentary rocks range from absent in some settings, to abundant in others, particularly Besshi-type deposits in Japan. From the recent classification based on the rock types associated with VMS deposits (Table 4.2), we can see that the setting varies from intra-oceanic arc and backarcs through continental margins to mature epicontinental backarcs. VMS deposit ages span most of geological history: the Big Stubby deposit in the Pilbara of Australia has an age of 3.5 Ga and is one of the oldest known ore deposits. Large and important deposits also formed in the late Archean and through the Proterozoic and Phanerozoic, and we know that deposits continue to form on the modern ocean floor.

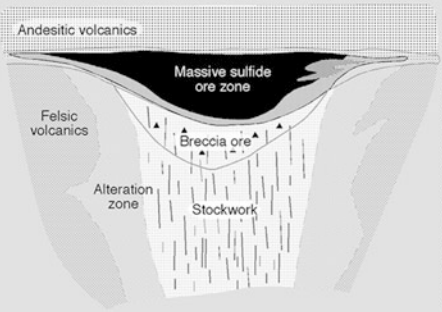
Box 4.4: Examples of Modern and Ancient VMS Deposits



TAG sulfide deposit. This deposit is currently forming on the rift valley of the Mid-Atlantic ridge at 26°N, the site of an field of active black and white smokers (hydrothermal springs). The deposit is located on the seafloor above pillow basalts of the oceanic crust. It has the form of a classic VMS deposit, comprising an upper lens of massive and semi-massive sulfide underlain by a vertical pipe-like stockwork. Anhydrite, chert and red clay co-precipitated with the sulfides. The deposit contains 3.9 mt of ore, 2.7 mt of massive and semi-massive sulfide (~2% Cu) and 1.2 mt of mineralized breccias (~1% Cu) in the stockwork



Cyprus VMS deposits. The Troodos ophiolite contains clusters of VMS deposits in pillow basalts that probably erupted in a Cretaceous back-arc basin. All deposits are Cu-rich (1-4%) with similar Zn tenors, as is normal for deposits hosted by mafic volcanic rocks. They are made up of a massive tabular cap overlain by sandy-textured and brecciated ore, in which the pyrite-rich massive core is cemented by chalcopyrite and sphalerite, and an underlying stockwork formed of a mixture of quartz and pyrite, with minor amounts of base metal mineralisation. Layers of *umber*, Fe-, Mn- and trace-metal enriched mudstones of volcanic exhalative origin cap the sulfide lens.



Archean VMS deposits. The Delbridge deposit is typical of VMS ore bodies in the 2.7 Ga Abitibi belt in Canada. The deposit formed at the contact between felsic pyroclastic rocks and andesitic volcanic lavas that were once part of an ancient island arc. The diagram to the left, redrawn from Boldy (1968), illustrates all the essential features of a VMS deposit and shows that Canadian geologists understood how these deposits formed well before the discovery of active black smokers in 1975. According to Boldy, the deposit is of "*volcanic exhalative origin*", an *example of "mineralization of a flank fissure which was the site of solfataric activity within which the various metals were rhythmically precipitated."*

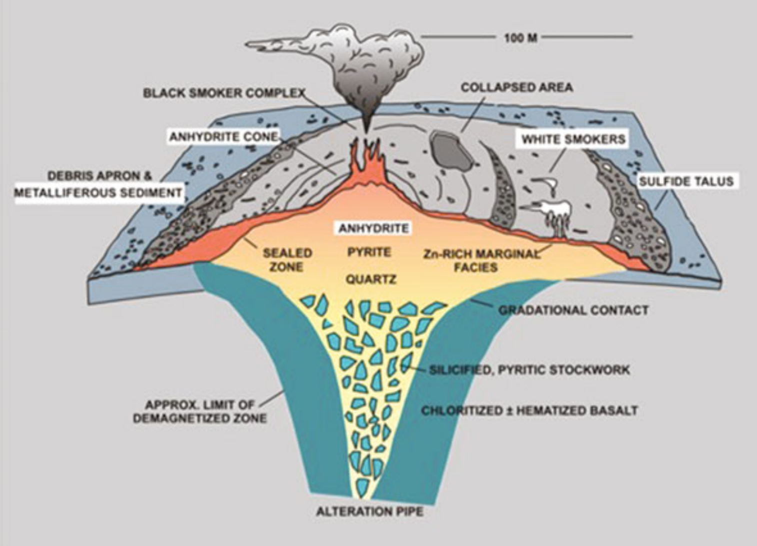


Fig. 4.8 Diagram of a typical VMS deposit, from the example of "TAG sulfide mound" on the Mid-Atlantic Ridge (modified from Hannington et al. 1998)

Most deposits have the very distinctive structure illustrated in Fig. 4.8. A tabular or mound-shaped body of stratiform, layered, massive sulfide overlies a crudely pipe-shaped feeder zone, which consists of a "stockwork" of mineralized veins that cuts vertically through highly altered host rocks. The massive ore can range from almost completely Fe sulfides as in some of the Rio Tinto deposits to Fe sulfides with large amounts of base metal sulfides. Some deposits are surrounded by a layer of chemical sediment similar to sulfide facies Fe formation known as exhalite that carries low base metal values locally. In many deposits later deformation and metamorphic recrystallization has destroyed original ore textures, but well- preserved examples preserve bedding and other sedimentary structures. In the remarkable deposits from the Urals and Ireland, the chimneys of black smokers are beautifully preserved (Fig. 4.9 and Box 4.5), to the extent that even the burrows of tubeworms, now replaced by sulfide, can be recognized.

The actual metal content of VMS deposits is directly related to their geological setting and host rocks. Ore bodies in mainly basaltic rocks are rich in Cu and contain only minor amounts of Zn and other metals, which leads to a parallel classification in which they are known as Cu–Zn deposits. Those in bimodal mafic-felsic settings are richer in Zn than Cu (Zn–Cu deposits); and those in sedimentary settings contain Pb in addition to the Cu and Zn (Zn–Pb–Cu deposits). The Pb content of VMS deposits also increases with decreasing age, reflecting the larger amount of felsic material in the host volcanic rocks.

The mineralogy of VMS ore is relatively simple. Pyrite or pyrrhotite make up about 90 % of the sulfide assemblage, and the main ore minerals usually include

Fig. 4.9 *Top* photo of section cut through a chimney of a black smoker VMS-type deposit (photo N. Arndt). *Bottom* photo of ore from deposits in the Yaman Kasy massive sulfide deposit in the Urals. The ore contains fossilized monoplacopherans and brachiopods (photo from Phil Crabbe)

chalcopyrite, sphalerite and galena, and in some cases and in minor amounts, bornite, arsenopyrite, magnetite and tetrahedrite. Zoning is common in VMS deposits, with Cu sulfides underlying Zn–Pb sulfides in the sulfide lens. In some cases, the Cu sulfides have replaced overlying Zn–Pb sulfides in a process that has been called “chalcopyrite disease”. As would be expected for deposits that form as sediments on the seafloor, wallrock alteration is not common around VMS deposits. However, feeder zones below the deposits do contain alteration assemblages that allow them to be distinguished from surrounding wallrocks. In unusual cases, where the VMS system was covered by a later lava flow soon after it formed and the hydrothermal system did not shut down, feeder zone alteration and even younger deposits are found in overlying rocks.

Box 4.5 VMS Deposits of the Urals

The Urals in Russia host six enormous VMS deposits, each containing more than 100 mt of ore, and many smaller deposits. These deposits formed in Silurian and Devonian volcanic sequences that formed as oceanic island arcs collided with the Precambrian continent of central Russia. Metal contents of the deposits can be correlated with both the associated volcanic rocks and their tectonic setting. In tholeiitic mafic volcanic rocks the dominant ore metals are Cu and Zn. Other deposits hosted by bimodal mafic-felsic, calc-alkaline volcanic rocks and sediments in forearcs or rifted arcs contain Pb, Ag and Au in addition to Cu and Zn.

A remarkable feature of many deposits is their excellent preservation due to an absence of metamorphism and deformation following deposition. Herrington et al. (2005) have described how clastic and hydrolytic processes that preceded diagenesis on the ancient sea floor modified the morphology and mineralogy of the deposits. The excellent preservation also allows recognition of fossilized tubeworms and other fauna that constituted part of the unique ecological systems surrounding the hydrothermal vents. The similarity between the Silurian vent fossils and modern vent fauna attests to the slow evolution of this part of the biosphere.

Origin: VMS deposits are among the best understood of all ore deposits. There are various reasons for this: the ore bodies are relatively simple, both in their structure and their composition and mineralogy, and they have also been studied intensively over the last decades. But more to the point is the fact that they are one of very few deposits whose formation, by way of precipitation of sulfides on the ocean floor, can be observed directly (other examples of active ore formation include the accumulation of heavy minerals in placer deposits and the accumulation of sulfidic sediments in sedimentary basins. These deposits are described in Chap. 5).

In the early part of the last century, when the opinions of American geologists like Lindgren held sway, these deposits were interpreted as epigenetic replacement bodies produced by the precipitation of sulfides from granite-sourced fluids. However, in the 1960s and 1970s geologists in Canada and Australia developed the hypothesis that these deposits in fact had formed on the ocean floor, an idea vindicated when scientists in the Alvin submersible discovered active hydrothermal vents on the sea floor in 1977 (Fig. 4.3). The discovery of these features, known as black smokers, had profound implications for our understanding of the origin and evolution of the ocean crust and for life in anoxic environments, and it also opened a window through which we could study, in real time, the processes that generate an ore deposit. Sulfides rich in Zn, Cu and Pb could be observed to precipitate in the chimneys that built up around each upwelling jet of hydrothermal fluid, and additional sulfides were seen to settle out of the hydrothermal plume onto the ocean floor. Most accumulations of sulfide minerals on the modern sea floor are relatively small: the TAG mound on the Mid-Atlantic ridge is estimated to contain about 3 million tons of sulfide grading 2 % Cu with smaller concentrations of Zn and Au, making it a medium-sized VMS deposit. If such a deposit were present on land (and not in a region hostile to mining), it certainly would be exploited.

These observations were augmented by Japanese geologists who undertook detailed studies of the Besshi and Hokuroko deposits in the 1960s and 1970s, and who developed a volcanic exhalative model for the formation for VMS deposits that is now widely accepted. This model has six main elements. (1) A heat source to drive the hydrothermal convective system and potentially to contribute some ore metals. In many deposits this is a shallow-level intrusion of mafic to felsic magma; (2) a zone of high-temperature reaction in which metals and other components are leached from volcanic and/or sedimentary by circulating seawater; (3) synvolcanic faults or fissures which focus the discharge of hydrothermal fluids; (4) footwall, and less commonly, hanging-wall alteration zones produced by interaction between ascending hydrothermal fluid and wallrock; (5) massive sulfide formed at or near the hydrothermal vent; and (6) distal bedded sediments formed by precipitation of sulfides and other components from the hydrothermal plume.

A VMS deposit forms in the following way. Magma intrudes at a shallow level in the oceanic crust. It heats seawater that is present in pores and fractures in the volcanic and sedimentary rocks and causes the water to circulate through the volcanic pile. As it does so, it draws down seawater into rocks flanking the intrusion, thus setting up a convective system. The cold seawater percolates down through the oceanic crust through open fissures and the slightly alkaline water precipitates its sulfates and carbonates as it descends. Its temperature progressively increases and as the fluid approaches the magma chamber at a 2–3 km depth, it has been transformed to hot hydrothermal fluid whose temperature is 350–400 °C and whose pH has decreased to 4–6. As it approaches the critical point its volume increases dramatically, driving it back up towards the surface. The hot, acid, corrosive liquid leaches metals from the volcanic or sedimentary rocks and these metals are transported upwards, probably as metal-halide complexes.

The fluids ascend along fractures until they reach the seafloor. On expulsion they cool rapidly and mix with cold seawater, which decreases the metal solubility abruptly, leading to the precipitation of metal sulfides together with barite, anhydrite and silica. Some of the sulfides accrete around the hydrothermal vents to build chimneys that reach tens of metres high before they collapse to form a layer of sulfide debris mixed with precipitated sulfide sediment on the seafloor. This layer has low permeability and hinders the ascent of fluid to the surface; the trapped fluid accumulates beneath the seafloor where it mixes with seawater and precipitates more sulfide. In this manner the main tabular or lens-shaped body of massive sulfide is built up. Some of the fluid escapes to form a hydrothermal plume that ascends many hundreds of metres above the black smoker and precipitates sulfide particles that settle out to form bedded "exhalative" sediments around the site. The stockwork beneath the ore body forms as high-temperature hydrothermal fluid interact with wallrocks and seawater in the conduits that transfer the fluid to the surface.

The order in which VMS metals precipitate depends on solubility and temperature. Cu and Au usually precipitate at high temperature in the stockwork beneath the chimney and Fe precipitates as pyrite at the base of the pipe. The chimney itself, as well as the 'smoke' from a black smoker, is composed of Zn and Pb sulfides, along with barite and anhydrite.

Analysis: VMS deposits

Source of metals—volcanic and sedimentary rocks of the oceanic crust
Source of S—seawater sulfate
Source of fluid—seawater
Cause of fluid circulation—convection, commonly related to high-level magma chambers
Precipitation process—cooling, change in redox state and dilution as hydrothermal fluid reacts with seawater

4.3.3 Magmatic Hydrothermal Systems—Porphyry Cu and Mo and Skarn Deposits

Introduction: Porphyry and skarn deposits are the world's most important source of Cu and Mo, and also produce significant amounts of Au, Ag, W and Sn. Porphyry deposits supply almost 75 % of world Cu production, 50 % of world Mo production and 20 % of world Au production (Sillitoe 2010). The world's largest porphyry Cu deposits include Andina (113 Mt Cu), El Teniente (106 Mt), Chuquicamata (60 Mt), and Escondida (52 Mt) all of which are in Chile. Other large deposits include Grasberg (40 Mt) in Indonesia, Oyu Tolgoi (39 Mt) in Mongolia and Bingham (19 Mt) in the United States. Cu grades in these deposits range from about 0.5 to 1.5 % Cu, with most deposits lower than about 0.8 % Cu.

Porphyry Cu deposits also contain important amounts of Mo and Au. For instance, Grasberg contains 111 Moz Au and 592 Moz Ag, making it one of the largest precious metal deposits on the planet. Au grades are usually 0.01 opt or less, although high-Au deposits such as Grasberg and Far Southeast in the Philippines, have grades of about 0.03 opt Au. In these high-Au porphyry deposits, Au grades are similar to those of a low-grade epithermal deposit, and the Au is almost as valuable as the Cu. Mo is also enriched in some deposits; Chuquicamata, for instance, contains almost 7 Mt of Mo.

Some porphyry deposits are enriched in only Mo with minor Sn, or in Sn. Porphyry Mo deposits, including the large Henderson (1.07 Mt Mo) and Climax (1.79 Mt) deposits in Colorado, supply almost all of world Mo production that does not come from porphyry Cu deposits. Large deposits with disseminated Au in the Maricunga belt of Chile have been considered porphyry Au deposits and similar disseminated deposits with Sn in Bolivia have been considered porphyry Sn. Skarn deposits are smaller contributors to world Cu production, although a few large deposits, including Ertsberg in Indonesia, are important individual producers. Among skarn deposits with other metals, only the Pb–Zn–Ag skarns, which have supplied an estimated 33 % of world production, are quantitatively important sources of metals (Seedorff et al. 2005; Meinert et al. 2005).

Many porphyry and skarn deposits are very large and are mined by open pit methods (Fig. 4.10), although a few higher grade deposits, including the El Teniente porphyry Cu deposit and the Henderson porphyry Mo deposit, are mined by underground operations. Production from these mines is usually at rates of tens to hundreds of thousands of tons per day, making them among the largest earth-moving operations in the world. Their low metal grades means that beneficiation generates very large volumes of waste in the form of tailings. For this reason and because of the need for open pit mines to have sloped sides, the typical mining and processing operation has an area of many square kilometers and consists of pits, waste piles and ponds for collection of tailings. The large size of these operations makes them a natural focus of environmental concern. One deposit that has attracted attention in recent years is Ertsberg-Grasberg, which occupies a

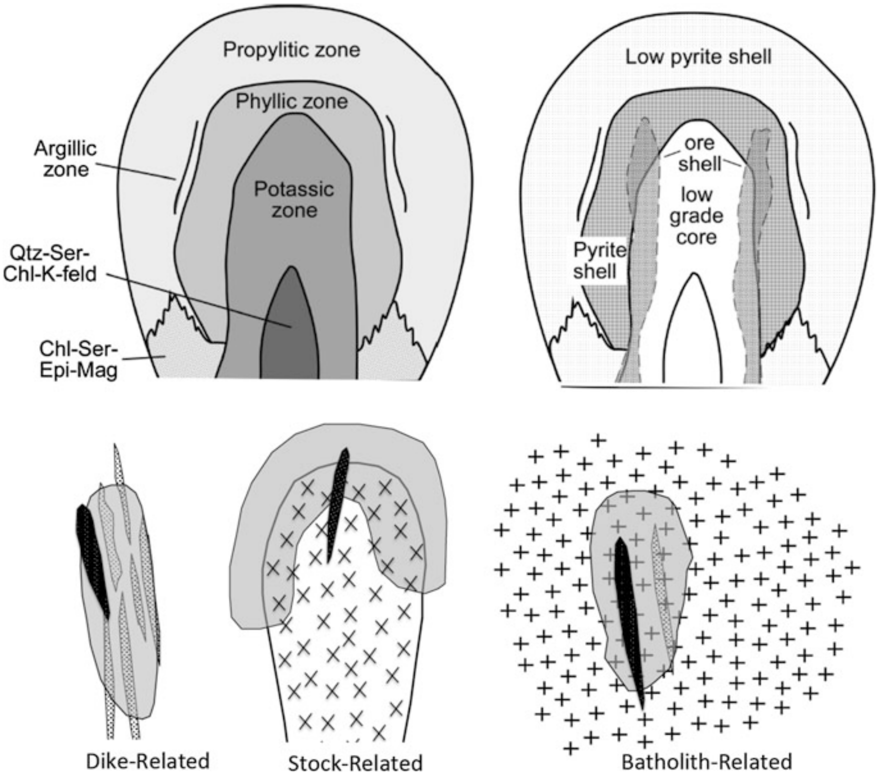


Fig. 4.10 Schematic Illustrations of: *Uppe*r Distribution of alteration zones (*left*) and types of sulfide mineralization (*righ*t) in a porphyry copper deposit (modified from Lowell and Guilbert 1970). This simplified diagram conflates a complex sequence of events that involves more than one fluid. *Lower* Relation between sulfide zone (*shaded*) and intrusive rocks, ranging from dike-related systems at depths of 1 or 2 km through stock-related systems to batholith-related systems at depths of as much as 6 km. *Dark intrusion* shows late-stage dike that wipes out some mineralization

region of fragile, high-altitude rain forest in Irian Jaya. Here, the unavoidable environmental damage of a large operation contrasts starkly with its immense economic benefit, including a contribution of 2 % to the gross domestic product of this poor country.

Box 4.6 Deposits in Environmentally Fragile Settings—The Puzzle of Pebble

Exploration for porphyry Cu deposits has extended to all parts of Earth and deposits have been discovered in remote, often environmentally fragile settings. The Pebble deposit in Alaska is an extreme example of the problem that such discoveries pose to society (Lang et al. 2013). Pebble is an exceptionally large porphyry Cu deposit, with almost 5 % of world Cu reserves. It has become the focus of controversy because of its location in the headwaters of the Bristol Bay watershed in southwestern Alaska, the largest salmon spawning run in the world.

Interestingly, land overlying the Pebble deposit is not unique; it consists of glaciated terrane with small lakes and ponds like much of Alaska, and it is 30 km from the nearest small communities. The problem, however, is the scale of the potential mining operation. Production from Pebble would almost certainly require a large open pit operation that could grow to be several kilometers wide and hundreds of meters deep, along with waste rock dumps and tailings ponds, containing as much as 10 billion tons of material, that would cover an additional several square kilometers. Can all of this be done without releasing sediment and dissolved metals that would damage the salmon runs on which much of the local economy is based?

Although the decision on whether to allow mining will be made largely by state environmental agencies, the real decision makers are the public, and a quick review of the internet shows that many groups are convinced that the Pebble mine is too large a risk for us to take. But, if we reject a deposit with nearly 5 % of total global Cu reserves, where will we get Cu for the next generation? Almost all other deposits that have been discovered recently have similar environmental challenges. Some are located in Arizona, near Tucson. Do we want mining there? Others are located in less developed countries with lower environmental standards. Maybe they should mine the Cu for us. But, should we expect these countries to send us their Cu if we are unwilling to mine our own in an environmentally acceptable manner? If we put someone on the moon, aren't we able to mine in an environmentally acceptable manner? For that matter, if a country will not accept the challenge to mine its own deposits, does it have the right to minerals mined by countries that do accept the challenge? These are uncomfortable questions, but they will become unavoidable as mineral resources dwindle.

4.3.3.1 Porphyry Deposits

Description: Porphyry deposits are predominantly associated with Mesozoic to Cenozoic orogenic belts in western North and South America, around the western margin of the Pacific Basin, and in the Tethyan orogenic belt in eastern Europe and southern Asia. They range in age from Archean to Recent, although most are Jurassic or younger. An age-frequency plot for porphyry Cu deposits shows a skewed distribution with a maximum (modal age) of about 12 million years. This does not mean that Earth formed more deposits at this time, however. Instead, the age-frequency distribution reflects uplift and exhumation. Deposits younger than 12 million years. have not yet been unroofed by erosion and most of those older than 12 million years. have been gradually removed as time passed. The strong control on the age distribution of porphyry deposits can be confirmed by dividing the average depth of formation for porphyry Cu deposits, about 2 km, into the modal age of deposits, 12 million years. This yields an exhumation rate of about 166 m/ million years, which agrees with estimates for erosion rates of mountain ranges based on sediment volumes and other parameters. Thus, if we did not mine it first, the late Miocene-age Grasberg deposit in Irian Jaya would likely be totally removed by erosion within a few million years (Kesler and Wilkinson 2008).

Porphyry deposits derive their name from the phenocryst-bearing felsic to intermediate, calc-alkaline to alkaline, intrusions with which they are associated. These intrusions commonly take the form of small stocks or dikes that are shallow-level offshoots from an underlying batholith. The shallow-level plutons are located in the lower parts of volcanic systems and no doubt supplied magma to overlying volcanism. Porphyry Cu deposits form at depths ranging from about 2–6 km within this intrusive-volcanic rock pile and their wallrocks reflect this setting. Deposits at the shallow end of the depth range, such as Panguna on Bougainville, are commonly hosted by volcanic rocks (Fig. 4.10). Deposits that form at intermediate depths, such as Bingham, are hosted by both volcanic rocks and earlier stocks, and deposits formed at greatest depth are sometimes surrounded by the parent batholith itself, as at Butte, Montana, and Lornex-Highland Valley in British Columbia. Porphyry Mo deposits are generally associated with more felsic intrusions and the most important Climax-type deposits are associated with highly differentiated, rare-metal type intrusions that are enriched in Sn, F, Li and related elements. Emplacement depths for these deposits are less well understood, but probably similar to the shallower porphyry Cu deposits. Although porphyry deposits are overlain or enclosed by volcanic rocks, controversy persists about the exact temporal relation between volcanism and porphyry Cu mineralization.

As with VMS deposits, there is a close relation between the composition of igneous rocks and their associated porphyry deposits. Low-silica, mafic plutons, ranging from calc-alkaline diorite and granodiorite to alkalic monzonite in composition, are associated with porphyry Cu–Au deposits; intermediate to felsic, calc-alkaline granodiorites and granites are associated with Cu–Mo deposits; and felsic, high silica, strongly differentiated granites are associated with Mo, W, and Sn deposits. The oxidation state of the intrusion, reflected by accessory minerals such as magnetite, ilmenite, pyrite, pyrrhotite, and anhydrite, also influences metal contents: most deposits are related to oxidized, magnetite-series plutons, but some Sn and Mo deposits are related to reduced, ilmenite-series plutons.

The ore zones in porphyry Cu deposits can take a range of forms including irregular, oval, solid, or "hollow" cylindrical and inverted cup shapes (Fig. 4.10). In its simplest form, the ore zone in these deposits is a thick-walled cup that is inverted over the parent intrusion. At Bingham, for instance, the ore zone is centered on the quartz monzonite porphyry intrusion. Not all ore zones are as clearly related to their source pluton, however, and some, such as Ray in Arizona, are hosted largely by wallrocks. Mineralization in the ore shell consists of chalcopyrite, bornite and molybdenite, disseminated or dispersed in small veinlets and replacement patches. Au is present, both in solid solution in Cu sulfides and in native form, usually concentrated along sulfide grain boundaries where it was exsolved from cooling Cu sulfides. In well developed deposits such as Bingham, the ore shell grades outward from a central low-grade core into successive shells dominated by bornite and then chalcopyrite, and finally into the surrounding pyrite shell, where pyrite can constitute up to 10 % of the rock. Molybdenite is associated with most Cu mineralization and its distribution can sometimes be shown as a Mo shell that overlaps part of the Cu zone. Peripheral Pb–Zn and Au–Ag mineralization is found outside the zone of porphyry Cu mineralization and pyrite halo. When the enclosing wallrocks are silicates, peripheral mineralization is rarely of modern economic interest. At Bingham, however, where the wallrocks include limestone, large Cu skarn deposits formed near the intrusions and carbonate-replacement galena-sphalerite chimney-manto deposits formed farther outward from the contact (Fig. 4.7).

Closely associated with the mineralization is moderate to intense alteration that extends several kilometers outside the zone of mineralization (Fig. 4.10). This alteration is commonly zoned with a central zone of potassic alteration containing K-feldspar, biotite and anhydrite and a peripheral zone of propylitic alteration containing chlorite, epidote, albite and calcite. The Cu-bearing ore shell is in and around the outer part of the potassic zone and it grades outward into the pyrite-rich zone, which is hosted by the inner part of the propylitic zone. In many island arc terranes, where intrusions and host rocks are more mafic, the distinctive mineral marking the central potassic zone is biotite rather than K-feldspar. All or parts of this potassic-propylitic alteration sequence can be overprinted by phyllic alteration consisting of quartz, sericite (fine-grained muscovite) and pyrite, with or without Cu sulfides, which often extends upward from the ore zone. Finally, advanced argillic alteration consisting of quartz, clay minerals and alunite, ranges from fracture-controlled in the ore shell to a pervasive lithocap that overlies the system at and near the paleosurface (Fig. 4.7). This lithocap can be host to HS epithermal deposits, a location that underscores the magmatic source for their fluids (Seedorff et al. 2005; Hedenquist and Taran 2013).

In Climax-type porphyry Mo deposits essentially the only ore mineral in the ore shell is molybdenite and it is hosted by intense quartz-K-feldspar alteration that has obliterated pre-existing textures. This grades outward into sericitic alteration with local Sn and W mineralization and, finally, into propylitic alteration.

Porphyry ore bodies and their associated plutons are composite structures built up from many individual pulses of magma and hydrothermal fluid. For instance, a sequence of five porphyritic intrusions was emplaced at Bingham, with each one providing less intense mineralization. The final intrusion, the quartz latite porphyry, has very weak mineralization and is largely unaltered. The multi-stage evolution of porphyry systems can be a positive or a negative feature. In the case of Bingham, its unusually high grade and large tonnage are the result of overlapping mineralizing intrusions. However, if a deposit forms early in this multi-stage intrusive sequence, and later intrusions are barren, they can “wipe-out” earlier mineralization, lowering the total grade of the deposit, as was the case at the Cerro Colorado deposit in Panama. In porphyry Mo deposits, overlapping intrusions and mineralization events are even more common, with a total of 12 reported for the Henderson deposit.

Weathering of porphyry Cu deposits plays a big role in their economic value. Oxidation of pyrite creates acid that destroys Cu sulfide minerals, sometimes precipitating them as secondary Cu minerals such as chrysocolla, atacamite, antlerite, brochantite and tenorite with lesser amounts of malachite and azurite. These minerals, a series of hydrated silicates, carbonates, sulfates and oxides, have beautiful green or blue colours and are prized by mineral collectors. If these minerals remain in sufficient abundance, an oxide Cu deposit such as El Abra in Chile can result. If, on the other hand, the Cu is carried downward by percolating solutions to deeper levels, it can replace minerals such as pyrite or even deposit directly to form a supergene zone containing chalcocite, covellite, native Cu and cuprite. In areas with long-lived, deep weathering profiles, such as southwestern United States and parts of the Andes, supergene enrichment was a major factor in developing ore that was high enough grade to be mined. Deposits such as Morenci in Arizona and Toquepala in Peru owe their economic status to this process. Depending on groundwater flow patterns, some Cu can be transported completely outside the original porphyry Cu deposit, producing “transported” Cu deposits such as Exotica (Mina Sur) at the Chuquicamata deposit in Chile (Fig. 4.10b).

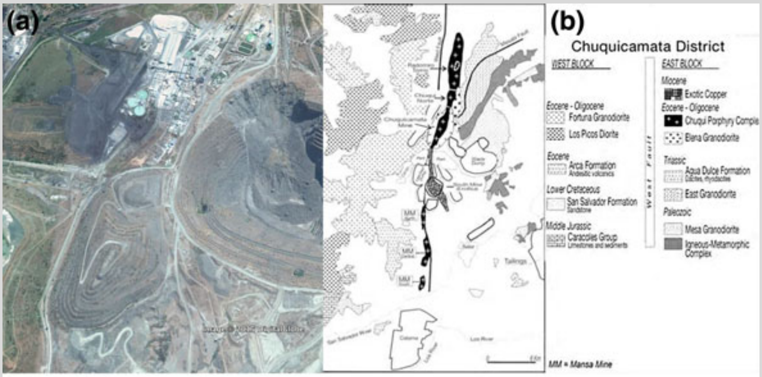
Box 4.7 The Long History of a Famous Porphyry Cu Deposit, Chuquicamata, Chile

The Chuquicamata Cu–Mo porphyry mine in the Atacama Desert of northern Chile has been described as the world’s greatest mine. With an annual production of Cu close to 600,000 tons, it is one of the world’s largest sources of the metal and one of the largest open pits in the world.

The discovery in 1899 of “Cu Man”, a mummy trapped in an ancient mine shaft and dated at about 550 A.D. reminds us that Cu has been mined in the region for many centuries. It is claimed that the conquistador Pedro de Valdivia obtained Cu for horseshoes from the natives when he passed through in the early 16th century. Mining was limited until the War of the Pacific when Chile annexed large parts of Peru and Bolivia. ‘Red Au Fever’ (La Fiebre del Oro Rojo) then drew numerous miners to the Chuquicamata region.

At the beginning of the 20th century only high-grade veins containing 10–15 % Cu were mined and disseminated ore was ignored. In 1910, C.S. Bradley, an American engineer, developed a method of processing low-grade oxidised Cu ores. He contacted Albert Burrage, a lawyer and industrialist, who approached the Guggenheim Brothers to finance the project. Initial reserves were estimated at 690 million tons grading 2.58 % Cu. The Guggenheims had also developed a process for extracting Cu from low-grade ores and in 1912 organised the Chile Exploration Company (Chilex) to mine the deposit. Chilex purchased heavy equipment (imported from the Panama Canal) and helped build the port at Tocopilla and a 90-mile aqueduct to bring in water from the Andes.

Production started in 1915 and reached 135,890 tons of Cu in 1929, the year of the Great Depression when demand fell. Companies owned by Guggenheim Bros ran the mine until 1971 when the Salvador Allende government nationalized the Chilean Cu industry. Since then, Codelco (Corporación Nacional del Cobre de Chile), the largest Cu producer in the world, has mined the deposit.



(a) Google Earth image of the main Chiquicamata open pit and the smaller Exotica deposit to the south; (b) geological map of the deposit (Ossandon et al. 2001).

Origin: Formation of porphyry deposits begins with crystallization of a hydrous magma. During this process, some water will be taken up by biotite and amphibole, but much of it concentrates in the residual melt where it will exsolve to form a magmatic fluid when the pressure of dissolved water exceeds the confining pressure. This can happen when the magma rises from depth into the shallow crust where confining pressure is lower than the pressure of its dissolved water, or when the magma simply crystallizes in place until the concentration and pressure of remaining dissolved water exceeds confining pressure. These two processes are distinguished by the terms *first boiling* and *second boiling*, respectively, and they both lead to exsolution of magmatic water or fluid. Escape of fluid increases the liquidus of the granitic magma, causing the remaining liquid to crystallize rapidly around already crystallized minerals, creating the porphyritic texture characteristic of porphyry deposits. The fluid phase may also migrate up through the silicate liquid, to concentrate at the upper part of the intrusion. The boundary between the magma and surrounding wallrocks is a ductile zone that acts as a valve, releasing water when vapor pressure exceeds its strength. In most cases, the released water expands rapidly. At depth, this expansion fractures the rock producing the intimate vein systems typical of porphyry Cu deposits and nearer the surface it can cause explosive volcanism.

Fluid inclusion and stable isotope studies have provided important information on the evolution of the magmatic fluid as it begins to form a porphyry Cu deposit. In the Bingham deposit, for instance, quartz veins at depths of 500–1300 m below the deposit contain CO_2-bearing fluid inclusions with salinities of 2–12 % that were probably trapped at temperatures as high as 590 °C (Redmond and Einaudi 2010). In the overlying deposit, two types of inclusions, one containing vapor and the other a very saline (38–50 %) fluid, were trapped together at temperatures of 350–560 °C. These inclusions record the separation of a magmatic fluid at depth into vapor and brine as it rose. Pressures estimated from these brines range from 550 to 140 bar, and probably represent episodic transitions between lithostatic and hydrostatic conditions at a depth of about 2.5 km. Chalcopyrite and bornite were deposited in the veins with a later generation of quartz at temperatures of 380–330 °C and pressures of 160–120 bar.

Stable isotopic compositions of the fluids also indicate a strong magmatic affiliation. For instance, at Bingham, fluid in equilibrium with the potassic core of the system has oxygen and hydrogen isotopic compositions similar to that of magmatic water. However, fluids in equilibrium with minerals in the propylitic zone have isotopic compositions that extend far outside the magmatic water zone toward the composition of contemporary formation and meteoric water. Similar results have been obtained at other porphyry Cu and Mo deposits (Fig. 4.11). Although other explanations for these relations can be based on changing water-rock ratios, the most likely explanation is that the rising magmatic fluids drive the circulation of a secondary meteoric or formation water system around the periphery of the porphyry deposit. As time passes and the magmatic system cools, the surrounding secondary system collapses onto the porphyry deposit itself, causing dilution and cooling that promotes the deposition of ore minerals. If the deposit consists of several different intrusive phases, this sequence of events might take place several times.

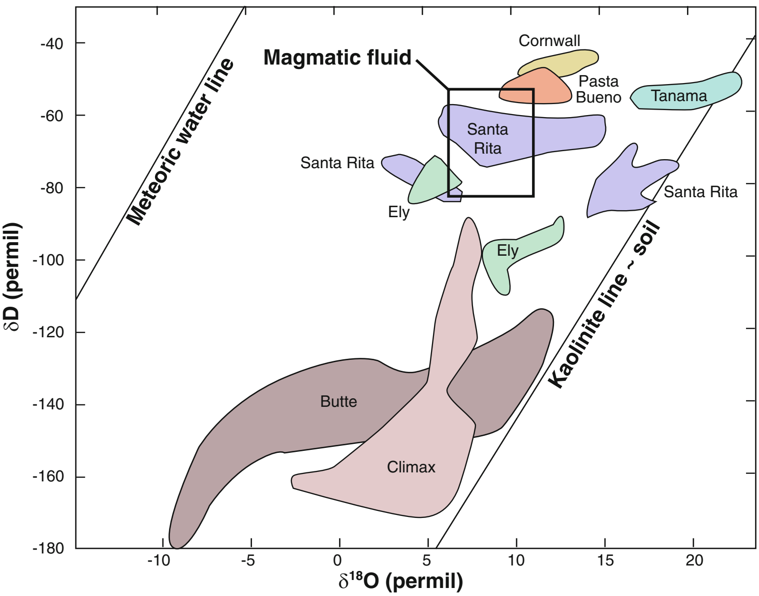


Fig. 4.11 Isotopic composition of oxygen and hydrogen in fluids associated with porphyry copper and molybdenum deposits (modified from Sheppard et al. 1971; Barnes 1979)

Analysis: Porphyry deposits

Source of metals—largely associated felsic intrusions (magmatic source)
Source of S—same
Source of fluid–mainly magmatic but locally important meteoric water in late stages
Cause of fluid circulation—expulsion of fluid from the magma, convection of heated groundwater/formation water
Precipitation process—cooling, boiling, change in fluid composition, mixing with other fluids

4.3.3.2 Skarn Deposits

Description: Skarn is a metasomatic rock consisting dominantly of garnet and pyroxene that develops in carbonate or clastic sedimentary rocks at and near the contacts of magmatic intrusions (Fig. 4.7), or more rarely during regional metamorphism. The resulting deposits are classified primarily according to the metals they contain, the most notable being Au, Cu, Fe, Mo, Sn, W, and Zn–Pb. Although most form in subduction-related settings, either oceanic or at active continental margins, some types are associated with anorogenic or rift-related intrusions.

In some areas, ore minerals form along with or slightly after these skarn silicates. The metal content of skarns is related to the composition of their associated intrusions. Fe and Au skarns are associated with gabbro or diorite; Cu, Zn and W with diorite or granite; and Mo and Sn with Si-rich granite. Several other factors also influence the type of deposit. For instance, W skarns form at greater depth and higher temperature than Cu skarns; Cu, Pb and Zn skarns are associated with oxidized intrusions; and Sn and Au skarns are associated with reduced intrusions. Although calc-silicate mineral assemblages can form in regional metamorphic settings, almost all skarn deposits of economic interest are concentrated along intrusive contacts. Where mineralization replaces the intrusive rocks it is called endoskarn, and that replacing wallrock is exoskarn.

The size and importance of skarn deposits generally follows the order of crustal abundance for the elements they contain. Fe skarns are the largest, containing up to one billion tons of ore grading 40–50 % iron. Examples include the Sarbai, Solovsk and Kachar scapolite-albite Fe skarn deposits of the Turgai region of Kazakhstan, which developed in calcareous tuffs and limestones, in some, but not in all cases, adjacent to dioritic or gabbroic intrusions. Some Fe skarns also contain significant amounts of Cu and other metals such as Co, Ni, and Au. Some contact-localized Fe deposits, such as the deposit at Bethlehem, Pennsylvania that started one of the first steel companies in the United States, consist almost entirely of magnetite or hematite with no skarn minerals, although they are associated with potassium metasomatism.

Cu and Pb–Zn skarns are the most common. They are usually associated with I-type felsic intrusions in island arc or convergent margins, similar to the settings of most porphyry Cu deposits, with which they are often associated (Fig. 4.6). Where both types of skarn deposits are present in the same area, ore compositions change with increasing distance from the contact, from proximal Cu–Au skarn to distal Au–Zn–Pb skarn, and with further distance to Zn–Pb–Ag or Au–As carbonate replacement deposits. At Bingham, for instance, porphyry Cu mineralization grades outward into the Carr Fork Cu skarn deposit and farther outward into the Lark and other Pb–Zn skarn deposits. In other large districts, such as the Grasberg-Ertsberg system in Papua-New Guinea, the Ertsberg, Big Gossan and other Cu skarns surround the Grasberg porphyry deposits, but large Pb–Zn skarns are absent.

In some districts, such as Antamina in Peru, Cu–Zn skarn is directly associated with a granitic intrusion, with no significant porphyry Cu mineralization. Pb–Zn skarn, in particular, can be located far enough from the source intrusion to cause confusion about its genetic association. The best examples of this phenomenon are the chimney-manto deposits of Mexico and Central America, in which sulfide minerals with or without associated skarn minerals form vertical tubes known as chimneys and horizontal tubes and layers known as mantos that replace thick-bedded, micritic limestone. Two famous deposits of this type in Mexico, Naica and Santa Eulalia, consist of chimneys more than 1000 m in vertical extent that are not rooted in obvious source intrusions. The nearby Providencia deposit, however, consists of similar long chimneys that extend upward from the contact of an intrusion that is the likely source of mineralizing fluids. One of the largest of the chimney-manto deposits is Tsumeb in Namibia, where the main chimney extends upward for about 2000 m through Proterozoic limestone and has no obvious igneous source.

Skarns containing W, Sn and Mo form a complex range of deposits ranging from those with only one of these elements to others such as the large Shizhuyuan deposit in Hunan, China, that contain all three. At Shizhuyuan, granites that intruded Devonian carbonates formed a polymetallic deposit including skarn with wolframite, cassiterite and molybdenite, followed by stockwork greisens that grade in composition outward from enrichment in W–Sn–Mo–Bi to Sn–Be–Cu–F. Typical skarn deposits that are enriched only or almost entirely in W, such as those at Cantung, Northwest Territories, and King Island, Tasmania, are associated with equigranular to porphyritic, intermediate, relatively deep intrusions with relatively little sulfide. Tin-only skarns are associated with more granitic intrusions and have a higher sulfide content.

Skarn deposits are not associated with widespread or easily recognized alteration other than the skarn itself. They are, however, subject to significant retrograde alteration that forms minerals such as epidote. Although some retrograde alteration degrades deposits, it can liberate additional metal in Sn deposits where metal substitutes in silicate minerals during prograde mineralization.

Origin: The close spatial and compositional association between intrusive rocks and skarn deposits points to an important role for magmatic fluids in their formation, as is confirmed by geochemical data. Fluid inclusions in silicate minerals in prograde skarn yield homogenization temperatures as high as 700 °C for Sn and W skarns and 500 °C for Cu and Pb–Zn skarns, along with salinities of greater than 50 wt% NaCl equivalent. Even retrograde skarn minerals such as epidote contain high-temperature, saline inclusions, confirming that similar fluids are present throughout the history of many skarn deposits. Daughter minerals and analyses in these saline inclusions show that they contain metals. In most deposits, the saline inclusions coexist with vapor inclusions that also contain metals. Stable isotope analyses yield $\delta^{18}O$ values of 4–9 ‰ for skarn silicates and $\delta^{34}S$ values of near 0 ‰, both of which are consistent with a magmatic source. The picture that results from these observations is one in which magmatic fluids form most prograde skarn, possibly with participation of both saline liquid and vapor. Later retrograde alteration involves dilution of these fluids by resident wallrock fluids or meteoric or basinal origin.

Analysis: Skarn deposits

Source of metals—mainly nearby granitic intrusions
Source of S—mainly magmatic
Source of fluid—magmatic with some groundwater or formation water in distal deposits

Cause of fluid circulation—expulsion of fluid from the magma, convection of heated groundwater
Precipitation process—cooling, change in fluid composition caused by reaction with limestone, mixing with other fluids

4.3.4 Basinal Water Systems—MVT, SEDEX, U and Shale-Hosted Cu Deposits

Introduction: Sedimentary rocks cover about 75 % of Earth's surface and contain large amounts of water. It is no surprise, therefore, that they form a wide range of hydrothermal systems. From a purely geological standpoint, basinal hydrothermal systems generate the widest array of deposit types and compositions, most of which are based on reduction of an oxidized fluid. Most sediments that were deposited after the Great Oxidation Event (discussed in Chap. 5) are largely oxidized and this means that most basinal waters are oxidized. Deposits form when these waters encounter reducing zones in the sedimentary sequence.

4.3.4.1 SEDEX Deposits

Description: The term SEDEX is an acronym that stands for "sedimentary exhalative"; it refers to the fact that most of these deposits form as chemical precipitates from fluid that flows out, or exhales, onto the seafloor in a sedimentary setting. SEDEX deposits contain about 50 % of the world's Pb and Zn reserves, although their contribution to mined metal is somewhat smaller at present. These deposits are particularly attractive because they have relatively high grades, with combined Pb + Zn of 10–20 %. These high grades are similar to those in VMS deposits, and they reflect the fact that most of the ore formed as a chemical sediment with little or no dilution from wallrock.

Most of the world's largest SEDEX deposits are in Australia where 7 deposits contain a total of over 112 Mt of ore, including the large deposits at McArthur River with 31.5 Mt of Pb + Zn, Mount Isa (15.7 Mt) and Broken Hill (43 Mt). Other important deposits include Sullivan (19.4 Mt) in British Columbia, Red Dog (35 Mt) in Alaska and Mehdiabad (20.7 Mt) in Iran. Pb/Zn ratios in these deposits vary widely from about 0.1 at Meggen in Germany to more than 1 at Sullivan. Ag is the most important by-product of these deposits, although grades vary greatly from almost nothing to 180 g/t at Broken Hill. Barite is also present in some SEDEX deposits and a few consist entirely of barite, including a large district of barite deposits in Devonian sediments of Nevada, as well as possibly similar barite

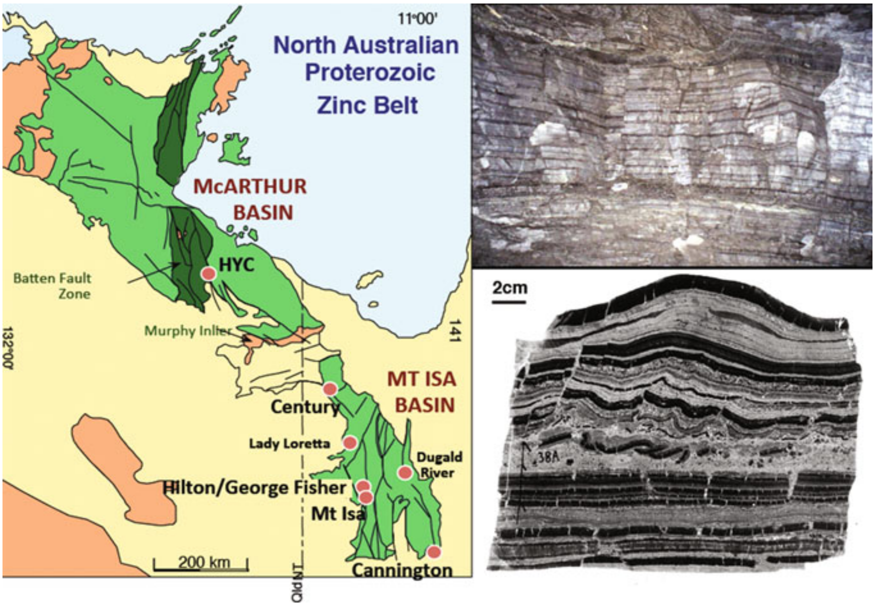


Fig. 4.12 Geological map showing the location of major SEDEX Pb-Zn deposits in northern Australia. *Above right* laminated high-grade Pb-Zn ore in an underground exposure in the HYC mine. *Below right* laminated, slightly metamorphosed and deformed ore from the Mt. Isa mine (photos by R. Large)

deposits that are forming today in the deep water parts of the sediment prism in the northern Gulf of Mexico.

Most SEDEX deposits formed in failed continental rifts or along rifted continental margins (Fig. 4.12), where deep faults apparently aided flow of exhaling fluids. The deposits range in age from Paleoproterozoic through Mesozoic, but tend to cluster in ages when suitable rift environments were forming. Archean deposits are absent, presumably because the ocean contained little sulfate at this time, as discussed below, and continents that could rift were scarce.

The main sulfide minerals in SEDEX deposits are sphalerite, galena and pyrite or pyrrhotite, along with carbonates and quartz. A striking feature of many deposits is the banding or, more correctly the layering, displayed in many ores. The sample shown in Fig. 4.12 has been folded during later deformation, but the alternation of bands of light-coloured sulfides and darker silicates is clearly visible. The form and structure of the layers strongly resembles thin sedimentary bedding, as in chemical sediments such as cherts or banded Fe formations, and this resemblance has led many workers to interpret the ores as chemical sediments deposited from plumes of hydrothermal fluid that precipitated sulfides as they mixed with seawater after emission from vents on the sea floor. Other researchers have argued for a syndiagenetic replacement origin for the ores; they recognize that the layering is sedimentary in origin but argue that the original sediments contained only barren Fe sulfides and silicates. According to them, ore metals replaced the original Fe sulfides as hydrothermal fluids circulated through unconsolidated sediments tens or hundreds of meters below the sea floor. Although the issue is not entirely resolved, it is likely that both processes operated to different extents in different deposits (Goodfellow and Lydon 2007; Large et al. 2005; Leach et al. 2005).

A characteristic feature of SEDEX deposits is the fine grain size of their original ore minerals. In the large McArthur River deposit, most sulfide grains are less than about 10 microns in diameter and individual sphalerite grains measure as little as 0.5 μm. At Mt Isa the average grain size is 100–500 μm and at Broken Hill, sulfide grains are up to centimeter sized (Fig. 1.6). The difference in grain size is due largely to the degree and grade of metamorphism that affected the deposits after their initial formation. The coarse grains of the Broken Hill deposit result from recrystallization during high-grade, granulite-facies metamorphism; the finer grains of the Mt Isa deposit are influenced by the sub-greenschist metamorphism of this region; and the minute grains of the McArthur River deposit probably are those of the original sedimentary ore minerals. (This difference in grain size strongly influences the economic viability of the three deposits. As mentioned in Chap. 1, the coarse Broken Hill ores were easily mined and refined, in contrast to the ultra-fine McArthur River ores, which for many years could be mined but could not be beneficiated to make a sulfide concentrate that was suitable for smelting).

Most SEDEX ore deposits are tabular bodies that lie parallel to their enclosing sediments, although some deposits also have mineralization in underlying feeder zones. Alteration haloes consisting of Fe–Mg–Ca carbonates are most common in the underlying sediments and in sedimentary layers that formed outward from the deposit itself, and can extend into overlying rocks if the system persisted after burial. These distal sediments are enriched in Zn, Mn, Tl and other elements that can be used to vector toward deposits.

Origin: The precipitation of sulfides from black smokers is not the only setting in which we can observe the formation of an ore body. Almost 100 million tons of sediment containing 2 % Zn, 0.5 % Cu and significant amounts of the Au and Ag has precipitated from hot dense brine that accumulated in the “Atlantis II Deep”, a 10 km diameter depression on the floor of the Red Sea. Were this deposit on land and in a politically stable part of the world, it would constitute an attractive ore body. A related process is taking place in the Salton Sea, a large shallow lake in southern California that formed in 1905 when a canal transporting water from the Colorado River breached and flooded a saltpan. The water became brackish as it dissolved the salt, and large-scale hydrothermal circulation was set up as water in the underlying sedimentary basin was heated by the high prevailing geothermal gradient caused by rifting and volcanism along the landward extension of the Gulf of California. At depth the circulating fluid, a hot (up to 350 °C) dense Na–Ca–K–Cl brine, has dissolved Fe, Mn, Pb, Zn and Cu from the lacustrine sediments that underlie the lake. When the fluid mixes with cooler, dilute surface waters about 100 m below the surface, it precipitates these metals in veins of sulfide. Although an actual ore body has not yet been recognized, the process is relatively clear.

Fluid inclusion studies of SEDEX deposits are limited because of the small grain size, a lack of clearly coeval transparent minerals, and metamorphic overprinting in many deposits. Reported temperatures range as high at 400 °C and salinities vary from nearly 0 to 45 % total dissolved solids. Recent surveys of numerous studies have concluded that the most likely range of conditions for SEDEX mineralizing fluids are temperatures of 100–200 °C and salinities of 10–30 % total dissolved solids. One study of solute contents of inclusions from several major deposits concluded that the inclusions contain Ca–Na–Cl brines with compositions similar to those of evaporatively concentrated seawater. Relatively dense brines are necessary for these deposits, if they indeed formed as chemical precipitates in isolated depressions in the seafloor. S isotope analyses range from moderately negative to strongly positive values and are interpreted to result from biogenic or possibly thermogenic reduction of seawater sulfate to form H_2S, which is typically enriched in anoxic water columns and in black shales associated with some deposits. Radiogenic isotopic tracers indicate that the metals were derived from surrounding clastic sedimentary rocks.

The processes implicated in the formation of a SEDEX deposit are illustrated in Fig. 4.13. The key is the deep circulation of fluids that rise beneath the zone of deposition, although opinion differs on what drove this circulation. Possibilities include free convection, topographically driven flow or flow driven by compaction of surrounding sediments. If the fluids consist of evaporatively concentrated seawater, as suggested by fluid inclusion data, free convection aided by the density of recharge fluids is more likely. This would also require that conditions during formation of many SEDEX deposits were warm and arid enough to generate brines at the surface. The mineralizing episode was probably triggered by tectonic events that activated major faults and generated rapid subsidence in the sedimentary basin. The subsidence, perhaps aided by local heating from mafic dikes that were emplaced into the same fault system, set the circulating system into motion. Saline fluids become enriched in Fe, Zn and Pb probably leached from Fe oxides coating detrital sedimentary minerals. The metals are transported in the hydrothermal fluids as chloride and variable SO_4^{2-} complexes. When the fluids are discharged along faults to the basin floor, metal sulfides precipitate at or above the seafloor by reaction with H_2S in the overlying reduced anoxic layer at the base of the water column or, in some deposits in shallow water, by boiling and loss of CO_2 from the fluid. Formation of rift-bounded basins with abundant biological activity makes it more likely that they could contain reduced, H_2S-bearing seawater.

Analysis: SEDEX deposit

Source of metals—detrital sedimentary rocks
Source of S—biogenically reduced marine sulfate
Source of fluid—evaporatively concentrated seawater
Cause of fluid circulation—compaction(?), convection due to magmatic intrusions
Precipitation process—cooling, reaction of oxidized fluid with H_2S in anoxic seawater

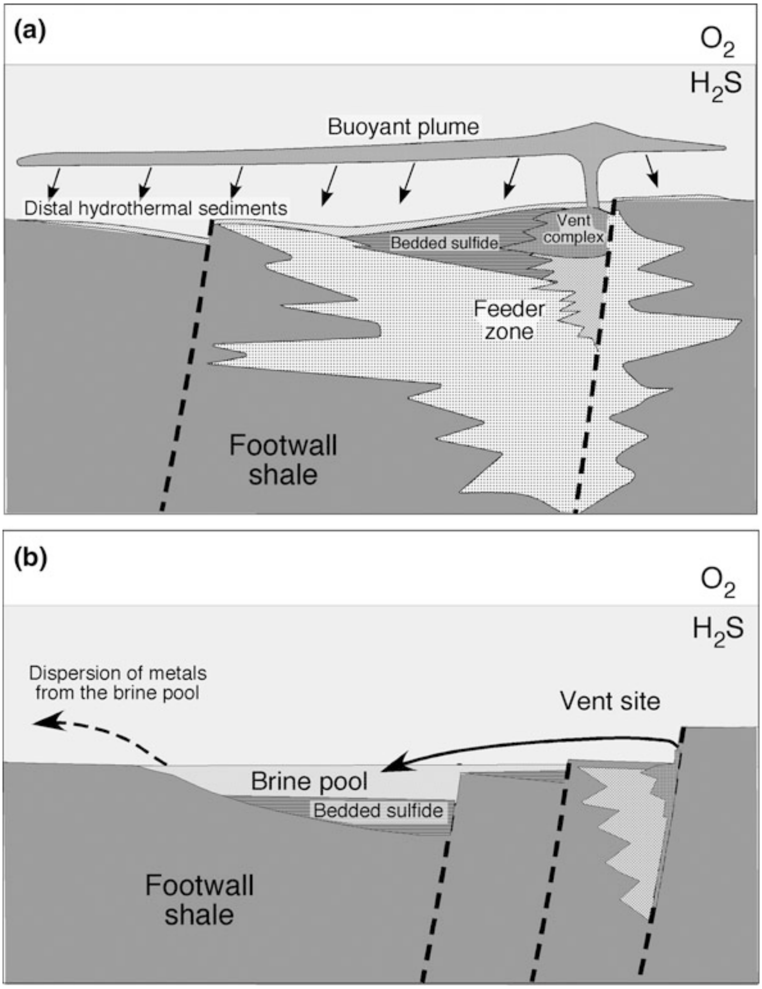


Fig. 4.13 Illustration of the origins of proximal and distal SEDEX deposits (modified from Goodfellow and Lydon 2007)

Box 4.8 Indium from Pb–Zn Deposits

Indium has become a key technological metal in just the last two decades. Along with Sn, it forms ITO (In–Sn oxide), which is a used widely in flat-panel displays in smart phones, computers and televisions. ITO contains about 90 % In, which makes manufacturers of flat-panel displays heavily dependent on a good supply. But, where to go for this supply? In does not form many minerals of its own. Instead, it substitutes for Zn in sphalerite and, to a lesser extent, for Sn in stannite and cassiterite. This makes In a by-product of Zn and, to a much lesser extent, Sn production. The volume of by-product In depends on both the In content of sphalerite and the amount of Zn produced. In general, Zn deposits that form at high temperature, especially VMS deposits like Neves Corvo, yield the most In. Smaller, but still important amounts come from SEDEX and other Zn-rich deposits.

4.3.4.2 Mississippi Valley Type (MVT) Deposits

Description: MVT deposits get their name from the deposits of this type that were first mined in the broad drainage system of the Mississippi River. They also form from basinal fluids, but at depth along the flanks of sedimentary basins. MVT deposits are enriched in Zn and Pb, with small but locally important amounts of Cu, Co, Cd and Ag. Historically, they have accounted for about 15–20 % of the Zn and Pb in known deposits.

Information on the size and grade of MVT deposits is complicated by the fact that many deposits are parts of districts that contain numerous deposits, a situation that contrasts with SEDEX deposits, which tend to be more solitary. MVT districts cover hundreds of square kilometers and the terms “district” and “deposit” are used interchangeably without critical definition. This is a problem in most types of ore deposits, of course, but it reaches its apex with MVT deposits. For instance, the Viburnum Trend (16 Mt Pb + Zn) district measures about 1 km wide and 50 km long and contained seven ore bodies or deposits that were further separated into mines based on ownership boundaries that had little to do with geology. The largest mine in the trend was Buick with 3.2 Mt Pb + Zn. Other large MVT districts with multiple deposits include Upper Silesia (40.8 Mt) in Poland, and East Tennessee (16.5 Mt) in the United States. Some MVT deposits are more solitary and, so far at least, do not appear to be part of large districts. One example is Polaris (4 Mt) in the Arctic of Canada.

Compared to SEDEX deposits, the other major source of Pb and Zn, MVT districts and deposits are about 25 % smaller on average and, most importantly, they are lower grade. Whereas SEDEX deposits have grades of 10–20 % Pb + Zn, most MVT deposits contain 5–10 % Pb + Zn. Pb/Zn ratios vary even more widely in MVT deposits, from almost infinity in the Old Lead Belt in the United States to more than five at Touissit-Bou Bekker in Tunisia. These ratios have geologic as well as economic importance; high Pb contents generally require a more felsic and coarsely clastic source material for the metals and high Zn contents are generally more desirable because of both the greater value of Zn and the environmental issues related to Pb production.

MVT deposits are epigenetic and stratabound and are found in dolostones, or less commonly in limestone or sandstone, at shallow depths on the margins of sedimentary basins (Leach et al. 2005). A common depositional setting is in platform carbonate sequences, commonly reef facies, located either in relatively undeformed

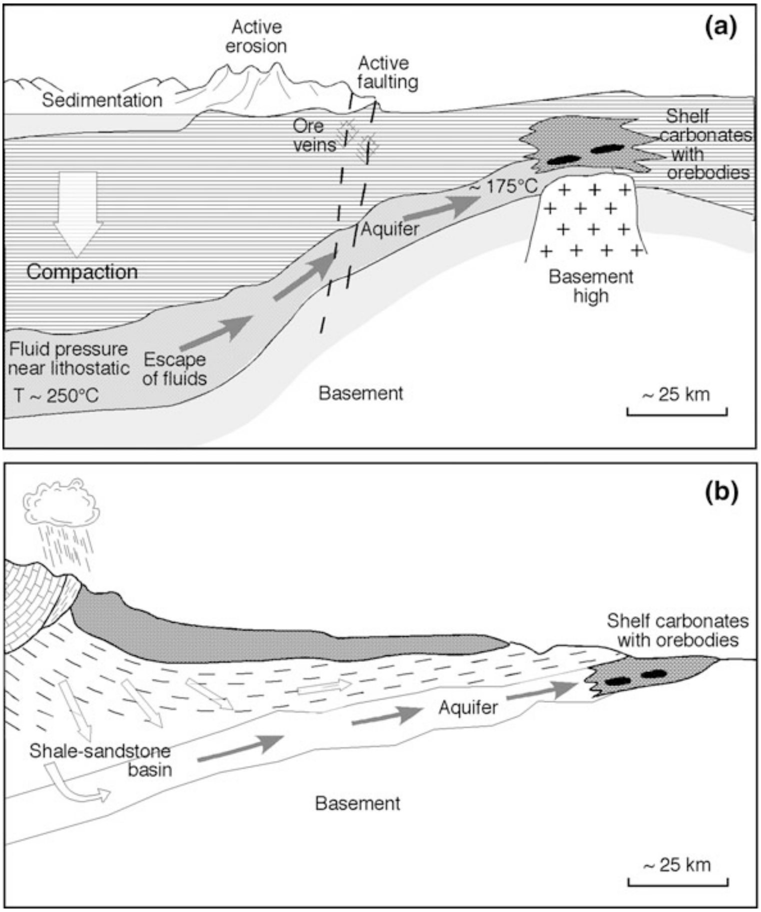


Fig. 4.14 Schematic illustration of the basinal geologic setting of MVT deposits showing possible fluid driving mechanisms (after Evans 1993)

foredeeps or in foreland thrust belts (Fig. 4.14). Ore districts are usually limited by geologic features such as facies changes from shale to carbonate at basin margins, large faults and basement highs. Most deposits are of Cambrian to Triassic age, with a few younger deposits of Cretaceous age in Algeria and Tunisia. Precambrian MVT deposits are relatively rare; the oldest are Brushy Park and Pering, which are hosted by the 2.6–2.3 Ga Transvaal Supergroup in South Africa and appear to have formed at about 2.0 Ga (Christensen et al. 1995; Leach et al. 2005).

MVT deposits are mineralogically simple; dominant minerals are sphalerite, galena, pyrite, marcasite, dolomite, calcite, and quartz. Barite and fluorite are abundant in a few districts such as Illinois-Kentucky and Sweetwater in the United States, but are absent from most. Cadmium is found in solid solution in sphalerite, and Ag is a rare constituent of galena, usually in complex solid solution with As or

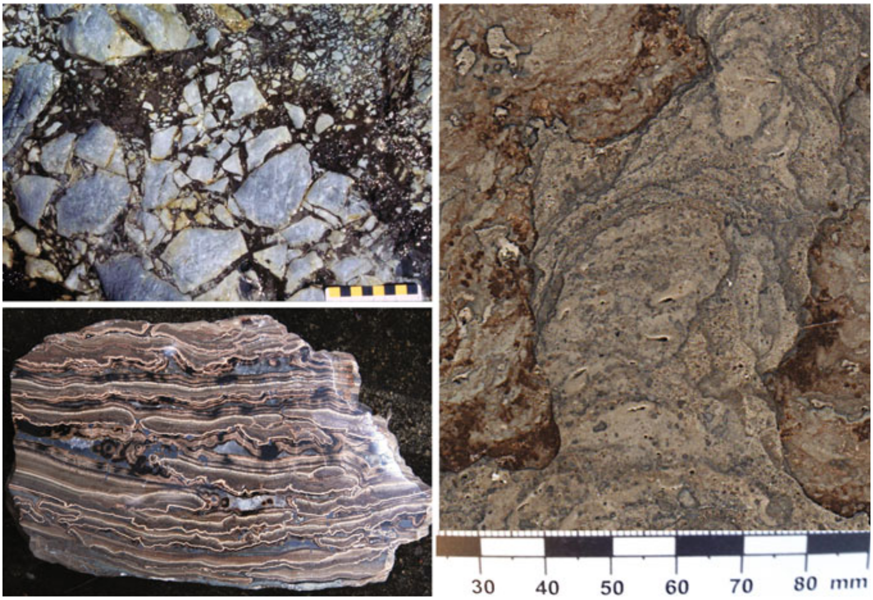


Fig. 4.15 *Top left* Breccia-hosted ore from the Robb Lake MVT deposit in Canada showing fragments of dolomite in a matrix of sphalerite and galena *Bottom Left* Colloform ore from the Cadjebut deposit in Australia. *Right* Sphalerite filling porosity around a stromatolite from the Viburnum Trend (photos by Chris Arndt and S. Kesler)

Sb. Sulfide mineral textures are extremely varied, ranging from coarse and crystalline to fine-grained, massive to disseminated. Banded (layered) and colloform structures typical of deposition in open spaces from fluids are found locally (Fig. 4.15). In some deposits, ore minerals and hydrothermal dolomite (called sparry dolomite) form alternating layers that can be correlated for great distances. In the Upper Mississippi Valley, growth layers within sphalerite were even correlated from deposit to deposit. One interpretation of these layers is that they represent successive pulses of fluid that were introduced into the deposits. Alteration associated with ore bodies consists mainly of host-rock dissolution and brecciation, dolomitization and the dissolution or recrystallization of feldspar and clay.

Origin: Some MVT deposits contain large crystals that were among the first to be studied for fluid inclusions. The fluid inclusion studies indicated relatively low ore temperatures for deposition of the host minerals (50–200 °C). Nevertheless, the temperatures were higher than would be expected for typical thermal gradients in the host sedimentary pile, and this suggested the possibility that they had come from deeper, warmer regions of the sedimentary basin. Salinities of the fluids ranged from about 10–30 % total dissolved solids consisting largely of Na–Ca–Cl brines typical of many sedimentary basins. Metal contents of the brines were surprisingly high, in the hundreds of ppm range. This is important because it places an upper limit on the amount of fluid that must have passed through the ore zones.

Na–Cl–Br compositions indicate that salinities were generated by both evaporation of seawater, probably in sabkha (salt flat) environments along basin margins, and by dissolution of evaporites. Pb and S isotopic data indicate that the metal and reduced S were derived from sedimentary rocks of the basin.

Even the mechanism that triggered the precipitation of ore sulfides in most deposits is well understood. Basinal fluids are relatively oxidized and they probably transported the metals as chloride or sulfate complexes. At the low temperatures typical of MVT brines, reduced S could be carried in the same solution only if the brine was relatively acid, a condition that does not appear to have prevailed in many deposits. Thus, it is generally agreed that deposition of MVT ores required an external source of S or that the sulfate in the metal-bearing brines was reduced at the site of ore deposition (Anderson 2008). Rocks that now host MVT ores appear to have provided just this sort of geochemical environment; they were reduced and contained abundant reductants in the form of hydrocarbons (oil or gas) and other organic material and supplied abundant H_2S causing precipitation of Pb and Zn sulfides. Platform carbonates are often highly porous, due to the presence of the breccias and cavities that develop during dolomitization, and the ores were precipitated in these cavities or in zones of reaction between the fluid and the carbonate rocks.

There has been considerable debate about the process that set these basinal fluid migrations in motion. Any process has to meet several requirements. Firstly, fluid inclusions indicate that ore minerals were deposited from fluids that were warmer than the surrounding rocks. Second, large amounts of water must have been moved to provide the metal, and the movement might have involved pulses of fluid. Finally, the large scale of most districts and the fact that there are many generally similar districts in some areas, suggests that the flow was probably on a regional to continental scale. Possible driving mechanisms for such large-scale fluid migration include topographic uplift and recharge, sediment compaction, orogenic squeezing, over pressured gas reservoirs, and thermal and density reflux drives. Of these, topographically driven flow, possibly related to collisional margin tectonism, is considered most likely to deliver anomalously warm fluids over long distances. In the United States, for instance, ages of deposits appear to have coincided with major mountain building events. The duration of the individual warm ore-fluid pulses seen in some deposits were probably too short to have been formed by these regional processes, and imaginative alternatives have been suggested to account for them, such as flooding of the basin by warm seawater following changes in the movement of major ocean currents or transgression following melting of continental ice caps.

Analysis: MVT deposits

Source of metals—detrital sedimentary rocks of the basin;
Source of S—biogenic H_2S derived from thermogenic or biogenic reduction of seawater sulfate, or sedimentary sulfide
Source of fluid—basinal water

Cause of fluid circulation—topographically driven recharge aided by compaction (?) and local changes in sea level(?)
Precipitation process—reduction of sulfate in the brine to H_2S at the site of ore deposition, or mixing of sulfate-bearing bring with H_2S in natural gas or other environment

Box 4.9 The Legacy of Pb

Pb was the first metal to be used on an industrial scale. It was used in plumbing and roofing by early societies including the Romans, and went on to be used in bullets, and to become the preferred metal for automobile batteries. The oxide of Pb, which is a dense, white powder, was also used as a filler in paints. More recently, it has been used as shield against nuclear radiation, as a weight in everything from scuba gear to sailboat keels, and most importantly, as an additive to gasoline to increase combustion efficiency of internal combustion engines. Pb is truly a versatile element, with the ability to help people in many ways.

Unfortunately, Pb is one of several elements that have no good biological function in humans and for which even small amounts are toxic. The wide use of Pb has spread it around the planet and put us in contact with it in many ways. Pb pipes added Pb to water, scaling paint left Pb-rich dust in old houses, and Pb emitted from gasoline engines entered the atmosphere and was scattered all over the world. Analyses of corals and from drill cores in polar ice and lake sediments provide a history of the global dispersal of lead. Ice cores from Greenland show that Pb contents rose from nearly nothing to reach levels of about 300 pg/g by 1970, almost 300 times higher than pre-industrial levels.

Fortunately, society has recognized the harmful role of Pb and we are gradually moving away from a Pb-polluting society. Pb emissions have declined in most parts of the world, especially because of removal of Pb from gasoline, although Mexico and other countries that were late to remove Pb from gasoline retained high Pb levels into the 1990s. Unfortunately, Pb polluted soil remains around roadways and old structures, especially in urban, often poor areas. If we do not do more to isolate this Pb from human contact, the legacy of Pb might include significant mental impairment, especially in children from these areas.

4.3.4.3 Sedimentary Rock-Hosted Stratiform Cu Deposits

Description: Sedimentary rock-hosted stratiform Cu deposits rank just behind porphyry deposits as a source of Cu and represent our most important source of mined Co. Although deposits are widespread, virtually all of the known Cu resource is in the Paleoproterozoic Kodaro-Udokan basin in Russia, the Neoproterozoic Katangan basin in Zambia and Democratic Republic of Congo (DRC) and the Permian Zechstein basin of northern Europe (Box 4.10). These deposits are essentially extensive sedimentary layers that are enriched in Cu, but they constitute actual mineable districts and deposits only where they are thick enough and contain a high enough grade. The largest single district is Lubin in Poland with 52 Mt of Cu, which is part of the Zechstein basin. The Katangan basin contains the most districts, including Tenke-Fungurume (36.7 Mt Cu, 3 Mt Co), Kamoa (28 Mt Cu) in the DRC and Konkola (22 Mt Cu) and Nchanga-Chingola (18 Mt Cu) in Zambia.

Total Cu contents of these deposits are about half of the amount that is found in large porphyry Cu deposits, but their average grades of 2–3.6 % Cu are much higher. Counterweighting the high grades is the fact that mining of the deposits must extend over much larger areas than for porphyry Cu deposits because the ore bodies are so thin. The Kamoa district in the DRC, which ranges in thickness from 2 to 15 m, occupies an area of 81 km^2. Mining is particularly challenging in areas where the layers are folded and open-pit operations must remove very large amounts of overburden to reach deeper ore. In addition to Cu and Co, some deposits are enriched in Pb, Zn, Ag, U and Au. White Pine, a smaller deposit of this type in the Keweenaw basin around Lake Superior in the United States, contained only 8 Mt of Cu, but almost 900 M oz of Ag and produced a special type of Cu known as “lake Cu”, prized for its high electrical and thermal conductivity.

Stratiform sediment-hosted Cu deposits are found in intracontinental rift-related or, more rarely, passive margin sedimentary sequences containing oxidized basal red beds and volcanic rocks overlain by or interbedded with reduced shales and carbonates of marine or lacustrine origin and, in some basins, with a cap of evaporites (Hitzman et al. 2010). Cu mineralization is found in two main settings. Most commonly, it is located at the contact between underlying oxidized and overlying reduced rocks. Less commonly, it is found in the red beds surrounding zones containing plant debris, bitumen and other possible reductants. Actual ore consists of very fine-grained Cu minerals including chalcocite, bornite and chalcopyrite, either in veinlets or disseminated through the rock. In some cases, it is part of a regional-scale zonation ranging from hematite through Cu sulfides to Pb–Zn sulfides and pyrite. Sulfides are hosted by veinlets or replace earlier, possibly diagenetic, pyrite that varies from disseminated through framboidal to laminated and that clusters around possible reductants such as fossils and carbonaceous material. Where original textures are preserved, replacement ore in fine-grained shales adopts the sedimentary textures of the parent rock. This made it very difficult to determine the origin of these ores until larger-scale studies located the replacement front between original pyrite- or organic-rich rock and mineralized Cu-bearing rock. In the Katangan basin, in particular, determination of original textures and understanding of paragenesis is complicated by deformation and greenschist facies metamorphic overprints, and by the likelihood that more than one fluid event affected the deposits.

Origin: The fine-grained nature of the ore and the lack of transparent minerals has complicated fluid inclusion studies that might provide information about the mineralizing fluid. Available observations indicate temperatures of 50–400 °C and salinities of 5–30 % total dissolved solid, with most of the high temperatures coming from the Katangan basin. These ranges are improbably large and probably reflect overprinting of an original basinal fluid at temperatures of 100–200 °C by a hotter fluid related to deformation. Theoretical and experimental studies suggest that Cu can be carried in oxidized brines at relatively low temperature, and genetic models have been developed based on this information. According to these models, basinal fluids leached metals from underlying red beds or from underlying granitic basement where sufficient red beds were not present, as in parts of the Katanga basin. The fluids deposited metals where they underwent reduction by reaction with pyrite, organic matter, oil or natural gas or by mixing with H_2S generated by reduction of sulfates in the sediments or derived from a second fluid. S isotopic analyses show a very wide range of values from strongly negative to positive, which probably reflects biogenically reduced seawater sulfate. As for SEDEX deposits, there is considerable debate about the driving force and timing for basin water circulation, although recent isotopic measurements appear to confirm that circulation took place very shortly after original sedimentation.

Analysis: Sedimentary rock-hosted Cu deposits

Source of metals—detrital sedimentary rocks of the basin;
Source of S—biogenic reduction of seawater sulfate, including replacement of diagenetic pyrite
Source of fluid—basinal water
Cause of fluid circulation—topographically driven recharge aided by compaction(?) and local changes in sea level(?)
Precipitation process—reduction of sulfate in the brine to H_2S at the site of ore deposition, or mixing of sulfate-bearing bring with H_2S in natural gas or other environment

Box 4.10 Kupferschiefer in Central Europe and the Central African Copperbelt

The Kupfershiefer stratiform sediment-hosted Cu district is part of the Zechstein basin, which covers an area of about 800,000 km^2 in central Europe. Economically important Cu mineralization of the Kupferschiefer district occupies only about 0.1 % of this area along the southern margin of the basin in Germany and adjacent Poland. Deposits of the Kupferschiefer have been mined more or less continuously since the Middle Ages, and they were mentioned in the 16th century by Georgius Agricola, who laid the foundation for the systematic and scientific study of geology and mining. His remarkable book *De Re Metallica*, published in 1556, describes miners and mining of deposits in the Kupferschiefer. He notes, for example, a spatial relationship between bituminous shales and the Cu mineralization, anticipating, by over five hundred years, modern ideas of ore formation.

The history of exploitation of the deposits of the Copperbelt in Zambia (initially Northern Rhodesia) and the Democratic Republic of Congo provides some interesting, and troubling, lessons. During much of the 20th century, the deposits were the backbone of the economies of what were then British and Belgian colonies. Up until the 1970 s the mines were run efficiently (though most of the wealth went to the colonial rulers) and their presence fueled economic hopes for the post-colonization period. Their importance was severely diminished, however, by a crash in global Cu prices in 1973, compounded by nationalization of the Cu mines by governments of the newly independent nations. During the following 30 years, production in these enormous and rich deposits fell almost to zero as a result of corruption, neglect and mismanagement. Only at the beginning of the 21st century has mining revived, hopefully initiating a new period of economic development.

4.3.4.4 U Deposits

U is very different from the other elements discussed in this chapter: it is an energy source, and not a metal used in industry or finance like Cu, Zn or Au; and because it is radioactive and used in bombs and nuclear reactors, it is the target of the ire of some environmentalists (a moustachioed French politician who became famous for tearing down a MacDonald's and brandishing his roquefort cheese at anti-capitalism demonstrations, learned his trade in anti-nuclear protests). U forms a wide variety of deposits, some of which are described in Table 4.3. Those in magmatic rocks and in purely sedimentary settings are mentioned in other chapters; here we discuss just two types, unconformity-related deposits and sandstone deposits, both of which formed from hydrothermal fluids. Together, these two deposit types account for just above 50 % of world U production and resources.

These two deposit types have an unusually wide range of grades, from very low to very high. Some of the richest are the unconformity-related deposits in the Athabasca Basin in Saskatchewan, Canada. These deposits are not large, usually less than one million tons of ore, but their relatively small size is compensated by high grade. Cigar Lake contains only about 875,000 tons of ore but the average grade is 17.4 % U_3O_8 (U ore grades are quoted in this compound, which is known as

Table 4.3 Types of uranium deposits

	Age	Grade	Percent of global U resources	Geological setting and characteristics	Important deposits or districts
Unconformity-related	Proterozoic	0.4–24 %	30	Near unconformity at base of clastic sedimentary basin	Athabasca Basin (Canada), McArthur Basin (Australia)
Sandstone	Paleozoic-Cenozoic	0.05–0.4 %	15	Continental fluvial or marginal marine sandstones	Wyoming Basin (USA), Colorado Plateau (USA), Central Europe, Kazakhstan
Quartz-pebble conglomerate	Paleoproterozoic	0.01–0.15 %	10	Basal conglomeratic zones in clastic sequences	Witwatersrand (S Africa), Elliot Lake (Canada)
Iron-oxide copper-gold	Proterozoic	0.04–0.08 %	40	Hematite-rich granite breccia	Olympic Dam (Australia)
Intrusion-associate	Proterozoic	0.03	5	Veins in leucogranite	Rossing (Namibia)
Volcanic	Precambrian to Cenozoic	0.02–0.2 %	<1	Veins and breccias in felsic to intermediate volcanic rocks	Streltsovskoye (Russia), Dornod (Mongolia)
Surficial (calcretes)	Tertiary to Recent	0.15	5	Near-surface concentrations in alluvium, soils or sediments	Yeelirrie (Australia)

yellowcake) and McArthur River has about 1 million tons with an average grade of 16.4 %. In addition to U, these deposits contain Ni, Co, As, Pb, Au, Pt, Cu and REE, sometimes in recoverable amounts and sometimes dominating the economics, as at Serra Pelada (Berni 2014). Similar deposits in the Northern Territories of Australia, are larger, reaching almost 20 million tons, but have far lower grades, averaging 0.4 % U_3O_8. Sandstone U deposits are smaller in all respects. Even the large deposits commonly contain only about 10 Mt of ore with grades of only about 0.25 %.

You might think that the ultra-high grade Athabasca deposits would dominate the U market, but their mining has been complicated by major problems ranging from massive flooding of the mines to the need for remote controlled operation in areas with high radiation. Mining turns out to be a big factor in the economics of U; some small deposits with grades of only 0.1 % U_3O_8 that are mined by in situ solution methods are able to compete with the high-grade deposits. Finally, we cannot forget the Olympic Dam deposit, an IOCG deposit that is discussed in a later section of this chapter. Olympic Dam contains a full order of magnitude more U than the largest of the U deposits, but the U is a by-product and the mining operation cannot respond as readily to changes in demand.

Description: Unconformity-related and sandstone U deposits can be discussed together because they are very similar in mineralogy and mode of origin. The primary U ore mineral in both types of deposit is uraninite (UO_2) or pitchblende (UO_3, U_2O_5). Other U minerals include carnotite $K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$) and complex oxides or titanates rich in rare trace elements such as davidite-brannerite-absite, and the euxenite-fergusonite-samarskite group.

Unconformity-related deposits are found in and below Proterozoic-age intracratonic basins such as the Athabasca Basin of Canada and the Kombolgie Basin in Australia. They get their name from their close association with the unconformable contact between basal conglomeratic sandstones in the basin and underlying metamorphosed basement rocks. In fact, some deposits are above, some are at, and some are as much as 400 m below this basal contact, although the highest-grade deposits are generally at the contact. One of the first of these deposits to be discovered, at Rabbit Lake in Saskatchewan, was in basement rocks below the unconformity in an area where the basin had been removed by erosion, a setting that complicated early views of how the deposits formed. Deposits consist of pods, veins, breccia bodies and semi-massive replacements of uraninite (Fig. 4.16a). Alteration around the deposits includes a clay cap with accessory hematite, illite and chlorite, as well as either silicification and introduction of tourmaline, or quartz dissolution and collapse brecciation. One possible reason for the large variation in alteration mineralogy and zoning appears to be direction of flow of the mineralizing fluids. U–Pb analyses of uraninite and Ar–Ar analyses of associated illite show that the Athabasca and Kombolgie deposits formed about 150 million years after deposition of the host basin, and that U was remobilized and enriched locally during several intervals after that (Cuney and Kyser 2009; Richard et al. 2011).

Sandstone U deposits are found in medium to coarse-grained sandstones that were deposited in a continental fluvial or shallow marine sedimentary environment. They are particularly well developed in the Powder River Basin and Colorado

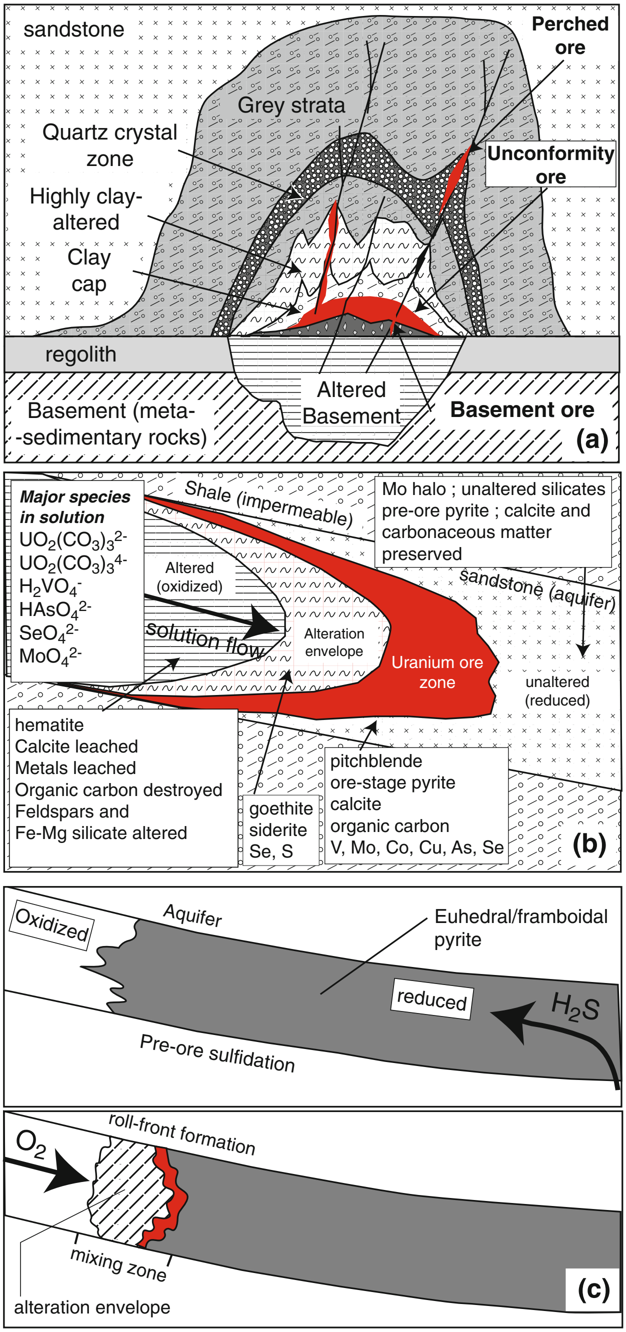


Fig. 4.16 Schematic illustration of geologic features and processes that form uranium deposits **a** unconformity, **b** roll-front, **c** gas-related roll-front (modified from Jefferson et al. 2008; Robb 2005)

Plateau of the western United States. There are two main types, referred to as "tabular" and "roll-front" deposits. In the tabular type, U mineralization is concentrated along the margins of impermeable shale or mudstone units that are interbedded in the sedimentary sequence. In roll-front deposits, U mineralization forms an arcuate front that appears to be flowing down dip in a sandstone layer or sequence of layers. In both types of deposits, the U concentrates along what were originally redox boundaries between oxidized and reduced rocks. The redox control is especially clear in a few deposits where U ore concentrates in and around plant debris ranging from logs to leaves. In the case of roll-front deposits, the layer up-dip from the deposit contains hematite whereas the same layer down-dip from the deposit contains pyrite and other reduced phases (Fig. 4.16b).

Origin: The key to the formation of both types of deposits is the vastly different solubility of U in oxidized and reduced fluids. U occurs in two valence states, the reduced form U^{4+} and the oxidized form U^{6+}. The latter is highly soluble in oxidized fluids where it forms stable complexes with fluoride, phosphate or carbonate ligands; in this condition it is readily transported in the oxidized fluids that circulate in sedimentary basins. The reduced form, in contrast, is highly insoluble, such that when an oxidized fluid comes into contact with a reductant, the U precipitates.

Fluid inclusions show that unconformity-related deposits formed from fluids in the 100–200 °C range with salinities of about 25 % total dissolved solids, which are interpreted to be basinal brines. Inclusion evidence for fluid types in sandstone-type deposits is poor, but the setting of the deposits suggests that it was dominantly low-salinity fluids of basinal or meteoric origin. It is possible that these two fluid types are simply end members of a continuum of fluids that formed sandstone and unconformity-related deposits. Both types of water are oxidized and leach U from detrital minerals such as monazite, allanite and apatite, which were derived initially from granites of the basement. Deposition takes place when this oxidized fluid contacts a reduced fluid in the basement rock or around reduced sediments or organic matter. The U minerals initially precipitate at the front between the two fluids, which continues to migrate down and along the sandstone layer (Fig. 4.16b). As it moves it sweeps up the dispersed U in the reduced material concentrating it at the redox front, thus creating a richer and richer deposit. In some roll-front deposits, deposition takes place when downward migrating solutions contact H_2S gas migrating upward from deeper levels of the basin (Fig. 4.16c).

Analysis: Unconformity-related and sandstone U deposits

Source of metals—leached from surrounding granitic rocks or detritus
Source of fluid—meteoric or basinal
Cause of fluid circulation—small-scale basinal flow, usually recharge down dip
Precipitation process—reduction of solution caused by mixing with reduced fluid or contact with reduced sediment or organic matter

4.3.5 Metamorphic Hydrothermal Systems—Orogenic Au Deposits

Description: Orogenic Au deposits derive their name from their setting in accretionary, collisional, continental margin orogenic zones where they generally form following the peak of metamorphism. They are the most widespread of Earth's hydrothermal Au deposits, both in time and in space, and are estimated to have supplied about 30 percent of world Au production.

Some of the best known deposits and districts in the world are members of this class, including the Ashanti (68 Moz) in Ghana, the Golden Mile (64 Moz) in Australia, Homestake (39 Moz) in the United States, Sukhoi Log (34 Moz) in Russia, McIntyre-Hollinger (32 Moz) in Canada and Morro Velho (22 Moz) in Brazil. The largest of these deposits is Muruntau in Uzbekistan, with over 170 Moz (Morelli et al. 2007). All of these districts contain more than one deposit, although the number of deposits is surprisingly small. For instance, as Muruntau, at least three separate ore bodies (Muruntau, Besopan and Miutenbai) occupy a single silicified zone that is about 10 km long and 1–3 km wide. Orogenic Au deposits were the source of Au in Phanerozoic-age placer deposits in California, USA and Victoria, Australia, and smaller uneconomic deposits of the same type were probably the source of placer Au in the Klondike in Canada. In fact, recent exploration in unglaciated areas south of the Klondike have found interesting vein systems of this type. They have also been considered as a possible source for the Witwatersrand and similar Archean and Paleoproterozoic paleoplacer deposits, as discussed in the next chapter.

Average grades of large orogenic Au deposits range from about 0.08–0.8 opt and the entire group has an average grade of about 0.28 opt. These deposits have been mined over many decades, however, and the average grade is not representative of modern mining. Deposits that are being mined today have grades of about 0.2–0.3 opt for underground and less than 0.1 opt for open pit operations.

Orogenic Au deposits that are exposed at the surface have been mined to depths of more than 2 km in some places, and the maximum vertical extent of large orogenic Au systems is probably about 3 km. Pressure estimates suggest that the deposits form at depths in the crust ranging from about 4–18 km and averaging about 10 km. The fact that they formed at such deep crustal levels makes them difficult to remove by erosion. Thus, whereas epithermal and Carlin-type Au deposits are rare in Precambrian and older Phanerozoic rocks, orogenic Au deposits are very common. They are particularly widespread in rocks that formed during Phanerozoic and latest Precambrian (47–850 Ma), middle Proterozoic (1730–2090 Ma) and Archean (>2500 Ma) time when global orogenic activity was greatest.

Most deposits are hosted by metamorphosed mafic to intermediate volcanic and related sedimentary rocks in what are referred to as greenstone or metavolcanic belts, often at or near the transition from greenschist to amphibolite facies (Goldfarb et al. 2005). The deposits are in veins that are associated with continental- to

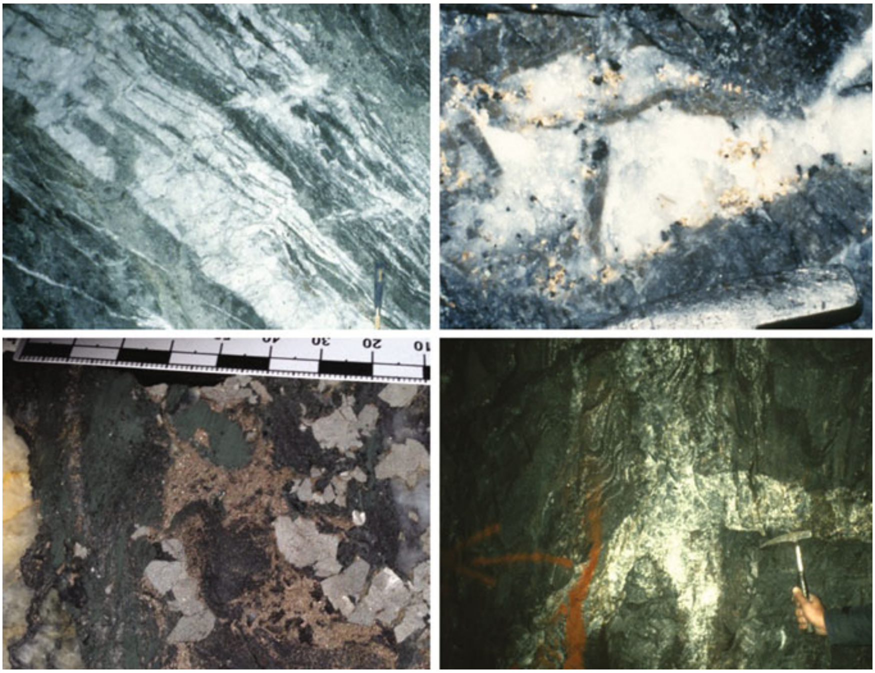


Fig. 4.17 Orogenic gold deposits. Sheeted (crack-seal) vein *top left* and very high-grade pod of gold ore that occupies a jog in crack-seal vein *top right* from the Pamour mine, Porcupine district, Ontario. Hammer in lower right provides scale in both photos. *Bottom left* Pyrrhotite and arsenopyrite formed by sulfidation of wallrock around vein (white material on left) at the Homestake deposit, South Dakota. *Bottom right* Vein at the Lupin mine, Northwest Territories, Canada, showing a vertical vein cutting an earlier horizontal vein indicating transient supralithostatic pressures (photos by S. Kesler and E. van Hees)

regional-scale transcurrent fault zones, where they occupy second- and third-order branches. Individual vein systems have a maximum horizontal extent of about 8 km and districts containing several veins can extend for tens of kilometers. Deposits at the top of the 4–18 km depth range consist of breccia zones and stockworks and those at greater depth include crack-seal veins reflecting episodic fluid injection probably caused by fluid overpressures (Fig. 4.17a). Although most veins are vertical or steeply dipping, horizontal veins that are present locally probably resulted from these overpressures (Fig. 4.17d).

By far the most important vein mineral is quartz with lesser amounts of carbonate and two to five percent sulfides, mainly pyrite and arsenopyrite with minor base-metal sulfides, and local tellurides and scheelite. Au is present in the veins largely as electrum that averages about 90 % Au and it can form small, but very high-grade concentrations that appear to be largely controlled by structural features (Fig. 4.17b). Alteration surrounding the veins includes large amounts of Ca–Mg–Fe carbonate that replaced silicate minerals, and alkalis that formed feldspar or micas.

Minor but important amounts of S, As and B were also introduced, replacing original mafic minerals with pyrite or arsenopyite and forming tourmaline. Au is commonly associated with these alteration sulfides and can be ore-grade in banded Fe formation or mafic wallrocks.

Origin: The fluid inclusion record for most orogenic Au deposits has been complicated by later deformation and fluid flow, although careful work has converged on some general characteristics. Most importantly, the fluids were a mixture of H_2O and CO_2 with minor CH_4 and H_2S. Although most inclusions are H_2O-dominant, the relatively common presence of CO_2-rich inclusions suggests that the fluid underwent episodic boiling or immiscibility. In some deposits, pseudosecondary planes host coexisting CO_2-rich inclusions and blebs of Au suggesting an association between boiling and Au deposition. Temperatures ranged from about 250–400 °C with Phanerozoic deposits at the lower end of the range and Archean deposits at the upper end, perhaps because the Archean crust was warmer. On the basis of these observations it appears that the main processes that deposited Au in these deposits were sulfidation and boiling or immiscibility. Sulfidation was clearly important in Fe-rich wallrocks and probably in veins that were enclosed by them (Fig. 4.17c). Boiling (or, more appropriately phase separation) was most important inside the veins, as indicated by high concentrations of Au in small jogs or other openings in the veins (Fig. 4.17b), as well as by the identification of CO_2-rich inclusions in native Au.

The source of the orogenic Au mineralizing fluid and its dissolved constituents is not as well defined, although there has been a general convergence toward a metamorphic source. Isotopic tracer studies yield ambiguous results. Analyses of quartz and carbonate minerals and fluid inclusions indicate that the fluid had $\delta^{18}O$ values of 6–13 ‰ and δD values of −20 to −80 ‰, and vein-hosted sulfides have $\delta^{34}S$ values with a wide range of values, mostly between 0 and 10 ‰. Unfortunately, most of these isotopic compositions could have been derived by equilibration of the fluid with surrounding wallrocks, a conclusion that is in agreement with other isotopic and element tracer analyses. In the absence of control from tracer studies, models for fluid source have been based largely on geologic relations in the deposits and surrounding terranes. The main suggestions include: (1) metamorphic fluids released by prograde reactions that accompany greenschist through granulite facies metamorphism, (2) magmatic fluids from deep granitic intrusions, (3) CO_2-rich fluids from a mantle source, and (4) deeply circulating meteoric water.

Although all models have their adherents and supporting observations, prograde metamorphic devolatilization seems to answer more questions more simply. H_2O is released by conversion of clays and micas to feldspars or chlorite to amphibole, CO_2 can be released by conversion of carbonate minerals to calc-silicates, and H_2S can be released by the breakdown of pyrite to pyrrhotite, and the breakdown of other sulfides to oxides and silicates. Finally, analyses of metamorphosed rocks and their unmetamorphosed protolith show that Au, As, Ag, Sb, Mo and W are lost at about the same time that pyrite and other sulfides break down, probably because these metals were present in the sulfides (Pitcairn et al. 2006). The location of many deposits at or near the greenschist-amphibolite facies boundary in their host rocks is further support for the role of metamorphic devolatilization. Despite the apparent favorability of this model for most deposits, other fluids might be involved. The most obvious possibility includes deposits in Alaska such as Donlin Creek, which are closely associated with relatively shallow, felsic intrusive rocks.

Analysis: Orogenic Au deposits

Source of metals—metamorphic devolatilization, possible local magmatic
Source of S—same
Source of fluid—same
Cause of fluid circulation—supra-lithostatic pressures and release at brittle-ductile transition
Precipitation process—boiling/phase separation and sulfidation of Fe in host

4.3.6 Transitional Hydrothermal Systems

Introduction: Classification of hydrothermal systems according to their fluid type provides insights about the difference among mineralizing processes, but also shows that many systems have overlapping characteristics. In most cases, one fluid source seems to be dominant, even if it might not have been the source of all of the ore constituents. In this section, however, we encounter two important ore deposit types that just do not fit into our categories, either because they are clearly transitional in character or because we do not have enough information to be sure of their classification.

4.3.6.1 Carlin-Type Au Deposits

Description: Carlin-type Au deposits, although found almost exclusively in Nevada, are extremely important sources of Au, accounting for about 8 % of present global production. The deposits range greatly in size and grade but include some of the largest or highest grade hydrothermal Au deposits in the world, including Post-Betze-Screamer, which is a single continuous body that contains about 44 Moz Au, Gold Quarry (20 Moz) and Twin Creeks (16 Moz). These deposits are very poor in Ag, but have significant amounts of As, Sb and Hg, of which only Hg is recovered. Grades vary from only 1 g/t to as high as 20 g/t in some deposits. Smaller Carlin-type deposits have also been found in China and Iran, but none rival the Nevada deposits in size or grade (Cline et al. 2005).

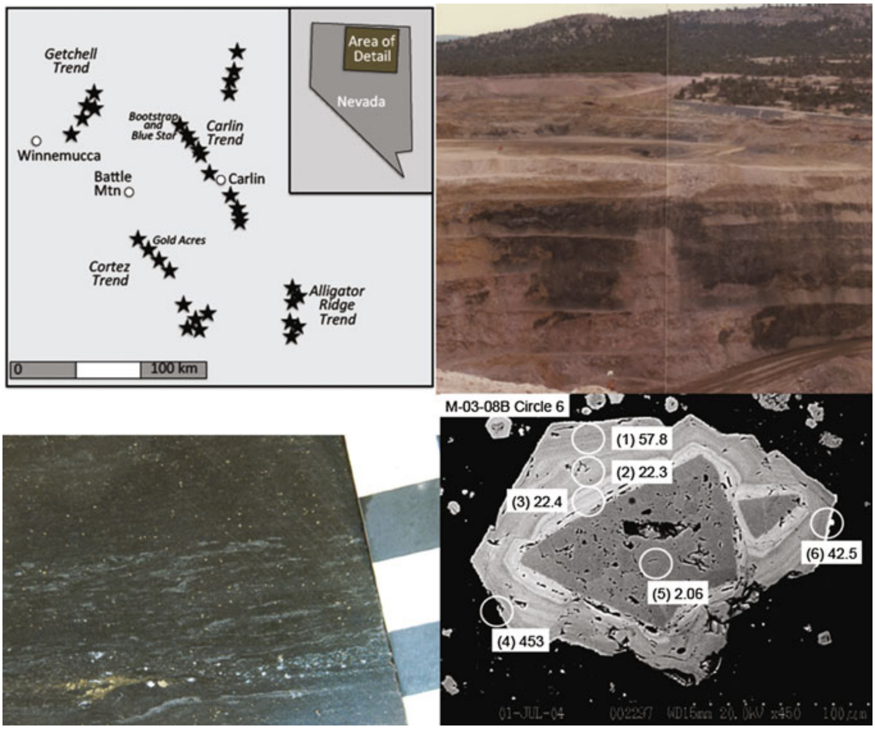


Fig. 4.18 Carlin gold deposits. *Top Left* Map showing linear distribution of Carlin-type deposits; *Top Right* View of the Vista 1 Pit at Alligator Ridge showing oxidized ore (*light color*) below sulfide ore (*dark color*), apparently formed by rising meteoric water. *Lower Left* sample of ore from the Betze-Post-Screamer deposit consisting of layered carbonaceous sediment with minor pyrite; *Lower Right* SEM BSE image of pyrite grain from the Meikle Carlin-type deposit (grain diameter 200 μm) showing central core with no arsenic surrounded by later pyrite with growth zones containing different amounts of arsenic (increased arsenic indicated by *lighter gray*). Gold contents in parts per million determined by SIMS analyses are shown in circles. Note very low gold values in core and higher values in arsenic-rich overgrowth (photos by S. Kesler and Z. Ye; Au analyses by S. Chryssoulis)

The Carlin-type deposits in Nevada are found in a sequence of Paleozoic sedimentary rocks along the western margin of the ancestral North American continent. Their distribution is amazingly linear, with most of the deposits clustered along four linear zones that might be reactivated basement rift structures (Fig. 4.18a). This area has undergone a series of Mesozoic and Cenozoic-age orogenic and magmatic events, and determining the relation of these to mineralization was a major challenge because of the lack of easily dateable material in the ore. It is now generally agreed that most mineralization took place during Eocene time, when the region was undergoing extensive intrusive and volcanic activity.

Despite their large size and locally high grades, most Carlin-type ore samples are among the least attractive and most deceptive in all of geology. To the unpracticed eye, a good ore sample, grading more than 1 oz of Au per ton, looks like a fine-grained, carbonaceous mudstone (Fig. 4.18b). On closer look, fine-grained pyrite might be visible and the rock would appear to be slightly porous, with a tendency to absorb water. Compared to similar rock in the immediate vicinity that did not contain Au, the rock would be distinctly lower in carbonate and possibly higher in clay minerals. Microscopic examination would show that original sedimentary carbonate minerals in the mudstone have been dissolved, that original silicate constituents have been argillized and silica has been added to the rock locally. Higher-power microscopy would show that the pyrite has been variously recrystallized and overgrown, that new pyrite has been added locally. In fact, the pyrite is an unusually As-rich variety known as arsenian pyrite and the Au is almost entirely in solid solution in the pyrite (Reich et al. 2005), a process that is aided by incorporation of As into the pyrite lattice (Fig. 4.18c). In some places, orpiment, realgar and stibnite are also present, but they are not usually strongly correlated with increased Au grades. Other elements, including Ag, Cu, Hg, Sb, Te and Tl are also present in the Au-bearing pyrite.

The resulting Carlin-type ore deposits are zones of carbonaceous carbonate rock that have been partly to totally decarbonated (remember that decarbonated means that carbonate has been removed; it does not mean that reduced carbon in organic matter has been removed), argillized and silicified and in which Au is hosted almost entirely by pyrite. They are located in what appear to be favorable horizons in the Paleozoic sequence, in most cases below a regional thrust fault where a combination of appropriate lithology and possible overlying zones that impeded the flow of hydrothermal fluids led to extensive mineralization. Carbonate that was leached from the rocks forms swarms of veinlets surrounding some deposits, and silicification, including complete replacement of limestone to form jasperoid, is common in others. Neither is a particularly dependable guide to ore. Structural control of mineralization is apparent at the ore deposit scale, where faults appear to have fed solutions upward into the ore zone; the large Post-Betze-Screamer deposit extends outward from the prominent Post fault.

Box 4.11 Exploration for Carlin-type Au Deposits

The Carlin Au story began in the late 1930s, when U.S. Bureau of Mines geologists reported ore that was indistinguishable from waste rock at the Gold Acres mine, which was in what would become the Cortez Trend. In 1946, Au was found in Sb ore from the Bootstrap mine at the north end of what would become the Carlin Trend. Prospecting and small-scale mining in the area during the 1950s showed the potential for Au in what looked like barren rock, especially at the Bootstrap and nearby Blue Star deposits. Then, mapping in northern Nevada by Ralph Roberts and other USGS geologists recognized a regional thrust fault overlying carbonate rocks with extensive silicification, which provided a geologic framework for exploration. In 1961, John Livermore and Alan Coope of Newmont found widespread Au values of at least 1 g/t in grab samples of rock that ranged from silicified to porous.

In 1962, after much mapping and sampling, the third hole above the Carlin deposit intersected ~30.5 m averaging slightly more than 31 g/t Au. Follow-up sampling recovered surface material grading as much as 62 g/t that outlined the up-dip extension of the Carlin deposit. That rock outcrops with such high grades could have remained undiscovered until the 1960s is a testimony to the "invisible" nature of Carlin Au. A longer history of this process, written by Alan Coope is available at http://www.nbmg.unr.edu/dox/sp13.pdf

The Carlin discovery stimulated exploration that has discovered more than 1,500 tons of Au in at least 26 deposits along the Carlin-trend and at least as much in the other trends elsewhere in Nevada. Recognition of these trends has led to widespread application of "trendology" in exploration in northern Nevada, which has been surprisingly effective. As the price of Au has increased and assays have become more sensitive, the trends continue to grow.

Origin: It has been hard to gather information on the exact nature and source of the Carlin mineralizing fluid because the fine-grained ore is difficult to study by conventional methods. A few deposits contain quartz that is sufficiently coarse-grained to allow fluid inclusion study, and these indicate temperatures of about 180–240 °C, which is generally consistent with the stability range of sulfide mineral assemblages (Lubben et al. 2012). The lack of evidence for boiling requires emplacement at depths of at least 3 km. (This is slightly deeper than epithermal deposits and accounts for their older ages and greater preservation.) Fluid salinities were low, probably less than 4–6 equivalent weight percent NaCl, and CO_2 contents were also low, probably below a few mole percent. Unfortunately, this information presents us with a rather generic set of data that could point to many origins, and isotopic analyses do not resolve the uncertainty. Oxygen isotopic analyses of the quartz yield a wide range of values from at least 0–25 ‰ that are interpreted to indicate multiple sources or mixing of an ore fluid with a resident fluid, and S isotope values of −4 to +13 ‰ permit either a magmatic or sedimentary source.

At this stage, it is generally agreed that Carlin-type deposits formed when a relatively acid fluid invaded reactive carbonate-rich sedimentary rocks. The fluid dissolved carbonate, argillized silicate minerals and deposited Au. The main questions that remain concern the source of fluids and Au and the mechanism of deposition. The source question has converged on various combinations of magmatic and sedimentary. In the simplest magmatic model, the main mineralizing fluid separated from a parent magma at depths of about 10 km and then differentiated into a vapor containing Au and brine containing iron (Muntean et al. 2011). The vapor then moved upward away from the brine, and the absence of Fe in the vapor allowed it to cool without causing deposition of pyrite, a process that would have stripped Au from the solution. In the opposing sedimentary model, Au was released from diagenetic pyrite in carbonaceous sedimentary rocks by fluids of unspecified origin, possibly magmatic, metamorphic or sedimentary (Large et al. 2011). Many deposits in China, which are hosted by sedimentary basins with no evidence of igneous activity, are especially amenable to a model involving basin fluids. Both models allow for extensive mixing with meteoric water during later stages of mineralization.

Deposition of Au probably involved a combination of several processes. The main possibilities are mixing with resident meteoric waters and reaction with surrounding rocks. The main reaction with surrounding rocks is thought to have involved sulfidation. In some deposits, sulfidation is clearly indicated by Fe–S relations. Analyses show that almost all Fe in high-grade Au ore is in pyrite, whereas much of the Fe in barren rock is in original sedimentary minerals. Because high-grade and barren samples contain the same amount of total Fe and the only site for S in both rocks is pyrite, S must have been introduced to the rock, taking up Fe to form pyrite. If Au were transported as a bi-sulfide complex in the sulfidizing solution, this would have deposited Au. In other deposits, Fe–S relations are not as clear, and Fe for sulfidation and Au deposition might have been introduced by a second fluid, making the process essentially fluid mixing. Regardless of the exact depositional mechanism, the presence of Au in solid solution in pyrite (rather than in native Au) means that Au was probably deposited from a solution that was undersaturated with respect to native Au. This would have made the mineralizing process more effective and might account for the large size and relatively high grade of Carlin-type deposits. It also suggests that any process that stabilizes arsenian pyrite in the presence of a solution with even a low Au concentration could make a Au deposit.

So, at this stage in our understanding, Carlin-type deposits must be classified as hybrid. Not only are we debating the source of the main fluids involved in their formation, but we are also uncertain about the source of their main metal, Au.

Analysis: Carlin-type deposits

Source of metals—either magma or pyrite in carbonaceous shales
Source of S—possibly Fe in the wallrocks, whether proximal or distal
Source of fluid—magma or sedimentary (basinal) with possible meteoric involvement
Cause of fluid circulation—deep magma or basinal processes
Precipitation process—sulfidation of Fe in host rocks aided by mixing, dilution and cooling

4.3.6.2 Iron-Oxide Cu Au (IOCG) and Iron-Oxide Apatite (IOA) Deposits

Description: Hydrothermal deposits with abundant Fe oxide and locally abundant Cu, Au or U have been known for many years but it was not until discovery of the giant Olympic Dam deposit with 78 Mt Cu, 94 Moz Au and 2 Mt U in South Australia (Box 4.12) that geologists began to see enough similarities among deposits of this type to put them into a new IOCG classification. Unfortunately, the new class attracted so many deposits that, by the start of the 21st century, the new IOCG class had a disconcertingly wide range of characteristics.

At one apex of this spectrum of deposits was Olympic Dam, which is in a funnel-shaped, hematite-rich hydrothermal breccia that formed close to the surface through progressive, polyphase fracturing and alteration of the upper part of a granitic intrusion. The deposit contains over 30 varieties of Cu, U, Au, Ag, Ni, Co sulfides, sulfosalts, oxides, carbonates and native metals in veins, disseminations, irregular patches and breccia fillings associated with intense calcic-sodic, Fe and potassic alteration.

At another apex was the giant Kiruna Fe deposit (864 Mt Fe) in Sweden, which consists almost exclusively of magnetite and apatite, with no Cu or other metals. Kiruna has the form of several lenses that parallel layering and local tectonic trends in a sequence of Proterozoic-age intermediate to felsic volcanic rocks. Although the host rocks and deposit have undergone low- to medium-grade regional metamorphism, it appears to be surrounded by hydrothermal alteration consisting now of assemblages containing chlorite, biotite, amphibole and fluorapatite. The only obvious intrusive rock in the vicinity is younger than mineralization, as indicated by the presence of xenoliths of massive magnetite-apatite ore.

Somewhere between these apices were deposits such as Vergenoeg (55 Mt Fe) in South Africa, where a fluorite-fayalite-ilmenite-magnetite pipe with minor sulfides and REE enrichment cuts granites of the Bushveld Complex, South Africa, and Raul-Condestable (425 Kt Cu, 238 Koz Au) in Peru, where massive magnetite with Cu-sulfides and minor Au is associated with albite-scapolite-amphibole-hematite alteration. Vergenoeg has an uncertain relation to Bushveld granites, whereas Raul-Condestable is directly adjacent to a possible source intrusion.

Recently, opinion has converged on a more restricted view that these deposits can be divided into two groups (Groves et al. 2010). The iron-oxide apatite (IOA) group includes Kiruna and Malmberget in Sweden, Pea Ridge and Benson Mines in Missouri, El Laco in Chile and Cerro Mercado in Mexico. These deposits are characterized by massive magnetite and apatite hosted by felsic volcanic rocks ranging from submarine to subaerial. Associated hydrothermal alteration is present but not intense and not clearly zoned. The other group, known as IOCG deposits *sensu strictu*, includes Olympic Dam, as well as Candelaria and Manto Verde in Chile and Salobo in Brazil, all of which have economic Cu and Au concentrations. These deposits are more clearly associated with felsic to mafic, alkaline to subalkaline intrusive rocks and have more intense hydrothermal alteration. Zoning of ore and alteration is not as obvious as it is in porphyry Cu deposits, but generally

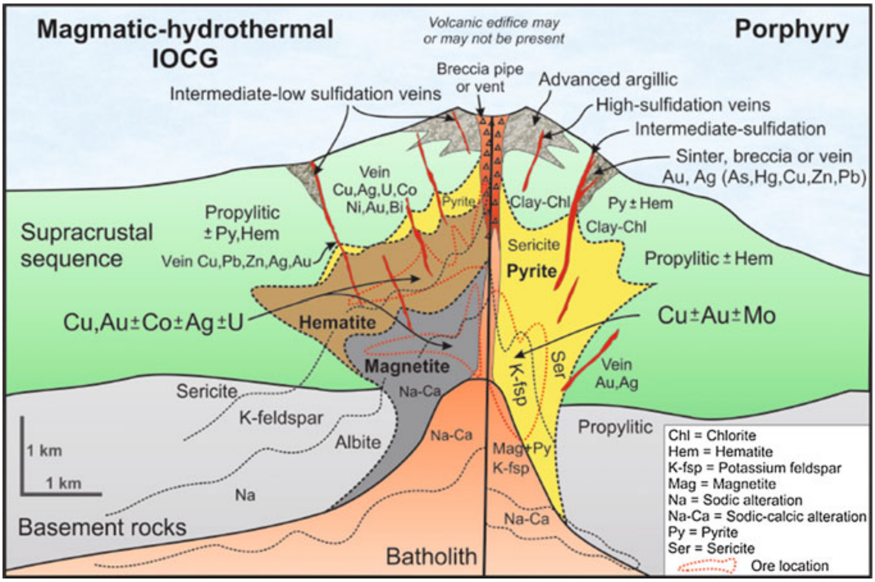


Fig. 4.19 Schematic diagram comparing ore and alteration zoning in IOCG (*left*) and porphyry copper (*right*) deposits (from Richards and Mumin 2013)

consists of proximal magnetite and distal hematite, both of which can be associated with Cu, Au and other metals, that are associated with alteration that ranges from proximal Ca–Na feldspar or other silicates, some of which are also regional in extent, to distal K-feldspar and sericite (Fig. 4.19). Precambrian deposits of this type, which are by far the most abundant, were emplaced in craton-interior, anorogenic magmatic provinces. The Chilean deposits, which are Mesozoic in age, are hosted by an unusual extensional to transtensional zone in the otherwise convergent Coastal Cordillera. The predominance of Precambrian deposits of this type has been ascribed to the more reduced nature of magmas of this age, reflecting the overall lack of oxygen in the atmosphere and paucity of sulfate in the ocean and ocean crust.

Origin: Theories for the origin of these deposits are strongly divided between magmatic and hydrothermal camps, a division that might reflect the two types of deposits. The magmatic theory, which has been applied mostly to massive Fe oxide-apatite ores of the Kiruna type, involves formation of an immiscible Fe oxide magma followed by its injection into surrounding rocks or onto the surface (Naslund et al. 2012; Jonsson et al. 2013). It was put forward first for Kiruna, but gained considerable strength from field work at Cerro Mercado in Mexico and El Laco in Chile, both of which contain textures that have been interpreted to resemble flows and pyroclastic eruptions of magnetite. Experiments have shown that an iron-rich magma can exist; there is a large field of two-liquid immiscibility in the Fe oxide-felsic silicate system. However, the Fe oxide magma would be more dense than the silicate liquid and it could be made buoyant enough to extrude only if it contains dissolved gases that exsolved to form a low-density magnetite froth. The best support, at present, for the magmatists comes from oxygen isotope analyses indicating that magnetite in some deposits formed at temperatures as high as 800 ° C, which are more likely to be magmatic than hydrothermal.

The hydrothermal theory appears to be most suitable for IOCG deposits *sensu strictu*, although confirmation of fluid involvement is spotty. In Olympic Dam, abundant brecciation, veining and alteration suggest the presence of a fluid; fluid inclusions contain low-temperature, saline fluid, but it is far too cool to be magmatic. One possibility suggested for this fluid is recharge of evaporite fluids from overlying playa systems in arid terrain. Others include fluids derived from metamorphism at depth or from deep basinal circulation. At deposits such as Vergenoeg in South Africa and Cloncurry in Australia, paragenetically early minerals coexisting with Fe oxides contain highly saline, fluid inclusions that homogenize at temperatures of nearly 600 °C, suggesting a magmatic source or, at the very least, strong magmatic heating.

At this stage, IOCG deposits definitely deserve their transitional classification. It appears that the hydrothermalists have prevailed for many IOCG deposits *sensu strictu*, but it is not clear whether the fluid is magmatic, basinal or meteoric, and the source of the Fe is even less certain. For IOA-type deposits, no such convergence has occurred and we can anticipate continued controversy between magmatists and hydrothermalists. With time, perhaps IOCG deposits will be divided into two genetic groups, IOCG deposits *sensu strictu* that belong in the magmatic-hydrothermal class and iron oxide-apatite (IOA) deposits that move back one chapter into the purely magmatic.

Analysis: IOCG deposits

Source of metals—probably magma, either immiscible melt or hydrothermal fluid
Source of S—low-S systems, possibly magmatic
Source of fluid—magmatic, possibly recharge of evaporite fluids
Cause of fluid circulation—magmatic heat or recharge of surface fluids
Precipitation process—cooling and reaction with wallrocks

Box 4.12 Discovery of One of the World's Biggest Mines

In 1975 geologists and geophysicists from Western Mining Corporation, then a medium-sized Australian mineral-exploration and mining company, were exploring for Cu deposits in the Gawler Block of South Australia. The target was elusive, in the desert, hidden beneath 300 m of younger sedimentary formations, and 100 km away from the closest known mineralization. Doug Haynes, a geologist who had just completed his PhD degree, had developed the idea that Cu deposits might form from a basaltic source via the oxidation of magnetite. The first hole they drilled intersected a magnetite breccia containing a small concentration of Cu—a tantalizing hint—but then holes 2–9 found nothing. Finally persistence (and unusual support from the Melbourne head office) paid off and hole number 10 intersected 200 m of ore containing 2 % Cu and significant tenors of Au and U. The team had discovered one of the richest ore bodies in the world and an entirely new type of ore deposit.

The Olympic Dam IOCG deposit contains about nine billion tons of Cu–U–Au ore: it is the world's biggest U resource, the 5th largest Au deposit, and one of the biggest Cu deposits. Polymetallic deposits such as Olympic Dam are particularly attractive to mining companies because the prices of metals normally do not vary in unison—the Au price, for example, tends to increase during periods of recession thereby protecting companies from the full effect of economic downturns. The discovery of Olympic Dam set off exploration programs for similar deposits throughout the world, although no similarly large deposit has yet been found. (For a more complete account of the Olympic Dam discovery, see http://www.science.org.au/scientists/interviews/w/woodall.html#9)

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Chapter 5
Deposits Formed by Sedimentary and Surficial Processes

5.1 Introduction

In this chapter, we focus on three main types of deposits that form at and very near Earth's surface. Two groups of deposits form by sedimentation and consists of either detrital grains or chemical precipitates in rivers, lakes and oceans. The third group comprises deposits that form in zones of weathering just below the continental surface, usually in humid tropical environments. Table 5.1 summarizes the three broad types of deposits that form in these environments, which are listed below.

1. *Placer deposits*—A placer ore body is a concentration of particles of valuable minerals in an alluvial or eluvial deposit of sand or gravel. The ore minerals in such deposits form initially in the crust, in magmas or metamorphic rocks or from hydrothermal fluids. These minerals are released from their host rocks by weathering and erosion and are then concentrated in ore bodies by soil forming and sedimentary processes. In some cases concentrations of the placer ore minerals in these source rocks are higher than normal, as in a gold-quartz vein or diamond-bearing kimberlite, but in other cases the minerals are accessory phases present in normal concentrations. Placer gold deposits in river sands and gravels, and deposits of heavy Zr and Ti minerals in beach sands, are examples of this type of deposit.
2. *Chemical sediments*—Other ore minerals precipitate from lake water or seawater to form chemical sedimentary rocks. The metals or other valuable minerals in such deposits are soluble in surface waters but precipitate when they reach saturation levels, when the composition or physical conditions of the water changes, or when organic activity causes minerals to form. Examples include NaCl and KCl evaporites, which result from the evaporation of waters in lakes or shallow seas, and Fe- or Mn-rich sediments that form when these elements are precipitated from water, with or without biological activity.
3. *Products of weathering*—The third type of ore body is made up of minerals that are stable in zones of intense weathering at the surface of the Earth. Particularly in hot and humid conditions, many rock-forming minerals dissolve partially to

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Table 5.1 Deposits formed in surficial settings

Type	Subtype	Commodity	Process	Examples
Placer (and paleoplacer)	Gold	Gold	Accumulation in river or beach gravels	Klondike, Sierra Nevada, Bendigo-Ballarat, Witwatersrand
	Ilmenite, Zircon	Titanium, Zircon, REE	Same	Western and Eastern Australia, Florida, South Africa
	Diamond	Diamond	Same	Namibia, South Africa
Sedimentary	Precambrian Iron Fin (BIF, GIF)–Algoma and superior type	Iron	Deposition of chemical sediment and clastic reworking	Hamersley, Quadrilatero Ferrifero, Krivoy Rog, Kursk Magnetic Anomaly (KMA), Transvaal, Lake Superior, Labrador Trough
	Phanerozoie Iron Fin	Iron	Reworking and redeposition of lateritic oolites	Lorraine, Clinton
	Manganese Fin	Manganese	Deposition of Mn-rich chemical sediment	Kalahari, Groote Eylandt, Moanda, Urucum, Molango, Varna-Nikipol
	Evaporite	Halite, Sylvite, Bittern Salts	Evaporation of seawater	Widespread globally
	Evaporite	Nitrates Uranium	Evaporation of water in soil	Atacama Desert, Yeelirie, Langer Heinrich
	Evaporite	Lithium, Boron	Evaporation of fresh or saline water in playas	Atacama, Qaidam, Searles Lake, Green River Fm
Laterite	Bauxite	Aluminium	Extreme weathering of soil on granite, tuff or shale	Australia, Brazil, Indonesia, India, Guinea, China
	Ni-laterite	Nickel, Cobalt	Extreme weathering of soil on ultramafic rock	Philippines, Indonesia, New Caledonia, Dominican Repubic

(continued)

Table 5.1 (continued)

Type	Subtype	Commodity	Process	Examples
Supergene	Native Metal	Gold	Upgrading by removal of soluble material during weathering and oxidation of pyrite	Many Carlin-type deposits, Ok Tedi gold zone
	Oxide, Carbonate	Copper, Zinc	Release of metal from original sulfide and redeposition in oxides and carbonates	Exotica, Silesia
	Sulfide	Copper	Reprecipitation of copper replacing pyrite	Supergene zones in many porphyry copper deposits

release elements into solution creating new more stable minerals, and leaving residual minerals and a strongly weathered soil called laterite. The most common ore elements concentrated by the process are Al, Ni and Fe. When the weathering process acts on ore deposits, it can redistribute the ore elements, sometimes greatly enriching near-surface parts of the deposits. This process is called supergene alteration or supergene enrichment and it is most effective on Cu deposits, as we mentioned in the previous chapter.

5.2 Placer Deposits

A placer ore body is a deposit of sand, gravel or soil containing eroded particles of valuable minerals. These minerals are able to survive in the surface environment because of their chemical and physical properties, as illustrated in Table 5.2 and discussed by Garnett and Bassett (2005). They are not necessarily thermodynamically stable but their rates of reaction are long compared with the duration of erosion, sedimentary transport and deposition. An example is diamond, which, although thermodynamically unstable at low pressure (James Bond had it wrong, diamonds are not “forever”), is able to survive long enough to be transported first from the mantle into a kimberlite body in the shallow crust, and then from a kimberlite source to a site of deposition in beach sands and off-shore gravels and finally from a mine into a gem. Other minerals found in placer deposits include gold, which occurs in the native or metallic form, and oxides or silicates such as rutile, ilmenite, zircon, and monazite, which are the sources of Ti, Zr, Nb and other high-technology metals. Diamond and the Zr-Ti oxides are moderately to extremely hard, which allows them to resist abrasion as the grains are released from their host rocks and carried along in rivers or ocean currents. Gold, of course, is very soft but it is also highly malleable and ductile, which makes it durable during sedimentary transport.

Table 5.2 Physical properties of minerals in placer deposits (from Garnett and Bassett 2005)

Mineral	Commodity	Density (g/cm^3)	Moh's hardness	Tenacity	Grindability	Remarks
Diamond	Diamond	3.5	10	Brittle	1	Very hard but only moderate density; brittle
Gold	Au	15–19	2.5–3.0	Malleable	11	Very dense, soft, malleable
Platinum	PGEs	14–19	4.5–4.5	Malleable	10	Dense, moderately soft, malleable
Cassiterite	Sn	6.5–7.1	6–7	Brittle	6	Rare as placer
Rutile	Ti	6–6.5	6–6.5	Brittle	3	Common in beach sands
Zircon	Zr	4.7	7.5	Brittle	2	Common in beach sands
Monazite	Th, REE	5–5.3	5–5.5	Brittle	9	Common in beach sands
Ilmenite	Ti	4.7	5.5–6.0	Brittle	8	Very common in beach sands
Garnet	Abrasive	3.5–4.3	6.5–7.5	Brittle	4	

Minerals are arranged in order of their survivability in the fluvial environment. Grindability refers to resistance during grinding in laboratory tests with ball mills

In addition to being resistant in surface settings, the ore minerals in placer deposits are significantly denser than most other common minerals like quartz and feldspar that are transported by sedimentary processes (Table 5.2). It is this characteristic that allows the ore minerals to be sorted out from grains of rock and rock-forming minerals that make up most of the sediment load and to be concentrated in ore bodies. Diamond is only slightly denser than detrital minerals like quartz or feldspar, but its extreme hardness allows it to persist longer and accumulate. Gold is the counter example, its density being six times greater than that of common rock-forming minerals. This high density contrast allows river currents to sort and concentrate even small particles of gold from other detrital grains, thus producing placer zones with gold concentrations several thousand times greater than normal continental crust. Sorting of moderately dense minerals like zircon and rutile is less efficient and placer deposits of these minerals are far less enriched, containing concentrations of Zr and Ti that are only 10–100 times greater than in normal crustal rocks.

5.2.1 *Gold Placers*

Placer and paleoplacer deposits have produced two thirds of all the gold that has ever been mined. There are two types of gold placers, modern placers and paleoplacers. Modern placers have been mined heavily and are largely exhausted. They are among the easiest deposits to mine. Free gold, the term used to describe separate particles of native (elemental) gold in stream beds, is readily extracted using simple methods such as the gold pan or sluice box, a simple wooden frame with a rough base that traps gold from passing gravel and sand. In the Old World mining started in ancient times; deposits of placer gold at Las Medulas in Spain were mined by the Romans for two centuries after they conquered the region in 25 BCE. Modern placer deposits in the New World were not worked as extensively by aboriginal populations but were exhausted rapidly by European settlers in gold rushes such as those in the Sierra Nevada of California, USA and Bendigo-Ballarat in Victoria, Australia. Present gold production from modern placers is largely artisanal and makes up a minor fraction of global gold production. Much of this artisanal placer mining is in developing countries, where the use of cyanide and mercury to extract the gold is a source of river pollution.

Paleoplacers continue to contribute significantly to global gold production, although from only one area, the Witwatersrand of South Africa (Fig. 5.1).

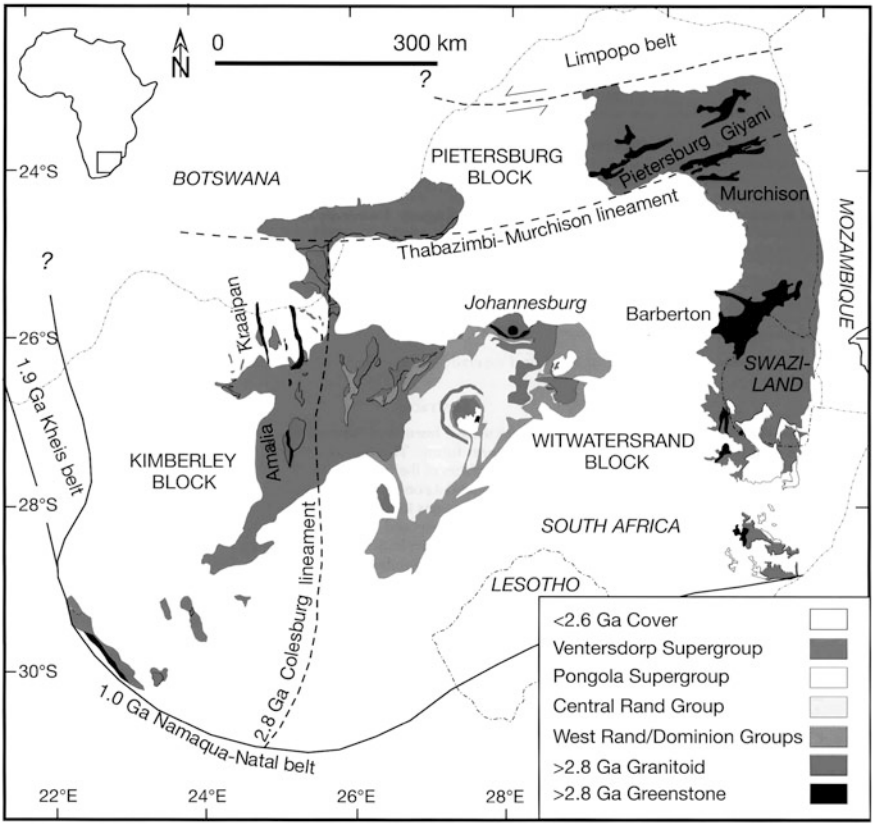


Fig. 5.1 Sketch map of the Witwatersrand basin, showing the central disposition of sands and conglomerates of the Central Rand and West Rand groups, flood basalts of overlying Venterdorp Supergroup and surrounding granites and greenstones that were the source of sediment and probably the gold (modified from Schmitz et al. 2004 and Frimmel et al. 2005)

Paleoplacers of the Witwatersrand are the largest known accumulation of gold in Earth's crust and they have produced nearly a third of the gold that has ever been mined. Production is declining, however, because rich, near-surface deposits have been exhausted and mining is reaching unusually deep levels. In 1970, Witwatersrand deposits accounted for half of global production but by 2013 the figure had fallen to about 5 %. China is now the largest gold producer, followed by Australia, United States, and Russia, all producing largely from non-placer deposits.

Box 5.1 Great Gold Rushes, Mother Lodes and Glaciation

Stories of miners making their fortune after finding enormous nuggets attracted hundreds of thousands of prospectors to the alluvial gold fields of California, Victoria and the Klondike. Most of these modern placers were in stream gravels that led prospectors up the drainages to the source of their gold in veins known as the mother lode, the name applied to much of the orogenic gold deposits of the Sierra Nevada in California. Another type of placer deposit formed through alluvial processes in desert sands in the flat dry plains around Kalgoorlie and Coolgardie in Australia, fueling a gold rush to this region at the start of the 20th century. This gold also came from orogenic gold deposits in the Archean greenstone belts of the region (Chap. 4). Similarly large and rich orogenic gold deposits in Canadian greenstone belts such as those around Timmins and Yellowknife are not associated with known placer gold because Pleistocene glaciation removed soil and regolith. Placer gold that had formed above these deposits before glaciation is scattered through the glacial gravels and sands that cover much of middle North America, and small, non-economic amounts of gold are present in most gravel mines in this area.

Some placer gold deposits did not lead to a mother lode. Foremost among these is the Klondike, which yielded almost 10 million ounces of placer gold but insignificant lode gold. However, recent exploration south of the Klondike has recognized several areas containing orogenic gold deposits that might represent Klondike-type source material. Actually, it is a surprise that the Klondike placers exist at all in view of the widespread glaciation that covered northern North America. However, much of the northern Cordillera, including large parts of the Yukon and Alaska, was not glaciated. The abundance of placer gold that remained in Alaska is often cited as a major reason that the area was populated relatively rapidly (by gold seekers) after it was purchased from Russia.

Modern gold placers consist of accumulations of gold particles in Quaternary and Tertiary gravel, sand or soil, and their consolidated equivalents. Two broad types can be distinguished; alluvial deposits, in which the gold is transported by river or ocean currents and is separated from grains of other minerals by the action of these currents; and eluvial deposits, in which the gold remains more or less in place at the site of exposure of the primary deposit while the other minerals are removed. One type of eluvial deposit forms on hill slopes immediately below the exposures of gold-bearing veins: gravity sliding and the action of wind or water remove the lighter components leaving the denser gold particles. Another type forms on desert plains where winds or occasional floods remove the less dense or soluble minerals.

In alluvial placers in river or stream beds, hydraulic processes concentrate gold at locations where the water velocity decreases markedly or where currents with contrasting flow rates or flow styles (laminar or turbulent) are juxtaposed. Examples include sand or gravel banks on the interior of meanders, pools below boulders, rapids and falls, and fractures, joints or ridges in stream beds. In all of these locations, the less dense or finer particles are transported away from the site of deposits by fast-flowing water leaving the denser or larger grains in regions of reduced water velocity. One special feature of placer gold deposits is the tendency to concentrate gold along the bedrock that underlies the stream, even in areas where the stream gravels are very thick and not part of the active sediment load. These "bedrock placer values" are thought to form during storms when flow increases greatly and moves the entire stream load, shaking gold to the bottom of the pile.

Gold in placer deposits is almost entirely in the metallic form and occurs in a range of grain sizes, from minute particles or flakes to large nuggets. The "Welcome Stranger", the largest lump of gold ever found, measured 61 cm by 31 cm and weighed almost 70 kg. This nugget was found accidently in a cart track in Victoria, Australia, in 1869. Gold in placers is very pure, normally containing 80–85 % Au, the rest being mainly Ag. In places where the original source of placer gold can be identified, the placer gold usually contains a higher proportion of gold than is found in the bedrock source. This enrichment apparently takes place in part during erosion and transport because silver is more soluble than gold under these conditions.

Paleoplacers of the Witwatersrand are conglomerates with rounded pebbles of quartz, chert, volcanic rocks and abundant pyrite (Fig. 5.2) in a matrix of quartz, muscovite (in places rich in fuchsite), chlorite, and locally important chloritoid and pyrophyllite. They also contain native gold, pyrite and other sulfides, arsenides and sulfosalts, uraninite (UO_2), brannerite $(U^{4+}, Ca)(Ti, Fe^{3+})_2O_6$, small nuggets of the platinum group elements and (for reasons explained below) pyrobitumen. Most gold is in the matrix of the conglomerates although minor amounts of gold are in the pyrite and other sulfide minerals. Two morphological types of gold can be distinguished, well-rounded grains that resemble small nuggets in young placer deposits, and irregular aggregates and well-crystallized euhedral overgrowths that resemble gold of hydrothermal origin. Figure 5.1, a sketch map of the Witwatersrand basin, shows the location of the predominantly siliciclastic metsedimentary rocks of the Central Rand and West Rand groups, which contain the auriferous conglomerate beds that are called reefs by the miners. It also shows the overlying Ventersdorp flood basalts that protected the reefs from erosion; and the surrounding granites and greenstones that form the bedrock for the Witwatersrand basin and that are a possible source of the gold. Sediments of the Central and West Rand groups were deposited between 2.8 and 3.0 billion years ago in a system of braided rivers and alluvial fans. Fluctuations in sea level repeatedly changed the

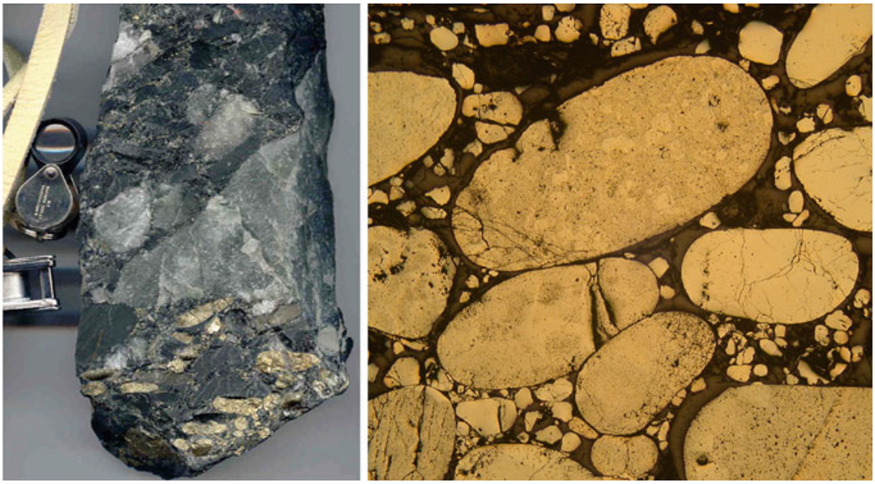


Fig. 5.2 *Left* Photographs showing Witwatersrand conglomerate with white and black cobbles of quartz and chert and large rounded pebbles of pyrite. Hand lens provides scale (photo by S. Kesler). *Right* Polished section showing rounded pebbles of pyrite. The field of view is 8 mm across (photo by A. Hofmann)

position of the coastline, building up a 5 km-thick sequence of deltaic sands, shales and conglomerates. The gold-bearing horizons are located in lenses of oligomictic quartz-pebble conglomerates at several different stratigraphic levels in the upper part of the Witwatersrand Supergroup. Other quartz pebble paleoplacer gold deposits with similar appearance include the Archean(?) Jacobina in Bahia, Brazil and the Paleoproterozoic Tarkwaian System of Ghana.

Box 5.2 Exercise—Gold Mining and Value Production

Witwatersrand ore has averaged less than 10 ppm Au during the life of mining. That is equivalent to 10 grams of gold per tonne of rock. This means that more than three tonnes of rock must be dug out and treated in order to extract an ounce of gold that would be about the size of a sugar cube! Mining the gold requires considerable disturbance of the land, including large piles of waste rock, and possible pollution from mine water. Although much of this can be restored and reclaimed, there is no question that mining of this type has a large impact on the environment. Many people are totally against mining for this reason and they are especially bothered by gold mining because much of the metal is used for jewelry.

However, mining uses only a very small part of Earth's surface, and it produces huge returns in terms of both monetary and social terms when compared to other large-scale uses for land such as farming or timber harvesting. Wheat farms are not environmentally benign, of course; they were put in at the expense of original forest or grassland, they are ecologically sterile in that they support only one species, and they generate pollution in the form of fertilizer and pesticide runoff. And, there are many more wheat fields than mines.

So, what are the relative values of these two uses of land; let's make a quick comparison. The total surface of land used in a gold mine is not very large, roughly the size of a large US wheat field. The amount of wealth generated by the gold mine is many orders of magnitude greater than that produced by the farm. For instance, the mine site, tailings dumps and infrastructure of Telfer, a moderate size gold mine in Western Australia, cover about 30 km^2. The mine has produced about 1 million ounces of gold per year, which, at \$1200/oz, is worth 1.2 billion dollars. Several big wheat fields cover about the same area (30 km^2) and produce about 800 tonnes of wheat per km^2 per year, a total of 24,000 tonnes of wheat per year. At a price of about \$100/tonne, the wheat production is worth about \$2.4 million. The wealth created by the gold mine is 500 times greater. In addition, the Telfer mine employs 1000 workers while the wheat fields employ about 50. Thus, mining plays an important role in the economy, especially in terms of the space that it occupies.

And, if you are still worried about the use to which gold is put remember that some is indeed used in industry (each computer that we are using to write this book contains about half a gram), and gold is used in pharmaceuticals and construction. It is also a "crisis metal", a refuge that investors seek in times of economic turbulence. During 2008–2009, as the price of ferrous and base metals plunged, the price of gold approached record heights.

How can we balance the positive and negative aspects of gold mining? Discuss the geological, economic and ethical aspects of this activity.

Although we have chosen to describe the deposits of the Witwatersrand basin in this chapter on surface ore-forming processes, the origin of these deposits is controversial. There are two competing hypotheses for the origin of gold, the placer model and the hydrothermal model. Arguments for and against each are summarized in Table 5.3. Papers by Frimmel et al. (2005), Law and Phillips (2005) review these competing hypotheses.

According to the placer model, detrital grains of gold and were transported into the basin and deposited in the matrix of the conglomerates. Placer proponents find support in the nugget-like form of some gold grains, Re-Os ages for gold grains that are older than the age of the conglomerates, as well as in the fact that the distribution of much of the gold in the sedimentary layers accords with the behaviour of gold in placer systems. According to the competing hydrothermal model, hot H_2O–CO_2 fluids, perhaps derived from dehydration and devolatilitzation of rocks in lower parts of the basin, flowed along the permeable conglomeratic horizons and deposited gold and other minerals in the pore space of these sediments. Hydrothermal proponents find support in the fact that much of the Witwatersrand gold does not take traditional

Table 5.3 Arguments for and against the hydrothermal and placer models for Witwatersrand gold deposits

Hydrothermal model	Modified placer model
Gold is late in the paragenetic sequence and is associated with zones of hydrothermal alteration	Coexistence of rounded gold nuggets and hydrothermal gold
Rounded pyrite grains and uraninite are of post-depositional hydrothermal origin	Pyrite morphology, crystallography and zonation patterns indicate detrital origin
Gold and uranium are closely associated with pyrobitumen that was remobilized during metamorphism	The association relates only to hydrothermally remobilized gold and uranium
Permeable conglomerate beds channelized the flow of hydrothermal fluids	Strong sedimentary control on gold distribution
Gold was deposited after sediment deposition	Re-Os ages of gold are older than the sedimentation
Gold was deposited during peak metamorphism	Metamorphism remobilized pre-existing detrital gold
Lack of suitable source of placer gold	Surrounding granites and greenstones were the gold source

Modified from Frimmel et al. (2005)

placer forms, that no good source has been identified for the gold, that the Witwatersrand contains far more gold than any other placer deposit, and that some gold is hosted by kerogen and pyrobitumen, which were probably microbial mats and could have precipitated gold from hydrothermal solutions.

Most participants in this controversy have come to accept the modified placer theory, in which much of the gold was deposited originally in some detrital form and subsequently remobilized, largely at a scale of centimeters, by hydrothermal fluids that flowed through the conglomerates on one or more occasions. Despite this growing agreement, the Witwatersrand is still a puzzle. What sort of geological source could have supplied so much gold, possibly 600 million ounces, which is many times larger than any known hydrothermal gold deposit or even district on the planet? Did the early Earth have different types of gold deposits? What form did gold have in the Witwatersrand source; why are there so few real nuggets when they are a common part of most placer deposits? Frimmel (2014) has suggested that these curious features are the result of an unusual combination of events starting with a mantle source region that was enriched in siderophile elements from meteorite bombardment and that released gold into the crust during Mesoarchean time when the mantle reached maximum temperatures. Intense weathering in a reduced atmosphere, including dissolution of gold, allowed more efficient extraction from the crustal source region, and concentration of gold to form the deposits was enhanced by the presence of abundant microbial mats.

Quite apart from its gold content, the Witwatersrand conglomerates merit attention for another reason. Figure 5.2 shows rounded grains of detrital pyrite. In an oxygen-rich atmosphere such as we have today, pyrite would have been weathered to iron oxides and could not have formed grains like this. Uraninite, another dense mineral that would form placer deposits if it did not break down in today's oxygen-rich atmosphere, is also found in the Witwatersrand conglomerates. The presence of pyrite and uraninite in the Witwatersrand conglomerates and their absence in younger paleoplacers and modern placers have been used as evidence for a reducing atmosphere and ocean during late Archean time and a transition to more oxidizing conditions in early Proterozoic time, a point that will come up again when we discuss sedimentary iron deposits.

5.2.2 Beach Sands

Most of the world's supplies of titanium and zirconium come from concentrations of heavy minerals in beach sands. These elements are known as 'high-technology" or "space-age" metals because their high strength-to-weight ratio makes them very suitable for the construction of aeroplanes and spacecraft, not to mention golf clubs, the casings of Macintosh computers and the masts of America's Cup racing yachts. The major market for titanium is not as a metal, however, but as an oxide: TiO_2 is the pigment that imparts a brilliant white colour to a wide variety of paints, papers, plastics and other materials. It replaces white lead [hydrocerrusite, $2PbCO_3{\cdot}Pb(OH)_2$)], which was used as the white pigment in paints until its toxicity became obvious. The rare-earth elements, which are finding increasing uses in superconductors, ceramics, batteries, magnets, phosphors in TV screens, and catalysers in petroleum refineries, are present in monazite, a minor component in beach sands.

Heavy mineral deposits in relatively young beach sands are the only significant source of zirconium in addition to being a major source of titanium. The latter is also mined in magmatic deposits of ilmenite ($FeO{\cdot}TiO_2$) in anorthosites in Canada and Norway and as anatase (TiO_2) in residual deposits overlying alkaline intrusions in Brazil. The principal ore minerals in heavy-mineral beach sands are ilmenite, leucoxene (approximately TiO_2, an alteration product of ilmenite), rutile (TiO_2), zircon ($ZrSiO_4$) and monazite (a phosphate of Th and the rare-earth elements). The concentrations of ore minerals in these placers are highly variable. Richest deposits contain up to 50 % ilmenite, 5–20 % of both rutile and zircon and 1–3 % monazite; more normal placers contain only a few percent of combined heavy minerals. Because the deposits are in unconsolidated sands at the surface, mining costs are much lower than those of typical, rock-hosted deposits where ore must extracted from deep mines, crushed and processed.

The heavy minerals in beach-sand deposits of this type are derived from normal igneous and metamorphic rocks where they are accessory phases making up less than 1 % of the rock. Grains of these minerals are released when the host rock is broken down by subaerial weathering. The grains are then transported by streams and rivers to the shorelines of lakes or oceans where the action of waves, wind, tides or long-shore currents winnows out the lighter quartz and feldspar, leaving the sands enriched in the dense Ti and Zr minerals. For the process to be effective, a large reservoir of the source rock must be subjected to long periods of chemical weathering. The best source is a Precambrian craton with abundant granite and granite gneiss in equatorial regions that has been weathered deeply and eroded to peneplain level. When similar rocks are exposed in younger mountain ranges or in temporal or cold climates, mechanical weathering dominates and the heavy minerals are not so effectively separated from other components. For these reasons, the largest deposits are located around old stable continents in equatorial regions, namely along the coastlines of Australia, South Africa and India, the major producers of Zr and Ti. Smaller or less rich deposits are located in southeastern USA, West Africa, Malaysia and China.

5.2.3 Alluvial Diamonds

The first diamonds discovered in South Africa were in gravels of the Orange River and its tributaries. Tracing these rivers back to their sources led first to discovery of primary diamond sources in kimberlites around the town of Kimberley in the centre of South Africa, and then to enormous beach placers on the western coast of the continent in South Africa and Namibia (Fig. 5.3). Placer deposits are the source of about a third of global diamond production. By far the largest fields are those along

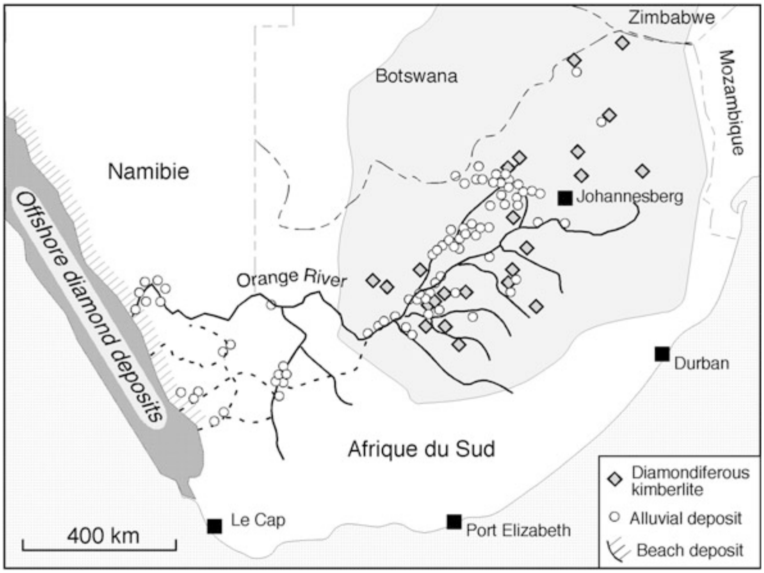


Fig. 5.3 Map of southern Africa showing the location of three different types of diamond deposits: primary kimberlitic diamond; alluvial deposits in present and ancient river beds, and alluvial deposits in beach and offshore gravels. Beach and offshore deposits to the north of the Orange River were formed by the Benguela Current. Those to the south formed when the ancestral Orange River reached the Atlantic Ocean farther to the south, as shown by the *dashed lines* (from Lynn et al. 1998)

the western coast of southern Africa, from north of Cape Town to Angola, but placer diamonds have been mined in India throughout history and also in Russia and Brazil. Placer deposits normally contain a high proportion of high-quality gem diamond (up to 97 %) because large flawless, single crystals survive the rigours of sediment transport and deposition better than smaller flawed crystals. Alluvial diamonds in the Orange River and tributaries in South Africa (Fig. 5.4) are mined by medium-sized commercial operations, and beach deposits in Namibia are mined on a larger scale. Beach mining starts with construction of large dikes of beach sand to isolate the beach from the ocean. Beach sand is then removed, all the way down to the underlying bedrock surface, which is vacuumed to remove detritus in crevices (Fig. 5.5). The best diamonds are found in this “bedrock placer” setting, similar to that of some gold deposits. Recovery of diamonds in active beach settings that do not contain enough diamonds to merit large-scale mining is carried out with small, tractor powered suction systems operated by divers (Fig. 5.5). Mining of offshore gravels, which are present at water depths up to several hundred metres, requires heavy equipment such as large ships that suck the diamonds from the sea floor (Fig. 5.5).

Fig. 5.4 Photos of alluvial diamonds. The *top* photo shows a heavy mineral concentrate of beach sediment from Namibia that contains five diamonds. Can you distinguish them from the more numerous quartz grains? Hint, the diamonds are below the coin (photo by S. Kesler). The *bottom* photo shows a group of gem quality diamonds that have been picked out of a beach gravel (photo from www.diamondfields.com)

Fig. 5.5 Techniques used to extract diamonds from beach deposits and offshore deposits. In the *upper* photo, large vacuum systems are being used to remove the last bits of sediment trapped on the bedrock surface beneath modern beaches in Namibia. The *middle* photo shows tractor-mounted suction equipment being used by a diver to vacuum up sediment in the active beach zone. The small white speck on the right horizon in the *upper* photo is an offshore mining operation similar to that shown in the *bottom* diagram

5.2.4 *Other Placers: Tin, Platinum, Thorium-Uranium*

The primary source of tin is cassiterite (SnO_2) a magmatic mineral that forms during the latest stages of crystallization and hydrothermal activity in highly evolved granites. The so-called “tin granites” have a restricted distribution, both in space and geological time; they are very rare in the Precambrian and become more abundant in later epochs. The best known examples are in the Malayan Peninsula, an endowment that has made Malaysia the world's greatest producer of tin. About half the deposits are in veins and disseminations in the granites themselves and the other half are in placers in rivers, beach sands and offshore deposits.

Much the same story applies to the platinum-group elements. The primary source is in ultramafic rocks such as those of the Bushveld Complex (Chap. 3) but in certain regions, nuggets of PGE alloys released by weathering and erosion of ultramafic rocks have produced viable placer deposits. In some cases the sources are ore deposits in their own right, as in the ultramafic complexes of Siberia; in other cases ophiolites with no known commercial ore concentrations have yielded placer deposits, as in New Caledonia and Colombia.

Thorium and uranium are hosted in uraninite in the Witwatersrand ore bodies, and in monazite in beach sands. The beaches flanking some parts of India contain high concentrations of monazite and the country has put a special effort into developing nuclear power based on thorium.

5.3 Sedimentary Fe Deposits

5.3.1 Introduction

Although global production of some commodities might have reached a maximum and be passing into decline, petroleum being the key example, this is not the case for iron ore. World production of iron ore, which was about 1.4 billion tonnes in 2006, reached almost 3 billion tonnes in 2013 and is expected to continue to grow (the proportion of recycled iron, currently 8–10 %, is also likely to increase). Global reserves of iron ore are estimated by the U.S. Geological Survey to be an enormous 170 billion tonnes, and global resources are estimated to be 800 billion tonnes, which are about 50–250 times, respectively, greater than current world production. Even with uncertainties about how production might increase in the future, it is clear that world iron reserves and resources are among the largest of any metals. This large cushion reflects, in part, the nature of many iron deposits, which are laterally extensive as we will see in the next section.

As with most mineral commodities, iron ore deposits are not distributed equally across the globe. China, the world's biggest producer, mined over 1.3 billion tonnes of iron ore from its vast domestic resources in 2013; but it is also the biggest consumer, thanks to the growing demand for the steel needed to build infrastructure for a rapidly industrialising society. Currently China imports about 750 million tonnes of ore each year, mainly from Australia and Brazil. India is entering a phase of reindustrialization similar to that in China, but many geologists and politicians believe that reserves of iron ore in that country are limited. The question of how to manage mineral resources is the topic of the following exercise.

Box 5.3 Exportation Versus Conservation of Mineral Resources

In 2011, exports of iron ore from India were banned by the government. Reasons for the ban were complex and included concerns about environmental degradation, illegal mining and possibility that iron ore resources were not sufficient for the domestic steel industry. Export bans of this type are often spurred by a fear that domestic production will not be adequate for long-term needs. In fact, the United States has banned most exports of crude oil for the last four decades for just this reason (although the recent increase in U.S. oil production from fracking is causing reevaluation of this policy).

One of the most famous mineral export bans was put in place by Australia in the 1950s. At the time, it was believed that reserves of iron ore in the country were very small, barely sufficient for domestic use. To conserve supplies, iron ore exports were forbidden. The local market for iron ore was not large. So, any company finding a new iron ore deposit would have competed for a place in a small market. As a result, exploration for new deposits came to standstill.

On 16 November 1952 Lang Hancock, a prospector and cattle rancher, was flying over the Hamersley Range in the rugged outback of the Pilbara in the northwestern part of the country. Bad weather forced him to fly at low altitude and as he did he wondered if the bands of bright red rock visible in nearby valley walls might be iron ore. A year later he returned and found that they were the exposed parts of a huge sedimentary iron formation, a discovery that led to the establishment of the iron ore mines in the Pilbara. Now, some sixty years later, Australia has huge reserves of iron ore and is the world's major exporter.

Question: how should governments manage the development of mineral resources? Should they guard known resources for future generations by banning exports, thus limiting the rate at which the resources are consumed, or should they free the market and encourage exploration in the hope of finding new deposits?

Iron can be concentrated into ore deposits by a wide range of processes of which three, hydrothermal, magmatic and sedimentary, are most important. Although we will focus on the sedimentary deposits in this section, a brief reminder about the other types is useful. Of the hydrothermal deposits, the best known are those along contacts with igneous intrusions. Contact-localized deposits associated with felsic intrusions, like the ones at Hannover, New Mexico in the US, are in skarns and formed largely from magmatic hydrothermal solutions. Other contact-localized deposits associated with mafic intrusions, such the large deposits at Bethlehem, Pennsylvania, commonly lack skarn alteration and probably formed from meteoric or basinal water that flowed through consolidated intrusions leaching iron. Massive IOA deposits that were discussed in the last chapter also contain iron, although there is debate about whether they form as immiscible oxide melts.

Kiruna, the enormous deposit in northern Sweden and El Laco in Chile, are examples of this group of deposits. Iron also concentrates as layers of magnetite in large igneous complexes. By far the largest of these are the magnetite layers in the upper part of the Bushveld Complex, are mined for vanadium (that substitutes in the magnetite). Despite their large size, all of these iron deposits take a back seat to sedimentary iron formations that are the focus of this chapter.

5.3.2 Precambrian Sedimentary Iron Formations

Sedimentary iron formations host about 90 % of world iron ore resources and are much larger than all other types of iron deposits, both individually as deposits and collectively in terms of reserves. The largest producing districts are in the Hamersley Range of Western Australia, Transvaal Basin of South Africa, and Quadrilatero Ferrifero and Cerro dos Carajas of Brazil, all of which produce high-grade enriched ore (as explained further below) and Krivoy Rog of Ukraine, Labrador Trough of Canada, and Mesabi-Marquette Ranges of the United States, which produce lower grade unenriched ores. Individual deposits in these districts contain hundreds of millions to billions of tons of ore with grades of more than 50 % Fe for enriched ores and about 30 % Fe for unenriched ores. Strictly speaking, the term iron formation applies to layered sedimentary rocks with at least 15 % iron and abundant interlayered quartz, chert or carbonate. Mining focuses on higher-grade parts of iron formations, either primary, unenriched or enriched, as discussed near the end of this section.

Sedimentary iron formations comprise chemical sediments that formed in the ocean. Iron formation that consists of alternating layers of iron minerals and silica and looks very much like chemical sediment is known as banded iron formation (BIF) (Fig. 5.6). Other, clastic iron formations that consist of fragments of BIF along with pisolites or oolites consisting of iron and silica minerals are known as granular iron formation (GIF). BIF and GIF can be divided into three facies, oxide, carbonate and silicate, depending on the composition of their iron minerals (Table 5.4). (Associated sulfide (pyrite)-bearing sedimentary rocks that were originally classified as a facies of iron formation are now considered to be related to volcanic exhalative processes.) Original minerals in BIF were probably ferric hydroxides, siderite and clays that were converted to their present mineralogy during diagenesis or metamorphism. Layering in BIF is cyclical at scales ranging from macrolayers up to tens of meters thick through mesolayers that are centimeters in thickness to microlayers with millimeter thicknesses. Reasons for this cyclicity are controversial; possibilities include tidal, solar, annual, seasonal, upwelling and longer, possibly Milankovitch, sedimentary cycles. In some areas, chert mesolayers can be correlated for distances of tens of kilometers, suggesting quiet, deep water conditions for deposition of BIF. In contrast, GIF sedimentary textures indicate deposition in shallower water above storm and even fair-weather wave base. Detrital material from these shallower environments also found its way into deeper parts of the basin as density current deposits that are found in some BIF.

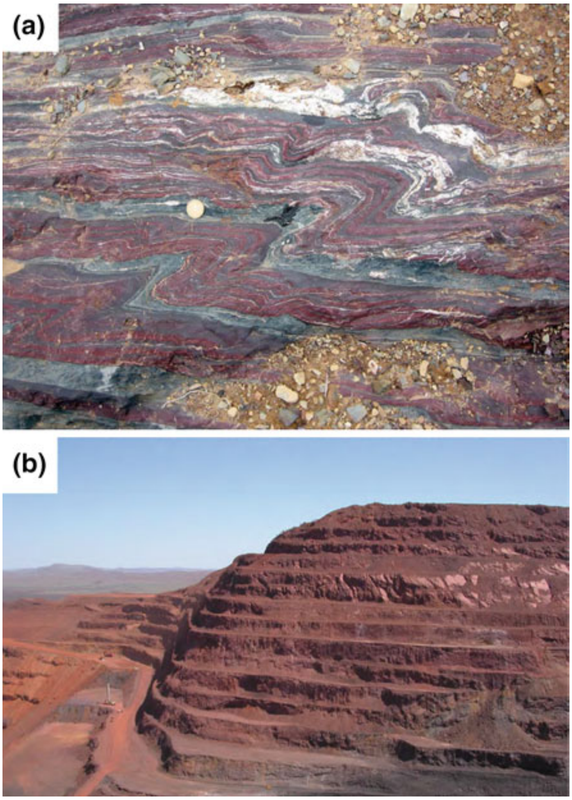


Fig. 5.6 Photos of banded iron formations. **a** Outcrop of BIF from the Mt Tom Price mine of the Pilbara, Western Australia **b** General view of the mine (photos from K. Konhauser)

Most Precambrian iron formations were deposited in one of two very different geologic environments that have become the basis for a secondary classification, as summarized in Table 5.4 and reviewed by Klein and Beukes (1993), Clout and Simonson (2005), Bekker et al. (2010), Evans et al. (2013). Algoma-type iron formations are commonly associated with submarine volcanic systems and appear to have been deposited in deep water. They are named for the Algoma area of the Canadian Shield, especially around Wawa, Ontario, where they were first recognized. Superior-type iron formations are found in shallower water, continental shelf type settings; they are named for the extensive deposits around Lake Superior where iron formations can be traced for tens of kilometers along strike and the layers extend for similar distances to depth below the lake. Algoma and Superior-type iron formation have the same basic mineralogy but differ in texture and trace element composition. BIF textures are more common in Algoma iron formations and they have rare earth and other chemical signatures that are interpreted to indicate a significant volcanic input of iron into the sediment. GIF textures are more common in Superior-type deposits, as might be expected because of their somewhat shallower setting (although good BIF textures are also common) and

Table 5.4 Types of sedimentary iron deposits

Precambrian iron formations—The dominant source of Fe. The ore is sedimentary rock composed of finely laminated sediments containing alternating bands of chert or shale and iron minerals (banded iron formation—BIF) or fragments of this material and ooids (granular iron formation—GIF)	
Classification based on geologic setting	
Algoma	Hosted by submarine volcanic rocks; associated with exhalites; most common in Proterozoic rocks
Superior	Hosted by platform sedimentary rocks; no exhalites; most common in Archean rocks rocks
Rapitan	Associated with glaciogenic sediments; Neoproterozoic age Classification based on mineralogy (facies)
Oxide	Hematite and magnetite; most important type
Carbonate	Chert and siderite ($FeCO_3$)
Silicate	Greenalite (serpentine or clay with the composition (Fe^{2+}, Fe^{3+})2-3$Si_2O_5OH_4$), chamosite (phyllosilicate (Fe; Mg; Fe) Al(Si Al)O (OH; O), glauconite ((K; Na) (Fe; Al; Mg) (Si; Al) O (OH))
Sulfide	Pyrite; commonly associated with shale rich in organic matter; volcanic exhalative or formed by diagenetic replacement of earlier oxide and carbonate facies iron formation
Phanerozoic ironstones	
Ironstones—oolitic iron ores; Phanerozoic age; known as Minnette-type in Europe, Clinton-type in North America	
Bog iron deposits—Iron oxides and hydroxides that form at springs and swamps; early source of iron ore; no long	

trace element signatures for the source of iron are not as clear. Algoma-type iron formations are generally smaller, as would be expected for deposits that formed in small volcanic basins compared to the Superior-type deposits that formed on extensive continental shelves.

Iron formations are most abundant in rocks of late Archean and early Proterozoic age, just when Earth was undergoing the Great Oxidation Event (GOE) that transitioned us from a reducing to an oxidizing atmosphere, as discussed by Holland (2005). Early studies of iron formations suggested that this transition might have caused deposition of the iron formations, as oxygen in the atmosphere gradually oxidized the ocean, causing an ocean full of soluble ferrous iron to deposit as ferric iron. However, as ages became better known for both iron formations and the GOE, this story began to unravel. The GOE is now known have happened at about 2.4 Ga. In contrast, Archean and early-middle Proterozoic iron formations range in age from at least 3.8 Ga in the Isua greenstone belt of Greenland to about 1.8 Ga in the Animikie basin around Lake Superior. Within that range, most iron formations were deposited between about 2.6 and 2.4 Ga, just before the GOE. After a lull, another major phase of iron deposition happened near 1.8 Ga and, just to complicate things further, magnetite-hematite-rich Rapitan-type BIF and GIF deposits reappeared in Earth history at about 0.8–0.6 Ga in latest Proterozoic time. This temporal history might be even more complex because ages for many important iron formations around the world have not been determined.

The lack of a direct correlation between ages of the GOE and iron formations requires a more nuanced view of how they were deposited. One thing to keep in mind is that carbonate and silicate facies iron minerals contain only ferrous iron and would have deposited whenever submarine volcanic hot springs pumped enough ferrous iron into a basin that contained one or more of these anions. However, oxide iron formation is abundant in iron formation of all ages and it requires oxidation. As you can see in Fig. 5.7, oxidation of dissolved ferrous iron requires either an increase in pH or an increase in oxygen (Eh). An increase in oxygen is more likely for the numerous iron formations that formed at about 1.85 Ga because the post-GOE oxic atmosphere could have oxidized the ocean. The real question for these deposits is why the ocean was enriched in dissolved ferrous iron at that time. Perhaps the ocean remained stratified and deep parts retained ferrous iron for a long time after the GOE, or maybe this happened only in isolated parts of the ocean (most 1.85 Ga iron formations are along what would have been the southern margin of North America at that time); the answer is not obvious. For deposits that formed before the GOE, there was plenty of dissolved iron in the ocean, but oxidation was needed. One possibility is that Earth's atmosphere went through brief periods of oxygen abundance before 2.4 Ga and iron formations were deposited during these, but geologic observations do not provide much support for this coincidence. It is more likely that oxidation was caused by microbial processes, either microaerophilic iron oxidizers that use small amounts of dissolved oxygen, CO_2 and water, or anoxygenic oxidizers that operate in the absence of dissolved oxygen as shown in Fig. 5.8.

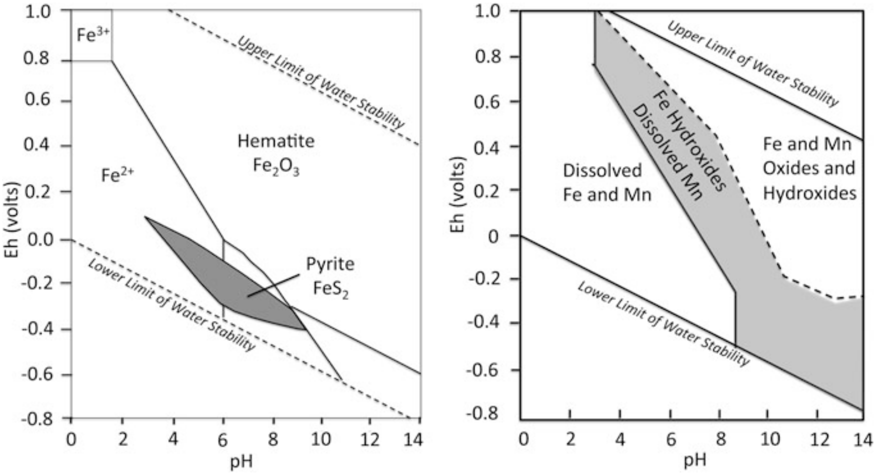


Fig. 5.7 Eh-pH diagrams showing stability relations for iron and manganese formations. *Left* diagram shows relations for minerals typical of sulfide, carbonate and oxide facies iron formations (from Garrels and Christ, 1965). *Right* diagram compares schematic stability fields for dissolved and oxide facies phases for iron and manganese, and showing the range of conditions under which iron is precipitated and manganese remains in solution (modified from Troester 1998)

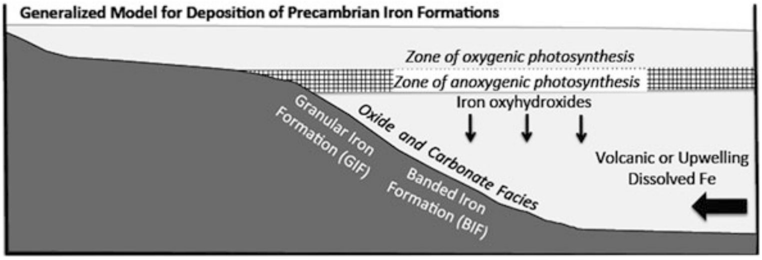


Fig. 5.8 Model for the formation of Precambrian iron formations showing two possible zones of oxidation, an upper oxygenic and a lower anoxygenic zone (modified from Klein and Beukes 1993 and Bekker et al. 2010)

Experiments suggest that both types of microbial processes could have oxidized enough ferrous iron to form older Precambrian iron formations. Thus, the appearance of iron formations around the time of the GOE is probably related more closely to processes that allowed large amounts of dissolved iron to accumulate in the ocean than to processes that deposited iron from solution. This helps explain why Rapitan-type iron formations appeared again at the end of Proterozoic time, when global-scale glaciation during the so-called “snowball Earth” period perturbed ocean chemistry.

5.3.3 Phanerozoic Sedimentary Ironstones

Phanerozoic ironstones formed largely from Ordovician to Devonian and from Jurassic to Paleogene time, and are sufficiently distinct from Precambrian formations that they have gained their own name. In Europe they are Minette ores and in the United States they are known as Clinton ores. Grades of these ores are about 30 %, similar to low-grade, unenriched BIF. Much of the iron in these deposits is present in silicate minerals that are difficult to process, and they have a higher phosphorous content that complicates steel making. With the discovery of the vast Precambrian deposits in Brazil and Australia, mining of European ores has became uncompetitive and one after another the mines in the Lorraine basin have closed, the last in the late 1990s.

Phanerozoic ironstones contain almost exclusively silicate and oxide facies iron minerals along with minor amorphous silica and almost all deposits contain abundant oolites or pisolites. These ironstones pose a problem in how to accumulate enough iron in the ocean, if indeed that happened. One possibility is that the world or local ocean was anoxic for a short period, something that did happen intermittently during Phanerozoic time. However, trace element evidence for a volcanic origin for the iron is not strong. This leads to another possibility, namely that the iron was derived from deep weathering of the continents and that it was transported as eroded soils into shallow waters in deltas or estuaries.

5.3.4 Ore Deposits of Sedimentary Iron Formations

If you analyzed pristine BIF that had not been changed much since it was deposited and lithified, Fe contents would range from about 15 to possibly as high as 45 %. Iron formations at the high end of this range are simply the ones with the largest number and thickness of original layers containing iron minerals, and they rarely reach large volumes. Instead, large, mineable ore bodies of this type commonly have grades of less than about 30 % as noted earlier. Deposits of this type that are being mined today are largely in North America and include Tilden and Hibbing in the United States. These iron formations are known as taconite in Canada and the United States and itabirite in Brazil.

In other parts of the world, especially in Australia and Brazil, BIF ore grades are much higher, ranging from 56 to 68 % Fe in many deposits. These grades are impossibly high for original sedimentary processes, and it is clear that these deposits resulted from some sort of "upgrading" or enrichment process that removed silica or added iron. Early mining in the Mesabi Range in the United States focused on small enriched pods of this type until they were exhausted and mining was forced to deal with lower grade unenriched iron formation. During early mining in the Mesabi Range debate raged over whether the upgraded ore was the result of downward-moving "supergene" solutions (presumably from weathering) or upward-moving "hypogene" solutions of uncertain, but generally hydrothermal origin. The hypogene camp found support in the setting of deep high-grade zones that were beneath fresh, unenriched iron formation.

The issue of high-grade, enriched iron ores was rekindled when mining began in Australia and Brazil, where careful study has shown that there are two different types of enriched ore. One type, which consists of deposits containing martite (hematite pseudomorphs after magnetite) and goethite and other iron hydroxides, is being mined at Maradoo and West Angelas in Australia. The other type, which consists largely of hematite, is much more widespread and is being mined at Whaleback and Mount Tom Price in Australia, the Carajas district in Brazil, Goa in India, Thabazimbi in South Africa and Krivoy Rog in Ukraine. A variant of the hematite-type deposit, which contains coarse-grained, platy hematite is being mined in the Quadrilatero Ferrifero of Brazil. Both types of enriched ore bodies range in size from a few million tonnes to as much as 2 billion tonnes, indicating that the enrichment (upgrading) processes took place at a large scale, geologically. The martite-geothite ores are thought to have formed by supergene processes in which gangue minerals, principally silica, were replaced by goethite. The hematite ores, which are far more abundant, remain controversial. Some were probably formed simply by removal of silica, which left a smaller volume of iron-rich ore. Others probably underwent multiple enrichment events that involved either removal of silica or addition of iron, or both, by solutions of basinal origin, assisted locally by burial metamorphism. Further concentration took place in some areas when post-enrichment erosion and sedimentation concentrated iron-bearing minerals and fragments into clastic deposits.

Box 5.4 Iron Ores and Cost Advantages

Higher grade, enriched ores from Australia, Brazil and South Africa have a major cost advantage to lower grade unenriched iron ores in Canada and the United States. For one thing, a much smaller amount of ore must be mined to get the same amount of iron. More importantly, however, the high grade ores are easier to mine and require less processing. Precambrian iron formations that have not been enriched have high silica contents that must be removed before the ore can be used in blast furnaces or other steel-making. This silica makes the ore very hard, which requires special tools for mining and crushing. In addition, the iron mineral concentrate is very fine-grained and is usually rolled into balls with clay and baked to form pellets that are used as blast furnace feed. In contrast, iron formations that have been enriched and consist largely of goethite and hematite are softer and easier to mine. Some of these are sufficiently high-grade to be shipped directly to blast furnaces, although fine-grained ores must be agglomerated or sintered to prevent loss of ore particles into the atmosphere during operation of the blast furnace.

Among the high-grade ores, Australia has the greatest advantage because it has the shortest shipping distance to China and Japan, the major importers of iron ore. Vale, the main Brazilian iron ore exporter, has competed by discounting prices and by using very large ore carriers. At 400,000 deadweight tonnes (safe weight of a fully loaded ship), 360 m long and 65 m wide, the Vale-class ore ships are the largest bulk carriers in the world, exceeded in size only by a few crude oil tankers.

5.4 Other Sedimentary Deposits: Manganese, Phosphate, Marine and Lacustrine Evaporites

Manganese forms sedimentary deposits that are similar to banded iron formations, but that formed during Phanerozoic as well as Precambrian time, as discussed by Holland (2005) and Gutzmer and Buekes (2009). This suggests that manganese behaves differently in seawater, and especially that it is easier to dissolve, which is indeed the case. Manganese has three oxidation states; Mn^{2+}, which forms minerals such as pyrolusite (MnO_2) and the pink carbonate rhodochrosite ($MnCO_3$), and Mn^{3+} and Mn^{4+}, which form oxides like hausmannite (Mn_3O_4) and the complex oxide psilomelane [$(Ba, H_2O)_2Mn_5O_{10}$]. These minerals precipitate at higher pH and more oxidizing conditions than the equivalent iron minerals (Fig. 5.7). In other words, manganese is more likely to remain dissolved in the ocean. Some manganese deposits are associated with iron formations, although they appear to be in more distal, oxidizing settings, suggesting that initial precipitation of iron left seawater enriched in manganese that formed the deposits. Another reason that manganese can remain dissolved in reduced solution is that its sulfide mineral (alabandite, MnS) is more soluble than pyrrhotite and pyrite. The constraints can be observed in operation today in the Black Sea where highly reduced (euxinic) deep waters precipitate pyrite-rich muds as more oxidized surface waters precipitate manganese oxides.

The largest manganese deposits are the Paleoproterozoic ore bodies of the Kalahari in South Africa, Late Proterozoic ores of the Moanda district in Gabon and Serra do Navio district in Brazil, Jurassic rhodochrosite ores of the Molango district of Mexico, Cretaceous ores of Groote Eylandt in Australia, and the Oligocene deposits at Varna, Nikopol and others areas around the Black Sea. This wide range of ages shows that manganese was not cleaned out of the world ocean during the GOE. During later phases of Earth history, manganese deposits could form whenever reduced waters gained manganese and moved upward into more oxidizing shelf environments. The source of the manganese was probably alteration of volcanic rocks and the original manganese precipitates were probably combinations of Mn-oxyhydroxide and organic carbon that were converted during diagenesis to carbonates and oxides. Many of these deposits have been upgraded by weathering to form Mn-oxide deposits.

Phosphate deposits are the source of phosphorus, which is used largely in fertilisers. Most phosphate deposits consist of limestones with abundant apatite $[(Ca_5(PO_4)_3 \cdot (OH, F, Cl)]$ in limestone, and they are commonly referred to as phosphorites. These deposits form in shallow water on continental shelves where phosphorus-rich water upwells along the continental rise. Although simple inorganic reactions can be written to account for deposition of the apatite through loss of CO_2 as the water rises, actual deposition is largely a result of biological productivity. In modern areas of upwelling, such as the west coast of Peru, phosphate deposition is so intense that photographs of the water look like a snow storm. The largest phosphate deposits being mined today, which are in China, the United States, and Western Sahara and adjacent Morocco, are thought to have formed in the same way.

Evaporation of seawater produces chemical precipitates that are mined for gypsum ($CaSO_4 \cdot 2H_2O$), halite (NaCl), sylvite (KCl), and if evaporation goes to completion, for complex salts of calcium, magnesium and bromine known as bittern salts. Evaporite deposits usually form when evaporation exceeds seawater inflow in shallow arms of the ocean, a process that has varied through geologic time as discussed by Warren (2010). Some evaporite deposits are hundreds of meters thick, which requires that the basin subsided over a relatively long period of time at a rate about equal to the rate at which evaporite deposits accumulated. Evaporites are mined in many parts of the world, usually by underground operations because of their relatively soluble nature. In some areas, such as the Michigan Basin, where seawater did not evaporate completely, residual brines occupy pore spaces in the evaporites. These can be pumped up and treated to recover dissolved elements of the bittern salts. Evaporites also form in water that fills lakes on the continents.

If the lakes are close enough to the ocean, their dissolved salt composition is dominated by sea spray and resulting evaporites are similar to those formed by seawater. Many lacustrine evaporites differ significantly from seawater evaporites, however. If they formed far from the ocean away from the effect of seaspray, their main anion is carbonate or sulfate rather than chloride. If so, their evaporites contain sodium sulfate (thenardite) and sodium carbonate (trona or soda-ash) evaporites; Green River Formation in the western United States was a lake of this type. If the surrounding rocks contain unusual elements and if enough hot water flows through the rocks to leach these elements into the drainage system (as happens in areas of recent volcanism or active faulting), the unusual elements will show up in the evaporites; the most common are lithium and boron.

Nitrate deposits comprise another strange type of evaporite that does not really form in a body of water. The world's largest and really the only example of this type of deposit is in the Atacama Desert of Chile, one of the driest regions of the world. Here, nitrate thought to form by photochemical processes in the atmosphere is dissolved and falls to Earth during rare precipitation events. The precipitation does not recharge the groundwater and instead wicks back upward and evaporates quickly, leaving a crust of nitrates that cements surface gravels and residuum along the sides of valleys. The mining of these generated great wealth for Chile for over a century, until the 1940s when the German chemist Fritz Haber developed a process to produce ammonia from atmospheric nitrogen.

5.5 Laterites

Laterites are soils that develop through prolonged and intense weathering in hot humid climates. Most laterites are relatively rich in iron and few of these have economic value, but some laterites that develop on granites or clay-rich shales form bauxite, the ore of aluminium, and some others that develop on ultramafic rocks form lateritic nickel deposits. Aspects of laterites and their ore deposits are discussed by Butt et al. (2000), Freyssinet et al. (2005).

5.5.1 Bauxite

Table 5.5 is a list of the world's largest producers of aluminium metal. Included in the list are the large industrial countries like China and the USA and several countries with large reserves of bauxite, like Australia, India and Brazil. But also included in the list are countries in northern climates including Canada and Norway, where Pleistocene glaciation has removed much of the soil and there are no laterites to mine. Most obvious of these is Iceland, a small, volcanic island in the middle of the north Atlantic Ocean. What is it doing in the list? The reason is simple: to extract aluminium metal from the oxides and hydroxides that are the ore minerals in bauxite requires a lot of electricity, a commodity that Iceland has in excess. So, bauxite or its refined product alumina (Al_2O_3) is shipped halfway around the world from Australia, where it refined in Iceland into aluminium metal

Table 5.5 List of aluminium-producing countries (2013)

Rank	Country	Production (tonnes)
1	China[a]	21,500
2	Russia[a]	3950
3	Canada	2900
4	USA	1950
5	Australia[a]	1750
6	United Arab Emirates	1800
7	India[a]	1700
8	Norway	100
9	Brazil[a]	1330
10	Bahrain	900
11	Iceland	825
12	South Africa	820

[a] Major bauxite-producing countries
Source http://minerals.usgs.gov/minerals/

and then shipped to markets in Europe and America. Does this make any economic sense? And what is the impact on the environment of these "bauxite miles"?

In Iceland the cost of industrial electricity is about 4 US cents/kWh, among the lowest in the world. But the real advantage is seen when we consider environmental issues. In Iceland, electricity is produced in hydro or geothermal energy plants that release almost no CO_2 into the atmosphere whereas in Australia, about two-thirds of the electricity is produced from coal, the worst greenhouse gas emitter of all. Just how big this CO_2 advantage is can be seen in Box 5.5. Canada and Norway have the same advantage in aluminium production. The Persian Gulf countries of Bahrain and the United Arab Emirates also produce aluminium, in their case using electricity from natural gas that would otherwise be wasted. Their CO_2 advantage is smaller, but still measureable because natural gas has a lower CO_2 footprint that coal.

Box 5.5 Carbon Footprint of Aluminium Production from Bauxite: Iceland Versus Australia

Transport by ship produces about 25 g of CO_2/t/km. Electricity from coal produces about 1000 g of CO_2/kWh, while electricity from geothermal or hydropower produces virtually none. (None of these estimates take into account the carbon footprint of construction, maintenance and dismantling of ships or power plants). Four tonnes of bauxite and 15,000 kWh of electricity are needed to produce 1 tonne of aluminium. The round-trip by sea from Australia to Iceland is about 40,000 km.

Use these figures to determine whether it is more advantageous, in terms of carbon emissions, to produce aluminium in Australia (using electricity produced from coal), or to export bauxite and produce aluminium in Iceland (using electricity produced without emitting CO_2). Watch out for units in your calculations! Your results will not take into account the lower cost of electricity in Iceland and the shorter shipping distance for the refined metal to consumers in European and American markets.

Solution: When producing aluminium in Australia, the transport costs are negligible, but to refine 1 tonne of metal from 4 tonnes of bauxite consumes 15,000 kWh of coal-produced electricity, which emits about 6.75 tonnes of CO_2. Transportation to Iceland emits only about 4 tonnes of CO_2 and emissions from electricity production are negligible. This back of the envelope calculation suggests that it is a good idea to ship bauxite half-way around the world to benefit from the low cost—both financially and in terms of CO_2 emissions—of electricity in Iceland.

Just as for iron, there is little chance we will ever exhaust our resources of aluminium. Global reserves of bauxite are enormous, about 28 billion tons, enough to last more than 100 years at present levels of consumption. And even if bauxite were totally mined out, larger amounts of Al are present in clay and feldspar, whose abundance is much larger. Even now, Russia, the third biggest aluminium producer, produces some aluminium by mining feldspar in alkaline intrusions.

The world's bauxite deposits are found mainly in equatorial regions of Guinea, Australia, Brazil and Jamaica, which have tropical climates. The biggest and richest deposits formed on continental peneplains that were subject to long periods of alternating wet and dry seasons, conditions that caused the water table to oscillate. As the level of groundwater rose and fell, the more soluble components were leached out of the rock, leaving a lateritic soil that retained only the most insoluble components. In parts of Africa, South and Central America and Australia, laterization on flat peneplained surfaces has persisted for up to 100 million years resulting in a layer of deeply weathered residuum known as saprolith (or saprolite, a material that is entirely weathered material but that retains the textures of the parent rock) up to 150 m thick.

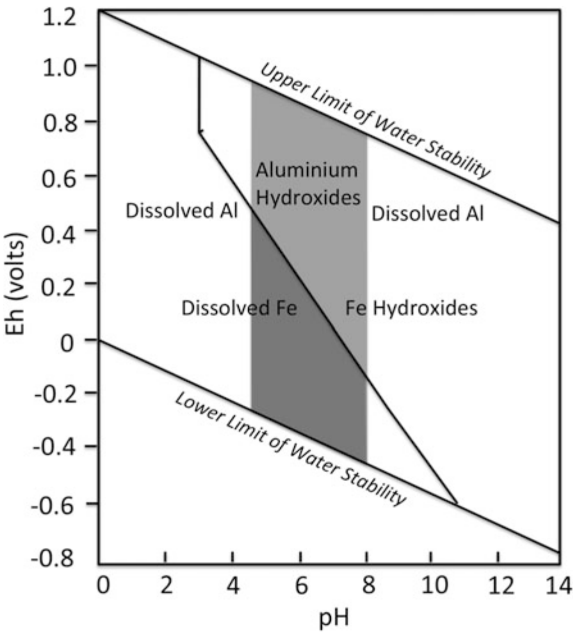
Most major rock-forming elements, especially Si, Mg, Ca, Na and K, are moderately to highly soluble in the near-neutral (pH 5-9) waters during lateritic weathering. The oxides of these elements make up about 80 % of felsic rocks such as granite, gneiss or shale and if they were totally removed, the concentration of Al_2O_3 would increase fourfold, from about 15 %, the level in unweathered rock, to close to 60 %, the level in rich bauxite. The best bauxites are mixtures of Al hydroxides, gibbsite ($Al(OH)_3$), and two polymorphs with the composition AlO (OH), boehmite and diaspore.

The most important "problem" element in many bauxite deposits is iron; even moderate iron contents makes bauxite unsuitable for the recovery of aluminium. It helps to develop a laterite on Fe-poor rock, and granites and shales meet that criterion. However, even small amounts of iron can be a problem and the best bauxite deposits form where iron is leached out of the soil but aluminium stays. As it turns out, the ideal conditions for this can be distinguished on Eh-pH diagrams, much like those that we used to show the behavior of Fe and Mn in seawater. Petersen (1971) pointed out that the boundary between soluble and insoluble Fe is sloped in Eh-pH space whereas it is vertical for Al (Fig. 5.9). This means that soils forming in relatively low Eh (reducing) conditions can remove Fe without removing Al, thus producing clean bauxite. This means, in turn, that bauxites developed in areas with heavy vegetation, where recharging waters are reduced by organic matter, are likely to be lower in iron than those that form under oxidizing conditions. Thus, the best bauxites require a combination of factors and processes; (1) the presence of Al-rich (and Fe-poor) parent rocks; (2) an appropriate balance of temperature and rainfall (high temperatures favour Fe-rich laterites); (3) a pronounced alternation of wet and dry seasons; and (4) abundant vegetation to reduce the weathering zone.

In practice, even the best laterite-forming conditions leave some impurities in the bauxite, including partially weathered rock, quartz, and insoluble minerals such as ilmenite. It is these impurities that are usually removed in the first step of bauxite processing, which produces alumina (Al_2O_3) to be refined to aluminum metal. As noted above in our discussion of Iceland, alumina is sometimes produced at the mine because it does not require as much electricity, and then transported to aluminum refineries where electricity is less expensive.

Although the processes that form laterites can be explained relatively easily, the actual products are somewhat more complex than these explanations might suggest. In Fig. 5.10 we show profiles through two lateritic ore deposits, one containing

Fig. 5.9 Schematic Eh-pH diagram showing differing conditions under which iron and aluminium are soluble (modified from Petersen 1971 and Takeno 2005). Note that iron is soluble in near-neutral water under reducing conditions, whereas aluminium is insoluble. This diagram does not take into consideration other anions such as carbonate or phosphate that might restrict the mobility of iron



bauxite and the other a Ni laterite, which illustrate these complexities. The saprolith zone at the base of the bauxite profile consists of highly weathered rock that preserves much of its original texture and structure. Feldspar and the ferromagnesian minerals are destroyed and the soluble components are partially removed while Si and Al are retained in clays and some Fe is retained in goethite and hematite. In the upper part of the saprolith and in the pedolith (the soil) all but the most resistant primary minerals are destroyed and the rock in composed entirely of clays, Al and Fe oxides and hydroxides, and minor amounts of residual quartz. The original texture is completely lost and the rock has a pisolitic or nodular structure that results from repeated episodes of dissolution and accretion. The uppermost pedolith consists of unconsolidated or cemented Fe-oxide-rich gravels and duricrust.

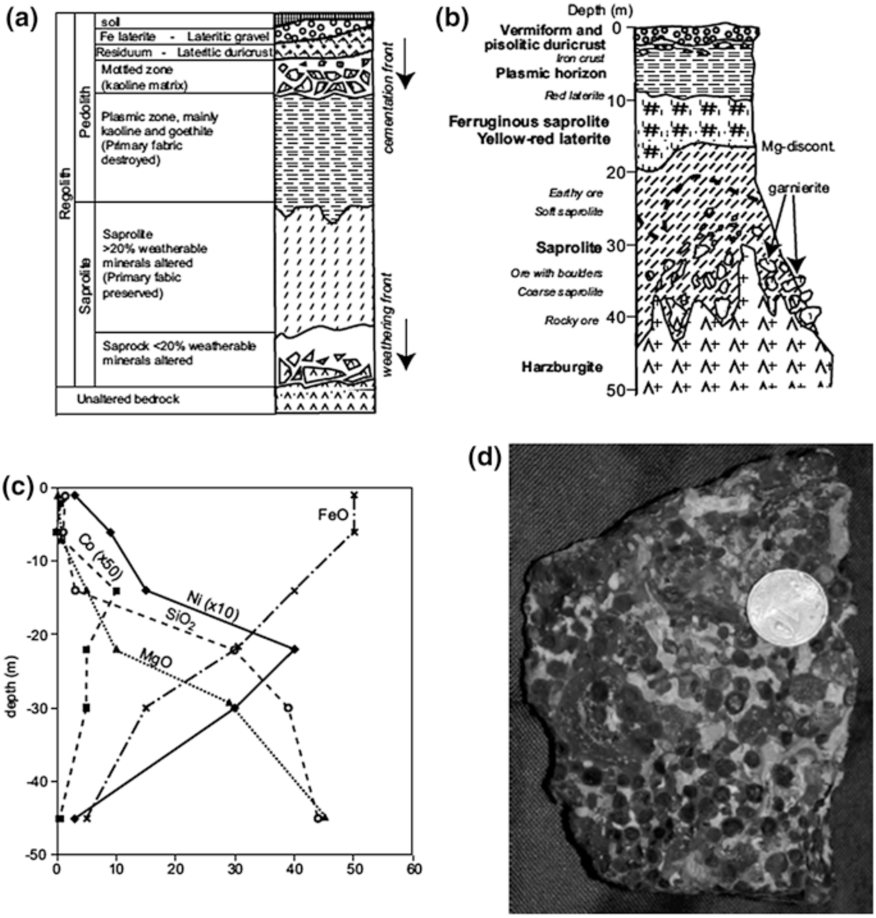


Fig. 5.10 Profiles through **a** bauxite (from Butt et al. 2000) **b** nickel (from Freyssinet et al. 2005) laterite deposits showing typical rock textures **c** chemical profile through nickel laterite showing distribution of major elements (plotted from data of Freyssinet et al. 2005) **d** photo of pisolitic bauxite

5.5.2 Ni Laterites

If it is accepted that an island half-way across the world is part of the French nation, then the biggest mines in France are in New Caledonia. The nickel deposits of New Caledonia were recognized in 1864 by Jules Garnier who gave his name to the main ore mineral, a mixture of pale green to apple-green phyllosilicate minerals with the approximate composition of $(Ni, Mg)_3Si_2O_5(OH)_4$. The deposits in New Caledonia have been mined almost continuously since 1875 and have been the focus of many innovative procedures for the extraction of Ni from lateritic ores. They are thought to contain about a third of the world's remaining supply of nickel ore; and when other major lateritic deposits in Indonesia, Cuba and Australia are included, the figure reaches 50–60 % (Golightly 1981; Berger et al. 2011).

Just as with bauxite, the extraction of Ni metal from the silicates and hydroxides that constitute lateritic nickel ore requires abundant energy. The lateritic ores contain large amounts of bound water, which must be driven off, and they have high magnesium contents, which require high temperatures to melt (magnesium silicates such as olivine are used to line furnaces!). A wide variety of alternative extraction processes have been developed in New Caledonia and Cuba, and these are being applied with variable success in the extraction of ore in other countries. Because of the high energy consumption, the viability of a nickel laterite project depends crucially on the price of energy, which in most areas is dictated by the price of oil that is used to generate electricity; when oil prices are low, lateritic deposits gain a competitive edge over magmatic deposits. Table 5.6 lists the advantages and disadvantages of the two types of Ni deposits.

Nickel-bearing laterites develop when ultramafic rocks are exposed to protracted weathering in hot humid climates. In most areas where deposits are known, such as New Caledonia, Indonesia and Cuba, the ultramafic rocks are the lower portions of ophiolite complexes that have been obducted to the surface. A notable exception is the deposits in Western Australia, which have formed on intrusions of komatiitic lineage, the same rocks that host the magmatic nickel deposits in the area.

During weathering of ultramafic rocks, primary olivine or pyroxene or secondary serpentine that replaces these minerals release elements such as Si, Mg and Ca, which make up 90 % of the rock, leaving the less mobile Ni (and Fe). The laterization process is comparable to that of bauxite formation and the parallel is brought out in the comparison of the two profiles in Fig. 5.9. One difference between the two elements in laterites is that some nickel does move downward during weathering. This nickel formed the rich garnierite ores, which are present in the lower part of the saprolith (Fig. 5.10). Other nickel remains in the upper part of the weathered profile where it is adsorbed onto goethite and makes up iron oxide ores. During the early years of mining in New Caledonia, very rich garnierite ores containing up to 15 % Ni and averaging 2.5 % Ni were exploited, but these are now largely exhausted and mining has turned to goethitic ores. Even though these goethitic ores are lower grade (1.3–1.6 % Ni), their grades are still high compared to most of the laterite deposits. Weathering is a very important upgrading process for nickel;

Table 5.6 Comparison of magmatic and lateritic Ni ores

	Magmatic	Lateritic
Origin	Segregation of Ni sulfides from mafic-ultramafic magmas	Concentration of Ni in soil during long weathering in hot humid climates
Ore minerals	Ni-Cu-Fe sulfides 0.5–5 %	Ni-bearing phyllosilicates 1–7 %
Ore grade		
Locations of major deposits	Canada, Russia, Australia, China	New Caledonia, Indonesia, Cuba, Australia
Economic aspects		
– Mining onditions	Underground (rare open pit) mining of discontinuous deposits in hard rock	Open pit mining of continuous layers of shallow poorly consolidated soil
– Cost of refining	Relatively low	High (depends on oil price)
– By-product metals	Cu, PGE	Co
– Toxic waste products	Sulfur	Acid or strong alkalis (from refining)

it increases the Ni content from 0.2 to 0.3 % in the parent ultramafic rock to an average of 1–3 % in the ores. Cobalt is also concentrated chemically by this process (Fig. 5.10) and is an important by-product of some operations. Chromium, which commonly remains as chromite that is not dissolved during weathering, is also concentrated in the laterite but is not usually recovered.

Mining of laterites is a particularly big environmental problem simply because the laterite material forms a relatively thin layer at the immediate surface (Fig. 5.11). Removal of this layer leaves essentially bare, partly weathered rock at the surface. Although this is unsightly, it must be kept in mind that most areas of original laterite soils are very poor in nutrients and do not support much vegetation,

Fig. 5.11 *Left* Thin layer of iron-rich nickel laterite overlying serpentinite at the Guanajibo deposit, Puerto Rico. *Right* Air view of nickel laterite mine, Bonao, Dominican Republic showing extensive surface disruption caused by mining shallow deposits such as laterites (photos by S. Kesler and M. Seaward)

and almost certainly no productive agriculture. Some species of pines and eucalyptus will grow on lightly reclaimed laterite parent rock, and these are usually used to establish a first-growth forest on mined land.

Box 5.5 Exercise—Exploration for Nickel Deposits

Imagine that you are a geologist in a multinational mineral exploration company and that your boss, the exploration manager, has asked you to plan a future exploration program. The company economists have decided that the price of all base metals will double in the next 10 years, that nickel will be a main beneficiary of this increase, and so the company has decided to explore for nickel. Your tasks are to decide: (1) what type of deposit to target (magmatic or lateritic), and (2) which part of the world has the best geological and economic/political characteristics for exploration.

To decide on the type of deposit you will need to consider the pros and cons of each type of deposit, and, because the extraction of Ni from laterites requires so much energy, the future oil price, or the possible availability of alternative sources of electricity. Regardless of which type of deposit you select, it will be necessary to decide whether to conduct "greenfields" exploration (i.e. the search for deposits in parts of the world where no deposits are known), or "brownfields" exploration (the search for new deposits or extensions of deposits in regions known to contain deposits). (Many exploration geologists feel that elephant country is the best place to look for elephants.) To decide on the region you will need to consider the geology of possible target regions including ages and tectonic characteristics, the types of ultramafic rocks they contain, and the climate over the past 100 million years. Most difficult of all, you will need to summarize your arguments in a single page, which is the maximum length of a report that the upper management will want to read.

5.6 Other Lateritic Deposits

Any element that is relatively insoluble during protracted weathering might form residual (eluvial) and colluvial concentrations that could become an ore deposit. Gallium, which substitutes for aluminum in minerals, is relatively insoluble and is recovered from some bauxite deposits. Platinum group elements are also relatively insoluble and are concentrated in lateritic soils over ultramafic rocks in the Carajas region of Brazil. Other elements that are relatively insoluble include Nb, Sn, Th, V, W and Zr. Examples are known for some of these, including Nb in residuum above deeply weathered pegmatites in Nigeria, and Sn in eluvial and colluvial concentrations above granites in Malaysia.

The champion element, however, is gold, which remains behind during weathering of many deposits. In hot humid climates, especially, weathering can remove so much material that unweathered gold-bearing protore (rock in which the gold grade is too low to mine) is transformed into ore. Examples of this type of deposit are found in West Africa. Sometimes elements such as gold in a laterite can be a signal of something in underlying rocks. At the Boddington bauxite mine in Australia, gold values in the aluminum ore led to exploration of the underlying basement rocks, which turned out to contain an orogenic gold vein deposit.

This is a good place to remind you that the insolubility of gold is an important part of the geology of gold deposits. In deposits that contain only gold and pyrite, such as many epithermal, orogenic and Carlin deposits, oxidation destroys pyrite releasing any gold that it might contain (recall that arsenian pyrite is an important host for gold in Carlin and some epithermal gold deposits). Gold can be recovered from oxidized ore by crushing it and mixing it with cyanide solutions, which dissolve only the gold. In arid areas, such as Nevada where Carlin deposits are common, oxide ore is placed in piles that are sprayed with cyanide in the process known as heap leaching. As noted in the previous chapter, this simple ore processing method has made gold deposits with very low grades economically mineable.

Another type of surficial deposit is "calcrete", the name given to calcified, calcite-rich soils that develop in arid environments. Chemical zoning in soils in arid regions consists largely of calcite that forms in the upper part of the soil from water that moves upward after precipitation and evaporates. In some areas, the calcite layer is very concentrated and cements that residuum. If trace elements come along with this water, they also might be concentrated. The only element known to do this is uranium, which is found in deposits that consist of carnotite ($K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$), the vivid yellow uranium mineral, in calcite-cemented residuum. Examples include the Langer Heinrich (Namibia) and Yeelirie (Western Australia) deposits.

5.7 Supergene Alteration and Supergene Deposits

So far, we have focused on immobile elements like iron and gold in weathering sulfide deposits. What about the other elements in common sulfide deposits, such as copper, lead and zinc, which are not immobile during weathering? When ore bodies containing these elements are exposed at the surface and weathered, their sulfide minerals oxidize and release metals into groundwater. If sufficient new anions are available, such as hydroxide, carbonate, sulfate, phosphate or even chloride, the newly dissolved metals will precipitate "oxide" minerals and remain in the weathered zone. We already know that iron does this, combining with hydroxyl ion in water to form goethite and other iron oxides and hydroxides. If iron is abundant

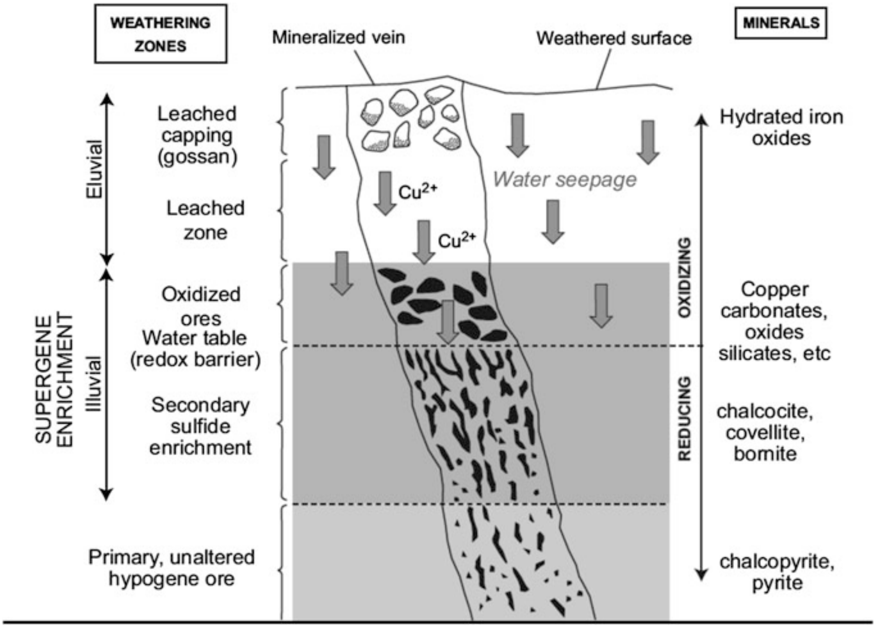


Fig. 5.12 Generalized cross section of a supergene enrichment zone above a copper sulfide deposit containing primary chalcopyrite and pyrite (from Webb and Rowston 1995)

in the weathering deposit, this residual concentration forms massive iron oxide known as gossan (Fig. 5.12). In some cases, iron oxides in the gossans preserve frameworks that mimic the cleavage of the parent sulfide minerals. This is valuable in exploration because it allows gossans derived from pyrite to be distinguished from those derived from chalcopyrite, for instance, which might overlie a copper deposit. Some weathered zones and gossans above ore deposits retain enough gold and silver to be ore deposits themselves. For instance, the oxide zone above the Ok Tedi mine in Papua New Guinea was sufficiently enriched in gold to be mined separately.

Many of the secondary carbonates, silicates, sulfates, and phosphates that form in the oxide zone above sulfide ore deposits are well crystallized, brightly coloured, and highly prized by mineral collectors. The formation of these minerals during weathering of sulfide deposits depends on the balance between acidity of the weathering solution, which is produced by weathering of pyrite, and availability of new anions, which come from the atmosphere or wallrock. In MVT deposits, where pyrite is limited and wallrocks consist of easily dissolved limestone, weathering solutions are not very acid and zinc is often deposited at or near the site of oxidation as carbonates such as smithsonite ($ZnCO_3$). Zinc "oxide deposits" of this type are relatively common as discussed by Hitzman et al (2003). Galena in these deposits might release lead to form cerussite ($PbCO_3$) or anglesite ($PbSO_4$), although it is more difficult to dissolve and sometimes remains as kernels of galena. The copper carbonate malachite formed above some of the sediment-hosted copper deposits in Zambia and the Democratic Republic of Congo for the very same reasons, relatively low pyrite content and proximity to limestone.

If pyrite is more abundant in the sulfide deposit, the weathering solution will be more acid and will carry dissolved ore metals downward. This happens in many VMS and porphyry copper deposits, which have abundant pyrite as well as silicate wallrocks that provide very little in the way of anions to precipitate the newly released ore elements. Most elements released under these conditions leave the system and are lost, but copper commonly precipitates in a shallow horizon known as a zone of supergene enrichment at the water table (Fig. 5.12). In this zone, original iron-bearing sulfides such as chalcopyrite ($CuFeS_2$) are replaced by secondary Cu-bearing sulfides that are iron-free or iron poor. Examples include chalcocite (Cu_2S), covellite (CuS) and even bornite (Cu_5FeS_4). Enriched zones in porphyry copper deposits in some parts of Chile and southwestern North America have been partially redistributed and re-enriched by tectonic movement that uplifted the deposits and exposed them to further weathering. In some deposits, silver is also enriched, although to a lesser degree. Titley (2009) provides a good review of these processes.

Good supergene enriched copper zones have metal grades that are two to five times higher than the primary ore and they are conveniently located close to the surface where they can be recovered at the start of the mining operation. Such high-grade zones are very important to the economics of mining. Developing a mine is a long and complicated procedure that requires a huge investment, often billions of dollars. For instance, it is estimated that development of the Resolution deposit in Arizona will cost $6 billion. The time from the start of the operation to the recovery and sale of the first metals may be 5–10 years and development money is tied up paying no dividend during that period. So, the possibility of mining a layer of unusually rich ore at the start of the operation provides welcome financial relief for the company and often makes the difference between a viable and an uneconomic operation. Unfortunately, Resolution does not appear to have an enriched zone, although it does contain Cu-rich sulfides of apparently hypogene origin.

One of the best-known examples of supergene enrichment is at the Chuquicamata porphyry copper deposit (discussed in Chap. 4). Primary ore at Chuquicamata, which contained only about 0.8 % Cu, was overlain by a thick layer of supergene enrichment in which the copper grade was 2–3 %. In addition, the flow of acidic, weathering solutions from the main ore body transported dissolved copper downstream where it was redeposited in gravels to form a secondary ore body called the Exotica deposit. This deposit contained an additional 300 Mt of ore, also with about 2 % Cu.

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Chapter 6
The Future of Economic Geology

6.1 Introduction

When we wrote the first edition of this book in 2008–2009, the world was in the depths of the financial crisis, and activity of the minerals sector was at a minimum. We nonetheless painted a positive picture of the future of mining, mineral exploration and the study of ore deposits, arguing that society will always require metals and other mineral products. We recognised that recycling and substitution will meet an increasing proportion of these needs, but the remainder would need to be mined. We discussed whether (not when) our mineral resources will be exhausted and concluded that this is unlikely to happen, at least for most metals. This issue forms the subject of the first section in this chapter.

In the first edition, most of this chapter was devoted to two types of metal that had captured the attention of geologists and politicians. The first were the rare-earth elements, which had been catapulted into public perception by China's decision to restrict exports of these metals. The second was lithium, an essential element in the batteries that were to power the fleets of electric vehicles that were expected soon to appear on our streets. Both of these issues now appear to have been rather overblown, and in this chapter we will talk about them in less detail; instead we will focus on several other issues that are having, and will continue to have, a major influence on the mining of metals and on global trade in minerals. These are the continuing debate about whether we will exhaust our supplies of raw materials, the growing role of China in the global minerals sector, and the "social licence to mine".

6.2 Peak Oil and Related Issues

The term "peak oil" expresses the idea that resources of mineral resources such as petroleum will in the near future be in short supply if not totally exhausted. As shown in Fig. 6.1, the basic idea is simple: global population is increasing

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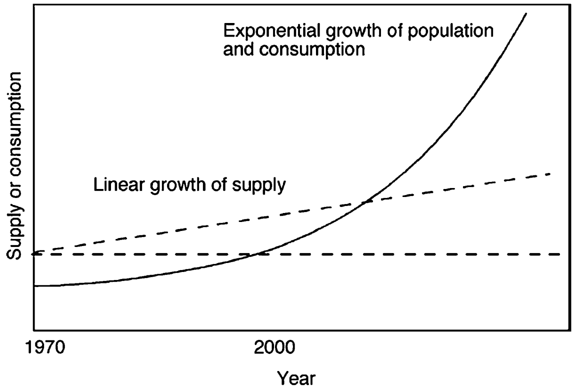

Fig. 6.1 Diagrams illustrating the thesis of Meadows et al. (1972) according to which, if the supply of a mineral product remains constant or increases linearly, it will be exhausted by an exponential increase in population and consumption

exponentially and if it continues to grow, the demands of this expanding population will inevitably consume any natural resource, which manifestly is finite.

The notion that we will run out of natural resources, including metals, is not new. Malthus, in his celebrated article written in 1798 (*An Essay on the Principle of Population, as it Affects the Future Improvement of Society with Remarks on the Speculations of Mr. Godwin, M. Condorcet, and Other Writers; Malthus* (1830)) predicted that the increase in human population would rapidly exhaust supplies of food and natural resources, and the theme has been revisited many times since then. In the report of the 'Club of Rome' published as the book "Limits to Growth", Meadows et al. (1972) also used a model in which human population and consumption of resources increased exponentially while the rate of discovery of new resources increased at best linearly. The consequence, if the assumptions are correct, is rapid depletion of these resources, as shown in Fig. 6.1. According to the more pessimistic prediction made in 1972, the year that the book was published, global supplies of copper would now have become scarce, of not totally exhausted. Clearly this has not happened—copper is still mined in deposits all over the world in amounts that satisfy global demand. In 1972, the total amount of copper known to exist in clearly identified and readily exploitable deposits was sufficient to ensure supplies, at the rate of consumption estimated at that time, for only the following 21–48 years, depending on the assumptions that are made. Table 6.1 compares the predicted times before exhaustion of copper and six other metals, as estimated by Meadows et al. (1972), with another set of estimates made using recent data from the United States Geological Survey (2013). To make this estimate we simply divided the estimates of global reserves of the metal by the annual production. Despite more than 40 years of consumption, the estimated times before "exhaustion" of these metals have barely changed and in some cases they have increased. How can this be?

One product that went through a peak of production then dramatically declined is, paradoxically, renewable. Spermaceti, a wax present in the head cavities of the

Table 6.1 Predicted lifetimes of reserves of selected metals

	Meadows et al. (1972)				USGS mineral	
	Lower estimate		Higher estimate		Commodity summaries	
	Number of years (from 1972)	Year when metal becomes scarce	Number of years (from 1972)	Year when metal becomes scarce	Number of years (from 2013)	Year when metal becomes scarce
Aluminium	31[a]	2003	55	2027	106	2119
Copper	21	1993	48	2020	40	2053
Gold	9	1981	29	2001	19	2032
Iron	93	2065	173	2145	57	2070
Nickel	53	2025	96	2068	36	2049
Silver	13	1985	42	2014	23	2036
Zinc	18	1990	50	2022	19	2032

[a] Predicted number of years before the metal becomes expensive and in short supply

1972 (S)—the predictions of Meadows et al. (1972)

1972 (L)—the predictions of Meadows et al. (1972) assuming 5 times known reserves

2013—Estimates made using data from USGS Mineral Commodity Summaries 2013

sperm whale, was an important product of the whaling industry throughout the 18th and 19th centuries. It was valued as high-quality lamp oil and later used as a lubricant in several types of machine. "Peak spermaceti" occurred at the start of the 20th century when overfishing drastically reduced the number of sperm whales. As spermaceti became scarce, the price rose drastically and this led to a search for substitutes; electric lighting replaced oil lamps, and oil from the jojoba plant was used as a lubricant. The demand for the product diminished, in part a consequence of social pressure to ban or restrict whaling. Now, as stocks of sperm whale slowly rebuild, not even Japanese whalers talk of hunting them.

Box 6.1 Peak Spermaceti and Peak Oil

We have drawn a comparison between the production and consumption of two very different products, petroleum and spermaceti. One is a natural product, essentially renewable (if sperm whales are not hunted to extinction). The other is a fossil resource that required millions of years to accumulate. One is a product that was used widely in the 19th century, but only by a small and privileged part of the world's population. The other is currently used throughout the world. It is consumed by people rich and poor and is essential for our modern industrialized society. The exhaustion of petroleum resources, were this ever to happen, would have a far more drastic impact than an absence of spermaceti.

Is it ridiculous to compare spermaceti and petroleum (as suggested by one reviewer of the book), or does the comparison have some merit? Discuss.

A parallel can be drawn with the exploitation of any natural product, including metallic ores and other raw materials as well as petroleum. Julian Simon, a vocal opponent of "peak" theories, provides another example. He noted that at the end of the 19th century, the ivory used to manufacture white billiard balls was becoming scarce and expensive. The shortage led to the development of celluloid, a cheap plastic whose widespread use helped, for a short time at least, to save elephants.

A similar dynamic has affected mineral resources. Most obvious is the continuing competition between coal, oil and natural gas as the energy source for electric power. As the price of one of these commodities rises, another with a lower price will be substituted, taking some pressure off the search for new resources. More recently, climate change issues have encouraged a move away from coal to other energy sources. Similarly, as the price of copper rises, aluminium can be used as a substitute in many of its applications, again decreasing worries about exhaustion of the resource. Even slate, a common rock, has experienced a shift in markets. In the past, it was widely used as a roofing material, but around the start of the 20th century, it gave way to other materials. No one would argue that this took place because "peak slate" had been reached. The cost and effort of constructing slate roofs could not compete with alternative roofing materials. Or, to repeat the commonly cited adage, the Stone Age did not end for want of stone.

Although there can be little doubt that the production of oil and gas will eventually pass through a peak, maybe this decade, maybe far later, it is by no means clear that the cause of the peak will be the progressive exhaustion of petroleum resources. When we wrote the first edition, we thought that the main mitigating factor would be market forces. As supply diminishes, or is perceived to diminish, prices will increase and this will inevitably, sooner or later, lead to a drop in demand. Use of petroleum will decline as we learn to waste less energy or find alternative energy sources; and, in much the same way as pressure from public and scientific bodies led to the banning of whaling, pressure from similar sources will lead us to limit petroleum use so as to decrease the rate of global warming. Because of the damage to the global environment caused by the release of CO_2 associated with the burning of fossil fuels, many groups now advocate that even currently known resources of petroleum should never be completely exploited but should be left in the ground or used for petrochemical production. Over the long term, these factors will certainly influence global consumption of petroleum products.

It now seems more likely that many apparent peaks in production and consumption of minerals and other raw materials resulted because of exhaustion only of known deposits of the type being exploited at that time. Take the oil and gas industry as an example. When we wrote the first edition, we had little knowledge of the dramatic changes that were soon to impact on global energy resources. At that time, it was generally believed that the global rate of production would soon start to decline, if it had not already done so. Access to large petroleum resources, which were concentrated in the Middle East and in other regions of potential instability, had a major influence on global politics, and was partly responsible for the catastrophic incursions into the region by the USA.

Since then the situation has changed dramatically. New discoveries of enormous oil fields off the coast of Brazil, and the potential to find other deposits from Africa to the Arctic, suggest that the supply of conventional oil and gas was not as limited as originally thought. But the real game-changer has been the discovery of vast reserves of unconventional natural gas and oil in the USA. For much of the last decade, US authorities were preoccupied by the dependence of their country on imported natural gas, often from suppliers in unstable or politically hostile countries. They had started to build a series of new terminals to accommodate tankers that would deliver liquefied natural gas to the USA from the Middle East, Indonesia, Australia and other exporting countries. They estimated that within the decade, the USA would have to import a major portion of its natural gas. At the same time, European leaders were concerned about the dependence of their countries on imports of gas from Russia—concerns exacerbated by the pressure applied by the Russian firm Gazprom on the Ukraine and indirectly on the rest of Europe. Then, quite suddenly, technological advances allowed the extraction of gas from a new source—shale and tight (impermeable) sand. This resource had been known for over a century but previously the gas could not be extracted economically from such low-permeability rocks. Newly developed horizontal drilling methods provided better access to flat-lying sedimentary strata, and "fracking" or hydraulic fracturing increased their permeability, allowing gas and oil to be extracted.

The huge increase in USA gas production in the last 2000s caused the price of gas to start dropping in 2008 in the USA, although it remained high in other parts of the world. Increased oil production from shales and tight sands took longer to impact the price, but by late 2014 it had declined precipitously from over $100/bbl to below $65/bbl (Fig. 6.2). The USA now satisfies a much larger fraction of its domestic consumption and has returned to its earlier role as the world's biggest petroleum producer. The availability of cheap and abundant energy has boosted US industry: according to some sources, it led in 2013 to a remarkable one-percent increase in gross domestic product.

The shale and tight sand boom has been slower to impact the rest of the world Shale gas provides about 15 % of Canada's natural gas production and some shale

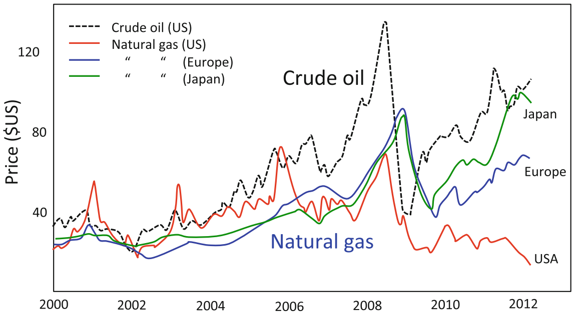

Fig. 6.2 Changes in the price of oil (US$ per barrel) and natural gas (US$ per million btu) in the USA over the past decade. After the 2008 financial crisis, the price of oil rebounded rapidly but the price of natural gas remained constant because of the availability of shale gas. In Europe, which has relatively small domestic supplies of natural gas and hesitates and is hesitant to exploit shale gas, the price is about 3 times higher. Japan has even fewer options and has renounced nuclear energy: there prices are even higher

gas (<1 %) is produced in China. European countries such as Poland and Great Britain, as well as South Africa, Australia, Argentina and China, have large potential reserves of shale gas and oil, and in some of these countries steps have been taken to evaluate these resources. But in other countries, France being the prime example, vocal public opposition to the possible extraction of shale gas has led parliament to ban even the exploration for this resource. The main fuel for this opposition is environmental issues, with ecologists expressing concern about the high consumption of water, potential leaks of the chemicals used in the process, and possible contamination of ground and surface waters.

Why do we write in so much detail about shale gas and oil—a product that is somewhat apart from the main theme of this book? The reason is that the controversy surrounding the supply and demand for oil and gas, and the public perception of these issues, has much in common with the mining of metals and other mineral products. Recent changes in the global petroleum sector relate directly to the question we posed at the start of the chapter: why hasn't growing global population and growing demand for metals in developing countries already exhausted our supplies of these metals? In addition, the growing public opposition to the exploitation of shale gas in some countries finds a direct parallel in similar opposition to domestic mining. We will discuss both these issues later in this chapter.

Box 6.2 Reserves and Resources

A *mineral reserve* is a concentration of ore minerals that has been shown on the basis of geological and other information to be legally, economically and technically feasible to extract.

An *ore resource* is a concentration of ore minerals that is potentially valuable, and for which reasonable prospects exist for eventual economic extraction (Fig. 6.3).

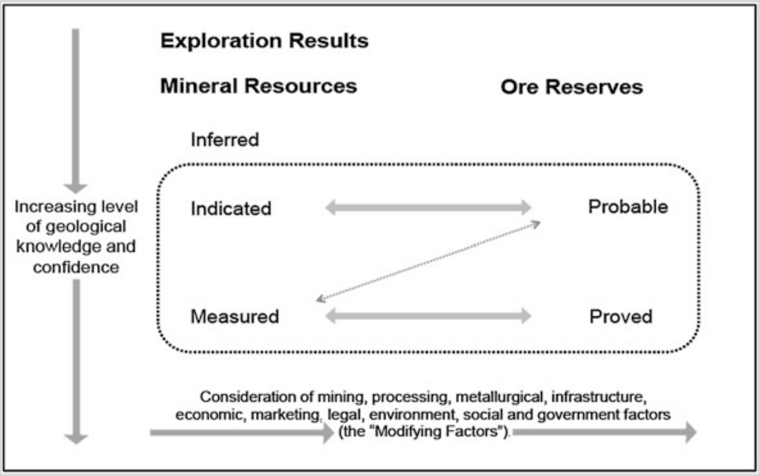

Fig. 6.3 Diagram illustrating the differences between reserves and resources. From JORC (2012). Australasian code for reporting of exploration results, mineral resources and ore reserves http://www.jorc.org

6.3 Peak Copper

Several factors have pushed back the date of copper depletion predicted in the Meadows et al. (1972) Club of Rome report which we discussed earlier in the chapter. First and foremost, over the past 30 years, new copper deposits have been found and developed at such a rate that the predicted exhaustion time of known copper sources has remained constant. The estimated reserves have remained nearly constant, despite accelerating production and consumption of copper. How can this be?

What was not fully appreciated by Meadows and co-authors is the difference between mineral reserves and mineral resources. It makes little sense for a mineral company to spend money to find ore deposits that will not be exploited in the relatively near future. If a company has found sufficient copper for the next two to three decades, in deposits that can be exploited using current technology, there is no point in spending money to find more. In addition, the reserves that Meadows et al. counted were limited to well-known, conventional deposits; they did not take into account lower grade material in known deposits, deposits that had not been discovered yet, and new types of deposits, all of which are resources. They also did not fully appreciate the degree to which technological improvements would expand mineral reserves. All of these have been very important in extending the period of mineral production, and there is every indication that they will continue to be important in the future.

For reasons such as these, many authorities now predict that supplies of metals and other mineral products are sufficient to meet societal needs for many decades or possibly even centuries. However, we should not let this liberal interpretation of resources free us from concern. First, we have to find these deposits and develop them before the metals can be used. The wave of anti-mining sentiment that is sweeping the world will impede these efforts. Considerable research will be needed to develop methods for finding and mining new deposits, especially those buried beneath the surface. Second, the inventory of all types of ore deposits is finite. Recent estimates of the total number of conventional deposits of gold and copper in the crust suggest that there are enough for a few hundred to a few thousand years at current rates of consumption. These numbers are impressive, but need to be put into perspective: they are small in relation to the age of the Earth and even to the period of time that humans have inhabited the planet, but large when the rapid pace of technology change is taken into account. Who knows which materials society will need in the 22nd century? Consider how our uses of metals have changed since 1910, when TV was unknown, cars were rare and aviation was in its infancy. Will we still consume large amounts of copper or gold in the year 2150?

Box 6.3 Sustainable Mining and the Exhaustion of Mineral Resources
Sustainable mining can be defined as exploitation of minerals at such a rate and in such a manner that resources remain to meet the needs of future generations.

Some time in the next 50 years or so, global population will peak and then reach something approaching a steady state. At the same time, barring catastrophe, we can hope that the gap between developing and developed countries will have diminished. Because of increased rates of recycling and substitution of metals, global demands for raw minerals will have stabilized. From the statistics published by the US Geological Survey and similar organizations, we can estimate the total amount of metals like aluminium or copper that have been produced in the past 100 years (see Box 6.2). Very crudely, this is the amount that has been mined since the birth of humanity (the amount produced before the 20th century was very small), and is also equivalent to the amount that will have to be produced to satisfy demand for the coming 50 years (assuming production at twice the current rate for this period). The quantities are enormous: for copper, five hundred million tons will have to be mined and for aluminium over a billion tons will be mined.

But how do these amounts compare with the total amount of metal present in the crust? We can calculate these amounts if we know the average concentrations of Cu and Al in the crust and the total mass of the continental crust (3×10^{19} tons). The total amounts are also given in Table 6.2. By comparing the two columns, we see that the amounts of metals needed to satisfy the demands of society are less than a millionth of that in the crust. Of course, we can only expect to mine metals from the upper part of the crust, but if we place a limit of 300 m (about 1 % of the total crustal thickness), the numbers are still very small; 10^{-5} for copper and 10^{-7} for aluminium. To speak of "exhaustion" of these metals is clearly unreasonable.

In practice, all mining is focused on ore deposits that contain metal concentrations that are many times greater than those in normal crustal rocks. Evaluations such as those of Tilton (2003) and Kesler and Wilkinson (2008) show that conventional ore deposits will indeed become scarce in the future and that we will have to count on improvements in technology, the exploitation of new types of deposits, and more efficient recycling to satisfy the demands of future generations.

Even though the rate of population increase will diminish as the level of education improves in developing countries, the addition of 1–3 billion people will put a severe strain on the earth's resources. Competition for water and food, increasing effects of pollution, growing climate change, increased energy requirements for processing low-grade ores, and decreased availability of fossil fuels will severely test humanity's capacity to adapt. Nonetheless, although the long-term outlook is difficult to predict, we argue that imaginative use of geological, engineering and environmental

Table 6.2 Production of Al and Cu in proportion to the total amount in the crust

	Production 1910–2010 (tons)	Total production in 2060 (tons)	Concentration in the crust	Total amount in the crust (tons)	Production as fraction of total amount
Copper	5×10^7	1.5×10^8	60 ppm	2×10^{15}	10^{-7}
Aluminium	5×10^8	1.5×10^9	10 %	3×10^{18}	10^{-9}

principals will allow us to maintain supplies of most mineral products far into the future, particularly if we are able to explore widely in the world.

Box 6.4 provides another example. All the metals and other mineral products needed by industry and modern society are found in the crust of the Earth, though normally in very small concentrations. A competent geochemist or materials scientist can extract all of these metals from any sample of rock, though at enormous cost.

Box 6.4 How much Neodymium is in the Continental Crust and What is the Cost of Extracting it?

Neodymium (Nd), one of the rare earth elements, is essential for the manufacture of the high-performance magnets used in numerous high-technology products. The granitic rocks that make up most of the continental crust contain about 30 parts per million of Nd or 30 g per ton. The mass of the continental crust is 3×10^{19} tons. 1. *Calculate the total amount of Nd in the continental crust.*

Current global production of Nd is about 10,000 tons per year. The approach adopted by Meadows et al. in the Club of Rome to calculate the lifetime of a resource is to divide the total known amount (reserves) by the annual production rate (lifetime = tonnage/annual production). 2. *Assume we could extract all the Nd for the upper 1 % of the crust and calculate the time it would take to exhaust all this Nd.*

How much would it cost to extract this Nd? Research geochemists routinely extract Nd from rock samples in their laboratories. The amount of sample is very small, typically 100 mg (10^{-6} kg) and again, the sample can be considered to contain 30 ppm of Nd. It costs a geochemical lab about $US50 per sample to separate the Nd. 3. *Calculate the cost per kg of Nd extracted in a geochemistry lab.*

Answers:

1. The continental crust contains many trillions of tons (10^{14}) of Nd.
2. There is enough Nd in the uppermost crust to satisfy global demand for the next ten billion years!
3. The cost of this Nd is a stupendous 1.7 trillion dollars per kg.

The point of this exercise is that although elements like Nd are present in the earth's crust, the cost of extracting them from normal rocks is totally prohibitive. For that reason, mining companies explore for deposits in which the concentrations of these elements are many orders of magnitude greater than in normal rocks. But the exploration and mining of these deposits commonly encounters numerous technical, economic, political and environmental problems. In the following sections we discuss two groups of minerals that have received global attention in the past decade and aptly illustrate the challenges of mining in the 21st century.

6.4 Rare Earth Elements (REE)

This group of elements, well known to geochemists who use them as tracers of geological processes in the mantle, crust and oceans, has become crucial for many branches of modern industry. They are used in a wide variety of applications, mostly in electronic components, but also in a range of industrial processes. Some typical examples are listed in Table 6.3.

In geochemical terms, the rare earths are classed as incompatible elements, which means that they become concentrated in low degree partial melts of the mantle and in the water-rich silicate liquids that remain after a magma has almost completely crystallized. They are abundant in some pegmatites (the products of crystallization of aqueous melts expelled from granitic magmas) and in carbonatites and related rocks (alkaline magmas composed mainly of carbonate minerals with few silicates). They also are concentrated in phosphates such as monazite and apatite in detrital sediments, or are absorbed on clays. Table 6.4 lists the REE-bearing minerals in various types of ores.

Bayan Obo, a giant polymetallic (Fe-REE-Nb) deposit, is located in Inner Mongolia on the northern edge of the North China craton, about 600 km northwest of Beijing. The deposit was found in 1927 and was first mined, and continues to be

Table 6.3 Uses of the rare earth elements

In 2006, the three main uses for REE in the USA were catalytic converters in cars (25 %), catalysts in petroleum refining (22 %), and various metallurgical additive and alloys (20 %). The emergence of new technologies will rapidly change the situation. Consider, for example, the following list
Lanthanum (La)—water treatment, rechargeable batteries
Cerium (Ce)—glass polishing, heavy 'mud' in oil drilling, catalysers
Neodymium (Nd)—small electric motors, magnets, hard drives in computers, headphones of iPhones
Europium (Eu)—red phosphor in flat TV screens
Dysprosium and terbium—alloys and phosphors in lamps and TV tubes, magnets and in the cooling systems of nuclear reactors
A Toyota Prius contains 1 kg of neodymium and 10 kg of lanthanum
A wind turbine contains over 600 kg of rare earths

Table 6.4 Compositions of minerals mined for REE

	Minerals rich in light REE			Minerals rich in heavy REE		
	Bastnaesite	Monazite	Apatite	Ionic clay	Xenotime	Fergusonite
	Bayan Obo (China)	Orissa (India)	Arafura (Australia)	Middle Y (China)	Pitinga (Brazil)	Thor Lake (Canada)
La	26.9	23.7	20	30	tr	0.3
Ce	50.9	44	48.2	3	0.6	4.4
Pr	5.0	5.85	5.9	7	tr	1.7
Nd	15.2	18.7	21.5	26.4	0.4	15.6
Sm	1.15	5.09	2.4	5.1	0.4	10.4
Eu	0.23		0.41	0.65	tr	1.6
Gd	0.32	1.55	1	4.2	1.1	14.3
Tb	0.03		0.08	0.7	0.8	1.8
Dy	0.09	0.31	0.34	2.9	11.2	9.8
Ho	0.01	tr	tr	0.4	3.4	1.2
Er	0.01	tr	tr	1.4	15.4	1.4
Tm		tr	tr	0.3	3.0	0.7
Yb	0.005	tr	tr	1.1	20.4	4.1
Lu		tr	tr	0.2	2.7	0.7
Y	0.20	0.75		17.3	40.6	29.0

mined, for its iron. Current reserves are estimated at about 1.5 billion tons of ore grading 35 % Fe. This grade is less than that of the richest iron deposits in Brazil and Australia, but was sufficient for mining in China. In addition to the Fe, the deposit contains a vast amount of REE, a total of some 48 mt with an average grade of about 6 wt% of rare-earth oxides. This makes it one of the largest known REE deposits on earth, representing 30 to 40 % of the world's REE resources, depending on the source of information. The deposit also contains large amounts of Nb. The cost of extracting the REE ranges from about 10 US$/kg for La and Ce, to about 1000 US$/kg for Eu and Dy. Bayan Obo is an iron-oxide copper deposit (IOCD); the geological context and proposed theories for its origin are discussed in Chap. 4.

China contains several other significant REE deposits including Mianning, a carbonatitie-hosted deposit in Sichuan province, and smaller but economically significant deposits such as Xunwu and Longnan in Jiangxi province in southeast China. The latter are of a type described as "ion-adsorption clay" that develops in lateritic weathering crusts on granitic and syenitic rocks in the tropical areas. These oxide ores are economically important because they contain relatively high proportions of the heavy REE. In principle they are easy to mine, being composed of soft materials exposed at the surface; in practice their exploitation, often in an artisanal manner, has generated major pollution and serious environmental problems. China currently produces most of the world's REE (Fig. 6.4) and exerts a major control in global trade in this commodity.

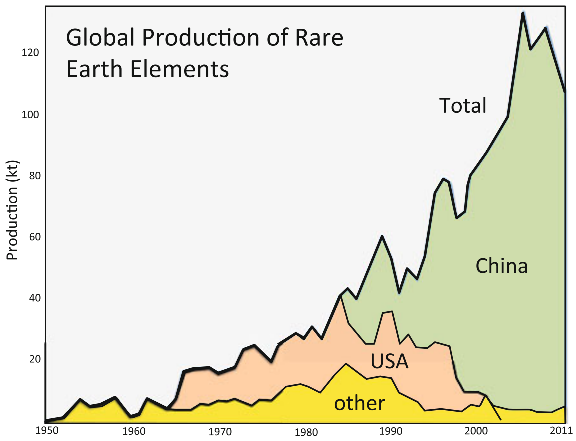

Fig. 6.4 Global production of REE in the past 60 years showing the recent dominance of China. Redrawn from Gambogi, Joseph. "Global Rare Earth Oxide (REO) Production Trends," U.S. Geological Survey. 16 April 2012. http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/ree-trends-2010.pdf

Evaluation of future mining of REE requires that short, intermediate and long-term prospects are considered separately, and that a distinction be made between the various types of rare earth elements. Different applications require different REE, and many require elements like dysprosium, which is one of the less abundant heavy REE (Gd through to Lu). However, the majority of currently active deposits, and those likely to come on stream in the next 5 years, produce mainly the light REE. With the reopening of the Mountain Pass deposit and development of new deposits like Mount Weld in Australia, global demand for these elements may soon be satisfied. In contrast, the only major source of the heavy REE that is currently exploited is the Chinese ion-adsorption clay deposits. The Kvanefjeld deposit in Greenland contains large amounts of heavy REE, but no realistic estimates see this deposit coming on stream within the next 5–10 years. During this period, there will be a shortfall of REE elements and the opportunity for the sole major supplier to control, if not distort, the global market.

The rare earth elements thereby provide a very interesting example of how the development of industry and new technologies require the use of previously little exploited minerals, and how the global industry reacts to this demand.

6.5 Lithium

The occurrence and exploitation of this element provide another example of the complications—geological, geographic, economic and political—that will influence the global minerals industry in the early 21st century. Until recently this element had only been used in specialized applications, and in relatively small quantities (Table 6.5).

Global production of about 20,000 tons per year was able to meet this demand over the past decade, but in the near future the situation may change. The push to reduce

Table 6.5 Uses of lithium

• As a flux in aluminium smelting
• As a heat-transfer medium in nuclear reactors (because of its very high specific heat)
• In many types of battery (because of its high electrochemical potential)
• In pharmaceuticals, as mood stabilizer
• As a specialized lubricant
• In alloys with Al and Mg to produce strong and light aircraft parts
• In specialized ceramics and glasses (telescope lenses)
• As LiOH which absorbs CO_2 in submarines and spacecraft

petroleum consumption and CO_2 emissions by the world's growing fleet of automobiles has led to the development of hybrids such the Toyota Prius the Tesla and a growing list of electric vehicles that use lithium batteries. Li-ion batteries offer important advantages, including greater power and smaller size and weight, over other types of battery. The battery of a hybrid vehicle contains about 2 kg of Li and that of a fully electric vehicle about 3 kg. To convert the world's fleet of vehicles from petrol to electric would require a vast increase in the demand for Li, up to ten times current production according to some estimates. Where will all this Li come from?

Currently two main types of Li ore are mined. The first consists of deposits of the mineral spodumene, a Li silicate with a pyroxene-like composition ($LiAlSi_2O_6$), that occurs in pegmatites; the second is Li carbonate which occurs in evaporitic sediments and residual brines in high-altitude, inland lakes. Past production has been mainly from spodumene, but this has been largely supplanted by the second source, because, just as with Ni ores (Chap. 2), the energy requirement to mine and refine the hard silicate mineral is greater than for the alternative. At present about 75 % of the world's Li reserves are in South America, in the Andean "Altiplano", the high flat plain that extends through Bolivia, Chile and Argentina. Geological factors, such as the presence of siliceous volcanic rocks that are the source of Li, and climatic conditions, favour the concentration of Li in the shallow lakes of the Altiplano. The high altitude, strong winds and arid climate promote rapid evaporation. Lithium is separated from the brine by a process that starts with evaporation of the brine in closed pens, very much like the production of sea salt. The Li is then extracted from the concentrated brine and separated from other salts by a series of chemical reactions. The process is long (1–2 years are required for the initial evaporation stage), but relatively cheap.

The concentration in this part of the world of deposits of a metal that may become essential for global industry raises numerous questions. More than half the total resource is located in Bolivia, a country with a long, troubled history of mining and mineral exploitation. From the 16th to early 19th century the Spanish colonialists exploited the incredibly rich silver deposits of "Cerro Rico", briefly making Potosi in the high Andes one of the richest cities in the world but leaving only mine pollution as the long-term legacy. Following the Bolivian revolution and through to the present, the mineral deposits of the country have been managed or mismanaged by a succession of owners and governments. During long periods when foreign government or companies were in charge, most of the wealth left the country; in periods when the mines were nationalized, inefficiency and corruption prevented the local population from receiving the benefits generated by the industry. Despite being granted world heritage status by UNESCO, most of Potosi has now become a sad and dilapidated place as its fine colonial buildings fall into disrepair.

In 2005, Evo Morales was elected the first indigenous president of the country and he immediately took steps to nationalize the oil, gas and mining industry. He launched an active campaign to renegotiate contracts with the foreign buyers of these natural resources that guarantee a greater proportion of the profits remain in the country.

Several attempts had been made in the past to develop the largest lithium deposits, which are found in the Salar de Uyuni saltpans in central Bolivia, but each has failed for various political and economic reasons. At the time we wrote this book negotiations were underway to raise the funds needed to develop the deposits and thus to help meet the expected demand for Li batteries, but progress has been slow. Bolivia, a very poor country, does not have the millions of dollars needed to start the operation and foreign sources are reluctant to invest in a country where the political climate, from their point of view, is so uncertain. On one hand government representatives have said they will oppose any future program in which cheap Bolivian resources are used to build expensive cars in rich countries; on the other hand the governments of the latter countries do not wish to see Bolivia set up a stranglehold on a energy product that in some ways would be comparable to that of the Middle East oil producers.

Other factors impinge on the potential economics of lithium production from the Salar de Uyuni. One issue is the relatively high Mg/Li ratio of the ore. Separation of Li from the Mg makes the process more complicated and costly, and the Mg has to be disposed of as a waste product. On the other hand the saltpans contain large amounts of potassium salts, which are used as fertiliser, and sodium salts, which could be used in industry, if they could be transported to markets. At its location high in the sparsely populated Andes, the Salar de Uyuni deposits are far from potential consumers.

Environmental issues compound the problem. The lakes of the Altiplano constitute a unique ecological system that hosts rare fauna, including large flocks of particularly pink flamingos. The extent to which mining would disrupt these systems is unknown but is likely to be substantial, thus adding an additional reason for the Bolivian government to resist large-scale industrialization of the region. The growing tourism industry in the region also opposes any move to mine the deposits.

Meanwhile, as the situation in Bolivia remains unresolved, Chile and Argentina, which both have governments that are far more open to mining, have facilitated development of their deposits, and deposits in China are under active development.

6.6 Mining and Mineral Exploration in the Future

The graphs reproduced in Chap. 1 starkly illustrate the challenge faced by the global minerals industry. As world population increases and as people in the third world aspire to a lifestyle like that in developed countries, the demand for metals will increase. We have argued that more efficient development of existing deposits, opening of new mines, and discovery of new resources will meet this demand. If the trends that have persisted over the past century continue, improvements in mining and extraction technology will allow metals to be produced from deposits with even lower grades than those currently mined, or from deposits in more hostile or remote locations. The tapping of underwater deposits such as metal-rich nodules on the seafloor will, sooner or later, provide a vast additional source of Ni, Co, Cu, Mo, Mn and related metals, and the mining of recently formed, still submerged exhalative sulfide deposits will provide a source of Cu, Zn, Pb, Au and other metals.

But before these deposits can be mined they must be found. As explained in the first part of this chapter, known reserves of most metals are enough to meet the world's consumption for only the next few decades. At present, and probably through the first part of this century, mineral exploration companies will conduct the search for new deposits, assisted by national geological surveys. The goal of most companies will be to find better deposits; i.e. deposits with relatively high grades and geological settings that will allow them to be mined easily and efficiently. The driving force for this search is of course profit, the *raison d'être* of a private company, but other factors come into play. The mining of a large low-grade ore body involves the extraction of vast amounts of rock, with consequent use of large amounts of energy, water and other resources. To extract copper from ore containing 0.4 % Cu produces well over twice as much waste as ore containing 0.8 % Cu (over half because the recovery of the metal is not 100 % efficient) and the waste must be disposed of one way or another. The environmental impact of mining high-grade ore is therefore less than that of mining low-grade ore. The environmental consequences of a mining operation now play an important role in the planning and execution of any new mine.

The techniques used in this search for new deposits are rapidly evolving, with ever greater reliance being placed on remote sensing techniques and geophysical methods capable of finding deposits hidden beneath barren surface rocks. The mode of operation of the major companies is currently changing and there has been an unfortunate tendency for them to abandon active exploration and research, leaving these tasks to junior companies. Nonetheless, at one level or another, geologists will continue to play an important role in the industry.

Two other factors will have a major impact on mineral exploration and mining in the future. The first is the growing role of China in the global minerals sector, and the second is the need for minerals companies to obtain what is known as the "social licence to mine".

6.7 The Position of China in the Global Mineral Market

China contains vast resources of most mineral resources. In 2012 China was the world's leading producer of 22 metals or mineral products including aluminium (metal), antimony, barite, bismuth, cement, coal, fluorite, gold, graphite, iron and steel, lead, magnesium, mercury, molybdenum, phosphate rock, rare earth elements, salt, talc, tin, tungsten and zinc. It was also a major exporter of many of these products, notably antimony, barite, fluorite, graphite, indium, rare earth elements and tungsten. Yet for iron ore and coal—two products vital for Chinese industry—despite being the world's leading producer, domestic production was not sufficient to meet local demand and China has to import vast amounts of both commodity. For other mineral products, namely chromium, cobalt, copper, manganese, nickel, platinum-group metals and potash, local production falls far below needs and China imports a large fraction of what it consumes.

Because of the massive demand of 1.3 billion consumers, China is one of the few countries whose domestic supply and demand for a variety of mineral commodities affects the world mineral market (USGS Minerals Yearbook 2012). For example, the global price of iron ore is strongly influenced by negotiations between Chinese state-owned steel companies and the multinational companies that mine iron ore in Australia and Brazil, and the price of gold is strongly influenced by the demands of consumers in China (and India) and by the measures taken by the governments of these countries to control access to the metal. And, of course, the price of the rare-earth elements is strongly influenced by China's restrictions on the export of these elements.

Figure 6.5 shows China's position as a supplier and consumer of critical metals as defined by the European Commission. The country is the leading producer of 6 of the 19 critical metals but of these, only tungsten, and to a lesser extent antimony and graphite, are of major economic importance. China lacks supplies and is a major importer of four economically important critical metals or mineral products—coking coal, chromium, nickel and potash—and is both a major producer and a major importer of iron and aluminium. China's point of view is that the country is obliged to compete in a hostile world market to meet its growing needs for raw materials, and has to deal with trading practices and an international trading network that are biased in favour of the USA, Europe and other "western" countries.

What is little appreciated is that although China is rich in natural resources, the amount is relatively small in comparison with the enormous population. In addition, the low grade of most Chinese ore deposits makes extraction difficult, expensive and more resource-intensive. Typical iron mines contain ore with only 30–40 % Fe, compared with close to 60 % in the best mines in Brazil and Australia, and other types of ore are similarly poor. This means that the amount of rock that must be moved, the amount of ore that must be treated and the amount of energy required are all far greater than for the other mines. Only partially do the lower labour costs compensate. It is in part for this reason that China is seeking to import new ores and metals and to search for new deposits in Africa and elsewhere.

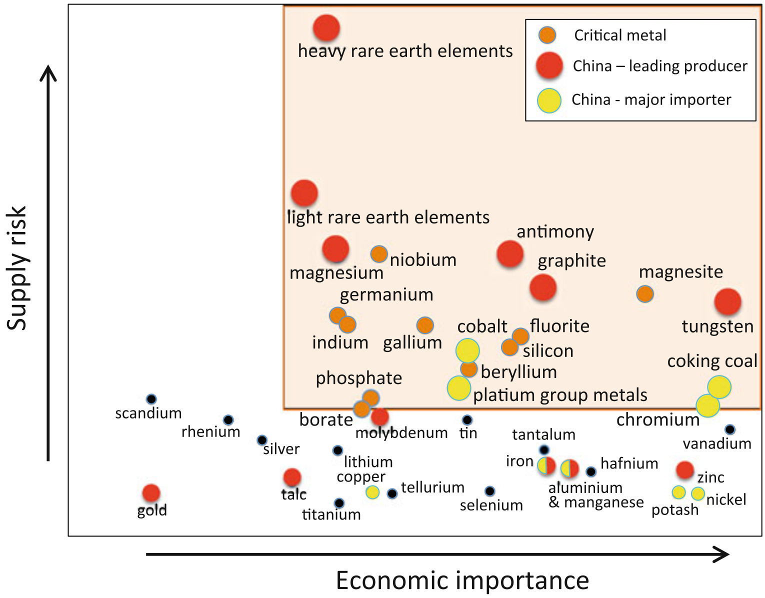

Fig. 6.5 China's position in the production and consumption of critical metals

In 2010 China drastically decreased its export quotas for the rare earth elements, from over 60,000 tons in 2005 to a limit of 30,000 tons from 2010. It was able to do so because at that time, China produced over 95 % of the world's rare earths. The rationale given by the Chinese government was that the volume of exports had to be reduced for environmental reasons (the pollution caused by radioactive Th in ores from Bayan Obo and the difficulties of mining the sparsely dispersed and low grade ion-absorbtion ores) and the need to preserve a declining natural resource. According to China's Information Office of the State Council (2012) "outdated processes in the mining, beneficiation, smelting and separation of the rare earths have severely damaged surface vegetation, caused water loss, soil erosion, pollution and acidification, and reduced or even eliminated food crop output."

The authors of an article in the Economist magazine think differently: "China's rare earth policies are part of a complex web of Chinese government industrial policies that seek to promote the development of domestic industries deemed essential to economic modernization" and the restrictions are "all about moving Chinese manufacturers up the supply chain, so they can sell valuable finished goods to the world rather than lowly raw materials". The World Trade Organization recently ruled in favour of Europe and the USA, who had complained that the Chinese export restrictions violated the rules governing world trade.

Fig. 6.6 Chinese investment in Africa

To meet the mineral country's needs, the Chinese government has actively encouraged mining companies to acquire stakes in mining operations in Australia, South America and other regions, and to conduct exploration for new mineral resources in many parts of Africa. In 2002 China initiated its 'going global' policy to promote overseas investment. The Chinese government has signed numerous deals with African governments to secure rights to mineral resources (and farmland) in exchange for infrastructure.

Figure 6.6 shows China's direct foreign investment in Africa in 2005: note the concentration in countries with large petroleum resources and, in many cases, repressive governments. China's overseas investment is governed by the "Beijing Consensus" (or "Chinese economic model") that emphasises a pragmatic approach to promote “equitable, peaceful, high-quality growth”, “defence of national borders and interests” and “the use of stable, if repressive, politics”. Little attention is given to human rights and the quality of government in recipient countries and for this reason China has been able to invest heavily in countries that are closed to European or North American enterprises such as Zimbabwe for diamonds and PGE, and Sudan for petroleum.

There is a growing feeling, however, that the Chinese ventures in Africa have not been a success: according to one estimate over 80 % did not realize the intended goals. The reasons are diverse, and include poor infrastructure, political instability and corruption in host countries, important cultural differences that hindered working relationships, and political and legal complications. As a consequence, the level of Chinese activities in Africa has declined significantly in the past few years.

Box 6.4 Global Perception of China’s Activities in the Minerals Sector
The measures taken by the Chinese government to restrict exports of the rare earths and other metals and its adventures in Africa have been well publicized. The media speak of “China’s monopoly of global resources”, and, in the words of a French mineral economist, “Australia has become a Chinese quarry”. China is accused of not “playing by the rules” and the European Commission is calling for firm measures to assure that “a level playing field” is reinstated for the global minerals market. In fact, China’s relationship with mineral suppliers has been criticized as being very like those of the old colonial powers, with China buying raw materials from Africa and shipping back manufactured goods.

Use the following discussion, and information you can obtain from other sources, to discuss whether these accusations are firmly grounded.

The 2010 OECD inventory of export restrictions on raw materials contains over 9000 entries. European countries are missing from the list, but USA, Canada, Australia, Thailand restrict export of forestry products, and Argentina, to take one example, restricts the export of 37 metals or mineral products. These restrictions, however, are applied only to waste or processed metals, not ores or raw minerals. Only a few countries restrict the export of ores and concentrates: South Africa restricts export of diamonds, gold and the PGE; India restricts export of chrome metal and minerals; and Bolivia restricts export of ores of Sn, W and Sb. China tops the list, applying various types of export restrictions (quotas, tariffs, etc.) to 38 metals and 10 mineral products, both raw minerals and refined products. This disproportionate and excessive use of export restrictions forms the basis of the complaints to the WTO and the negative standing of China in the global minerals sector.

The well-publicized restrictions on REE exports have in fact had very little effect on global supplies. When originally imposed, the restrictions caused an immediate and sharp increase in the prices of most REE, but since then these prices have dropped to a quarter of peak values. Partly because of the financial crisis and global downturn in economic activity, official exports of REE from China never reached the levels set by the quotas. The situation is complicated by illegal mining, which adds significantly to overall supplies, with the consequence that the amount of REE available for non-Chinese users exceeds official estimates. In parallel, mines in the USA and Australia are slowly coming on stream, with the result that China's proportion of global production has fallen to 80–90 % from about 95 % in 2008 (Fig. 6.4). As mentioned earlier in the chapter, the consensus is that these mines, and others in South Africa, Canada and other regions, will soon reduce the pressure on the supply of light REE, but that supplies of HREE will remain tight for the next decade. Measures taken to find substitutes for both light and heavy REE will compete against growing overall demand, if or when global economies recover.

In 2014, Indonesia introduced a ban on the export of raw minerals designed to develop downstream refining and smelting industries with the aim of increasing the country's benefits from mining. The ban applies to nickel and bauxite, but copper, which is produced in large porphyry copper deposits, has been exempted until 2017. Before the ban, Indonesia was the world's top nickel ore exporter and the largest bauxite supplier to China, accounting for around 12 % of the global market. Japan and perhaps China as well are said to be planning to take Indonesia to the WTO over the export ban. The influence that these events will have on global trade in raw materials remains to be established: it will be interesting to see how China reacts when on the other side of a mineral export controversy.

6.8 The Social Licence to Mine

Throughout the world it is becoming more difficult to mine. Almost everywhere governments, national and international organisations, and the public in general have become less willing to accept unfair or environmentally damaging mining practices, and have imposed new conditions and rules in an attempt to ensure that future mining is done better. Measures are taken to minimise environmental impact and to assure that a greater proportion of benefits is passed on the local community or nation where mining takes place. For the most part these measures are necessary, but some anti-mining movements may go too far.

Behind many of these movements is the idea that mining should be "sustainable"; i.e. it should proceed at such a rate and in such a manner that reserves of mineral products are left for future generations. This requires that some deposits should not be mined immediately, if at all, and that the methods used should include only those that do not leave lasting effects on the environment.

It has to be accepted that mining, and to a lesser extent all other parts of the mineral extraction process, have a negative impact on the environment. On the other hand, without mining, modern society would grind to a halt. A telling example is the increasing use made of a wide range of metals in new technologies: without reliable sources of REE and a range of exotic elements, the construction of the vast numbers of wind turbines and solar panels needed for conversion to a low-carbon society will not be possible. The infrastructure needed for the production of "renewable" energy consumes enormous amounts not only of well-publicised critical metals (REE, In, Li etc.) but also of basic raw materials such as steel, aluminium, concrete and sand.

Another complicating factor is the association of mining with multinational companies whose reputation, for reasons valid or not, is poor. Some of the groups opposed to mining in their constituencies recognise that metals are needed, but put faith in recycling or on production in far-away places (not in their back yard). Recent experience has shown that if local or national groups cannot be convinced that mining can be accomplished in a manner compatible with environmental prerogatives, and that mining will bring benefits to the community, they are very capable of stopping it. The following examples illustrate the issues, the diverging priorities of interested parties, and the paradoxes associated with the need to obtain the "social licence to mine".

Box 6.5 Locavore Minerals

The locavore movement promotes consumption of food from local suppliers, with the aim of supporting the local farmers and reducing "food-miles"—the distance that food travels from producer to consumer. European locavores argue that the environmental, social and economic costs of transporting tomatoes from northern Africa or apples from New Zealand are unsustainable. Putting aside the validity of these claims, is it reasonable to shun Kenyan green beans while consuming copper from the Congo?

Domestic mining reduces the financial and environmental costs of transporting metals from distant sources while providing jobs and wealth to the local community. Much of the pollution associated with mining is now out-sourced to regions where controls on mining and its environmental impact are lax. Just as European legislation and industrial practices generally assure a supply of safe food that is produced in a manner that minimises environmental impact, mining in Europe should and can be undertaken in an environmentally responsible manner. An example is Boliden's Aitik mine. Located in the harsh climate of northern Sweden and respecting the stringent environmental and societal norms of Scandinavian "green mining" programs, it uses efficient modern technology and highly mechanised procedures to profitably mine ore containing only 0.27 % Cu, far lower than the global average of about 0.6 % (Fig. 6.7).

Fig. 6.7 The Aitik mine in northern Sweden

6.8.1 *Pebble Prospect, Alaska*

Exploration for ore deposits has extended to all parts of Earth and many deposits have been discovered in remote, environmentally fragile settings. The Pebble prospect in Alaska is perhaps the most extreme example of the problem that such discoveries pose to society. Pebble has been described as the largest known undeveloped Cu ore body on Earth and few other deposits of this type remain to be discovered close to the surface where they are accessible to current exploration and mining methods.

Pebble is a porphyry deposit, like those distributed all along the American Cordillera, from Alaska to Chile. Since its discovery in 1988, Northern Dynasty Minerals, the company that owns the prospect, has invested close to 400 US million dollars and has shown that the deposit contains an astounding 5.94 billion tons of ore grading 0.78 % Cu, and significant amounts of Au and Mo. The deposit contains a large fraction of world copper reserves and the total value of these metals is estimated at over 300 billion dollars. The following numbers put this sum in perspective. Alaska currently imposes only 1.5 % royalties on mining operations but even at this rate, the mine, were it were ever to open, would return about \$4.5 billion to the state. The deposit contains enough ore for about 90 years of production and for every year of this period, it would transfer \$50 million to the Alaskan government. During the construction of a mine, the project would create close to 5000 jobs and for the life of the mine, 2000–3000 people would be directly employed; all this in SW Alaska, a region where employment is scarce.

The land overlying the Pebble deposit is glaciated terrane with small lakes and ponds, like most of Alaska, and it is 30 km from the nearest small communities. Production from Pebble would require a large open pit operation that could grow to be several km wide and hundreds of meters deep, along with waste rock dumps and tailings ponds, containing as much as 10 billion tons of material, which would cover several additional square kilometers. There would also be a transport route, possibly a railroad, to take copper concentrate to the coast for shipment to smelters. But taken together, the mining operation cover perhaps 10–50 km^2, a minute fraction of the 1.7 million km^2 of the biggest US state.

In January 2014 the US Environmental Protection Agency (EPA) concluded that mining of the Pebble deposit would harm the salmon habitat in Bristol Bay, the world's largest salmon-spawning run. The fishing industry, which harvests herring and other species as well as salmon, provides about 75 % of the jobs of the 7000–8000 people who live in the region. The EPA assessment was released before Northern Dynasty Minerals had released its own environmental impact statement, and at the time of writing, the entire process was open to litigation from supporters and opponents of the mine.

Opponents of the mine are diverse and include the Renewable Resources Coalition, some local native groups, and commercial and sport fishing and tourism agencies. These groups argue that mining is not possible in an environmentally sustainable way and they believe that it poses an unacceptable risk to the salmon fishery. The Bristol Bay salmon fishery contributes about one third of the world's salmon catch and $250 million per year to the local economy, about five times that of a future Pebble mine.

The critical question is whether mining of the Pebble deposit would inevitably ruin the fishing industry or whether the two could be conducted together or even in sequence. Who has to make this decision? The land is owned by the State of Alaska and held by the exploration company using the state claim system. Although the formal decision on whether to allow mining will be made largely by state environmental agencies, the real decision makers are the public. A quick review of the internet shows that many groups are convinced that the Pebble mine is too large a risk for us to take.

6.8.2 Roșia Montană, Romania

Gold deposits in the 'Golden Quadrilateral' of Transylvania were first mined by the Romans and then on and off through the centuries until a state-run enterprise was closed in 2006. In 2000, a tailings dam at Baia Mare burst, spilling some 100,000 m^3 of cyanide-contaminated water into the Danube, killing fish and damaging the river system for hundreds of miles downstream.

In the late 1990s, a Canadian company planned to open a very large modern open-pit mine to exploit the deposit, a project that would become Europe’s biggest gold mine. In 2003, the company began the long procedure to obtain a mining permit, and only in 2013, a full ten years later, the Romanian government gave tentative approval. This led immediately to massive public protests that drew many thousands of people into the streets of several Romanian cities. In the face of this opposition the government backed down and withdrew the authorization. The project is now stalled if not abandoned and in 2014 the company began laying off its workers in Romania.

Once again the arguments for opening the mine centred on the wealth it would generate—$US500 million per year according to the company—and the jobs and new infrastructure it would create in one of the poorest parts of Europe. The mining company asserts that the mine would operate using modern techniques in accord with European regulations that would assure that catastrophes like Baia Mare would not be repeated. The company has already cleaned up some of the abandoned waste dumps and tailings ponds left from earlier mines and proposes to continue to restore these polluted areas during a future mining operation.

Opponents of the mine have little confidence that the Romania government, which has been troubled by a series of claims of corruption and accusations of incompetence, will be able to guarantee that the mining will be undertaken in an environmentally acceptable manner. Much of the debate focuses on the use of cyanide in the treatment of the ore. The protest movement questions whether the company has the experience needed for a major operation in an environmentally sensitive region, and has reservations about the proportion of the benefits from a mine that would remain in Romania.

A factor unique to the Roșia Montană operation is the galleries that remain from mining in Roman times. Both sides recognise these as a national archeological treasure; the question is how best to preserve them. The mining company has identified about 7 km of galleries that escaped destruction during mining by the communist regime but had been left abandoned and decaying. The company recognises that some galleries would be destroyed if a new mine were to open but point out that the company has already invested a large sum to identify Roșia Montană’s cultural heritage and has preserved some galleries that were falling into ruin; they propose to do the same with other archeological relicts and argue that the Romanian government has neither the funds nor the incentive to do this properly.

As an alternative to the revenue generated by a mine, the protest groups put their faith on forestry and tourism. This raises the following question: are industries such as these totally incompatible with mining, or can they coexist, if both are managed correctly?

6.8.3 Fe Mines in Northern Sweden

The town of Kiruna in northern Sweden advertises as local attractions wilderness hiking, white-water rafting, an introduction to the Sámi culture, and "a popular tour that takes you down into the world's largest underground iron ore mine". TripAdvisor lists numerous generally positive reviews of the mine tour, together with information about the Ice Hotel in nearby Jukkasjärvi and other local attractions. Throughout northern Scandinavia and tourism operate in parallel and the Swedish National Heritage Board supports and promotes good examples of mining tourism.

Since its discovery in the 1880s, Kiruna has produced 950 million tons of high-grade magmatic ore, and its estimated reserves exceed 600 million tons grading ca. 48 % Fe. For a new phase of mining to go ahead, the old town and its population of about 20,000 will be moved 2 km to a new site. The transfer will be conducted after ten years of planning, with extensive consultation with the town people. Three thousand houses and apartments are being relocated, including the town's historical old church. Inhabitants express some nostalgia for the old site but, to the astonishment of some journalists, accept that the move must happen. They are fully conscious that without the mine, Kiruna would not be there.

To be sure, there are some conflicts. The Sámi, the indigenous people of northern Scandinavia, have protested against exploration for new iron mines, but recent legislation, and communication between the groups involved, should allow the Scandinavian mining industry and the Sámi people to share the northernmost part of Scandinavia.

6.8.4 Tennie Prospect, France

The last metal mines in France closed in the 1990s. A talc mine, a Li mine, and many quarries that extract industrial minerals are still active, but all the metals currently used in France, as in many parts of Europe, come from foreign sources. The Chinese REE export restrictions alerted European governments to the economic danger posed by this situation, and this has led to programs such as the European Innovation Partnership for Raw materials. In 2012 Arnaud Montebourg, the French Minister of "Industry Revival" announced that France would "once again become a mining country." In that year new exploration permits, the first for 15 years, were issued and a small company, Variscan Mines, started work in several parts of France. One of these was the Tennie region in the centre of France, where mining had been conducted in the past and where there are reasonable prospects of finding new VMS or SEDEX deposits.

Exploration started in March 2013 and within a few weeks, groups totally opposed to the entire project had been organized in villages surrounding the prospect. Polls show that some 85 % of the local population opposes exploration for ore deposits in the region.

Box 6.6 Sustainable Mining

Current metal prices are low because known reserves of raw materials are huge and demand has slowed. Therefore, there is little incentive to save or recycle. In this context, environmental constraints and opposition to new mines can be seen as a good thing. Consider the Pebble deposit, a deposit that alone would meet the world's needs of copper for several years. An important question is whether fishing and mining can coexist. An enormous open pit is planned but is this the only way to extract the metals? Is it possible to use other mining methods—the "invisible" mine (totally underground or in situ leaching). Perhaps the crucial issue is not whether to mine or not, but the type of operation.

The "raison d'être" of any company is not sustainable and responsible mining, but profit. In this sense, social pressure has a positive effect because it forces companies to develop techniques that have less impact on the environment. This, in turn, will increase the cost of metals to society, something that protestors might not yet realize.

Projections of our future needs for metals are very uncertain. Individual needs will certainly be lower than those of today (at least in the West) but total demand will be higher. This might be an argument for leaving Pebble in the ground for future generations, but only if a "replacement" deposit can be found. In making these decisions, we should also remembered that mining is a temporary use of the land and, although it does damage the land, it will be available for other uses after mining, especially if reclamation is done properly.

6.9 Conclusion

Whether we like it or not, mining must continue. As stressed in earlier sections, recycling and substitution cannot satisfy society's current and future needs for metals. The critical questions are where the mines will be, how they will be managed, who they will benefit, and who will bear their environment and social impacts. In much of North America and Europe, there has been a growing tendency to oppose future mining operations on the grounds outlined in the examples discussed in this chapter. But if we reject a deposit like Pebble that contains a large fraction of total global copper reserves, where will we get copper for current and future generations? Almost all other deposits that have been discovered recently pose similar environmental challenges.

Many deposits are located in less developed countries with lower environmental standards. Do the developed countries have the right to expect other countries to mine their copper when they are unwilling to mine their own metals in an environmentally acceptable manner? If a country will not accept this challenge, does it have the right to copper, or rare earths, mined by countries that do accept the challenge? These are difficult questions, but as we reject mining in more and more locations and resource scarcities increase, they will become ever more important. As we ponder these questions, it might help to recall that if we could put a man on the moon, we might well be able to find environmentally acceptable ways to produce our mineral supplies.

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