Geochemical Perspectives

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Future Global Mineral Resources

Geochemical Perspectives

Each issue of *Geochemical Perspectives* presents a single article with an in-depth view on the past, present and future of a field of geochemistry, seen through the eyes of highly respected members of our community. The articles combine research and history of the field's development and the scientist's opinions about future directions. We welcome personal glimpses into the author's scientific life, how ideas were generated and pitfalls along the way. *Perspectives* articles are intended to appeal to the entire geochemical community, not only to experts. They are not reviews or monographs; they go beyond the current state of the art, providing opinions about future directions and impact in the field.

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About the cover

New tunnel at El Teniente, Chile, in operation for over a century and now the largest underground Cu mine. This development will add 50 years of mine life and 17 Mt of Cu metal from ~2 km depth using panel caving, a new style of mass underground mining. This development illustrates a "light at the end of the tunnel" for supply of a large fraction of the world's minerals, as mining shifts underground and reduces its surface footprint.

Photo credit: Codelco www.codelco.com

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PREFACE

This volume was written to provide an overview of Earth's mineral resources – their origin, discovery and development, and their role as a source of materials that are crucial to everyone's way of life in our modern society. For some time, pessimistic viewpoints have been expressed about long-term global mineral supplies, as illustrated in a recent *Geochemical Perspectives* volume by Sverdrup and Ragnarsdóttir (2014). In this article, the authors suggested that many important minerals are becoming scarce and that their production "…*has either peaked already or will peak within the next 50 years.*" In their opinion "… *the world is heading towards a restricted access to the key resources that are used by humanity today and these restrictions will have a profound impact on the world economies and life styles of future generations.*" Laherrère (2010) and Kerr (2011) proposed similarly pessimistic scenarios and the Club of Rome famously supported a publication, *The Limits to Growth* (Meadows *et al.*, 1972) that predicted copper and aluminium would be exhausted in 21 and 31 years, respectively. Yet current reserves of these metals are larger than in 1972, despite four decades of continually increasing yearly production. Is it then reasonable to warn of imminent peak production of important mineral commodities?

Our collective experience (see information about the authors on the back cover) in modern ore deposit research, exploration, discovery and production leads us to believe that Earth has a much larger endowment of mineral resources than is often claimed, and that any peaks in production of a given mineral or metal lie much further in the future. In this volume, we review prospects for long-term global mineral supply with an emphasis on ways that geoscientists in

general, in both research institutions and industry, can help meet the mineral demands of society. Most importantly we argue that geoscientists can act as well-informed advocates to society as a whole by developing an understanding of mineral deposits and responsible mining.

Most mineral exploration and discovery has focused on the upper few 100 m of Earth's crust, whereas a similar density of many deposit types almost certainly is present in the upper few km. Recent technological advances allow low-grade mass mining to depths of 2-3 km to recover many of these deeper deposits, which will reduce the surface footprint and impact of mining. This is a "light at the end of the tunnel" (see cover photograph) for the future supply of a significant part of the world's mineral resources. Similar radical changes in mineral processing and metal extraction, energy and water efficiency, and innovative social contracts will permit more resources of multiple commodities, both near-surface and at depth, to be mined economically in the future.

We reach the fundamental conclusion that mineral supplies will be maintained at levels that satisfy demand well into the future, and that any peak of production of individual commodities will probably result from declining demand caused by technological or societal developments, rather than exhaustion of the resource.

The volume comprises five sections that treat different aspects of the subject. All authors contributed to the writing of each section, but to different extents, with one person having final responsibility for content and organisation.

Section 1 – *Introduction*, presents an overview of the subject and focuses on a thorny issue of crucial importance – the difference between reserves and resources. We then explain why we have chosen the metal copper to illustrate many of the points we wish to make. Steve Kesler was the main author of this section.

Section 2 – *Formation of Mineral Deposits*, defines an "ore deposit", presents methods for classifying ore deposits, describes some typical examples, and gives an overview on current thinking on how these deposits formed. All authors contributed to this section.

Section 3 – *Mineral Exploration: Discovering and Defining Ore Bodies* describes how mineral exploration companies go about finding new ore deposits and evaluating their potential, plus the reasons that mining for many commodities will increasingly shift underground over the coming decades. Dan Wood and Jeff Hedenquist wrote this section.

Section 4 – *Exploiting Mineral Deposits*. This section, written by John Thompson, explains how ore deposits are mined and how metals and other valuable mineral products are extracted. This relates to resource availability and to the broader impact, from environment to community and society. All authors contributed their insights.

Section 5 – *Determining Reserves and Resources – Metals for Future Generations* considers in more depth the long-term outlook for the availability, production and consumption of copper and other metals, and discusses the transition between metal concentrations in mineable deposits and normal rocks. Steve Kesler and Nicholas Arndt wrote this section.

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FUTURE GLOBAL MINERAL RESOURCES

ABSTRACT

Some scientists and journalists, and many members of the general public, have been led to believe that the world is rapidly running out of the metals on which our modern society is based. Advocates of the peak metal concept have predicted for many decades that increasing consumption will soon lead to exhaustion of mineral resources. Yet, despite ever-increasing production and consumption, supplies of minerals have continued to meet the needs of industry and society, and lifetimes of reserves remain similar to what they were 30-40 years ago.

In this volume, we discuss the reasons for this apparent paradox using our broad experience and expertise on both academic and industrial sides of the minerals sector. Many misconceptions arise from flawed estimates of the size of global mineral resources which stem from a lack of understanding of the critical difference between reserves and resources. Some authors use quoted reserves – the amount of metal proven to exist and to be economic for mining at present – when predicting imminent shortages. Resources – the amount that may be accessible in the upper few kilometres of the crust – are far larger.

Over the last 150 years, improved technologies, economies of scale and increased efficiency have combined to reduce costs hence allowing lower-grade ore to be mined economically. The net result is that the long-term inflation-adjusted price of most metals has decreased more or less in parallel with increasing production, a second apparent paradox that frequently is not well understood.

Using copper as the principal example and other metals as appropriate, we summarise the latest research on ore deposits and the activities of the minerals industry. Following a description of the numerous geological processes that form ore deposits, we outline the scientific methods used by the minerals industry to explore for new deposits. We also discuss how resources are mined and how minerals are processed, as well as recent efforts to reduce related environmental impacts. Economic and societal factors influence supply, and these are as important as the actual presence of a resource. Finally, we discuss the critical roles that geoscientists will play in assuring continued supplies of minerals. These include the development of new concepts and techniques that will assist the discovery, mining, processing, remediation, and management of mineral resources. It is essential that researchers help to educate the general public about the need for continued exploration to find new resources to meet growth in world living standards.

We demonstrate that global resources of copper, and probably of most other metals, are much larger than most currently available estimates, especially if increasing efficiencies and higher prices allow lower-grade ores to be mined. These observations indicate that supplies of important mineral commodities will remain adequate for the foreseeable future.

1. METALS AND MINERALS, NOW AND IN THE FUTURE

1.1 Introduction

Metals and mineral products are essential for modern society. They are found in the products we use every day, from kitchen utensils to cell phones to refrigerators. They are the basis for construction of homes, offices and bridges, and manufacturing of cars, trains and aeroplanes, and they are employed in more hidden ways as catalysts, medicines and fertilisers. Although *per capita* consumption of minerals has stabilised in developed countries, global demand will continue to rise, fuelled by the growing needs in developing countries and changing technologies.

Our mineral supplies come from ore deposits, and we must find new ones to replace those that are exhausted. To meet the growing need for copper, for example, a new, world-class deposit will need to be found at least every few years.

It is obvious that Earth's ore deposits are finite and will be exhausted if consumption continues long enough. But, how long do we have? Various government and commercial organisations provide estimates for common metals and mineral products. In most cases, these estimates amount to only 20 to 40 times current annual consumption, and this leads to the commonly voiced conclusion that supplies will be exhausted in a few decades.

This view reflects a lack of understanding of the terms "reserve" and "resource", which are used in these estimates of supplies, and a wider failure to understand the role of mineral exploration and production in supplying our global needs. It is this issue that we address in this volume.

1.2 Is Recycling the Answer?

Before going further, it is important to dispel the common misconception that we don't really need to produce mineral commodities from mines; why don't we just recycle more completely the enormous amount of mineral commodities that we have produced already? Such a circular economy would allow us to avoid the nuisance of mining and processing, and their associated environmental impacts (Fig. 1.1).

As desirable as this might be, it is not possible for several reasons. Most obvious are the issues of increasing population and improvement of the global standard of living. The demand for mineral commodities will likely continue to increase until the standard of living in less developed countries approaches the level in the more developed countries. For instance, the 2014 *per capita* use of refined Cu in the European Union is almost 9 times larger than in India, and it would require an increase of almost 50 % in world Cu production just for India

to reach this level of Cu usage. The magnitude of this demand is shown by the remarkable increase in Chinese Cu consumption to a level exceeding the USA (Fig. 1.2).
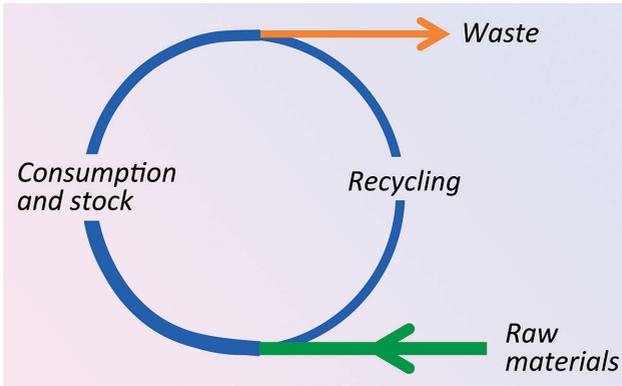
Schematic illustration of an economy that requires new long-term minerals and produces waste from production of these minerals. A true circular economy would require no new mineral supplies and have no production wastes.
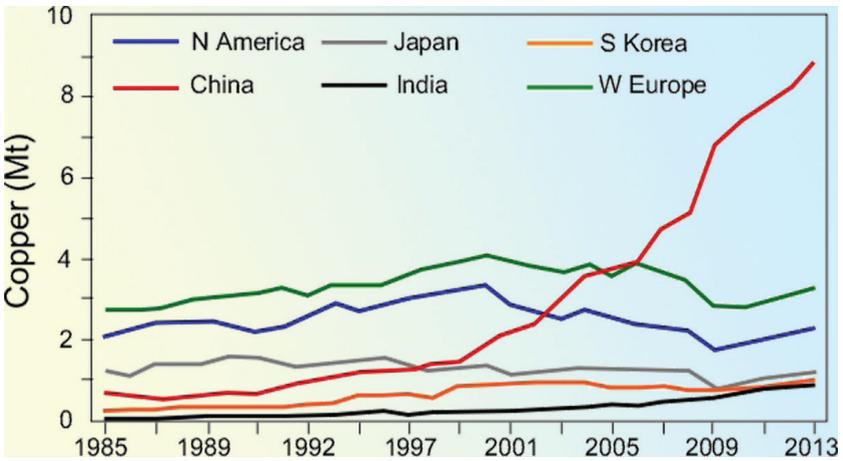
Copper consumption by major producers and consumers showing relatively constant use in the USA, Europe and Japan, and growing use in China and India (based on data of the U.S. Geological Survey (USGS); World Copper Factbook, 2015).

It is true that improvements in material use and recycling in more developed countries have allowed *per capita* consumption to stabilise and even decline (Auci and Vignani, 2013), but this relief is small in relation to the continually increasing demand as less developed countries grow. Furthermore, recycling can never reach 100 % because a variable proportion is lost in manufacturing or use. This proportion ranges typically from 10 % to more than 50 %; several mineral commodities are used in such a dissipative way that they are virtually impossible to recycle and others are totally decomposed during use and cannot be recycled (*e.g.*, pigments, fillers and fertilisers). Other commodities like Fe and Cu are more robust, but are susceptible to corrosion, which diminishes their quality and quantity at a surprisingly rapid rate (Davis, 2000).

> *Box 1.1 – New versus Recycled Metals* – Despite major efforts to recycle, primary mineral production is still the dominant source of most metals. Steel is produced from a combination of Fe ore, coal, limestone and recycled steel, as well as additives such as Mn, Ni, Cr, V and W. From 1950 to 2000, yearly world steel production increased from 189 to 850 million tonnes (Mt), after which it doubled to 1621 Mt in 2015 (https://www.worldsteel.org/en/dam/jcr:4f060d8b-3602-4ffe-9e87-7e93e0659449/Word+Steel+in+-Figures+2016.pdf). In 2014, 35 % of steel production was sourced from recycled steel. The steel industry reports that 92 % of the steel in automobiles is recycled (http://www.steel.org/sustainability/steel-recycling.aspx), although recycling from other applications is much lower.
>
> By contrast, only 17 % of the 22.5 Mt of refined Cu produced in 2014 came from recycled metal, with the balance originating from mines. At present, a total of ~13 Mt of Zn is refined annually, of which only 8 % is recycled scrap, with the balance coming from mined deposits (www.zinc.org). For Al, recycling has increased from about 20 % in 1950 to 30 % in 2010 due largely to energy savings and incentives to recycle packaging and transportation material. Annual production of Al in this period increased from a few Mt to nearly 60 Mt (http://recycling.world-aluminium.org/review/recycling-indicators.html). Lead is by far the most efficiently recycled industrial metal. World Pb production of about 5 Mt is sourced about equally from mines and recycled material. In the USA and Europe, recycled Pb accounts for between 80 and 60 % of total production. This high rate of recycling reflects the fact that about 85 % of Pb is used in batteries, which are easily recycled (http://ila-lead.org/lead-facts/lead-recycling). Platinum and Pd in auto exhaust systems might also be recycled efficiently, although export of used cars from developed to developing countries with fewer recycling systems complicates this effort.

We are almost certainly faced with a continuation of the long history of growing demand for minerals (Fig. 1.3). So far, the only mineral commodities that have experienced a decrease in use and thus in production are metals like Hg, which is toxic (Brodkin *et al.*, 2007). In coming decades, coal and crude oil production will decline because of their contribution to atmospheric CO_2 levels. For almost all other metals and mineral products, from antimony to zinc, however, consumption and hence production will continue to increase. Indeed, many of these elements play critical roles in the technological development of various new energy sources such as solar photovoltaic cells (Si, Cd, Te, Se) and wind turbines

(Fe, Cu, Al, REE), as well as light-emitting diodes (LEDs; Sb, In, REE), catalytic converters (Pt, Pd, Rh, REE, Ce), electric car batteries (REE, Li) and particularly smart phones, which contain at least 60 different elements. Even when production has declined temporarily during recessions or a change in applications, it rose again. Lead, for instance, went through a phase of declining production as it was removed from petrol and paints, but has found expanded markets in batteries for sustainable electric systems. Similarly, demand for Ge dwindled and then grew again as declining demand from the semiconductor industry gave way to increased demand for a range of new-technology applications, including special glasses, LEDs, photovoltaic cells and photoreceptors.
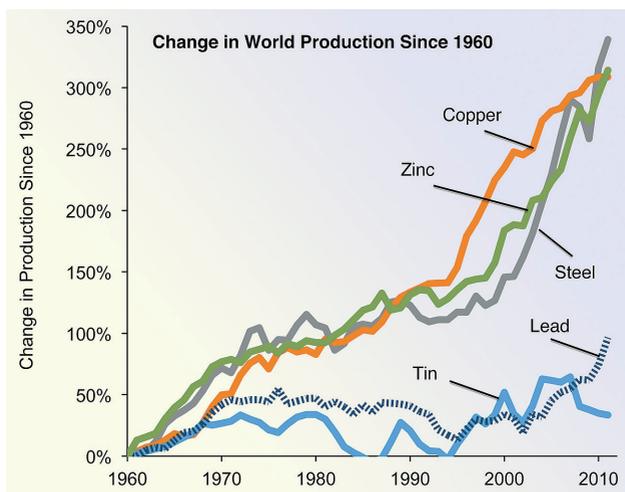
Figure 1.3   Change in world production of base metals and steel since 1960 (from USGS, 2016).

Mineral production to satisfy both this technological evolution and the growing demand from more consumers must come from *ore reserves* and *mineral resources*. These terms are at the heart of the problem in specifying long-term supplies and they require definition and explanation before we can proceed.

1.3 Reserves, Ore Reserves, Resources and Mineral Resources: Definitions Matter

The terms "reserves" and "resources" are widely used in publications by journalists and others with an interest in mineral supplies. Sadly, many of these publications fail to define the two terms, and some of them even use the terms interchangeably as if they mean the same thing (Box 1.2).

Part of the confusion reflects the different interests of the two main groups that deal with mineral supplies, government and industry. Industry provides most of the data on individual mineral deposits whereas government agencies like the U.S. Geological Survey (USGS) and other national organisations compile these and other measurements to make global estimates. So, it is important that we understand the difference between their methodologies and terminologies, and the reasons for the differences. (Note that the term "industry", as used here, includes publicly-owned firms like BHP Billiton and Rio Tinto as well as government-owned firms like Chile's Codelco, all of which have the goal of extracting metals from deposits at a profit.)

Industry's principal interest in evaluating a mineral deposit is to determine how much material is mineable at current prices, or potentially mineable if prices increase or decrease. As explained further in Section 3, quantification is done largely by drilling, which collects samples of material from the subsurface that can be analysed. Subsequent assessment then determines whether the amount of material is present at a sufficiently high concentration, and with the continuity, form and structure necessary for economic mining and processing (including associated environmental costs). Drill holes have to be close enough together, and sample recovery good enough, to provide a statistically valid sample of the volume of rock (the "tonnage") and its content of the element or mineral of interest ("grade", see also Kesler and Simon, 2015, Chapter 4). Depending on both the density of sampling and the quality of material that has been sampled, material is first described by industry as a "resource" and then part of this material might be reclassified as "ore" – i.e. material that can be mined and processed economically under present conditions and at assumed future metal prices. Material that fails this test may require more complete sampling, higher metal prices, better mining methods, or other economic or technological developments to qualify as ore. If prices increase significantly, some of this material becomes ore.

Clearly defined terms are needed to distinguish between bodies of mineralised material that are definitely economic and those that are potentially economic in the future (Fig. 1.4). The terminology used by industry is defined by national organisations in different countries and by security regulators who adjudicate on meaning and compliance (Meinert *et al.*, 2016). For instance, the Australasian JORC (Joint Ore Reserves Committee) Code for Reporting of Exploration Results Mineral Resources and Ore Reserves (http://www.jorc.org) only permits the term Ore Reserve to be applied to those parts of the two higher of the three classifications of Mineral Resource, defined by the Code, that have been subjected to a mining feasibility study (Section 3) and judged to be mineable. An Ore Reserve is reported as a subset of a Mineral Resource, which is a body of mineralised rock whose size and grade have been estimated with sufficient confidence that it satisfies one of three classifications of Mineral Resource.
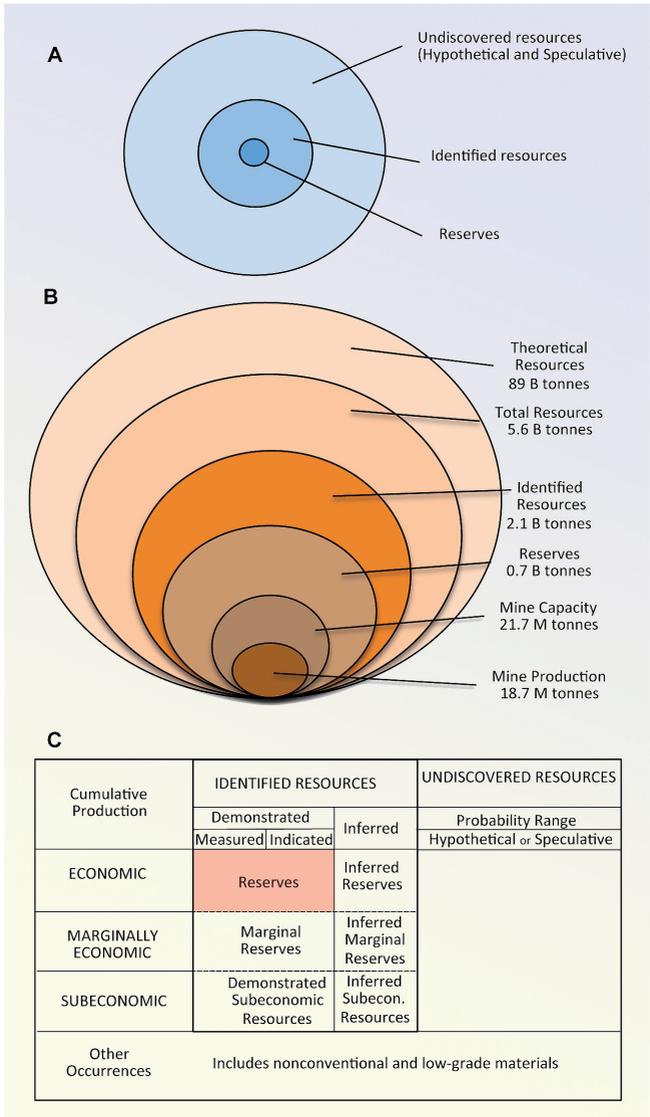
Figure 1.4   Different depictions of the reserve-resource spectrum. **(a)** Reserves, identified resources and undiscovered resources. **(b)** More detail for Cu, including yearly production, yearly mine capacity. **(c)** Resource-reserve classification of the U.S. Geological Survey (modified from Graedel *et al*., 2014; World Copper Factbook, 2015; USGS, 2016; B = billion, M = million; Mine Production and Mine Capacity are tonnes/year).

The distinction between Ore Reserve and Mineral Resource must be confirmed by someone who qualifies as a "Competent Person"; *i.e.* a geoscientist with sufficient experience working on the relevant style of mineralisation and who is a member of an accredited professional organisation. This is important because the estimates have direct implications for the asset valuation of a company, and this controls its ability to finance projects by borrowing funds and/or selling equity (shares). Application of these terms is closely monitored by government agencies, and Competent Persons and associated companies signing off on an Ore Reserve and related estimates have direct legal liability. In one recent high-profile case, Royal Dutch Shell was forced by the U.S. Securities and Exchange Commission to reduce its published oil reserve figures because of apparently inadequate delineation (Gupta and Gautam, 2004). In most cases, disputes over terminology are technical matters, although some deposits have been represented fraudulently, as in the case of the huge Bre-X gold scandal (Goold and Willis, 1997).

Industry terminology is not used by most authors who write about mineral supplies. The best informed employ governmental terminology, such as that of the USGS (Fig. 1.4c), which uses the term "resources" to refer to all mineralised deposits in the planet. Resources of this type obviously include both Ore Reserves and Mineral Resources as defined by industry. Most classifications, including that of the USGS, define resources in a two-dimensional framework with one axis representing geological knowledge and the other economic feasibility. On the geological axis, the USGS distinguishes between "discovered" and "undiscovered" resources. In the "discovered" category (on the economic axis in the left half of the diagram), there is a continuum downward from resources that have been shown to be economically mineable now (Ore Reserves) to marginal material that does not meet this criterion.

Reserve compilations by industry and the USGS differ in the degree of certainty because they have different objectives and apply to different scales. Whereas industry reports Ore Reserves and Mineral Resources for individual deposits, the USGS estimates reserves and resources for countries and the entire world using data of different degrees of certainty. Despite their uncertainty, we will use the USGS estimates in this volume because they are the most widely available global-scale estimates and they are revised annually. It is important to understand that the USGS does not actually measure and evaluate the material that is reported as reserves and resources. According to the USGS, these data are compiled from a wide range of sources, including *"…academic articles, company reports, presentations by company representatives, and trade journal articles, or a combination of these…"*. Thus, reserves reported by the USGS might include more material than industry and associated regulators would consider Ore Reserves. In addition, for most elements, the USGS publishes annual estimates of "identified resources" the meaning of which is discussed below. For most elements, USGS does not publish estimates on undiscovered resources.

In this volume, we have followed the USGS terminology: *resources* will refer to various estimates of all mineral material on the planet (whether known or undiscovered, and regardless of whether it is mineable or not) and *reserves* will refer to that part of the resource that is mineable under present conditions. Where reference is made to specific estimates made by industry, appropriate JORC terminology (noted above) will be used.

1.4 The Dynamic Nature of Reserves

It is important to keep in mind that reserve and resource data are dynamic. In the case of the USGS reports, even though the reserve figure for a deposit or country or commodity might remain the same from year to year, that figure does not represent the same material. We can show this by comparing reserve data since 1983 (when the USGS began to report estimates for most commodities) with their estimates of annual global production. Cumulative production for Cu, Fe and Zn, *i.e.* the total amount dug out of the ground, has increased steadily every year since 1983, gradually approaching the reserve estimate and even exceeding it in the case of Zn (Fig. 1.5); *i.e.* the amount mined is greater than the amount of mineable ore that had been proven to exist. This seemingly impossible situation reflects the fact that ore taken from reserves each year by mining is replaced by conversion of resources to reserves at known deposits or by discovery of completely new deposits (Section 3). The amounts of produced material and material newly found each year are often similar, and therefore the reserve estimate remains about the

same from year to year even though it contains different material. We can show this by plotting a curve (Fig. 1.5) representing the reserve estimate plus cumulative production. The "reserve plus production curve" shows that at least for the last few decades, by adding an amount similar to what we have produced, we have maintained reserves at near-constant levels, *i.e.* a relatively constant "reserve life". Similar relations prevail for other commodities. Graedel *et al.* (2014) noted that world reserve life for Cu and Ni has been roughly constant, between 30 and 60 years of supply, from the 1980s to 2011, despite a doubling of production for these two metals – which is exactly the point that we raised in the Preface.
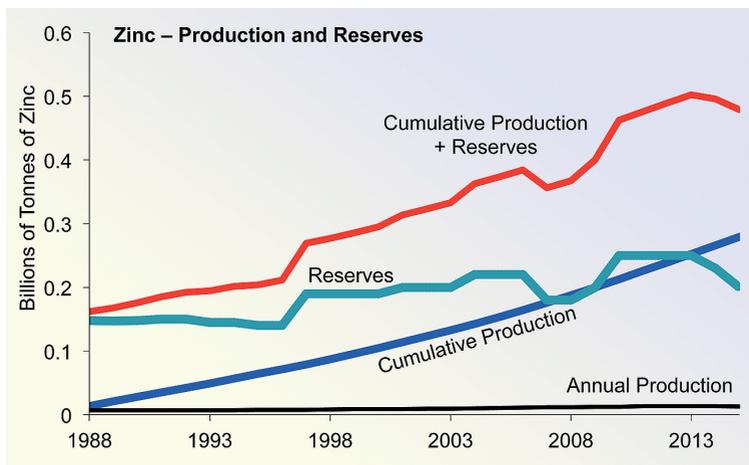
Figure 1.5   Production and reserves for Zn since 1988 (USGS, 2016). Note that by about 2007, the curve showing cumulative production had increased to the point that it exceeded the reserves value quoted by the USGS in 1988. The curve showing cumulative production plus reserves follows a trend similar to that of cumulative production, showing that reserves have remained relatively constant even though they must have consisted of different material as time passed.

You might ask what is going on here. If it is so easy to find new reserves, why don't we just go ahead and define them to begin with, rather than adding a little each year? There are several parts to the answer. First, some reserves result from the discovery of truly new deposits that would have been in the undiscovered or hypothetical resources area of Figure 1.4. Second, some resources become reserves as a result of a sharp increase in price of the material, or development of a new mining or processing method. In some mines, areas with potential may be known or suspected, but have not been evaluated; further drilling, assaying and feasibility analyses are required to convert such areas to reserve category (Sections 3 and 4). The most important issue is simple economics. As noted by Meinert *et al.* (2016), "*the time value of money makes it uneconomic to spend unlimited amounts to convert all identified ... resources into reserves.*" In other words, if a

company has sufficient reserves for the next few decades (and to justify the cost of building a mine to extract the ore), there is no point in spending large sums to find more unless it is planning to increase its production of the commodity. The market gives little consideration to a reserve life sufficient to supply more than 20 to 40 years of present consumption.

Exactly when reserves are exhausted for any specific commodity will depend on the ultimate size of the resource. One such estimate is the "identified resource" (Fig. 1.4) recently estimated by the USGS (Fig. 1.4). The identified resource includes marginally economic and sub-economic resources for which estimates of grade, tonnage and amenability to mining and processing are poorly known. Since 1973, the USGS has published an estimate of "world resources" that includes identified and undiscovered resources (Fig. 1.6). Both estimates are much larger than reserves, indicating that considerable material remains for future production if it can be discovered and shown to be mineable.
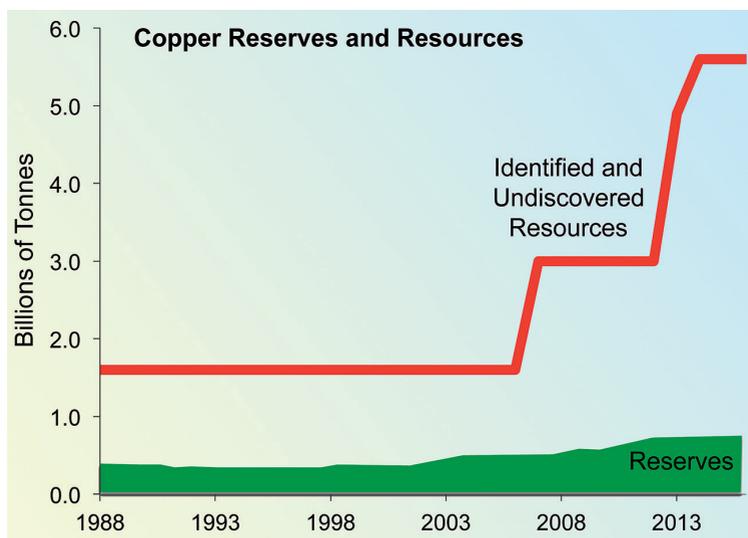
Figure 1.6   Comparison of Cu reserves and identified and undiscovered resource estimates of the USGS. The increase in the resource figure reflects the availability of more information through time, including the step-change with publication of the study of Johnson *et al.* (2014) (see Table 1.1).

However, even these identified resources are only a part of total resources, and our long-term mineral supplies will depend on the magnitude of still-undiscovered resources; *i.e.* mineral deposits that exist within the crust but whose presence has not yet been established (Fig. 1.4). Just how large is this vast and unknown category; what does it contain and why are we (the authors of this volume) so optimistic about longer-term mineral supplies? That is what we intend to cover in the following sections.

| | Table 1.1 | Recent resource estimates for copper (millions of tonnes, Mt, of metal). Consideration of what constitutes a resource, and the methods used, differ. Most estimates are for deposits at depths of 1 km or less, except for the Kesler and Wilkinson estimate, which is for deposits to a depth of 3.3 km. |

Amount	Source	Comment
89,000	Kesler and Wilkinson (2008)	based on tectonic diffusion model
6,380	Singer (2017)	extension of Johnson *et al.* (2014)
5,600	Johnson *et al.* (2014)	2,100 Mt identified and 3,500 Mt undiscovered
2,636	Copper Development Assoc. (2013)	
2,459	Schodde (2010)	compilation of public and other data
2,100	USGS (2016)	identified resources from compilations
1,781	Mudd *et al.* (2013)	compilation of public data
1,771	Northey *et al.* (2014)	compilation of public data
1,623	Gerst (2008)	reevaluation of Cox (1979), Lasky (1950b)
1,400	Laherrère (2010)	peak copper estimate

But first, we need to pare down the coverage a bit. The spectrum of mineral resources is so large that we cannot discuss all mineral commodities. Instead, and because we are discussing the issue from a geochemical perspective, we will focus on one widely used and versatile element, Cu, with occasional reference to other elements and commodities.

1.5 Why Do We Focus on Cu?

There are good geochemical and economic reasons for using Cu as the theme for this volume and a proxy for the broader mining industry. On the economic side, it is one of the most important industrial metals (along with Fe and Al) and was among the earliest to be used in a processed form (Renfrew, 1990; Smith, 2015), as discussed further in Section 4. Since its initial use, Cu has found a multitude of markets that depend in part on its excellent thermal and electrical conductivity and anti-bacterial properties (second only to silver). Current markets include electrical and electronic equipment (31 %), construction (30 %), infrastructure (12 %), transport (12 %), and industrial machinery (12 %) (World Copper Factbook, 2015). Because of its impressively wide array of markets and their close ties to the overall health of the world economy, the metal has been referred to as Doctor Copper (Radetzki, 2009).

Copper's importance as an industrial metal reflects its geochemical properties. Although a relatively scarce metal, with an upper crustal abundance of only about 28 ppm (Rudnick and Gao, 2003), it is strongly chalcophile and is found

largely in sulphide form in most rocks. For this reason, Cu can be separated from rocks and ores, even when its concentration is relatively low. It behaves incompatibly during most stages of magmatic crystallisation and enters either a magmatic hydrothermal solution or a sulphide melt depending on the oxidation state of the magma. It forms soluble complexes in hydrothermal solutions, mainly with chloride and hydroxide, making it mobile in the upper crust, and it can be deposited from solution by processes ranging from redox changes to cooling (Wood and Samson, 1998; Liu et al, 2001; Hack and Mavrogenes, 2006; Simon *et al.*, 2006; Evans *et al.*, 2008; Kouzmanov and Pokrovski, 2012). It can also be mobilised during weathering and re-precipitated at higher concentrations (Sections 2 and 4). As a result, we find Cu deposits in a wide range of geologic settings, including felsic and mafic igneous rocks, sedimentary rocks, and at seafloor hot springs (black smokers). The list of deposit types and the range of their characteristics continue to grow (Section 2), with some debate about the origin of several types of deposits.

World Cu mine production of about 18.7 Mt in 2014 came from about 450 mines in 53 countries (World Copper Factbook, 2015). Despite the widespread distribution of deposits, Chile accounts for almost a third of total world production (5.8 Mt), followed by China, the USA, Peru, Australia, Russia, the Democratic Republic of Congo (DRC) and Zambia. About 60 % of world production comes from porphyry Cu deposits and another 20 % comes from sediment-hosted Cu deposits. Copper production from the rest of the world comes mainly from other types of deposits, and is complemented by recycled material (called secondary refined Cu), which was 3.9 Mt in 2014, making a refined total of 22.5 Mt Cu.

Annual production of mined Cu, currently valued at about $100 billion, has been growing for decades, with occasional dips because of global recessions. The price of Cu has lagged behind the consumer price index over most of the past century due to technological improvements in mining and processing (Fig. 1.7). Starting shortly after 2000, the price rose rapidly in response to heavy demand, largely from China, although it has since returned to a level more consistent with the consumer price index (Fig. 1.7). The behaviour of Cu prices is typical for most metals, which have generally grown less rapidly than inflation during the past 100 years. Since early in the 21st century, China has been both the main producer of refined Cu (smelted from domestic production as well as imported Cu concentrates from around the world), and the major consumer of Cu (Fig. 1.2), reflecting its major construction and infrastructure enhancement programme.

A final reason for using Cu as the theme for this *Geochemical Perspectives* relates to the long-term resource issue that was the impetus for this volume. Because of its economic importance, global Cu resources have been the focus of more long-term resource estimates than any other mineral commodity with the possible exception of coal (Table 1.1). Most of these have concluded that world Cu production will peak within a relatively short time, usually on the order of decades. So, you could ask why we feel that these estimates underestimate Earth's potential to supply Cu to society.
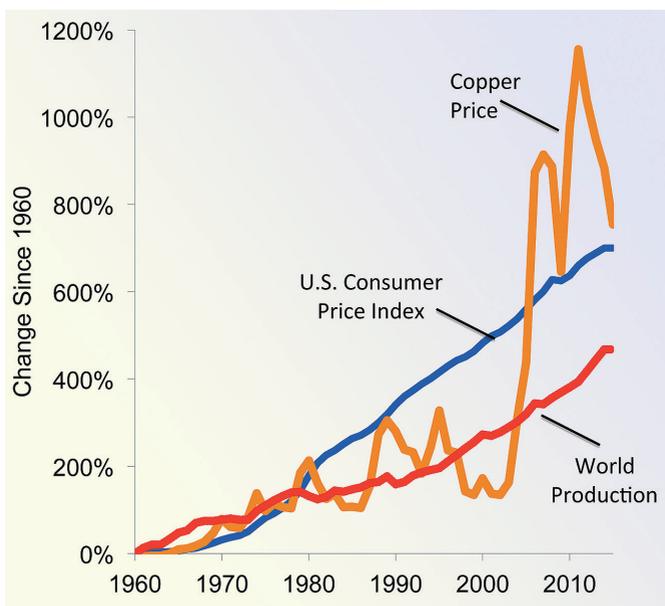
Figure 1.7 Change in price of Cu since 1960 compared to the U.S. consumer price index and global production (data from World Copper Factbook, 2015; U.S. Federal Reserve Bank).

Our response is that all of these estimates are based only on identified resources, with only one exception. Only the estimate by Johnson *et al.* (2014) includes a category of unidentified (undiscovered) resources, but these are mainly located in areas of known deposits, and at shallow depths. We have every reason to believe that many undiscovered deposits remain to be found in addition to the USGS predictions. Large areas of the crust have not been explored and we have only explored to very shallow depths, usually much less than 1 km (Section 3). Most known Cu deposits are at depths of 1 km or less (Fig. 1.8), whereas we know they actually form at depths of 2 to 3 km (Sillitoe, 2010a). Kesler and Wilkinson (2008) used this relation to estimate that undiscovered Cu deposits within 3.3 km of the surface contain a theoretical resource of at least 8.9×10^4 Mt of Cu, more than 10 times the total estimated by the USGS (Fig. 1.9).

Box 1.3 – Depth of Discoveries – Despite society's huge mineral consumption, we have only scratched the surface of the planet. Figure 1.8 shows the depth to Cu, Ni and Pb-Zn deposits that have been discovered since 1900. Note that most discoveries are at or near the surface, considerably above the average 2-3 km depth at which many deposits form. This suggests that many deposits remain to be discovered at relatively shallow crustal depths (Schodde, 2014b; see Sections 3 and 5).

Base Metal Deposits Found in the World Between 1900 and 2015
Depth of Cover (Metres)

- Copper
- Nickel
- Zinc/Lead

N = 1141

Note: Size of bubble refers to "Moderate", "Major" and "Giant"-sized Cu, Ni, Pb and Zn deposits.
Excludes Nickel Laterite deposits and undersea deposits
(a) Stratabound copper deposits in Poland, found while drilling for oil
(b) Admiral Bay zinc deposit in Australia, found while drilling for oil

Figure 1.8   Depth of Cu, Ni (except laterite deposits) and Pb-Zn deposits discovered since 1900 (modified from Schodde, 2014a and written communication, August 2016).
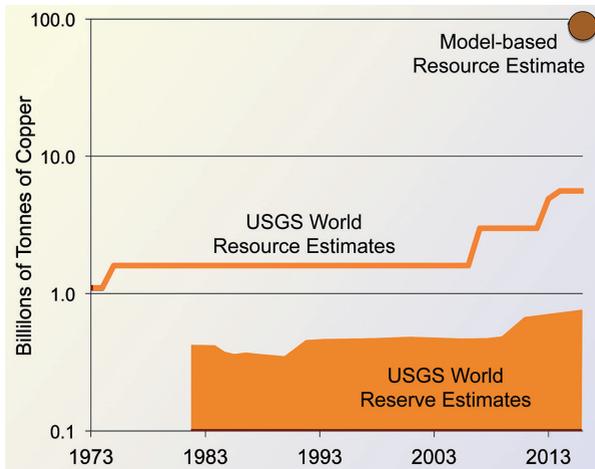
Figure 1.9   Comparison of changing USGS estimates for copper reserves (solid area), resources (line) and theoretical estimate of ultimate resource to depth of 3.3 km (circle, data from Kesler and Wilkinson, 2008). As explained in the text and detailed in Section 5, these estimates are based on grades similar to those of deposits exploited today. If lower grades become feasible to mine, as has occurred over the past century, the resource size could increase significantly. Note log scale.

1.6 Conclusion

Our optimism about global mineral supplies is based on the huge difference between the estimates of reserves made by industry (Ore Reserves) and the various estimates of global resources. To understand the magnitude of global Cu resources truly, we will have to expand exploration and research. In the following sections, we review this situation, starting with a discussion of how deposits form (Section 2), methods used to explore for them and produce them (Sections 3 and 4), and finally the truly long-term outlook for Cu resources (Section 5).

2. FORMATION OF MINERAL DEPOSITS

2.1 What is an Ore Deposit?

The term "ore deposit" has a specific meaning in the geological literature (Section 1), being a mass of rock that contains a useful element, compound or mineral with a grade (concentration) and total amount sufficiently high that the material can be mined economically. Copper, Au and Fe are the most important metals in terms of value of global production (Fig. 2.1a). As explained in Section 1, ore deposits are an important subset of the broader term "mineral deposits", which include natural concentrations of elements or minerals. Metals and minerals become concentrated by many processes into a wide variety of ore deposits that form in four main geologic environments, orthomagmatic, hydrothermal, sedimentary and weathering (Fig. 2.1b).

2.2 Ore Grades and Ore Minerals

The grade of ores varies by many orders of magnitude, from essentially 100 % for commodities like quartz for glass, solar panels and semiconductors and gravel for construction, to a part per million (ppm or gram per tonne, g/t) for valuable metals like Au and Pt. In Table 2.1 we compare typical present-day ore grades for some metals along with their average concentrations in rocks that make up the upper for some metals along with their average continental crust.

Table 2.1	Concentrations of ore metals in the continental crust and ores.			
Metal	**Concentration in the crust[1]**	**Grade in ores[2]**	**Enrichment factor**	**Price (US$/kg)[3]**
Al – aluminium	8 %	30 %	3-4	1.5
Fe – iron	4 %	50 %	10	0.1
Cu – copper	28 ppm	0.6 %	200	6
Nd – neodymium	27 ppm	1 %	300	100
U – uranium	2.7 ppm	0.2 – 2 %	100 – 1,000	80
Au – gold	1.5 ppb	6 ppm	4,000	50,000
Pt – platinum	0.5 ppb	5 ppm	10,000	50,000

[1] Upper continental crust from Rudnick and Gao (2004); Al and Fe recalculated from oxide values.
[2] From InfoMine.com.
[3] Typical price 2012-2016, from InfoMine.com.

a) Value of production by commodity
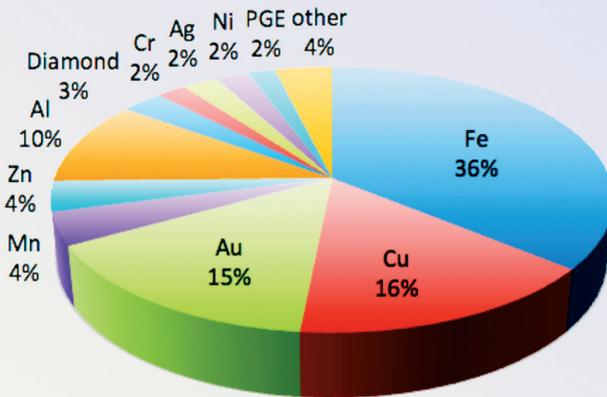
b) Value of deposit type
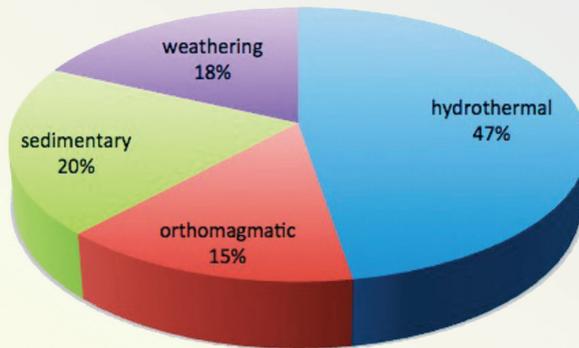
Figure 2.1 **(a)** Relative value of metal production for processed material (data from Ericsson, 2008, and USGS, 2016). **(b)** Relative value by deposit type, based on data in diagram (a) combined with our estimate of the relative contribution of the four deposit types to the production of each metal.

Elements like Fe and Al are major components of rock-forming minerals. Their concentrations in rocks like granite or basalt range from about 2 to 8 wt. % compared to grades in typical ores that are four to ten times greater. Bauxite contains up to 30 % Al and high-grade Fe ore contains >50 % Fe. These high concentrations make it relatively easy to extract the metals and this, combined

with the relative abundance of these deposits, is reflected in their low metal prices, only $1.5 per kg for Al and less than $0.1 per kg for Fe. Iron alone accounts for over a quarter of the value of all metals mined and refined in the world, followed by Al (Fig. 2.1a).

The next three metals in Table 2.1 are referred to as trace elements in the geochemical literature. Copper is a base metal; *i.e.* a metal present in moderate concentrations in the crust and used widely by industry (Section 4). The 2014 production of 22.5 Mt (18.7 Mt mined and 3.9 Mt secondary Cu; World Copper Factbook, 2016) accounts for about 16 % of the value of mined metals. Its concentration in the upper continental crust is estimated to be 28 ppm (Rudnick and Gao, 2004) but ores must have concentrations of at least 0.3-0.5 % (3,000-5,000 ppm) before they can be mined economically. Neodymium is one of the rare earth elements (REE) that acquired celebrity status, initially because of its use in magnets inside everything from smart phones to wind turbines, and reinforced by Chinese export regulations that restricted REE availability. The concentration of Nd in the upper continental crust is about 27 ppm, and ore grades are similar to those of Cu. Despite their critical importance for high-technology products, relatively small amounts of Nd and other REEs are used by industry (~123 kilotonnes [kt] of rare earth oxides were produced in 2015; Dutta, 2016). Uranium is classed as an energy-related element because of its use in nuclear reactors. Its concentration in the crust is lower (2.7 ppm) than the other two trace elements, and ore grades range from about 0.2 to more than 5 % in some exceptional deposits; 56 kt were produced in 2014 (www.world-nuclear.org). For all three elements, metal prices are about $US5 to $US100 per kg, reflecting lower ore grades and the difficulty and cost of separating the element from the ore.

The last two elements in the list are precious metals. Gold is not a major focus of geochemical studies but figures prominently in the ore deposit sphere because of its use in jewellery (about half of the ~4,000 t/y supply, one third of which comes from recycling), high technology (~8 %) and finance. Gold contributes 15-20 % to the mined value of metals, even though nearly half of global non-ferrous exploration expenditures are devoted to exploring for this element (Section 3). Platinum is an important tracer of petrological processes (it fractionates from other platinum-group elements (PGE) during mantle melting, particularly if sulphides are present), and it has important industrial applications as a catalyst in the automobile and chemical industries. It contributes 2 % of global mined metal value and has a large strategic importance; 190 t were produced in 2015 (USGS, 2016). Both precious elements are present at ~1 part per billion (ppb) in the continental crust and at the ppm level in ores. Their scarcity is reflected in their prices, which recently have oscillated around $US40,000 to $US50,000 per kg ($US1,200-1,500/oz).

The ratio of average grades of metals in their ores to the average concentrations in the continental crust is referred to as the "Clarke of concentration" in honour of P.F. Clarke, an American chemist, who first estimated the composition of the continental crust (Clarke, 1889). The high concentration factors of many ore-forming metals (Table 2.1) illustrate that in order for a metal or mineral to

form an ore deposit, its concentration must be many times, up to several orders of magnitude, higher than those in typical crustal rocks. The average grade of ores has generally decreased with time, as illustrated by Cu in inflation-adjusted terms (Section 5), largely because of improvements in mining technology and the economies of scale of large mines.

To produce the high degrees of concentration needed to form an ore deposit requires a confluence of geologic processes that are referred to as ore-forming processes. In most cases, this involves the formation of one or more ore minerals in which the ore element has a high concentration (compositions in Table 2.2). For base metals such as Cu, Zn and Pb, by far the most common ore minerals are sulphides; some oxides and carbonates can also be ore minerals. Hydrous silicates are the main ore minerals in Ni laterites, whereas most Au ores contain native metal or electrum (Au, Ag). In all cases, the nature of the ore mineral has an impact on the ease with which the desired element can be extracted and used (Sections 4 and 5).

Table 2.2 Selected alteration and ore minerals listed by ore environment and alteration or style of mineralisation. This is only a partial list – there are many sub-types and specific minerals for different ore environments and mineral assemblages (Meyer and Hemley, 1967). For more complete lists, see Atlas of Alteration (Thompson and Thompson, 1996) and Ore Mineral Atlas (Marshall *et al.*, 2004).

Hydrothermal Alteration Mineralogy			
	Ore environment	**Alteration type**	**Mineralogy**
High temperature 400-600+ °C	Porphyry core & IOCG core	K-silicate – *Potassic*	K-feldspar, biotite, magnetite, ferroactinolite, anhydrite, hematite
	Porphyry top	Lithocap zone – advanced argillic	quartz, alunite, kaolinite, pyrophyllite, diaspore
	Skarn	Calc-silicate – complex mineral relations	garnet, pyroxene, pyroxenoid, amphibole, epidote, scapolite
	IOCG and deep lateral porphyry	Sodic-calcic	albite, diopside, garnet, actinolite, scapolite
Medium temperature ~230-400°C	Porphyry lateral	Propylitic	actinolite, epidote, chlorite
	IOCG shallow	IOCG "Phyllic" equivalent	hematite, chlorite, calcite, muscovite/illite
	Porphyry and IOCG overprint	Sericite (white mica)-pyrite – *Phyllic*	muscovite/illite, chlorite, quartz, pyrite

Table 2.2   Cont.

Hydrothermal Alteration Mineralogy			
	Ore environment	**Alteration type**	**Mineralogy**
Medium temperature ~230-400°C	Orogenic Au	Carbonate ± local sericite	muscovite-illite, calcite, siderite, ankerite, chlorite, quartz (biotite, pyroxene, amphibole at higher temp)
	Carbonate replacement	Quartz-carbonate-clay	quartz, calcite (Mn-rich), dolomite, siderite, kutnohorite, rhodochrosite, rhodonite, illite, kaolinite
	VMS	Mafic host rocks	quartz, Fe-rich chlorite, sericite, chloritoid, siderite, cordierite
		Felsic host rocks	quartz, muscovite-illite, chlorite, chloritoid, andalusite
Lower temperature 180-270°C	Early leached and high sulphide-content epithermal	Residual quartz and advanced argillic alteration	quartz, rutile, alunite, sulphur, barite, kaolinite, illite-smectite
	Epithermal, low to moderate sulphide content	Quartz-adularia	quartz, adularia, bladed calcite (replaced by quartz), chlorite (Mn minerals with higher sulphide content), illite, smectite and other low-temperature clays
	Sediment-hosted Au	Jasperoid – de-calcified calcareous siltstone	quartz, hematite, kaolinite, illite-smectite, barite, realgar, orpiment
Hydrothermal Ore Mineralogy – considerable overlap between many systems			
	Ore Environment	**Style of mineralisation**	**Mineralogy**
	Porphyry	Hypogene	bornite (Cu_5FeS_4), chalcopyrite ($CuFeS_2$), pyrite (FeS_2)
		Shallow sulphide rich	enargite (Cu_3AsS_4), covellite (CuS), chalcocite (Cu_2S), pyrite

Hydrothermal Ore Mineralogy – considerable overlap between many systems			
	Ore Environment	**Style of mineralisation**	**Mineralogy**
		Supergene (20-40°C)	chalcocite, covellite
		Oxide enrichment (20-40°C)	malachite ($Cu_2(OH)_2CO_3$), atacamite ($Cu_2Cl(OH)_3$), cuprite (Cu_2O), brochantite ($Cu_4(SO4)(OH)_6$), chrysocolla ($Cu_2H_2Si_2O_5(OH)_4$), turquoise ($CuAl_6(PO_4)_4(OH)_8 \bullet 4H_2O$)
	Skarn/carbonate replacement	Multiple types with different metals – Cu and Zn deposits listed	chalcopyrite, bornite, sphalerite (($Zn,Fe)S$), galena (PbS), tetrahedrite ($Cu_{12}Sb_4S_{13}$), pyrite, pyrrhotite (FeS), magnetite (Fe_3O_4), hematite (Fe_2O_3)
	Orogenic Au	Veins and replacement	native gold (Au), electrum (Au,Ag), pyrite, pyrrhotite, arsenopyrite ($FeAsS$), stibnite (Sb_2S_3), sphalerite
	VMS	Massive sulphide and footwall stringers	pyrite, pyrrhotite, chalcopyrite, sphalerite, galena, tetrahedrite
Magmatic Sulphide Ore Mineralogy			
	Komatiite-hosted and mafic intrusions	Massive and disseminated sulphide	pyrrhotite, pentlandite (($Fe,Ni)_9S_8$), chalcopyrite, pyrite, Pt group minerals, chromite (($Fe,Mg)Cr_2O_4$), magnetite
Low-temperature and Weathering-related Ore Mineralogy			
20-40°C	Uranium deposits	Unconformities	uraninite (pitchblende)(UO_2)
	Bauxite	Blankets above groundwater table	gibbsite ($Al(OH)_3$), boehmite ($AlO(OH)$)
	Ni laterites	Blankets above groundwater table	garnierite (Ni-Mg-hydrosilicates)

2.3 Classification of Ore Deposits

Deposits may be grouped or classified by their geologic setting and the main genetic process that formed them (Table 2.3), as well as by the tectonic setting (Table 2.4) in which they formed, highlighting the relation of almost all ore deposit types to the secular evolution of the Earth (Sawkins, 1984; Richards, 2014).

Table 2.3   Ore deposits and formation processes.

Class	Type	Depth (T range)	Critical ore forming process	Examples	Recent reference
Ortho-magmatic	Cr and PGE deposits in layered mafic-ultramafic intrusions	5-15 km (~1200 °C)	Fractional crystallisation and magma mixing in a large (100s km³) magma chamber	Bushveld Complex, South Africa	Barnes and Lightfoot, 2005
	Cu-Ni sulphides in small mafic intrusions	1-5 km (~1200 °C)	Magma pulses through complex channels feeding overlying volcanism; probable wallrock source of S	Norilsk-Talnakh, Russia	Barnes et al., 2016
	Ni-Cu sulphides in ultramafic lavas (komatiite)	<0.1 km (>1500 °C)	Eruption of highly magnesian komatiite and assimilation of floor rocks forms sulphides at base of channels	Kambalda, Australia	Barnes et al., 2016
	Diamonds in kimberlites	>100 km for diamonds; kimberlites reach surface (~1000 °C)	Diamond formation in cratonic roots brought to surface in kimberlite magmas, emplaced in breccia pipes	South Africa, Russia, Canada	Gurney et al., 2005
Magmatic-hydro-thermal	*i) dominated by magmatic water*				
	Porphyry Cu-(Au, Mo) and associated epithermal base metal deposits	1.5-4 km (~600 to 300 °C) >1-2 km	Crystallisation of wet, oxidised arc-related magmas, releasing fluids to form vein and breccia mineralisation	Bingham, Utah Escondida, Chile Butte, USA, Colquijirca, Peru	Sillitoe, 2010a

Deposit type	Depth (Temperature)	Process	Example	Reference
Climax-type Mo-(W-Sn)	>3 km (~600 to 300 °C)	As above; magma composition more felsic and more reduced	Henderson, Colorado	Seedorff et al., 2005
Skarn Fe, Cu, Zn, Au, Mo, W	2-10 km (500-300 °C)	Magma-wallrock reactions replace contact zone with calc-silicate minerals and mineralisation	Ertsberg, Indonesia	Meinert et al., 2005
Iron oxide Cu-Au±U-REE (IOCG)	~1-10 km (~500 to 200 °C)	Extensive deep oxidised saline magmatic fluids mix with basin/surface fluids; regional alteration, focused deposits	Olympic Dam, Australia	Groves et al., 2010; Williams et al., 2005

ii) dominated by meteoric or sea water with magmatic component

Deposit type	Depth (Temperature)	Process	Example	Reference
Epithermal Au-Ag-(Se-Te) Ag-Pb-Zn-(Au) Au-Cu-As	0-1000 (1500) m (180-300 °C)	Shallow mineralisation from ascending magmatic and meteoric fluids; near surface T and chemical gradients	Hishikari, Japan Fresnillo, Mexico Yanacocha, Peru	Sillitoe and Hedenquist, 2003
Carlin-type Au	2-3 km (180-240 °C)	Meteoric dominant fluid + deep magmatic/metamorphic fluids; replacement of calcareous siltstones	Post-Betze, Nevada	Muntean et al., 2011
Volcanogenic massive sulphide (VMS)	0-300 m below seafloor (200-350 °C)	Seawater circulation below seafloor (+/- magmatic fluid), discharge at seafloor; metals precipitated by cooling + mixing	Brunswick #12, Kidd Creek, Canada	Galley et al., 2007

i) deposits dominated by meteoric water

Category	Deposit type	Depth (Temperature)	Process	Example	Reference
Amagmatic hydrothermal	Unconformity U	1-2 km (150-250 °C)	Oxidised basin fluids react with reduced basement and gases related to deep structures	Athabasca Basin, Canada	Cuney and Kyser, 2009
	Roll front and sandstone U deposits	100-500 m (75-150 °C)	Oxidised meteoric/basin fluids flow through reduced sandstone aquifers	Wyoming, USA	Cuney and Kyser, 2009

Table 2.3 Cont.

Class	Type	Depth (T range)	Critical ore forming process	Examples	Recent reference
Amagmatic hydro-thermal	*ii) deposits formed largely from basinal brines*				
	Clastic-hosted (or SEDEX) Pb-Zn-Ag-Ba	0-500 m (~100-200+ °C)	Sedimentary brines replace shale-siltstone units at or below seafloor, sulphides deposit on cooling, local exhalation	Red Dog, Alaska	Leach *et al.,* 2010
	Mississippi Valley-type (MVT) Pb-Zn-F-Ba	100s m to 3+ km (~100-150+ °C)	Oxidised metal-rich basin brines mix with reduced fluids, metal sulphides precipitated in open spaces and as replacement	Tri-state district, USA	Leach *et al.,* 2010
	Sediment-hosted stratiform Cu-Co-(Ag)	100s m to 5 km (125-200 °C)	Basin brines from deep oxidised units ascend and react with reduced unit; capped by impermeable evaporites	Tenke-Fungurame, DRC	Hitzman *et al.,* 2010
	iii) deposits formed largely from metamorphic water				
	Orogenic Au	1-15 km (250-400 °C)	Deep fluid of metamorphic origin (+/- mantle and magmatic components) focused through major crustal structures; Au precipitates during wallrock reaction	Kalgoorlie, Australia, Timmins, Canada, Ashanti, Ghana	Goldfarb *et al.,* 2005

Sedimentary (chemical or detrital)	Banded iron formations (BIF)	Seafloor (2-20 °C)	Direct Fe oxide precipitation from reduced Palaeoproterozoic/Archean seawater, possibly bacterially assisted	Hamersley, Australia; Carajàs, Brazil	Bekker et al., 2010
	Li-rich brines	0-200 m (10-30 °C)	Active evaporitic basin ("salar") with Li-rich volcanic input; concentration by evaporation	Chile, Bolivia, Argentina	Munk et al., 2016
	Phosphorites P (U, REE)	Seafloor (2-20 °C)	Platforms, marginal seas, with P upwelling in ocean currents	North Africa, Middle East	Pufahl and Groat, 2017
	Placers: Au, PGE, diamonds, Ti-Zr	Surface (0-25 °C)	Active streams and rivers with fluvial concentration of heavy metals and grains; similar concentration process in beach and shallow marine sands	California, Alaska, Colombia, Russia, Namibia	Garnett and Bassett, 2005
	Palaeoplacers: Au-U	Ancient surface	Placer concentration of Au and U in a reducing atmosphere and multiple reworking	Witwatersrand, South Africa	Frimmel et al., 2005
Weathering (above the ground-water table)	Al laterite (bauxite) and Ni laterite	Surface (15-30 °C)	Tropical weathering with warm rainfall exceeding evaporation; downward leaching of rocks (Ni-rich for Ni laterites) and residual concentration of Al or Ni	Al: Weipa, Australia Ni: Philippines, New Caledonia	Freyssinet et al., 2005; Retallack, 2010
	"Supergene" Cu enrichment	10-200 m (10-40 °C)	Rainwater oxidises pyrite, generates acid and leaches Cu; precipitated at watertable	Andes, SW USA	Sillitoe, 2005

Table 2.4 Tectonic setting of ore deposits.

Tectonic setting	Deposit type	Deposit sub-type	Major metal association	Geologic setting; main associated rocks	Most-endowed period(s)
Convergent margin	Porphyry systems	Porphyry	Cu±Au±Mo	Continental and island arc; intermediate calc-alkaline to alkaline	Mid Mesozoic to Pliocene
		Epithermal	Au-Ag-As-Hg-(Pb-Zn)	Continental and island arc; intermediate calc-alkaline some back arc (sulphide-poor), bimodal felsic-mafic	Mid Mesozoic (Cenozoic for epithermal) to Recent
		Skarn	Fe, Cu, Au, Zn, W-Sn, Mo	Continental and island arcs; carbonate rocks	Mid Mesozoic to Recent
		Carbonate replacement	Zn-Pb-Ag	Continental and island arc; carbonate sequences	Mid Mesozoic to Recent
		Silty carbonate hosted (Carlin)	Au-As	Continental and island arc	Tertiary
	Iron-oxide Cu-Au (IOCG)	Many variations	Fe±Cu-Au± U±REE	Transpresional to extensional settings (complex craton margins in older deposits; variety of host rocks	Late Archean, Early to Middle Proterozoic, Mesozoic
	Orogenic Au	Au-As	Au-As	Fore-arc, back-arc, accretionary wedge; greenschist facies	Late Archean, Early Proterozoic, Palaeozoic-Tertiary
Spreading centre and convergent-margin extension	Volcanic-hosted massive sulphide (VMS)	Cyprus	Cu-Pb-Zn ± Ag, Au	Mid-ocean ridge (Cyprus), bimodal mafic, mafic	Archean, Phanerozoic
		Kuroko		Back-arc (Kuroko); bimodal felsic, siliciclastic	
Foreland basin	Mississippi Valley-type (MVT)		Pb-Zn±Ba±F	Post-collision foreland basin; platform carbonate host	Mid Paleozoic, late Mesozoic

Setting	Deposit type	Host/process	Commodities	Geological setting	Age
Rifts, sag basins, passive margins	Sediment-hosted stratiform Cu		Cu±Co±Ag	Intercraton rift basin; red beds, carbonaceous units, evaporites	Late Proterozoic, Permian
	Uranium	Unconformity	U±Au±Co± Mo±Se±Ni	Sedimentary basin; redox front, contacts	Middle Proterozoic
		Sandstone	U±V±Mo	Closed basin; redox front, contacts	Mesozoic, Tertiary
	Clastic-dominated Zn-Pb (or SEDEX)		Pb-Zn±Cu±	Passive margin, back-arc and continental rift, sag basin; shale and carbonate rocks	Middle Proterozoic, Paleozoic
	Banded Iron Formation	(BIF)	Ag±As±Bi Fe-(P)	Passive margin, deep basin; carbonate and silica facies	Archean, Early Proterozoic
	Mn-rich sediments		Mn-(Fe)	Open shelf	Early Proterozoic, Paleozoic
Passive margin platform	Phosphorites		P-(U, REE, Se, Mo, Zn, Cr)	Platform; epeiric sea	latest Proterozoic-Miocene
Large igneous province (oceanic or continental)	Ni sulphide	Komatiite / Mafic intrusion	Ni±Cu±PGE / Ni-Cu-PGE± Co±Au	Greenstone belt; ultramafic / Plumes; sedimentary basin	Archean, Proterozoic / Proterozoic, Phanerozoic
Craton or craton margin	Layered intrusion / Diamond		PGE-Ni±Cu; Cr / diamond	Plume, craton / Cratons; kimberlites	Late Archean, Proterozoic / Late Proterzoic, Cenozoic
Land surface	Lateritic Al, Ni / Placer (palaeoplacer)		Al / Ni-Co / Au±U; Zr-Ti; diamond	Granite-gabbro, arkose / Ultramafic / Fluvial, marine	Tertiary to Recent / Mid Cretaceous to Miocene / Late Archean, Early Proterozoic, Recent

Review sources include Groves et al., 2005; Kerrich et al., 2005; Hitzman et al., 2010; Leach et al., 2010; Richards, 2014; Cawood and Hawksworth, 2015; Jébrak and Marcoux, 2015.

Box 2.1 – *An Ore Deposit Pioneer* – Waldemar Lindgren pioneered the use of ore-forming processes to classify ore deposits. He was born in Sweden in 1860 and showed a strong interest in the natural sciences, collecting samples from Cu and Fe mines by the age of 13. In 1877, he visited the famous Mining Academy at Freiberg, and took a trip through the mines of Saxony. The following year he returned to study geology, mineralogy, metallurgy and mining engineering at Freiberg. In 1883 he crossed the Atlantic to follow his dream to join mining and geological activities in the western USA. He studied numerous ore districts in the Americas and around the world, mostly for the USGS, gaining three decades of field experience and writing numerous seminal publications. His lectures at Stanford University and the Massachusetts Institute of Technology formed the basis of his famous and still referenced book, *Mineral Deposits*, which evolved over four editions from 1913 to 1933. Inset: Lindgren at Santa Rita porphyry Cu deposit, New Mexico, 1933 (courtesy of Göran Fredrikson).

Genetic classification. Classifying ore deposits by inferred genetic processes was common in Europe during the late 1800s and early 1900s (summary by Noble, 1955). As a wider range of ore deposit types became known, classifications became more comprehensive. The most influential of these was proposed by Lindgren (1933), largely based on his perceptive observations, both in the field and in the laboratory. He focused largely on hydrothermal deposits that formed from circulation of hot aqueous fluids, and grouped them in terms of temperature of formation and fluid composition. He also recognised deposit types formed by magmatic processes, sedimentation, evaporation and weathering. Most modern textbooks on economic geology follow similar general classifications (*e.g.*, Robb, 2004; Pohl, 2011; Ridley, 2013; Jébrak and Marcoux, 2015). The most common ore-forming process involves hydrothermal fluids, either exsolved by magmas or circulating through the crust. Orthomagmatic processes, physical and chemical sedimentation, and weathering also form significant deposits (Fig. 2.1b; Tables 2.3 and 2.4).

Hydrothermal activity is of relatively minor importance when considering the origin of common rocks. By contrast, this process generates over 90 % of all Cu ores (Singer *et al*, 2008; Mudd *et al.* 2013) and the majority of Ag, As, Au, Be, Bi, Cd, Ga, Ge, In, Li, Mo, Pb, Sb, U, W and Zn ores (Fig. 2.1), and it operates in diverse upper crustal environments. Some metals form only a single type of ore. Chromium, for example, occurs almost exclusively in orthomagmatic deposits. At the other extreme is Fe, which is deposited mainly by sedimentary processes but in many cases is further concentrated by hydrothermal and weathering processes. Gold mainly occurs in hydrothermal ore deposits, but also accumulates in weathered residuum above bedrock and in sedimentary placers, both of which form significant ore deposits.
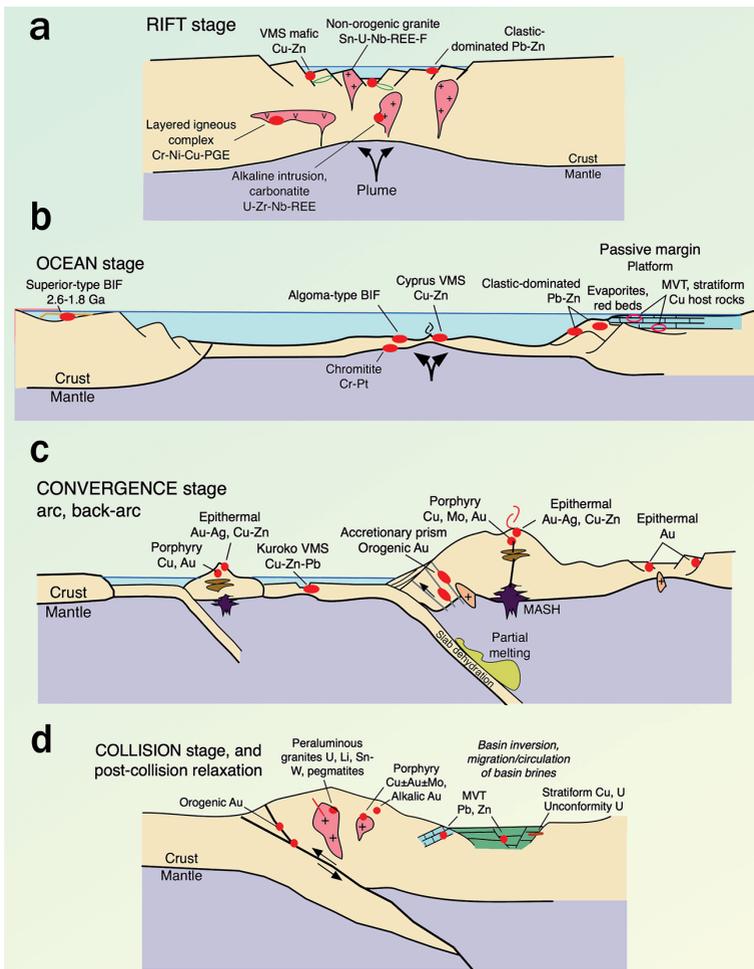
Schematic sections showing the association of selected ore deposit types of significance with their plate tectonic settings (adapted from various sources, including Groves *et al.*, 2005; Hitzman *et al.*, 2010; Leach *et al.*, 2010; Richards, 2011; Jébrak and Marcoux, 2015), based on the supercontinent cycle of rifting, ocean formation, convergence and collision (Richards, 2014); some intracraton-hosted deposit types are not considered here (Groves *et al.*, 2005; Table 2.4). **(a)** Rifting stage: crustal thinning due to plume ascent and creation of primitive magmas. **(b)** Ocean stage: generation of new crust, and passive margins. **(c)** Convergence, subduction and creation of volcanic arcs and back-arcs, both in oceanic and continental settings. **(d)** Collision as well as post-collision relaxation (extension), creation of anorogenic magmas and migration of basin-hosted brines in platform sequences. Formation environments of various ore types are shown with red dots.

Tectonic environments. By the 1970s, a growing understanding of the critical role that tectonics played in the formation, preservation and metallogenic evolution of ore deposits led to the use of plate tectonics as a basis to classify ore deposits (Sawkins, 1984; Fig. 2.2).

Box 2.2 – F.J. (Sam) Sawkins – Sawkins (1984) was prescient in his early tectonic synthesis of ore deposits based on the evolving understanding of the tectonic setting of ore deposits by many workers during the previous decade. He noted that the primary conceptual tool in exploration planning (Section 3) is lithologic association, the basis of all good descriptive models of ore deposits. *"The principal impact of plate tectonics on all this has been to broaden and deepen our understanding of the tectonic environments in which many of these lithologic associations develop (Dickinson, 1980), and to provide insights into their relative spatial associations. Metallogenesis can now be understood within the fundamental context of continental evolution, and this in turn permits the conception of exploration programmes aimed at specific types of ore deposits."* (p. 280). Inset: Sam Sawkins (courtesy of Ginny Sawkins).

We briefly describe the most significant types of ore deposits in terms of their genesis (Table 2.3) and tectonic affiliation (Table 2.4, Fig. 2.2). For each deposit type, we provide examples of the total contained metal to give an idea of the capacity of a single deposit to meet current global demand. These estimates illustrate the highly skewed nature of deposit sizes (Section 5), with most presently exploited resources contained in relatively few very large deposits, called world class or Tier 1. For example, the 20 largest Cu mines, out of about 450 total, produce 8.8 Mt/y, or 44 % of global output (World Copper Factbook, 2015). A more comprehensive coverage of deposit types is provided in review volumes, such as Robb (2004), Hedenquist *et al.* (2005) and Jébrak and Marcoux (2015).

2.4 Orthomagmatic Ore Deposits

These mineral deposits result from the accumulation of minerals or other phases during the solidification of magmas (Fig. 2.3). The prefix "ortho" distinguishes this class from deposits produced by magmatic-hydrothermal processes, *i.e.* from hydrothermal fluids exsolved from magmas. The Bushveld Complex of South Africa contains three types of orthomagmatic ores: chromite (the source of Cr) in the lower ultramafic cumulates (Fig. 2.4a); PGEs near the level where plagioclase becomes a cumulus phase; and V-bearing magnetite in the upper levels. Current theories for the formation of the Cr ores call on contamination of the magma with siliceous wall rocks, or magma mixing, which produce hybrid magmas

that crystallise chromite alone, combined with crystal sorting during flow into the magma chamber to concentrate the chromite in layers (Maier *et al.*, 2013). The PGE- and V-rich magnetite deposits also form through accumulation of magmatic phases, with PGE partitioning mainly into sulphide phases; the exact mechanisms of formation of PGE ores is complex and subject to much discussion (*e.g.*, Naldrett *et al.*, 2011).
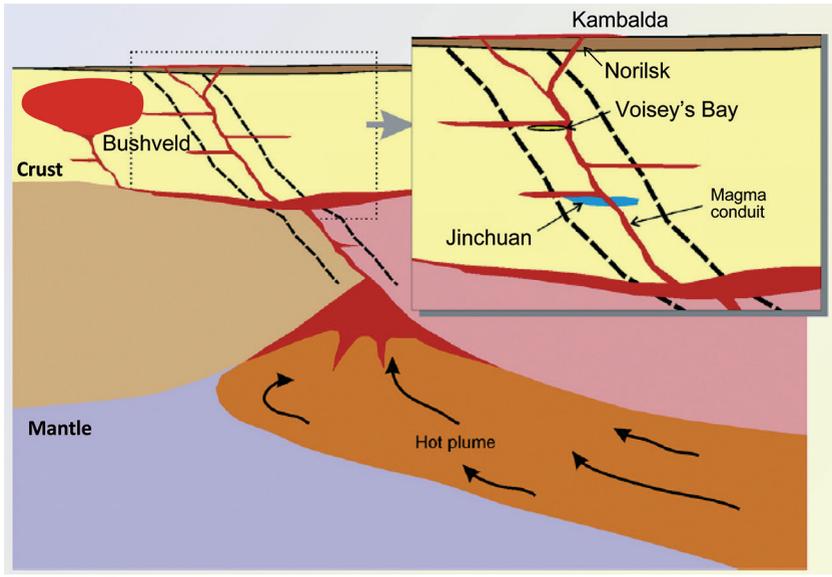
Figure 2.3 Orthomagmatic ore-forming environments. A mantle plume is diverted along the sloping base of the lithosphere and partially melts to give magmas that form ore deposits at various levels in the crust; *e.g.*, Jinchuan (China), Voisey's Bay (Canada), Norilsk (Russia), Kambalda (Australia) and Bushveld (South Africa) (modified from Barnes *et al.*, 2016).

There are no Cu deposits in the Bushveld Complex, but this metal is a major component of another type of orthomagmatic ore, Cu-Ni sulphides segregated from mafic intrusions (Fig. 2.4b). The deposits in the Noril'sk-Talnakh region of Russia are the type example, and are the most important world producers of Ni and Pd (a PGE). They are located in small gabbroic intrusions in a sedimentary basin that underlies flood basalts of the Siberian large igneous province (Lightfoot and Naldrett, 1994). The sulphides occur as disseminated blobs or massive layers in the lower parts of the intrusions and probably formed initially as droplets of immiscible Ni-Cu-Fe sulphide liquid which, being denser than the associated silicate melt, settled to the lower parts of the intrusions. Geochemical data suggest that Ni, Cu and PGEs came from the mafic magma
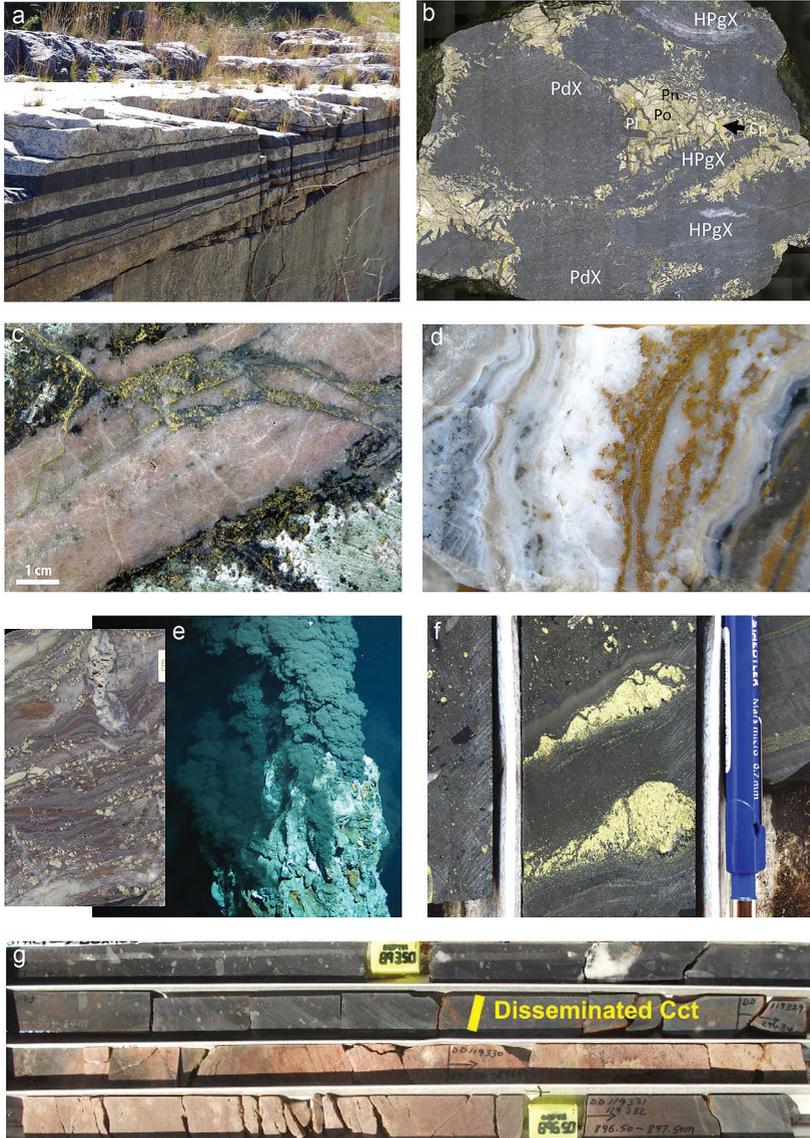
Figure 2.4 Typical textures and characteristics of ores. **(a)** Horizons of chromite hosted by anorthosite within the Critical Zone of the Bushveld Complex, Dwars River, South Africa (courtesy of J. Gauntlett; the thickest chromite layer is about 10 cm). **(b)** Typical massive sulphide matrix to silicate xenoliths (clasts),
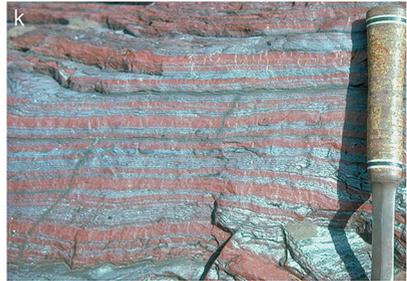
Cont. Ovoid deposit, Voisey's Bay, Canada (Box 3.1) (courtesy of S. Beresford and S. Barnes; PdX peridotite xenolith, HPgX hercynite paragneiss xenolith, Po pyrrhotite, Pn pentlandite, Cp chalcopyrite, Pl plagioclase; width 15 cm). **(c)** Quartz-chalcopyrite-pyrite vein stockwork, Far Southeast porphyry Cu-Au deposit, Philippines (courtesy of A. Gaibor; width 10 cm). **(d)** Colloform layers of quartz, adularia and Au (yellow), Kochbulak epithermal deposit, Uzbekistan (courtesy of V. Kovalenker; width 5 cm). **(e)** Turtle Pits black smoker vent, 5° S, Mid-Atlantic Ridge (400 °C, 2,900 m water depth) (courtesy of ROV Team, GEOMAR; visible height 1 m of 5 m-tall chimney). Inset: massive sulphide lens next to vent and sphalerite replacement of overlying volcanoclastic horizon at Kidd Creek VMS deposit, Canada (courtesy of M. Hannington; width 6 cm). **(f)** Sediment-hosted Cu deposit, replacement chalcopyrite along sedimentary layers, Kamoa, DRC (courtesy of D. Broughton, pencil for scale). **(g)** Redox contact between oxidised reddish sandstone, Roan Group, and overlying dark diamictite, Grand Conglomérat, the latter with 6 % Cu over 10 m, Kamoa deposit, DRC (courtesy of D. Broughton; Cct – chalcocite; width 1 m).

(h) Mississippi Valley-type (MVT) deposit, Pomorzany mine, Triassic Upper Silesia, Poland, showing infill of karst by colloform-banded yellow sphalerite enclosing dark grey galena, overgrowth of pyrite and marcasite, followed by dark sphalerite (courtesy of D. Leach; width 12 cm). **(i)** Clastic-dominated deposit, Sullivan mine, Canada, laminated sphalerite and pyrrhotite, sub-seafloor replacement of exhalative sulphides (courtesy of D. Leach; width 6 cm). **(j)** Orogenic vein quartz with coarse gold characteristic of greenschist facies metamorphic belts, North American Cordillera (courtesy of R. Goldfarb; width 5 cm). **(k)** Banded iron formation with layers that are rich in silica (red) or hematite (black), Negaunee jaspilite, Jasper Knob, Michigan (courtesy of B. Simonson). **(l)** Two bauxitic plateaux of duricrusts, Bougoumé, Guinea (courtesy of J.F. Labbé). Inset shows pisolitic bauxite from the type locality at Les Baux, France. **(m)** Resistant ferruginous duricrust in nickeliferous area, Oasis, New Caledonia (courtesy of C. Prognon).

whereas the S in the ores was derived from anhydrite-bearing evaporites of the sedimentary basin (Naldrett, 2004). A major but perhaps unique example is Sudbury, Canada, source of one third of the world's Ni resource and related to crustal melt caused by meteorite impact at 1.85 Ga (Barnes and Lightfoot, 2005).

Another class of large magmatic deposits comprises Ni sulphides in ultramafic komatiites, erupted mainly during the Archean and Palaeoprotero-zoic, which, together with diamond in kimberlite, are the only major ore types that form during volcanic eruptions. The best-known ore deposits associated with komatiite are at Kambalda in Western Australia (Lesher *et al.,* 1984). Their formation is related to the high Ni content of komatiite, and the high temperature and low viscosity of ultramafic melt. These characteristics allowed the magma to assimilate its wall rocks, which locally contain S-bearing minerals that promoted the segregation of ore sulphides (Lesher and Barnes, 2008).

Most orthomagmatic deposits are related directly to mantle plumes. The high eruption temperatures of the Kambalda komatiites imply generation from an abnormally hot Archean mantle source (Mole *et al.,* 2014) and the association of the Noril'sk-Talnakh deposits with the Siberian large igneous province links them to a more recent (250 Ma) plume (Saunders *et al.,* 2005). Many Ni sulphide deposits are located at the margins of Archean cratons (Begg *et al.,* 2011), whereas large layered intrusions like the Bushveld Complex were emplaced in the interiors of stable cratons from magmas also derived, in many cases, from mantle plumes (Hatton, 1995; Wilson, 2012).

2.5 Hydrothermal Ore Deposits

Aqueous solutions are widespread in the upper part of Earth's crust. They exhibit a range of temperatures (~50 to >600 °C) due to elevated geothermal gradients as well as heating by, or exsolution from, crystallising magmatic bodies. The water (H_2O) has several sources: magmas (magmatic water), sedimentary basins (basinal or connate water), seawater, prograde metamorphic reactions (meta-morphic water) and precipitation (meteoric water). Solutes have many sources, including magmatic emanations, interaction with wall rocks, and seawater or

its evaporitic equivalent. Magmatic hydrothermal fluids consist mainly of H_2O with variable amounts of NaCl and KCl as well as SO_2, CO_2, H_2S, and other trace constituents including HCl and metals (Hedenquist *et al.*, 1993). Basinal fluid solutes are sourced from dissolution of evaporites and wall rock interaction (Hitzman *et al.*, 2010; Leach *et al.*, 2010) and are Na-Ca-Cl dominant, with lower pH at higher salinity (Warren, 2016). Metamorphic solutions contain variable amounts of CO_2 and NaCl, reflecting the original sedimentary environment and metamorphic reactions (Yardley and Cleverly, 2013). Numerous ligands, especially Cl^- and HS^-, form complexes with metals that greatly enhance their solubility above that in pure hot water. In the case of Cu and other base metals, chloride complexes are the most common (*e.g.*, $CuCl_2^-$, $ZnCl_n^{2-n}$) although molecular sulphide complexes may be important at high temperature (Kouzmanov and Pokrovski, 2012).

2.5.1 Hydrothermal deposits in intrusive-volcanic environments

Intrusive-volcanic environments host a wide range of ore deposits, many of which contain Cu and base and precious metals. The deposits can be divided into those associated with subaerial intrusive-volcanic systems and those associated with submarine systems, with many intermediate types. In subaerial systems, magma compositions are intermediate to felsic, but can be bimodal mafic to felsic in submarine systems (Table 2.4). Hydrothermal fluids driven by shallow intrusions have a magmatic component that may mix with meteoric water or seawater depending on setting (Table 2.3), and most of these aqueous liquids boil during ascent. The wide variety of geologic settings and host rocks results in numerous ore deposit types, some closely associated such as porphyry and most types of epithermal deposits (Fig. 2.5).

Porphyry copper deposits. Porphyry Cu deposits are by far the most important source of Cu, now accounting for >70 % of world Cu production. These deposits are largely Mesozoic to Cenozoic in age and form in granitoid intrusive-volcanic rocks in convergent settings and the resultant volcanic arcs (Seedorff *et al.*, 2005; Sillitoe, 2010a). They get their name from the common porphyritic texture associated with the shallow intrusions that are the main host rock. The largest porphyry Cu districts are located in the central Andes and southwestern North America (see below), with other important provinces in the southwest Pacific region, central Asia and western Canada (Sillitoe, 2010a). The largest deposits range in age from Pliocene and younger (such as Grasberg and Batu Hijau in Indonesia), through Miocene (El Teniente, Chile) and Eocene (Chuquicamata, Chile), Laramide-age (55-80 Ma deposits *e.g.,* Morenci) in southwestern North America, to Late Devonian (Oyu Tolgoi) in Mongolia (Sillitoe, 2010a).

Among the largest porphyry Cu deposits/districts are Río Blanco-Los Bronces (220 Mt contained Cu), El Teniente (95 Mt), Collahuasi (85 Mt), Chuquicamata (135 Mt) and Escondida (144 Mt), all in Chile, followed by Grasberg (80 Mt), Morenci (42 Mt) and Oyu Tolgoi (39 Mt) (Sillitoe, 2012). Each initially contained more than a billion tonnes of ore with Cu grades from ~3 % to ~0.5 %. The highest grades in the past were commonly due to supergene enrichment

(see below), but high grades in deep (>300 m) portions of deposits unaffected by supergene processes are reported from recent discoveries at Río Blanco-Los Bronces, Oyu Tolgoi and Resolution, Arizona. Molybdenum and/or Au can add significantly to the value of the ore.
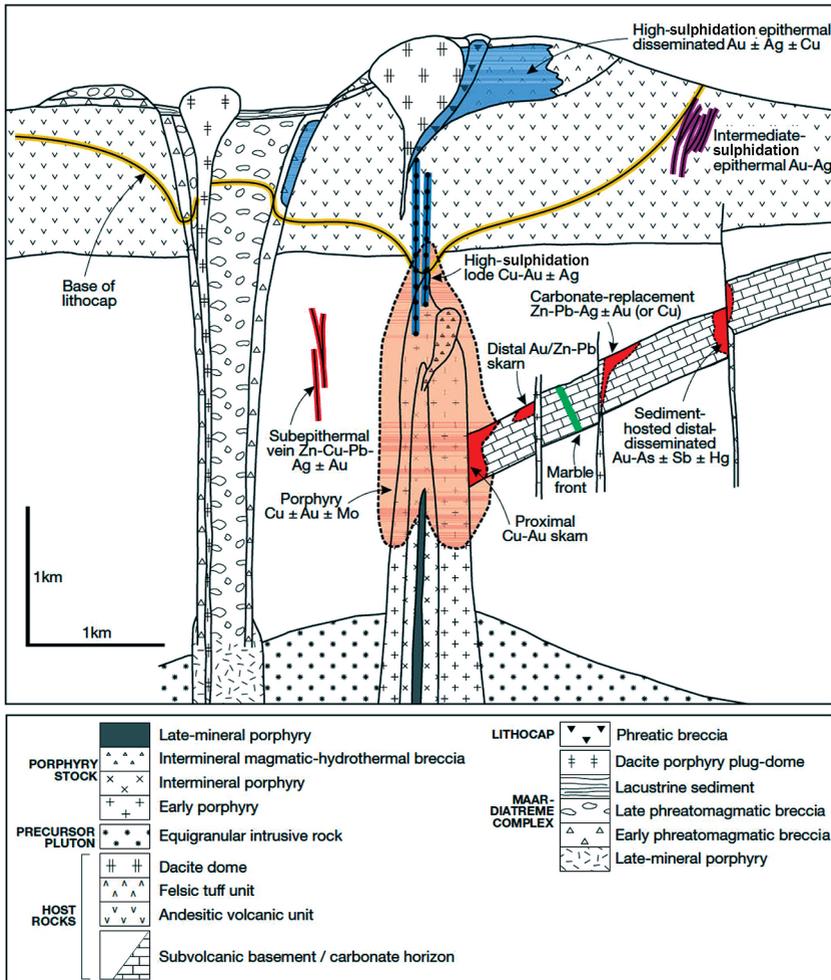
Figure 2.5   Volcanic-intrusive porphyry system in which porphyry Cu and epithermal Au-Ag deposits form, the former at the apex of the intrusions. Shallow alteration and leaching (lithocap) is related to volcanic degassing and vapour condensation. Epithermal deposits form in the same system at depths of <1 km. If carbonate rocks are intruded, a variety of skarn and replacement polymetallic deposits may also be generated in the system (from Sillitoe, 2010a).

The multiple stocks that host porphyry Cu deposits at about 2-4 km depth are parts of large and complex intrusion systems (Audétat and Simon, 2012) at depths of 6 to >10 km that commonly feed volcanoes. Erosion and rapid uplift of arc volcanoes, *e.g.*, in the southwest Pacific, now expose the tops of very young, ~1 Ma porphyry Cu deposits that formed over periods of ~100,000 years (Garwin, 2002). In addition, the upper parts of some arc volcanoes that erupted recently and cataclysmically, such as El Chichón, Mexico, in 1982 and Pinatubo, Philippines, in 1991, consist of altered rock similar to that of the uppermost parts of porphyry systems. Finally, measurements of metals in aerosols accompanying volcanic discharge, such as the quiescent eruption of White Island volcano in New Zealand, indicate as much as 1 Mt Cu and 300 t Au exsolved from the shallow magma chamber over its lifetime of about 10,000 years (Hedenquist *et al.*, 1993).

The hydrothermal solutions that form porphyry Cu deposits consist largely of magmatic water exsolved during hydraulic fracturing of the intrusion. The resulting hydrothermal solutions reacted with surrounding silicate wall rocks to form kilometre-scale alteration zones that grade outward from potassic to peripheral propylitic alteration (Table 2.2), and upward into caps of volcanic rock that have been extensively leached by highly acidic solutions derived from magmatic vapour condensates, *i.e.* advanced argillic lithocaps (Fig. 2.5). Copper minerals, typically chalcopyrite and bornite (Table 2.2), occur in fractures (Fig. 2.4c) or disseminated through altered rocks, precipitated at temperatures from 500 to 300 °C largely due to cooling and changes in fluid composition (Kouzmanov and Pokrovski, 2012), associated with an overprint of fine-grained muscovite (sericite) (Tables 2.2 and 2.3).

Other porphyry-type deposits (Table 2.3) associated with more felsic igneous compositions contain mainly Mo, W and/or Sn, and Au-only porphyry deposits are also known (Seedorff *et al.*, 2005). In addition, skarn deposits related to intrusions (some affiliated with porphyry deposits) and characterised by calc-silicate minerals such as garnet and pyroxene host a wide variety of commodities (Cu, Zn, Au, Mo, Sn, W, Fe), in particular where they cut carbonate rocks (Meinert *et al.*, 2005). Relatively primitive plutons are associated with Fe skarn, through Au, Cu, Zn, to W, Mo, to relatively evolved Sn skarn plutons; Cu, Zn and Mo deposits are more oxidised and Sn and a significant part of Au skarns are more reduced (Meinert *et al.*, 2005).

Epithermal deposits*.* Lindgren (1933) used the term epithermal (epi = over, above) for deposits that he deduced formed at relatively shallow depth and low temperature (Table 2.3). Fluids in the epithermal environment commonly discharge at the surface as liquids from hot springs and vapour from fumaroles in geothermal systems – mostly in volcanically active regions – that are tapped for their thermal energy. Since the analogous active systems are studied directly, they are the best understood deposits in terms of formation processes (Simmons *et al.*, 2005). Deposits that formed proximal to volcanic and intrusive activity were associated with high-temperature magmatic discharges and acidic alteration, such as in the Yanacocha district, Peru (51 Moz produced Au and resources in supergene oxidised rock) and Pueblo Viejo (38 Moz Au production and resource

in largely unoxidised rock) in the Dominican Republic. Where mineralisation occurred in more distal locations with respect to volcanic activity, such as at Waihi (8 Moz) in New Zealand and Hishikari (14 Moz) in Japan, there is evidence for surface discharge of boiling, near-neutral pH water of the type that discharges from hot springs today in Yellowstone National Park. Epithermal deposits are generated in the upper parts of porphyry systems (Fig. 2.5) and elsewhere, with ore occurring in veins (Fig. 2.4d) and disseminations in volcanic rocks and also in underlying basement rocks. Epithermal deposits account for ~20 % of primary Au production, and most of the world's Ag, the latter from similar quartz veins with Ag or polymetallic sulphides (Zn-Pb-Ag). During Spanish colonial time most Ag came from epithermal veins in Bolivia and Mexico; Mexico and Peru are now the two largest Ag producing countries from both epithermal and large complex porphyry-related polymetallic deposits.

Epithermal ores form in large part because of sharp temperature gradients at depths of less than ~1 km. The pressure decrease during ascent of the liquid results in boiling with vapour loss and cooling, causing both Au and silica to precipitate. Gold is mainly transported as a bisulphide complex $[Au(HS)_2^-]$; because H_2S is volatile, it partitions into the vapour phase during boiling, causing a sharp decrease in Au solubility in the liquid. Likewise, loss of the high-enthalpy vapour causes the liquid to cool, leading to amorphous silica saturation that triggers the precipitation of colloidal silica as colloform layers; these layers are associated with high Au grades in veins (Fig. 2.4d). Several clay minerals form at epithermal conditions (Table 2.2), from illite to smectite with decreasing temperature. Patterns of these alteration minerals can indicate the location of the hottest palaeo-upflow, guiding explorers to the most likely location of Au mineralisation (Simmons and Browne, 2000; Section 3).

Iron-oxide copper-gold (IOCG) deposits. These deposits account for about 7 % of world Cu resources. The type example is the enormous Mesoproterozoic Olympic Dam deposit in Australia (90 Mt contained Cu). Other important deposits include Candelaria (~7.4 Mt Cu) in Chile and Salobo (~8.4 Mt Cu) in Brazil. These deposits have ages from Archean to Cretaceous and occur in tectonic settings that range from convergent margins to stable cratons. IOCG deposits (Tables 2.3 and 2.4) form in magmatic-hydrothermal systems and, in addition to Fe, Cu and Au, may also contain other elements, including U and REEs (Olympic Dam is one of the largest U deposits in the world). Most deposits contain abundant magnetite and/or hematite in massive bodies associated with breccias and regional-scale sodic (albitic) alteration (Table 2.2). There is a temporal, but not close spatial relationship, with intrusions of diverse compositions; from mafic to felsic and from alkaline to subalkaline and calc-alkaline (Williams *et al.*, 2005; Groves *et al.*, 2010).

The wide range of characteristics of IOCG deposits (some consist of only iron oxide with no Cu or Au) has led to considerable debate about the process by which the deposits form. Although there is general consensus that they are hydrothermal in origin, the source of the fluid and metals, and the cause for ore deposition are uncertain. The putative main source of the ore-forming fluids is

magmatic (Groves *et al.*, 2010), but deeply circulated basinal waters have also been proposed (Barton and Johnson, 1996). It is likely that there are multiple settings and associations that form the range of deposits that are similarly rich in Fe oxide minerals and are collectively grouped as IOCG.

Volcanogenic massive sulphide (VMS) deposits. These deposits form in volcanic environments at shallow depths below the seafloor in oceanic crust, mainly in back-arc and submarine volcanic arcs as well as near mid-ocean ridge settings. The understanding of VMS deposits has improved thanks to the study of their active equivalents – black (sulphide) and white (anhydrite) smokers in hydrothermal vents on the seafloor (Franklin *et al.*, 2005; de Ronde *et al.*, 2014). Seawater penetrates deep into the oceanic crust where it is heated by intrusions and – at least in arc settings – it may mix with magmatic fluids (*e.g.*, in the Kermadec arc, SW Pacific; de Ronde *et al.*, 2014); metals may be derived from the magmatic fluid as well as leached from the volcanic rocks of the crust. Metals are precipitated due to cooling plus other processes below the seafloor, and locally at the seafloor. Where the hot fluids vent onto the seafloor, they mix with cold seawater and the sharp temperature decrease and change in composition cause sulphides to strip any remaining metals from solution. These sulphides replace subsurface rocks and sediments, or form chimneys on the seafloor (Fig. 2.4e) that ultimately collapse, resulting in an apron of chimney fragments. Sulphides exhaled through chimneys settle as sediments around the vent or in more distal locations on the seafloor (Fig. 2.4e, inset).

Most VMS deposits are relatively small, generally containing only a few million tonnes of Cu-Pb-Zn ore, but some are larger (>100 Mt) and can have relatively high grades. The sulphide mineralogy includes pyrite ± pyrrhotite with associated chalcopyrite, sphalerite and galena as the main ore minerals (Table 2.2). The two largest VMS deposits are both in Canada, Brunswick No 12 (230 Mt ore), with 0.46 % Cu, 3 % Pb and 8 % Zn, and Kidd Creek (148 Mt ore), with 2.3 % Cu, 0.2 % Pb and 6.2 % Zn. Many of the deeper deposits have sufficient grades to be mined underground. Other large examples occur in Europe and the Urals, including Rio Tinto in Spain and Portugal.

2.5.2 Hydrothermal deposits hosted by sedimentary rocks

Hydrothermal ore deposits in sedimentary environments formed from (amagmatic) basinal brines. They include two main groups: (1) sediment-hosted stratiform Cu deposits, and (2) Mississippi Valley-type and Clastic-dominated Zn-Pb deposits.

Sediment-hosted stratiform copper deposits. These are the second most important source of Cu, accounting for over 20 % of world resources, with host rocks formed in marine basins of intracontinental rifts or passive margin settings (Hitzman *et al.*, 2005, 2010; Fig. 2.2b,d). The most important deposits are found in the Central African Copperbelt in Zambia and Democratic Republic of Congo, which also account for about 35 % of the world's Co production, and in the Permian Zechstein basin in northern Europe, mainly Poland. Individual large

deposits include Udokan in Russia (~20 Mt contained Cu) and Tenke-Fungurume (16.7 Mt Cu; Hitzman *et al.*, 2010; Mudd *et al.*, 2013), plus the recently discovered Kamoa-Kakula deposit in the DRC (26.7 Mt Cu in the Indicated Resource at a grade of 2.8 % Cu; ivanhoemines.com/projects/kamoa-project). Ore in these deposits consists of Cu minerals that mainly follow sedimentary layers closely (Fig. 2.4f), a feature that led to the early hypothesis that the Cu was deposited syngenetically from seawater (Garlick, 1961). Later studies demonstrated that the ore zones actually cut across sedimentary layering on a regional scale, confirming that the Cu was introduced after the sedimentary rock was deposited. The Cu is thought to have been leached from underlying volcanic rocks, arkosic sediments and also the basement by oxidised basinal brines (Fig. 2.6a), with the salinity of the fluids derived from evaporation of seawater and/or dissolution of evaporites (Hitzman *et al.*, 2010). Metal was deposited in reduced sedimentary horizons (Fig. 2.4g) higher in the stratigraphic sequence (Fig. 2.6a).

Average grades for these deposits range from 1.2 to 3.6 % copper, but can be higher locally. Cobalt or alternatively Ag can be important by-products, *e.g.*, as in the Katangan Cu-Co deposits, which contain most of global Co resources. Ore bodies are laterally extensive but relatively thin and, in the Central African Copperbelt, are mostly affected by intense folding. These deposits are mined in open pits for near-surface material, whereas deeper ore bodies of sufficiently high grade are mined underground.

Mississippi Valley-type and Clastic-dominated Lead-Zinc deposits. These are the world's largest resources of Pb and Zn (Leach *et al.*, 2005, 2010). Clastic-dominated (CD) deposits (Leach *et al.*, 2010) commonly consist of thin laminations of sulphide minerals hosted largely by clastic rocks deposited on the slopes of passive margins (Fig. 2.2b). The sedimentary appearance of the laminations (Fig. 2.4i) led to early interpretations that the deposits formed exclusively by exhalation of basinal fluid onto the seafloor, hence the early term SEDEX deposits (Goodfellow and Lydon, 2007). Recent study of some deposits suggests that a portion of the metal was deposited by later, diagenetic replacement below the seafloor (Large *et al.*, 2005; Leach *et al.*, 2005, 2010). Notable examples are Broken Hill (51.8 Mt contained Zn + Pb) and Mt Isa (19.5 Mt) in Australia, Red Dog (35 Mt) in Alaska and Sullivan (19.4 Mt) in Canada; the first and last are highly metamorphosed, which resulted in increased crystal size that improves the processing characteristics.

The other group, known as Mississippi Valley-type (MVT) deposits after their type locality, consists of galena and sphalerite with locally abundant fluorite and/or barite. They formed as replacement and open-space (commonly karst) fill (Fig. 2.4h) of dominantly carbonate host rocks (Fig. 2.2d), long after the rocks were deposited in foreland basins (Figs. 2.2b and 2.6b). Important examples include the Upper Silesia district in Poland (40.8 Mt Zn + Pb), and the East Tennessee (16.5 Mt) and Viburnum Trend deposits (16 Mt) in the USA. The Tethyan orogenic belt is the most endowed region for MVT deposits and hosts large deposits (Mehdi Abad, Iran, with 20.6 Mt Zn + Pb; D. Leach, personal communication, 2016). A related type of stratabound Zn-Pb deposit in Ireland formed not long after sedimentation in extensional basins (Leach *et al.*, 2010).
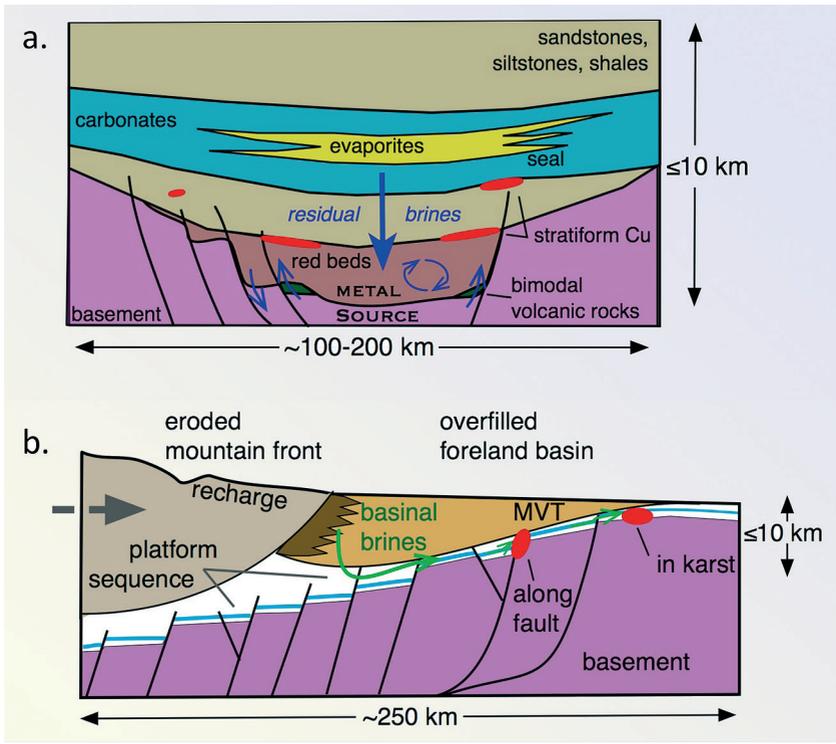
Figure 2.6 **(a)** Schematic diagram illustrating the formation of sediment-hosted strati-form Cu deposits in rift basins (adapted from Hitzman *et al.*, 2010), beneath evaporites and over basal red beds, associated with a reduced horizon that caused Cu to precipitate. **(b)** Tectonic setting of brine migration in carbonate sequences during collision, resulting in the formation of MVT Pb-Zn deposits, also related to locally reduced horizons (adapted from Leach *et al.*, 2010).

Clastic-dominated and MVT deposits began to form at about 2.0-1.85 Ga, after the first Great Oxidation Event (GOE) started at 2.4 Ma (Canfield, 2005), although most MVT deposits are much younger. A major period of CD Pb-Zn mineralisation between 1.85 and 1.58 Ga (about the timing of the second GOE) was due to: 1) enhanced oxidation of sulphides in the crust that provided sulphate to the oceans; 2) formation of red beds and oxidised aquifers that allowed oxidised brines to scavenge and transport base metals from detrital and basement rocks; 3) first formation of significant sulphate-bearing evaporites and related brines, and evolution of sulphate-reducing bacteria; and 4) formation of large and long-lived basins on and marginal to stable cratons at low palaeolatitudes (Leach *et al.*, 2010). The second oxidation event in the Late Proterozoic led to a sharp increase in the volume of coarse-grained and permeable carbonates on Palaeozoic carbonate platforms, which was instrumental to the subsequent formation of

MVT deposits due to continental-scale brine migration caused by collision-driven uplift (Fig. 2.6b; Leach *et al.*, 2010). The formation of MVT deposits reached a maximum during the final assembly of Pangea, from Devonian into the Carboniferous. Mixing of oxidised metal-bearing brines with fluids containing sulphide from thermochemical sulphate reduction is a common precipitation mechanism in MVT deposits (Leach *et al.*, 2010).

2.5.3 Hydrothermal deposits in metamorphic environments

Prograde metamorphism releases large amounts of fluid but there is debate about the importance of metamorphism in ore formation. Many orogenic Au deposits are related to dewatering events in accretionary and fore-arc zones (Fig. 2.2c,d) during post-peak metamorphism. Orogenic Au deposits are responsible for about half of global Au production outside of placer and palaeoplacer deposits (Goldfarb *et al.*, 2005). These hydrothermal deposits consist largely of sulphide-poor quartz-Au veins (Fig. 2.4j) with localised alteration of the wall rock, hosted by subsidiary structures related to first-order, deep-crustal fault zones up to 100 km long. Deposit styles vary from stockworks and breccias in shallow, brittle regimes, through laminated crack-seal veins in brittle-ductile crustal regions, to replacement and disseminated type orebodies in ductile environments that formed at depths from <4 km to >12 km (Goldfarb *et al.*, 2005; Table 2.3). Greenschist facies rocks host most orogenic gold deposits, although some are in lower or higher grade rocks. Gold was likely sourced from volcanic and sedimentary rock sequences, possibly derived in part from marine pyrite, then deposited by reaction with wall rocks (Goldfarb *et al.*, 2005).

The largest deposits commonly classified as orogenic include the Ashanti district in Ghana (2.07 kt contained Au), Golden Mile (Kalgoorlie) (1.98 kt) in Australia, Homestake (1.24 kt) and Mother Lode (>0.8 kt) in the United States and Hollinger-McIntyre (0.99 kt) in Canada.

2.6 Sedimentary Ore Deposits

Chemical and detrital sedimentary processes form a wide variety of ore deposits and are the principal source of Fe, Mn and P, as well as elements and compounds that are concentrated in marine (sodium, potassium, bromine) and continental evaporites (lithium and trona, a Na carbonate).

2.6.1 Banded iron formations and iron ore deposits

Banded iron formations (BIF), the main source of Fe, consist of alternating bands of chert (silica) and Fe minerals that include hematite, magnetite, siderite and/or Fe silicates (greenalite or stilpnomelane) (Fig. 2.4k). The largest deposits are in the Carajás and Quadrilatero Ferrifero regions in Brazil, Hamersley in Western Australia, Transvaal in South Africa, Krivoy Rog in Ukraine, Mesabi-Marquette in the United States and the Labrador Trough in Canada.

Most BIF deposits formed as shallow water chemical sediments on stable continental platforms (Bekker *et al.*, 2010). Original, unaltered BIF contains about 20 to 30 % or more Fe, but BIF in many areas has much higher grades, up to about 65 % Fe. Removal of silica and local remobilisation of the Fe by either basinal fluids or weathering by meteoric water increased the Fe content of remaining rock (Beukes *et al.*, 2003; Clout and Simonson, 2005; Bekker *et al.*, 2010). The dominant type of BIF in Brazil, South Africa, India and Western Australia have all been upgraded to Fe concentrations up to 65 %, whereas most BIF in the Mesabi-Marquette region is not enriched, with grades of ~30-50 % Fe. The latter is economic after beneficiation (taconite pellets) and because historical proximity to steel factories supported early development. An Fe ore type in Western Australia of increasing economic interest, called channel iron ores, represent Cenozoic oolitic hematite deposits formed along lateritic weathering profiles and concentrated in ancient low-lying fluvial channels. These ores contain about 58 wt. % Fe (Duclaux *et al.*, 2013) and are largely restricted to older weathering profiles, as in Australia.

The largest BIFs were deposited between about 2.6 and 2.4 Ga (responsible for ~70 % of Precambrian Fe deposits), followed by another brief pulse of large deposits at ~1.88 Ga (Bekker *et al.*, 2010). The creation of large, stable platforms after the period of major continental crust formation at ~2.7 Ga (Cawood and Hawkesworth, 2015) built the depositional sites for the BIF and may have led to a stratified ocean and circulation patterns that linked the source to the depositional sites of Fe (Fig. 2.2b; Bekker *et al.*, 2010). Seafloor hot spring activity contributed dissolved Fe to the euxinic ocean, with biological processes influencing oxidation and precipitation of Fe and silica. A majority of the Fe deposits formed prior to the first Great Oxidation Event. The second event at 1.88 Ga may be linked to homogenisation of the previously stratified ocean. A third relatively minor event (in terms of BIF size) was restricted to basins connected to submarine volcanism, with local reduction of the ocean caused by ice cover during the Snowball Earth event at ~740-600 Ma (Bekker *et al.*, 2010).

2.6.2 Placer deposits

The metal that initially fuelled the gold rushes to California, the Yukon and Australia was mined from gravels in streams and rivers. Gold occurs in its native (elemental) form as a very dense but malleable metal, and is stable in streams and rivers where it tends to accumulate in areas of weak currents to produce what are called placer deposits. Mining of recent Au placers, with much now artisanal, contributes less than 20 % of world production, but has a disproportionately large environmental impact (Section 4).

During the Archean, the erosion of forelands during long periods of stability resulted in large placer accumulations in braided streams that created the Witwatersrand Au-U palaeoplacers in South Africa, by far the largest Au province in the world (Frimmel *et al.*, 2005). Transport and preservation of U in the Witwatersrand and the Palaeoproterozoic Elliott Lake U palaeoplacers in Canada are ascribed at least in part to low oxygen contents of the early atmosphere. Other

minerals that form placers include diamonds, sapphires and rubies (which are not so dense but are very hard and resistant to weathering) and alloys of platinum group minerals. Beach sands can contain high concentrations of detrital heavy minerals such as rutile, ilmenite and zircon, and are the major source of the high-technology metals Ti and Zr.

2.7 Ore Deposits Produced by Weathering

In hot and humid tropical regions, particularly those with distinct wet and dry seasons, some metals are concentrated in laterites – a type of soil in which most elements have been leached – leaving only those elements that are immobile during weathering. Where the underlying rock is granite, clay-rich sediment or paragneiss, the groundwater leaches out soluble components, including Si, Mg, Ca, Na, K and some of the Fe, and leaves behind hard duricrusts (Fig. 2.4l) of insoluble Al and some Fe plus Si and Ti, resulting in the formation of bauxite (Fig. 2.4l, inset). Most of the world's bauxite comes from lateritic deposits in regions that are, or were once, tropical, including Australia, the Caribbean islands, equatorial Africa and South America (Freyssinet *et al.*, 2005). The grade and the quality of bauxite may vary but known deposits are sufficient to supply the world for several centuries at present rates of production (USGS, 2016).

Where the underlying rock is ultramafic, including komatiite, the residual product of weathering becomes enriched in Ni and, in places, Co (Fig. 2.4m). Weathering of ultramafic rocks that once were part of the oceanic lithosphere (ophiolites) produced the rich Ni laterite ores of New Caledonia, Indonesia and the Philippines (Freyssinet *et al.*, 2005; Marsh and Anderson, 2011).

Metal sulphide ore deposits exposed at the surface undergo weathering that releases metals into groundwater solution. In some cases, the metals, principally Cu, Pb, Zn and Ag, are precipitated by anions that are abundant in the weathering zone, including carbonate, sulphate, halides and oxide/hydroxide, to form supergene deposits. In the case of Cu, sulphide oxidation above the water table is mediated by acidophilic Fe and S-oxidising bacteria; this generates sulphuric acid that efficiently leaches Cu and transfers it downward to the reduced environment, at and below the water table, where sulphide enrichment takes place mainly through abiotic cation exchange (Sillitoe, 2005). This process, called supergene enrichment, can produce a metal-rich zone with a Cu grade up to two to three times greater than the tenor of the underlying hypogene ore and was pivotal in the formation of some of the highest grade ore in the world's two greatest porphyry Cu provinces, the central Andes and southwestern North America. The weathering-related histories of both provinces span 15-30 Ma, starting in the Eocene. The close linkage between the tectonic and climatic evolution of orogenic belts, which led to uplift, lowering of palaeo-water tables and efficient sulphide oxidation – mediated by bacterial processes and, in the case of the central Andes, followed by hyperaridity – was critical to the creation and preservation of these supergene deposits (Sillitoe, 2005).

2.8 Global Controls on the Distribution of Ore Deposits

Ore deposits are distributed unevenly, both in geologic time (Fig. 2.7; Meyer, 1981; Cawood and Hawkesworth, 2015) and in space (Sillitoe, 2008, 2012; Fig. 2.8; Wilkinson and Kesler, 2009). Periods characterised by abundant ore deposits are referred to as metallogenic epochs, and regions that contain a high concentration of deposits are called metallogenic provinces. As previously highlighted (Table 2.4 and Fig. 2.2), most types of ore deposit are restricted to specific tectonic settings. These associations have helped to guide exploration ever since we gained an adequate understanding of global tectonics (summarised by Sawkins, 1984; Box 2.2).
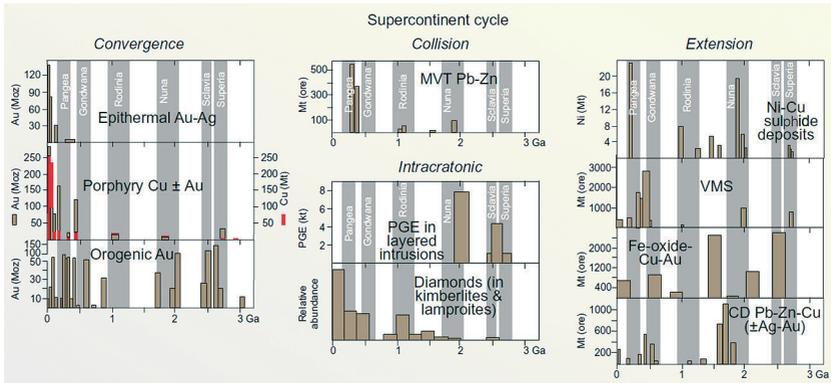
Figure 2.7   Distribution of selected ore deposits through time, arranged in terms of tectonic setting (Fig. 2.2); bands show the major periods of supercontinent assembly. Older examples of deposit types formed at relatively shallow depth (*e.g.*, epithermal and porphyry) have likely been eroded from the rock record (Section 5; from Cawood and Hawkesworth, 2015).

2.8.1 Ore deposits and Earth evolution

The secular evolution of different types of ore deposits and their occurrence (Table 2.4) reflect changes in geodynamic processes and environments in an evolving Earth, as well as factors affecting their preservation (Kerrich *et al.*, 2005; Kesler and Wilkinson, 2006; Groves *et al.*, 2010). Several processes were critical: rapid growth of the continental crust during and especially at the end of the Archean, and episodic growth through most of the Proterozoic (Condie and Aster, 2010), with continental arcs being the best preserved during orogenesis since the Archean (Condie, 2014); formation of stable cratons that supported shallow sedimentary basins (Leach *et al.*, 2010); and changes in the composition of the oceans and atmosphere (Canfield, 2005). Other factors included decreasing mantle temperatures and declining mantle plume activity (Herzberg *et al.*, 2010),

and a change from thick, buoyant sub-continental lithospheric mantle in the Precambrian to thinner lithospheric mantle in the Phanerozoic (Menzies, 1990).

The crustal growth record is characterised by pronounced peaks at 2.7, 2.5, 2.1, 1.9 and 1.1 Ga (*e.g.*, Condie and Aster, 2010; Fig. 2.7). There is also a good correlation between the ages of these growth peaks and the frequency of certain ore types, particularly those directly related to crustal growth, such as orogenic gold deposits in accretionary zones (Goldfarb *et al.*, 2005; Groves *et al.*, 2005). Since the ore deposits that we currently mine occur in the continental crust, the rate at which this crust formed influenced the temporal distribution of ore deposits, and from the mid-Proterozoic, the supercontinent cycle had an important influence on this tempo (*e.g.*, Condie and Aster, 2010; Cawood and Hawkesworth *et al.*, 2015).

The distribution of deposits associated with sedimentary rocks, starting with BIF and CD Pb-Zn deposits (Bekker *et al.*, 2010; Leach *et al.*, 2010), is associated mainly with changes in the compositions of the atmosphere and oceans, the development of large stable platforms on newly formed continental crust and a change in the circulation patterns of oceans. Banded iron formations are also linked both to the evolution of the biosphere, including silica – as well as S – and carbonate-precipitating organisms at the end of the Archean (Bekker *et al.*, 2010). Lead and Zn deposition in MVT is related to continent-scale flow of evaporite-related brines in host carbonate sequences deposited much earlier at passive margins (Leach *et al.*, 2010). Sediment-hosted stratiform Cu deposits in failed rift basins formed where oxidised brines leached Cu from basal red-bed sequences and basement rocks, followed by precipitation in organic-rich marine siltstones (Figs. 2.4g and 2.6a). Similar circulation also mobilised U from Precambrian basement rocks and formed the largest deposits where it was precipitated by reduction at and beneath unconformities.

Komatiite-hosted Ni deposits are restricted to the Archean and early Proterozoic because only during these periods was the mantle hot enough to produce ultramafic magma (Herzberg *et al.*, 2010). Nickel-Cu sulphide and platinum group element (PGE) deposits in large layered intrusions, and diamond-bearing kimberlites, occur in stable cratons in anorogenic settings, with diamonds largely restricted to the Phanerozoic (Gurney *et al.*, 2005). The formation of these deposits had to wait until stable continental crust and lithospheric mantle was generated around the end of the Archean (Condie and Astor, 2010).

The temporal distribution of other types of ore deposits is related to their development in geological settings where there is little chance of their long-term survival. This is the case for bauxite, Ni laterite and other deposits that result from weathering, which form at Earth's surface and consist of friable, easily eroded material. The dominance of Mesozoic and Cenozoic porphyry Cu systems and associated epithermal skarn and related deposits (Fig. 2.7) is probably due to the short survival times of these relatively shallow-formed (<2-3 km depth) deposits in rapidly uplifting convergent margin settings. If uplift proceeds for too long under pluvial climatic conditions, the deposits will be eroded. Thus, they tend to exist only during a relatively short geological interval. Compilation of porphyry

Cu ages suggests that these deposits reach the surface, on average, about 12 Ma after formation, and then many deposits are largely eroded within another 20 to 30 Ma unless preserved by changing tectonic conditions and burial (Kesler and Wilkinson, 2006; Section 5).

"In one aspect the science of mineral deposits is frankly utilitarian, but from the viewpoint of pure knowledge it records the principles governing the cycles of concentrations of the elements... and... the manifold complexity of the earth's crust." (Lindgren, 1933, p. 894.)

2.8.2 Metallogenic provinces

Locations that contain unusually abundant ore deposits reflect heterogeneous Earth processes related to both ore formation and deposit preservation. For example, porphyry Cu deposits are very irregularly distributed along the volcanic arcs of the *circum*-Pacific (Fig. 2.8; Sillitoe, 2012). Similarly, the Cordillera of the
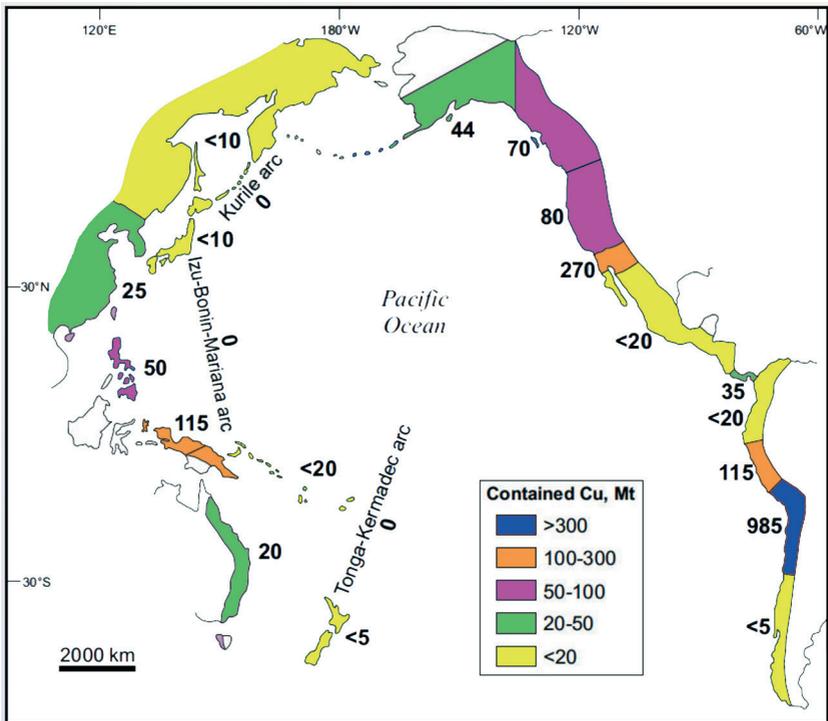
Figure 2.8   Distribution and known metal content of porphyry Cu deposits of the circum-Pacific, showing the heterogeneity of metallogenic endowment. The largest porphyry Cu concentrations in the world occur in Chile and southwest North America (from Sillitoe, 2012).

Americas contain several metallogenic provinces that host the great majority of gold deposits, but these deposits are confined to only about 5 % of the total area (Sillitoe, 2008; Wilkinson and Kesler, 2009).

2.9 Future Resources – New Types and New Locations of Ore Deposits

The deposits described above have supplied the world with all the metals it needed for past millennia and will continue to do so for long into the future. Exploration will continue, extending to regions that have been little explored in the past and to greater depth in older mining areas, as discussed in Section 3. Low-grade ores and complex deposits with processing, location or environmental challenges may become available as technology and new cleaner mining processes become available (Section 4).

Ultimately, however, increasing population and growing demand in the next decades will require that new sources and types of ore are identified. Some of these will be in rocks that have not previously been mined for metallurgical reasons, others will be in locations not yet accessible to mining, and still others will be minor components not currently recovered from conventional ores (Section 4). Advances in exploration techniques will help to probe to greater depths in the crust (Section 3), possibly even finding completely new types of deposits. A few potential examples are summarised below.

New sources. Some minerals emerge from obscurity when they are shown to contain metals that are needed for new technological applications. An obvious example is bastnäsite, a carbonate that was important only to a few mineral collectors until it began to be mined for REE. Phosphorites contain many trace elements that can, and are, being recovered during processing for P (Pufahl and Groat, 2017). Other examples are the clay minerals jadarite and hectorite in altered volcanic rocks that could be possible sources of Li and B. At the other extreme are common minerals that in the future may be the source of common elements. For example, clay and feldspar could become sources of Al if deposits of bauxite were ever exhausted. In addition, Cathles (2013) notes that both seawater and brines in major crustal aquifers contain substantial amounts of metals that could be extracted in the future.

New locations. The most obvious new location to explore for metals is the sea floor. As outlined in Section 4, efforts are underway to mine seafloor massive sulphides. In addition, seafloor nodules and crusts, known for several decades, are rich in Mn and can contain Ni, Co, Cu and, in some cases, PGEs and REEs (Hein, 2013). Their widespread occurrence and grade means that these resources may potentially be exploited in the future.

The final frontier may be extra-terrestrial. For building in space and outward travel, companies have already formed to examine the potential of extracting metals from asteroids, and mining on near planets may be a possibility

in the distant future. Whether these become necessary will depend on our need for selected commodities, their availability, technology and economics – the same factors that control earth-bound commodities.

Regardless, it is clear that we still do not fully understand the distribution and concentration of metals on Earth, *e.g.*, the causes of metallogenic hetero-geneity (Fig. 2.8). As we explore to greater depth (Section 3) and utilise new technology (Section 4), we will both discover new resources in familiar environ-ments and discover new environments with different mixes and concentrations of metals.

3. MINERAL EXPLORATION: DISCOVERING AND DEFINING ORE BODIES

3.1 Introduction

Mineral exploration is the first stage of wealth creation from mining (Fig. 3.1; Agricola, 1556 [Box 4.2]; Porter, 1985).
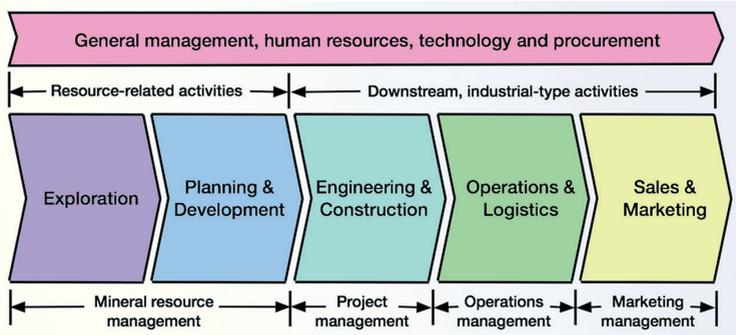
Figure 3.1   Mining Value Chain (modified from Camus, 2011).

Exploration and mining started in the Neolithic, preceding herding and agriculture. At first, native metals such as gold and copper were mined but the discovery of how to recover metals by smelting metal oxides that probably occurred at least 7,000 years ago (Section 4) increased ancient exploration targets. In the past a prospector with a good eye identified an area of anomalous metal concentration or altered outcrops to explore, but now earth scientists using multi-disciplinary tools conduct this work. Over time, mineral resource discovery and mining provided the foundation for all the great nation states and remains essential to our civilisation today and in the future.

Modern exploration is far removed from the simple visual prospecting of the surface that was conducted for centuries by prospectors. Exploration methods have become increasingly tailored to specific commodities and the type of mineral deposit being sought. Different methods are used, for example, in exploring for coal, diamonds, iron ore, bauxite, base and precious metals, and industrial minerals.

3.1.1 Purpose of this section

This section, written by geologists who have been involved in the discovery of orebodies, provides insights into the exploration and assessment process that in only very rare cases leads to discovery of a mineable deposit. We review the geological foundation of mineral exploration and how it is now conducted,

commonly by a team of economic geologists, geochemists and geophysicists. We also briefly explain the objective of exploration and its scientific basis, the techniques and tools that are used, the exploration process, how resources are assessed, the need for strategy and tactics when conducting exploration, and the importance of the exploration budget. We also explain why discoveries are very rarely made and how mineral resources will be discovered in the future. We often use the porphyry Au-Cu discoveries in the Cadia district of Australia to illustrate the points we make because one of us (Wood) has been associated with this project for much of its history.

We are confident that systematic exploration to depths of ~3 km (Sections 1 and 5) will result in the discovery of mineable metal resources that will far exceed what has been discovered to date. We base our confidence on the fact that only a small portion of this shallow crust has been fully assessed. Most known deposits have been discovered at <100-200 m depth (Fig. 1.8), with the majority wholly or partially cropping out. Even for the discoveries of the past decade, 20 % of base metal and 52 % of Au deposits cropped out; average depths of all recent discoveries are still relatively shallow, 130 and 40 m below surface for base metal and Au deposits, respectively (Schodde, 2014b). Our present ability to explore – and mine – to depths below 2 km means that a lot of crust with undiscovered deposits remains to be found. The continual improvement in our understanding of ore formation (Section 2) combined with technological advances support future exploration at greater depths below the surface.

3.1.2 Exploration objective

The objective of exploration is to discover economic resources cost effectively and this is the principal metric by which an exploration team is eventually judged. Being part of a team that makes an important mineral discovery is what drives exploration geologists and leads them to work in remote parts of the world under conditions that would be unattractive to many people in the modern workforce. The pinnacle achievement of those involved in a discovery is to take the deposit to the stage of mining, through numerous technical, regulatory, community-consultative, environmental, business, and political procedures, and thereby deliver valuable metals to society (see Section 4).

Exploration uses geology and related geosciences to discover anomalies related to mineralisation. Geologists make observations in the field and collect information to formulate and then test a hypothesis – usually about the type of deposit represented by the anomaly and the direction towards the centre of the deposit. Successful discovery relies on creativity to ask the right questions, aimed at achieving three objectives:

- detection of a geological, geochemical and/or geophysical anomaly related to a potential resource (which may or not be the target commodity or deposit type);

- identification and quantification of a possible economic resource by testing a target within an anomaly;

- conversion of an identified and quantified mineral resource to an ore reserve (Section 1), that provides the basis for developing a mine.

3.1.3 Discovery target

Conducting exploration without a clearly identified discovery target was normal until the mid-20th century, but is much less common today. Until the mid-1970s it made sense simply to examine a geographic area that had not been explored in any detail. Companies would explore for a range of resources depending on the geology of the area, previous discoveries by prospectors, and ideas about the area's resource potential based on geological similarities with other areas.

Old-time prospectors with little or no geological training were responsible for most discoveries, from long before Agricola's time in the 16th century until the mid-20th century. Until the 1960s, when metal consumption and thus production started to increase sharply (Fig. 1.3), required ore grades were much higher than today. Prospectors were mainly interested in high-value deposits that could be mined on a small scale. However, most prospectors were observant and curious and their activities resulted in discoveries that led to major mines and some modern prospectors continue to make important discoveries (http://www.nytimes.com/2011/05/15/magazine/mag-15Gold-t.html).

> **Box 3.1 – Discovery of the Voisey's Bay Deposit** – In 1993, when diamond prospectors Al Chislett and Chris Verbiski were returning by helicopter to camp in eastern Labrador they saw an Fe-stained outcrop which they marked on a map. When they visited the outcrop they found chalcopyrite and they staked a claim. This was a serendipitous finding, as they had been looking for diamonds, encouraged by a recent diamond discovery in another part of Canada (Kerr, 2003). The provincial Department of Mines and Energy had mapped the area in 1985 and recognised the colour caused by weathering of sulphides, but had not sampled the outcrop. The prospectors convinced Diamond Resources, a junior company, to investigate their claim and in late 1994 they started to drill. The second drill hole returned 41 m with a grade of 2.96 % Ni, 1.89 % Cu and 0.16 % Co. An electromagnetic survey then determined the size of a zone of massive sulphide, and in 1995, hole VB-95-07 returned 104 m of 3.9 % Ni, 2.8 % Cu and 0.14 % Co. This marked the discovery of the Ovoid, which contained 32 Mt of ore grading 2.83 % Ni, 1.69 % Cu and 0.12 % Co. Diamond Resources sold the Voisey's Bay discovery to Inco (now Brazilian-controlled Vale) in 1996 for $4.3 billion. Mining began in 2005 following negotiations with the provincial government and Labrador's Innu and Inuit people.

Modern exploration is now conducted mostly for a specific target resource and orebody type, using the tectonic and geological environment of each type (Section 2) as a basis for starting the search. This focus is facilitated by orebody models (Cox and Singer, 1986), developed since the late-1940s by researchers and mining company personnel. These models while valuable are best used as a guide to discovery rather than in a prescriptive way, to allow for unexpected variation – no two deposits are exactly the same. Driven by forward-looking strategic plans, many companies incorporate a range of economic and mining

parameters within their exploration programmes. For example, a company may target only large orebodies with low operating costs that will remain profitable when metal prices are low (defined as Tier 1 by major companies; Wood, 2014).

3.2 Exploration Techniques

Identification and assessment of an anomalous zone using various techniques may be followed by drilling to determine if the anomaly has the grade and size to be a potentially mineable deposit (*i.e.* a discovery). Additional drilling and testing is then used to quantify an Indicated and Measured Mineral Resource, and eventually an ore reserve (Crowson, 2008). These terms are discussed briefly in the following sections and the Appendix. No single technique or technology is used over others and many are used in combination. It is important to avoid dogma, as a technology that is useful in one discovery may not be appropriate for another, where the geological setting and ore type may differ. While various techniques may be involved, drilling is invariably the major discovery tool (Sillitoe, 2010b), since it is the only cost-effective method to measure the nature and extent of subsurface mineralisation.

3.2.1 Principal search methods

At the start of the 20th century, surface prospecting accounted for about 70 % of discoveries (Fig. 3.2; Schodde, 2014a), many of which were not close to known ore deposits (thus called a greenfield setting). After World War II, geophysical technologies that had been developed for war-related purposes, followed by
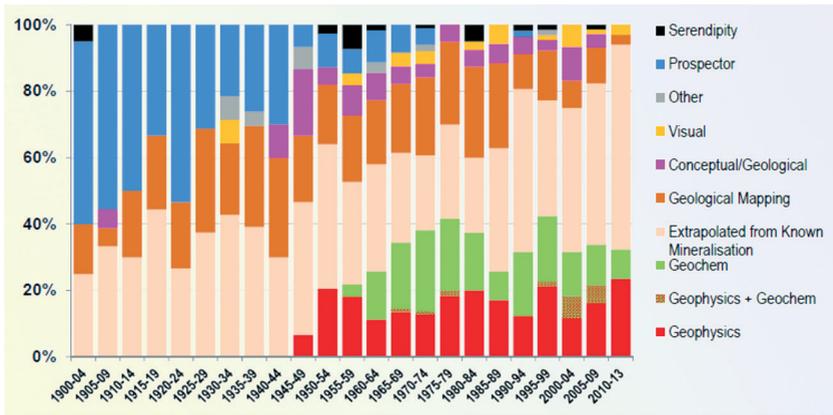
Figure 3.2   Primary search method used at the project scale for Cu, Ni, Pb and Zn deposits to decide what land to claim on which there was an eventual discovery (>0.1 Mt Cu equiv.; 930 deposits with data available out of 1568 discoveries; Schodde, 2014a).

newly developed geochemical techniques, played increasingly important roles in exploration and discovery. Their combined contribution to discovery reached a peak by the mid-1970s, contributing to about 40 % of discoveries. However, in the first part of the 21st century, exploration based on extrapolation from known mineralisation in near-mine (brownfield) settings has become the predominant discovery method, accounting for about half of discoveries (Schodde, 2014a).

3.2.2 Geology

Geological mapping at various scales and geological observation are integral to exploration, and provide a means of identifying mineral deposits that crop out (Schodde, 2014b). Of particular use to exploration geologists are the metallogenic maps that some government agencies produce. These maps provide valuable mineralisation-related information that geologists use in conjunction with orebody models to assess how prospective an area may be for different types of deposits.

Mapping also may identify geological evidence (*e.g.*, hydrothermal alteration) that leads to discovery of a sub-surface deposit. Typically, mapping at scales of 1:250,000 to 1:50,000 or larger is undertaken by state/provincial and federal geological surveys. Regional maps at scales of 1:100,000 up to 1:25,000 provide the geological framework for planning and conducting exploration programmes, with mapping onto an aerial photograph or topographic map now largely superseded by mapping onto high-resolution satellite-based imagery and digital elevation models (see Appendix).

Geological mapping (Fig. 3.3a-c) has three essential applications in exploration. The first is to provide a high-quality geological base for investigations and to indicate the presence of prospective geological environments and features, such as regional structures, favourable volcanic and intrusive rocks, or sedimentary basins, *etc*. The second is to identify and record evidence of mineralisation, ranging from traces of ore minerals to distinctive hydrothermal alteration, and to seek zoning in these features. At Oyu Tolgoi in the Gobi Desert of Mongolia, observations of this type directly led to discovery of a world-class porphyry Cu deposit (Perelló *et al.*, 2001).

The third application is to identify and locate geological features that may offset or obscure mineralisation, such as faulting or deposition of post-mineralisation cover material. Depending on the type of deposit targeted, the evidence for mineralisation may be difficult to recognise, with subtle clues often missed in initial mapping of larger areas.

Geological mapping during exploration is conducted at several scales, ideally starting at 1:10,000 where reliable regional maps are available from government agencies. Mapping at this scale typically will cover an area of 50 km^2 and will record mineralisation-related information, including old prospecting pits and abandoned mine workings, areas of veins/veinlets and associated hydrothermal alteration, as well as basic geological features including rock types, contacts and structures.

When an anomalous area (a prospect) is located, detailed geological mapping will be conducted at ~1:5,000 to 1:1,000 scale (commonly using differential GPS for location), depending on the type and potential size of the deposit target, to identify features related to mineralisation (Fig. 3.3d). Maps are usually produced at more than one scale, showing the location, shape and geology of all recorded outcrops, along with an interpretative map of the geology. This mapping is complemented by geochemical and possibly geophysical survey information, to be used in conjunction with the geology to decide if further investigation, possibly leading to drilling, is warranted.

Figure 3.3 Exploration methods. **(a)** Mapping a greenfield prospect in the southern Gobi desert, Mongolia. **(b)** Mapping (on a tablet) and sampling a brownfield prospect, high Andes of central Chile. **(c)** Examination of trench results from

a prospect adjacent to a discovery in Chile. **(d)** Geological field map from a dolomite-hosted massive sulphide prospect in Greenland (courtesy of Warren Pratt; map sheet about 1 km wide). **(e)** Stream-sediment sampling and float mapping, Indonesia. **(f)** Helicopter-borne magnetic survey (sonde in front of craft) over prospect in the Andes of northwest Argentina.

3.2.3 Geochemistry

Exploration geochemistry, or geochemical prospecting (Ginzburg, 1960; Kyser *et al.*, 2015), was developed in western countries in parallel with improvements in trace element analysis in the 1940s (Hawkes, 1957), about 15 years after analytical exploration geochemistry was first carried out on soils in the Soviet Union in 1932. Various types of geochemical survey are employed depending on the type of ore deposit target and its geological setting, using the most appropriate media – *e.g.*, drainage (stream sediment), soil or talus, rock, vegetation and ground water – for the environment (see Appendix). Increasingly, geochemical methods are being tested for use in terrain where ore deposits may be covered (Kelley *et al.*, 2006).

     Drainage geochemical surveys (Fig. 3.3e) followed by soil surveys are the most commonly used geochemical techniques – typically in complementary fashion – to focus the search for a partly or completely exposed deposit within a large area. Widely-spaced stream sediment sampling (one sample every several km^2) is conducted first to identify areas of anomalous metal value(s), with the anomalous areas progressively reduced in size by closer spaced sampling of streams (moving from a spacing of a few km to 100s of m). Anomalous areas are then investigated in greater detail using a combination of soil and rock sampling and attendant chemical analysis, by collecting samples either on traverses or a regular grid.

> **Box 3.2** – *Exploration Geochemistry at the Panguna Deposit* – An early example of the use of stream sediment and soil geochemistry to locate an orebody was the 1964 discovery of the Panguna porphyry Cu-Au deposit on Bougainville Island, Papua New Guinea (Hope, 2011). The deposit occurs in a mountainous, tropical rainforest environment undergoing rapid erosion (Fig. 3.4a). Stream sediment geochemistry (Fig. 3.4b) was used as the principal search technique to locate Cu anomalies in an area known to host Cu-Au mineralisation, previously mined on a small scale. The Panguna discoverer, Ken Phillips, had visited the Atlas porphyry Cu deposit in the Philippines prior to locating a large stream sediment Cu anomaly in the Panguna area, and when he observed the outcrop in Panguna Creek that was similar to what he had seen at Atlas, it was his "Eureka" moment. Phillips had been taken to the outcrop by local people, a history sometimes repeated with discoveries in remote locations. Stream sediment and soil anomalies (Fig. 3.4c) provided the hard evidence to support drilling, leading to discovery.
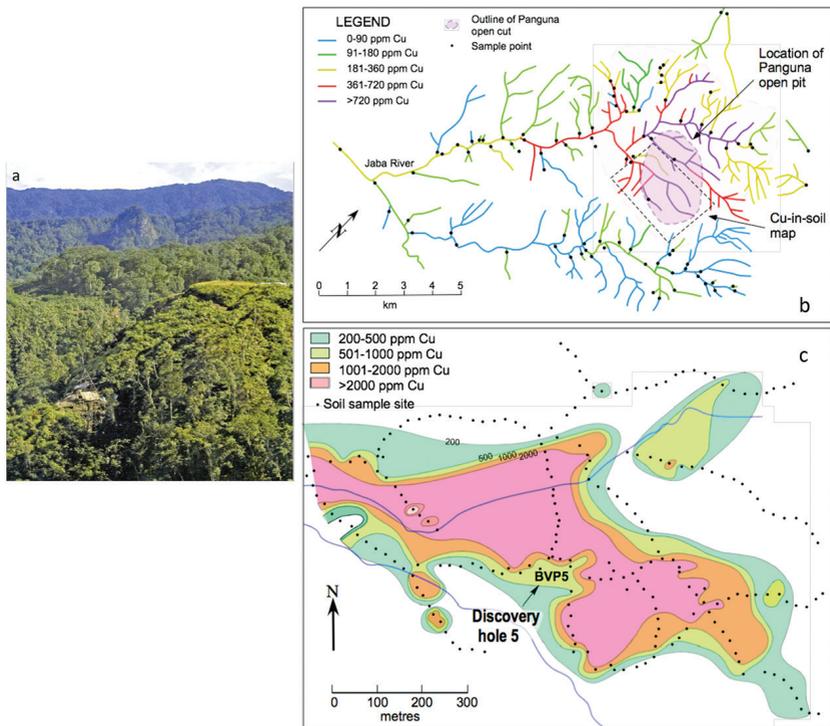
Figure 3.4 **(a)** Site of discovery drill-hole 5 at Panguna, PNG, looking to the north (Hope, 2011). **(b)** Stream sediment survey results, with location of soil grid and eventual open pit. **(c)** Soil grid and survey results with location of discovery hole 5.

Major advances in analytical chemistry over the past several decades have been applied to mineral exploration, with many high-quality commercial laboratories now available to provide analyses of a range of sample types with high accuracy and precision, detection limits for trace elements at the ppb level, and rapid turnaround times. One technique, called Bulk Leach Extractable Gold (BLEG), was developed in the 1980s for exploration in dry areas of Western Australia, but has since been applied elsewhere to regional exploration. The BLEG surveys collect large (multi-kilogram) stream sediment and soil samples that are leached with cold NaCN to test for fine Au – the method was developed to overcome analytical problems associated with Au-particle heterogeneity and low Au concentrations in samples.

Other technologies now available to exploration geochemists include those identified by numerous acronyms, including: ICP-MS, LA-ICP-MS and ICP-AES, μLRS, TIMS, IDTIMS, SHRIMP, SIMS, GS, and PIXE (see Appendix). For field work,

the most significant technology developments have been of hand-held analytical tools that enable real-time analysis of soils and rocks for the concentration of a range of major and minor elements using X-ray fluorescence spectroscopy (XRF), and mineralogical identification using short-wave infrared (SWIR) methods.

3.2.4 Geophysics

Geophysical techniques (Butler, 2005; Dentith and Mudge, 2014) can be used to measure gravity, magnetic intensity, radioactivity, and several types of electrical response, including those produced by magnetotelluric effects. Most of these surveys can be conducted from the air (Fig. 3.3f) as well as on the ground. Seismic surveys are ground based and, although useful in petroleum and coal exploration, distinguishing possible ore reflectors from geological units is a limitation in non-sedimentary environments.

In metals exploration, magnetic, radiometric and either induced polarisation (IP) or electromagnetic (EM) properties are most commonly used. The depth that is penetrated is dependent on the type of geophysical technique used and the rock being surveyed. Surface seismic, gravity and magnetic surveys will record data to depths of many kilometres, whereas electrical methods are restricted in their penetrating capacity, usually to <500 m. Deep-penetrating (>1 km) IP methods have been developed recently and the usefulness of EM and IP can be extended by applying the technique down drill holes. The proprietary and commercial electrical geophysical techniques developed by various companies have been applied to the search for metal sulphide orebodies with varying success.

With the continual increase in the development and use of geophysical techniques, additional measurements of the petro-physical properties of rocks are required in order to improve the modelling (interpretation) of geophysical measurements, now conducted using sophisticated inversion techniques that predict the most likely source responsible for the geophysical response (Dentith and Mudge, 2014). Brief details of the principal geophysical techniques used in mineral exploration are outlined in the Appendix.

> **Box 3.3 – *Exploration Geophysics at the Ridgeway Deposit*** – The small high-grade Ridgeway porphyry Au-Cu orebody at Cadia, Australia, is an example of discovery using IP to focus drilling (Wood, 2012). Other deposits discovered in the district were used for an orientation IP survey and included the Cadia East deposit (Fig. 3.5a), located beneath 200 m of covering shale. An IP anomaly was recorded at Cadia East, due to sulphide minerals associated with white mica alteration (Fig. 3.5b). A similar, but deeper, IP anomaly was observed 3.8 km to the northwest (Fig. 3.5c; the strong shallow anomaly is due to farm buildings). The deeper anomaly was investigated with 12 reverse circulation (RC) holes all of which intersected alteration, with one of the holes recording low Au and Cu values at its bottom. Follow-up deep core drilling intersected local quartz veins with higher Au values, which encouraged deeper drilling until the orebody was discovered 500 m below surface. IP had detected the pyritic alteration halo to the Ridgeway deposit, extending to shallow depth below 20-80 m of post-mineralisation basalt. IP did not detect the orebody itself, however, because it was located too deep for the method used.
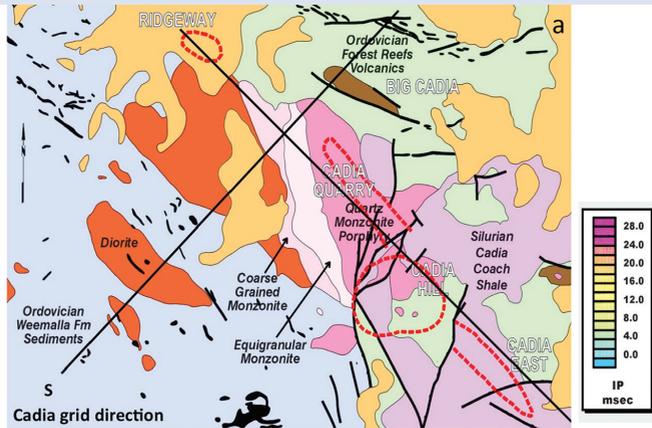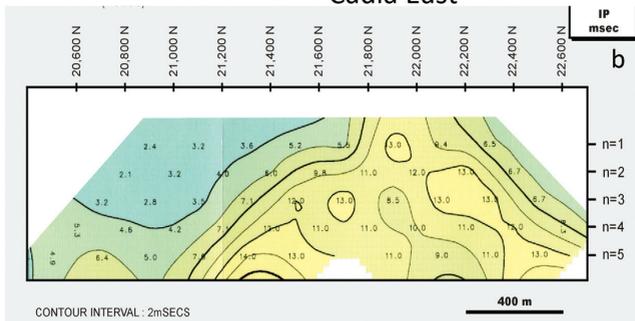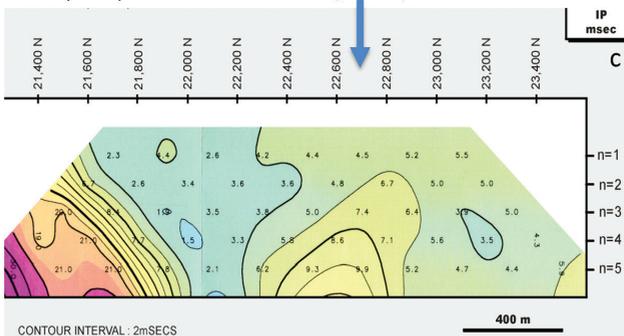
Figure 3.5   (a) Cadia-Ridgeway, location of deposits and local grid lines; IP dipole-dipole sections (looking NW). (b) Line 14,800E with surface projection of Cadia East deposit. (c) Line 11,000E, with location of Ridgeway deposit shown.

3.2.5 Drilling

Drilling is the principal discovery and assessment technique used in exploration (Fig. 3.6a) and also during the various stages of mine development and closure investigation, simply because it provides the only cost-effective and efficient means of collecting a large number of samples in the subsurface. After discovery, as a discovered mineral deposit advances through mining study stages, the purpose of drilling transforms from outlining an initial resource to detailed resource definition by infill drilling (Fig. 3.6b).

Drilling also is completed at this time to collect samples of mineralised rock for metallurgical testing and to determine the geotechnical properties and expected mechanical behaviour of ore and waste (non-ore) rock, during and after mining. Drilling also will test the area beneath proposed infrastructure sites to establish the absence of ore in the site area to the depth tested (so-called sterilisation drilling) – but this is not always done, sometimes to the detriment of the mine. Depending on its purpose different drilling methods are used. Air core (for geochemical sampling), percussion (reverse circulation – RC, and rotary air blast – RAB) and diamond core drilling (for collecting samples of mineralisation) are the most commonly used methods in mineral exploration.

Research into the use of a modified application of the oil and gas industry's coiled steel tube drilling method (which uses a single length of steel tubing rolled into a very long coil, weighing up to 80 t) during mineral exploration is being conducted and is expected to significantly reduce the cost of drilling to collect geological and geochemical data (Giles *et al.*, 2014). At present the technique only produces fine-grained drill cuttings, which are satisfactory for initial discovery purposes but not to define a mineral resource because of the potentially unreliable quality of the sample obtained. Recovery of high-quality samples is essential for estimating a mineral resource and is dependent on the type of rock being drilled and the expertise and experience of the driller. If <95 % of the rock that is drilled is recovered at the surface there is a much reduced confidence in the assigned grade, as some of the mineral of interest may have been lost.

A well-planned resource definition programme collects geotechnical information during core logging (Fig. 3.6c-e) and a high-quality photographic record of the core for subsequent analysis by geotechnical engineers. Most of the core is collected using orientated drilling which allows a deviation of the hole from its planned direction and declination to be determined and spatially-orientated core samples to be collected. This spatial information is critical to geological correlation, accurate determination of structural orientations, and to resource assessment. Geotechnical engineers and mineralogists add considerable value to resource evaluation through the study of diamond drill core. Similarly, mineralogists add value to both engineering and metallurgical investigations by identifying and quantifying minerals that will affect rock strength and hardness, as well as ore processing and metal recovery (Section 4).

Figure 3.6 Drilling stage assessment. **(a)** Exploration drilling at an epithermal vein prospect in the Afar region, Ethiopia. **(b)** Drill core examination at a recent epithermal Au greenfield discovery in northern Chile. **(c)** Drill core logging at a porphyry Cu brownfield project in the Andes of central Chile. **(d)** Core shed processing at a polymetallic greenfield discovery in southern Peru. **(e)** Definition drilling of a large Cu project in Pakistan (courtesy of Razique Abdul). **(f)** Downhole geophysical logging in Queensland; "neutro-temperature-deviation" sonde with radioactive Cs to measure OH content downhole (courtesy of Kinetic).

Down-hole geophysical logging technologies (Fig. 3.6f), which have long been used in the oil and gas industry, and when exploring for coal, are becoming more widely applied in metals exploration. These logging technologies use sondes to measure physical properties of rocks that have been drilled. Research is now underway to complement down-hole geophysical logging during metals exploration by providing X-ray fluorescence (XRF) geochemical composition and X-ray

diffraction (XRD) mineralogy from drill cuttings/mud onsite during drilling, in the same way that shortwave infrared (SWIR) has been used in the field and core logging shed for the past two decades (Giles *et al.*, 2014). It is anticipated that these analytical techniques eventually will be used down hole, in conjunction with down-hole geophysical sondes.

3.3 Exploration Process

The exploration process varies among companies, but generally follows a relatively predictable series of preliminary stages designed to identify a target for testing by drilling (Crowson, 2008). Unless targeting known mineralisation from the outset, the most likely initial stage of the process will be regional in nature and will be applied to an area measuring up to thousands of km^2.

3.3.1 Regional exploration

Regional exploration aims to collect information that reduces the search area size as quickly as possible, so as to identify one or more districts for detailed investigation and possibly achieve the first of the three exploration objectives – detecting anomalies. This reduction in size also assists in meeting deadlines in the timing of exploration concessions, permits or payment schedules, *etc*.

Companies prefer to explore where reliable geological and other maps are available from government geological surveys along with all prior exploration data, if retained – sometimes available through government reporting, but often needing to be purchased – since this results in regional assessments being much faster and more effective. Typically, results of regional stage investigations will be interpreted at scales of 1:10,000 to 1:25,000, although initial compilations may be made over larger areas at a smaller scale. Data interpretation is greatly facilitated if an accurate topographic map is available, either from a state agency or produced for the exploration programme using LIDAR (light detection and ranging) technology, for example (see Appendix).

Regional exploration invariably involves geological mapping supported by geochemical (drainage and possibly soil) and, in some cases, geophysical surveys (usually airborne) – the latter using one or more of the various magnetic (Fig. 3.3f), radiometric and electromagnetic (and increasingly gravity) methods. The purpose is to identify an anomaly of some sort – geological, geochemical or geophysical, or in the ideal case a combination of these. Anomalous areas, with or without surface indications of mineralisation, will be highlighted for prospect-scale exploration. Wall rock features indicative of mineralisation (especially hydrothermal alteration) that expand the target size account for most geological anomalies, and geochemical anomalies (commonly in stream sediments) for areas of mineralisation (see Box 3.2). Geophysical anomalies have the advantage of possibly providing evidence of mineralisation with no easily recognisable surface indication, either in outcrop or where there is post-mineralisation cover.

3.3.2 Prospect exploration

Prospect exploration seeks to constrain the source of an anomaly to a particular area for testing by drilling. A prospect will usually occupy an area of <10-20 km², depending on the orebody target.

Where mineralisation contributes geochemical anomalies in soil or rock, detailed geological mapping, possibly supported by shallow drilling to acquire subsurface samples, and EM and/or IP geophysical surveys, may follow to detect further evidence of mineralisation. After identifying a geochemical anomaly a decision usually is made on whether it is more cost-effective and efficient to test the anomaly immediately with drilling or conduct additional surface investigations. Where the results from initial drilling encourage further testing, deeper drilling almost certainly will be conducted.

If mineralisation occurs at depth without any recognisable surface indication, drilling targets will rely on results from geological mapping, geophysical surveys, previous exploration results (including drilling), and conceptual thinking. In this situation, orebody models are crucial adjuncts to identifying drilling targets, in conjunction with supportive geological and/or geophysical indications. It is expected that in the future very low-level geochemical anomalism that reflects the outermost halo of a deposit may become increasingly useful in providing support for drilling (Kelley *et al.*, 2006).

Subtle variations in the trace-element composition of minerals, such as epidote and chlorite around porphyry Cu deposits (Cooke *et al.*, 2014; Wilkinson *et al.*, 2015) and pyrite around sedimentary rock-hosted Zn-Pb deposits (Mukherjee and Large, 2016), have shown promise to indicate direction towards mineralised centres. To assess such trace-element signatures confidently, however, considerably more research on mineralogical variation and hydrothermal effects is essential before the full potential of this use of geochemistry will be realised.

3.3.3 Drilling for discovery

Once an anomaly has been identified – and examined if at the surface – and judged to have potential to be related to mineralisation, either percussion or diamond core drilling commonly is used to investigate further, and possibly achieve the second exploration objective. However, it is rare to only drill one hole to test the anomaly, since the position of the anticipated mineralisation is generally uncertain.

Many geophysical methods enable an estimate to be made of the position and depth to the source of their anomalies, which often means the amount of drilling that is required can be reduced. However, this is very much dependent on the assumed type, size, and geometry of the orebody target and the geophysical method used (see the Appendix). In the case of Ridgeway (Box 3.3), the IP anomaly only indicated the presence of shallow sulphide minerals that could have been contained within a halo around an ore deposit target, and seventeen holes were required to indicate the position and depth of the actual deposit. A

geophysical interpretation also depends on the degree to which geological knowledge is incorporated into the interpretation – *i.e.* when the geophysicist works with a geologist familiar with the area and orebody target type.

An important consideration in planning discovery drilling is a preliminary understanding of the possible dimensions of the target deposit (Wood, 2010). This planning also needs to consider the possibility that a drill hole may return non- or poorly mineralised material because the hole intersected the margin of the deposit, the mineralisation is not homogeneous, or is obscured by post-mineralisation intrusions, or other disruptive geological effects such as faulting. As a result, a sufficient number of holes need to be drilled to provide a realistic chance of at least one of the holes intersecting significant mineralisation, if indeed it is present.

Box 3.4 – Deposit Footprints – Possible dimensions of an economic target can be assessed by considering the size range of known orebodies of the commodity and ore deposit type being sought. For example, a small high-grade porphyry Au-Cu orebody, such as Ridgeway, has a plan dimension of about 200 x 200 m and extends vertically for >800 m. The initially-discovered orebody occupied a volume of ~32 Mm^3 and contained ~80 Mt of ore. By comparison, a large lower grade porphyry orebody of 1,000 Mt, for example, occupies a much larger volume, and will have a plan area of ~700 x 600 m if its vertical dimension is 1,000 m. This knowledge of the possible footprint size of the deposit being sought is essential to plan discovery drill spacing and pattern efficiently (Singer and Drew, 1976).

3.4 Discovery Assessment

If mineralisation of potentially economic grade is intersected in several holes during discovery-stage drilling – over sufficiently large intervals down hole that it may be part of an orebody –investigations will progress to the resource delineation and definition drilling stages of investigation. The goals of this work are to delineate and define Indicated and Measured Mineral Resources, and convert part or all of these into ore reserves by completing a feasibility study which demonstrates that the mineralisation can be mined economically. This stage will achieve the third and final exploration objective.

3.4.1 Resource delineation and definition

Almost always, resource delineation and definition drilling is conducted using a regular pattern of drill holes, with a hole spacing that reduces over time as the project progresses through three stages of mining evaluation. Delineation drilling establishes the boundary to the potential orebody and its possible size, while definition drilling specifically determines the grade and continuity of the mineralisation. The number of drill holes increases through each mining evaluation stage. The density of drilling necessary to achieve each evaluation stage milestone confidently is determined by the complexity of the deposit and statistical assessment.

While definition drilling is usually conducted using a consistent drill-hole declination and direction, it is important to drill a number of holes with other declinations and directions to confirm that those being used are optimal. Where cost-effective, an underground entry – horizontal or declined adit or vertical shaft – is made into part of the deposit to obtain large representative samples for analysis and metallurgical testing, to expose mineralisation for geological observation and mapping, and sometimes to more efficiently conduct definition drilling from underground.

3.4.2 Resource estimation

In most instances, diamond core drilling is used to collect the high-quality representative samples of mineralisation that are required to estimate grade when conducting mining studies. To confirm high quality a rigorous sampling and quality assurance-quality control (QA-QC) regime – managed by an experienced geoscientist with the requisite skills and professional qualifications – is established from the start of drilling and maintained throughout the resource definition programme. This is necessary to ensure that uncertainty in estimating grade and grade distribution is reduced to an acceptable level.

It is essential that the resource estimate evolves during resource modelling and is continuously tested and improved as new data are accumulated through drilling and analysis. Fundamental to all resource estimates is an accurate understanding of the geology of a deposit, including controls on the variability and continuity of mineralisation. For this purpose, geological, hydrothermal alteration, mineralisation, and structural sections are constructed from the start of drilling and continually updated as drilling proceeds. The geologist will use these sections to grapple with problems of correlation before the subsequent process of geostatistical estimation of mineral resources begins.

Mineral resource estimation is a complex process, deriving from the amount of computation now required to complete an estimate (Glacken and Snowden, 2001), and relying crucially on the availability of a high-quality geological database and geological model of the deposit, as noted above. Without this geological foundation, the resource estimate – not a calculation, although derived through a calculation process – is likely to be seriously compromised in its accuracy. Previously, simple estimates were made by assigning a volume of influence to a data point (*e.g.*, drill hole intersection) within the body of mineralisation, using a polygonal or area-of-influence method, and then summing these areas or volumes to generate a total.

Developments in geostatistical methods (Matheron, 1963) since the mid-1960s have changed the way that areas of influence are determined and summed (Glacken and Snowden, 2001), applying weighting functions to grades around the polygon. The principal changes involve estimation of the predictive value of nearby *versus* distant samples (drill holes) and use of this information to improve the size and grade of volumes indicated by the samples. Kriging is the standard geostatistical technique used in resource estimation, named by French

mathematician Matheron in honour of the South African mining engineer Danie Krige. As a result, geostatistical skills as well as sound geological abilities are now essential for conducting a mineral resource estimate.

Box 3.5 – Flow Design at Cadia – The process (Fig. 3.7) used to define the Cadia Hill porphyry Au-Cu resource (Moorhead *et al.*, 2001) involved drilling 369 diamond core holes and a total of 157,000 m of drilling – an average of 425 m per drill hole. An Indicated plus Measured Mineral Resource of 352 Mt grading 0.63 g/t Au and 0.16 wt. % Cu (6.8 Moz Au and 0.5 Mt Cu) was defined – from which ore reserves were estimated and subsequently mined profitably – about one hole/Mt of estimated mineral resource. The total cost of completing all of the work required to define the Cadia Hill resource, from start of exploration to completion of the resource estimate, was $28.5 million. The feasibility study added 50 % more to the cost; but today will cost $100s of millions for a large and complex deposit. Cadia Hill provides a good example of the standard of resource estimation required. From start of mining in late 1998 until mid-2010, 197 Mt of ore grading 0.73 g/t Au and 0.19 % Cu were mined and processed. The feasibility study estimate for the ore mined was 204 Mt at an average grade of 0.73 g/t Au and 0.17 % Cu (Malone, 2011). The close agreement between these results reflects the accuracy of the ore reserve estimate and is due to the amount of drilling completed, which allowed 90 % of the mineral resource to be classified as Measured.
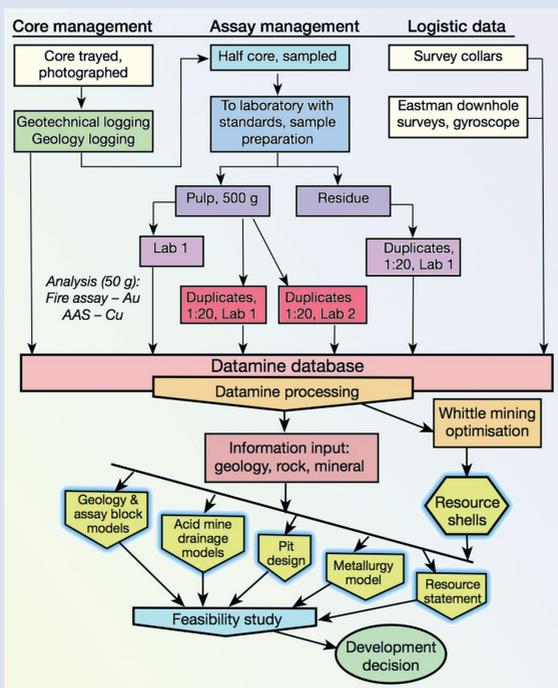

Figure 3.7   Process flow diagram for assessment of the Cadia Hill deposit, Australia (simplified from Moorhead *et al.*, 2001).

The resource terminology (Section 1) followed here is that mandated by the JORC Code in Australia, which uses Inferred, Indicated and Measured Mineral Resources for material delineated and defined by sampling, and Probable and Proved Ore Reserves derived from Indicated and Measured resources, respectively, that have been confirmed by a feasibility study to be economic to be mined.

Determining whether to classify a mineral resource as Indicated or Measured is a judgement made by the designated Competent Person, legally responsible for the estimate. The most direct and arguably best way to confirm that the estimate is properly classified as Measured (highest classification) is to select several locations within that part of the deposit so classified and predict the thickness and grade at those locations, using information obtained from adjacent parts also within the Measured domain. If the Measured status is justified, this will be established by drilling holes at these locations that confirm the prediction. If not, the classification should be Indicated, and additional drilling and sampling is required before the mineral resource can be upgraded to Measured.

The ore reserve estimation process progresses through cycles of iterative technical, financial, and risk assessments. A high-accuracy ore reserve estimate is crucial to the economic success of a mining operation. This need is even more critical when involving low-grade resources (*e.g.*, Cadia, Box 3.5), as these are closer to the limit of profitability. A relatively small overestimation of grade in the worst case could render the mine unprofitable because of material deemed to be ore at a high price that then falls below the economic cutoff grade, as the commodity price declines.

3.4.3 Mining studies

Following discovery of potentially economic mineralisation the possibility of mining is evaluated through three increasingly rigorous stages of investigation and study: *scoping*, *prefeasibility*, and *feasibility* (Fig. 3.8; White, 2001). As the mining study progresses through the three stages the mineral resource estimates gain the increasingly higher levels of confidence that are essential, in order to manage the financial risks associated with building a mine.

A *scoping study* considers several possible mining alternatives to a ±30 % level of the estimated final cost and is commonly conducted on a mineral resource which is at the lowest level of resource confidence. In a *prefeasibility study*, a comprehensive project assessment is undertaken using at least two feasible mine plans, to a ±20-25 % level of final cost, based on conceptual engineering but which is not optimised – a large part of the mineral resource will have been converted to a higher confidence by this stage through increased drilling and a variety of studies, including metallurgical and geotechnical. The final *feasibility study* evaluates and optimises one of the prefeasibility development alternatives in detail, to within ±15 % level of the final cost.
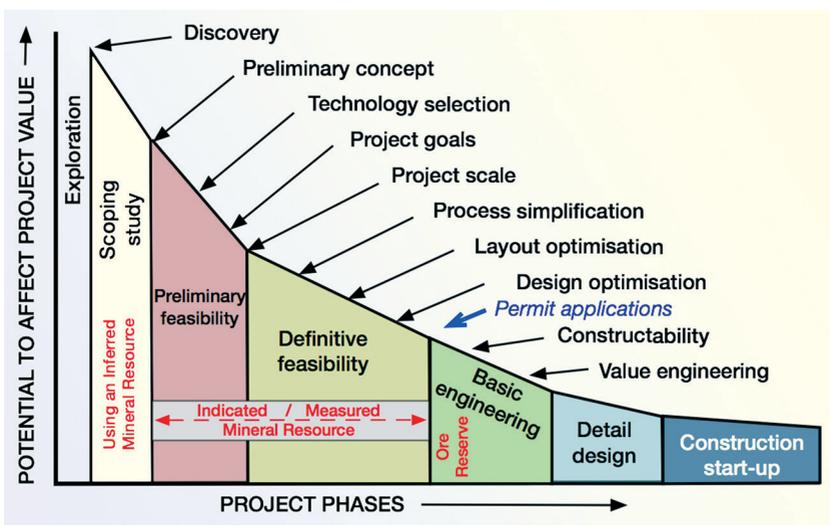
Figure 3.8 Potential influences of feasibility studies on the project value, with timing of resource quantification (modified from White, 2001).

The feasibility study enables a decision to be made about proceeding with mine development and obtain project financing to construct the mining operation and associated infrastructure. The study will be used to support an application to the government for a mining permit. By this time, much of the mineral resource will be at Indicated and Measured status. The feasibility study will determine whether the estimated Indicated and Measured Mineral Resources will convert in part or completely to ore reserves. In the event that none converts to an ore reserve the feasibility study will have failed and the deposit will not be approved by a company board for mine construction.

As noted, only Indicated and Measured Resources can be converted to an ore reserve in the Australian JORC Code, with Inferred Resources requiring upgrading through further drilling before they can be converted. When a mine underperforms the feasibility study prediction, which is common, the usual technical cause is inadequate geological and/or metallurgical understanding – reinforcing the need to collect comprehensive geological and mineralogical data from the earliest stages of investigation. A long-term decrease in the price of a commodity obviously also will have a negative impact on mine performance.

Typically, for a large project, a feasibility study will take about two years, and if positive, a further two years will be required to conduct a detailed environmental assessment and satisfy various regulatory requirements. If permits allow, mine construction will then usually take between two and five years, depending on location – but can take longer because of unexpected delays. In other words, development of a producing mine typically will take six to ten years, or more, after

the decision is taken to conduct a feasibility study – assuming each subsequent step is successful, and this may be several (or many) years after discovery (*e.g.*, Sillitoe, 2010b). Further delays can be related to a variety of factors, including periods of low commodity prices, delays in permitting, and the time needed to gain social license to operate.

3.5 Discovery Strategy and Success

If there was an endless supply of funding, exploration theoretically could be conducted as a game of chance and rely on luck to make a discovery. One should not be surprised that mining companies are reluctant to do this and even the largest company will wish to limit how much it spends on exploration before a discovery is made. This situation is exacerbated for smaller companies where securing funding for exploration is always difficult and dependent on investors – the issue of funding has been difficult for all companies, large and small in the few years leading up to writing this commentary.

A strategy and tactics that will increase the chance of success and thereby decrease the cost of discovery are essential elements of an exploration programme – the strategy and tactics that are employed by a major company, however, will differ from those used by a junior company.

3.5.1 Major versus junior company exploration

A major mining company is described as one with significant mining-related revenue and the internal/external financial capacity to fund development of a mine. Junior companies typically lack mining-related revenue and rely on equity financing for their funding. In between are mid-sized companies with mining-related revenue, but on a much smaller scale than a major company. Both junior and mid-sized companies lack the financial capacity to fund mine development, except on a small scale in the case of a mid-sized company, and to build a mine they both will need to raise additional equity as well as debt financing. For this reason, a junior company will often sell a promising project to a larger company.

Despite their small size, junior companies are now responsible for the majority of exploration expenditure worldwide, collectively accounting for more than half of expenditure during the 2005-2014 exploration boom, which peaked in 2012 (Fig. 3.9a), followed by a slide in commodity prices (Jennings and Schodde, 2016). Major companies typically account for about 30 % of exploration expenditure (Metals Economics Group, 2012). The remainder is spent by mid-sized companies and governments.

The division of responsibility for exploration effort between majors and juniors progressively widened post-1980s when merger and acquisition (M&A) reduced the number of large companies, and many of the remaining larger companies became more risk-averse to exploration investment. Following these

trends, discoveries by junior companies in the Western world have increased sharply from ~10 % 40 years ago, similar to the proportion discovered by Western government-funded efforts then, to >60 % today, with the balance of discoveries by large and mid-sized companies (Fig. 3.9b). Discoveries by groups funded by Western governments have declined significantly in the past 20 years (Sillitoe, 2010b; Schodde, 2014b).
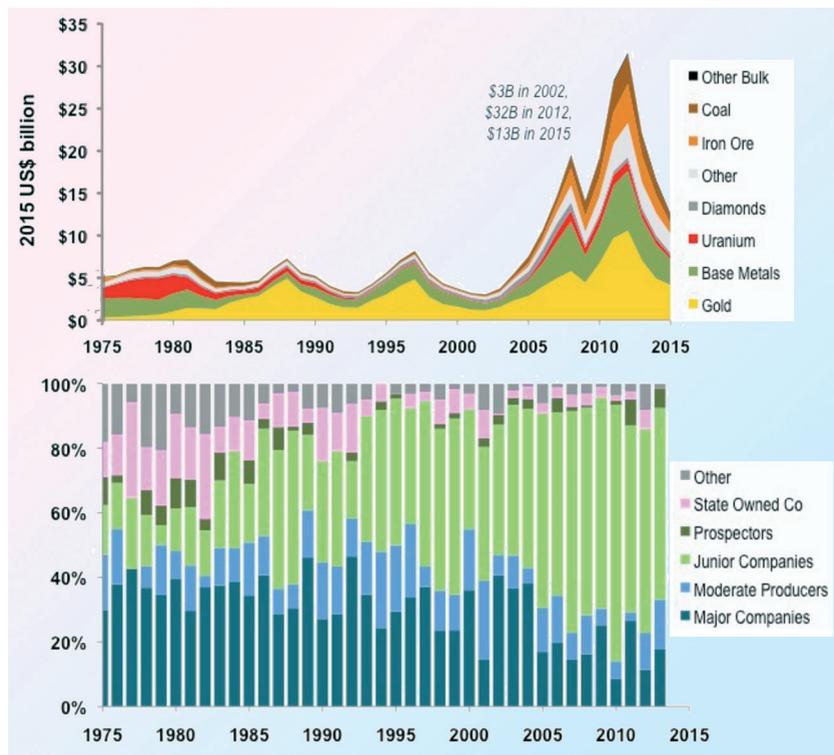
Figure 3.9   **(a)** World exploration expenditures by commodity, 1975-2015 (2015 US dollars; Schodde, 2014b; R. Schodde, personal communication, August 2016). **(b)** Group responsible for discovery (%) of giant, major and moderate deposits in the Western world (excluding bulk commodities), 1975-2013 (Schodde, 2014b).

3.5.2 Strategy and tactics

The factors that determine exploration strategy and tactics vary according to the type of mining company and the experience of its management and exploration leadership. Generally, they will include the commodity and type of deposit being sought and its possible depth, the exploration and mining methods best

suited to that type of target at the anticipated depth, the level of funding and time available, the local fiscal regime, and the suitability – both geological and non-geological – of the region for exploration and eventual production. A major influence is whether the company has cash flow from an operating mine or is reliant on investors to finance its exploration, as the source of funding will largely determine the amount of risk that it is prudent for the company to take (Wood, 2014) – an important part of both the strategy and the tactics that are employed.

The exploration strategy usually will be stated simply. The strategy of a major company, for example, may be to maintain the size of the mineral resources and ore reserves of its main commodities, over a stipulated period, by discovering new deposits in known districts (or even new mining districts) containing deposits of the commodities they mine. For a junior company, its strategy may be to discover a single deposit with the objective of selling the deposit to provide a return to investors and fund future exploration, or to joint venture a promising prospect to a larger company that will fund future assessment (a project generator model) – if a discovery is made the junior company often retains a minor, but potentially valuable, interest. The tactics a company employs to accomplish its strategy are multi-faceted and typically highlighted in corporate presentations.

Mining companies now explore for only a few specific commodities, mainly because they have mines that produce one or more of these commodities in which they control a large market share and have become specialists. Where the deposit type permits companies will seek deposits where there is potential to produce more than one commodity (*e.g.,* porphyry Cu-Au deposits; Section 2), as this will add value to the deposit. Very large mining companies also tend now to focus mostly on commodities that can be mined on a large scale in bulk, such as: iron ore (2014: Rio Tinto, BHP Billiton, and Vale, in order from largest producer), metallurgical coal (2015: BHP Billiton, Teck, Rio Tinto), Cu (2015: Codelco, Freeport McMoRan, Glencore, BHP-Billiton), Zn (2013: Korea Zinc Group, Nyrstar, Hindustan Zinc, Glencore), and bauxite (2013: United Co. Rusal, Aluminum Corp. of China, Rio Tinto, Alcoa, China Hongqiao Group). As stressed above development of large-scale mines involves large capital outlays – multi-billions of dollars – and usually takes considerable time for a mine to be brought into production after discovery. These considerations will have a major influence on a company's exploration strategy.

> **Box 3.6 – *Time to Production and Cash Flow*** – A simple example of time from discovery to production is demonstrated by the Cadia district. Discovery of the exposed low-grade Cadia Hill orebody in 1992 (production commenced in 1998) was followed three years later by discovery of the high-grade Ridgeway orebody (production in 2001). In 1994, the shallower part of the massive Cadia East orebody was discovered; the deeper part of the orebody was intersected in 1996 at a depth of 1,000 m by very deep drilling. Production from the Cadia East underground cave mine started in 2013, 17 years after discovery, 21 years after the first discovery in the district, and 22 years after exploration commenced (D. Wood, personal observation).

Some people may think that major mining companies have deep pockets and will continue to support exploration even if there is a low frequency of discovery. However, this is generally not the case and exploration teams in major companies will be under as much pressure to succeed as those in smaller companies. An additional challenge in working for a major company is the large size of the deposit that has to be discovered for it to have a significant impact on the company's profitability. It is mostly because of this fact that, rather than relying only on exploration discovery to provide growth, major companies will complement (or even replace) exploration by pursuing merger and acquisition (M&A) opportunities to expand the sizes of their Indicated and Measured Mineral Resources and ore reserves.

Paradoxically, it is commonly accepted within the mining industry that M&A is invariably a more costly way of adding mineral resources and ore reserves than is successful exploration and requires very careful due diligence of the opportunity to deliver real value to the company. In many instances, M&A activity is conducted when commodity prices are high – driven in part by market expectations, an aggressive CEO focused on growth at all cost, *etc*. Acquisitions in economically buoyant times are expensive, eventually leading to writing down the value of the acquisitions if profitability declines (*e.g.*, Anglo American wrote down the value of mining assets by $4bn; *Financial Times*, 16 July 2015). In recent years there have been several other major write-downs by large mining companies (many tens of billions of dollars) that appear to have destroyed considerable corporate wealth, even though increases in metal prices may recover some of the loss. Juniors commonly acquire projects from majors that the major considers too small, but with the major usually retaining a future interest of some sort.

The cost of development mostly explains the strong interest in discovering and mining Au because of the small scale at which some Au deposits can be mined economically, and the fact that they can be brought into production relatively quickly and cheaply, particularly if by heap leaching oxidised ore (Section 4). A junior company urgently needing a discovery to replenish its funds, or a producer because the only mine it has will shortly exhaust its ore reserve, logically should develop a strategy that increases the chance of success as quickly as possible and that also accommodates the company's appetite for risk.

> **Box 3.7 – *Junior versus Major Companies in Discovery of Oyu Tolgoi*** – Some deposits considered too small by a major company may be acquired by a junior in the hope of discovering a deposit the major had missed. This is the case with the Hugo Dummett porphyry Cu-Au deposit discovered by Ivanhoe Minerals in the Oyu Tolgoi porphyry district, Gobi Desert, Mongolia. Oyu Tolgoi was first identified by Magma Copper (acquired by BHP Billiton) in 1996 and which by the end of 1999 had defined 438 Mt grading 0.52 % Cu and 0.25 g/t Au as an Inferred Mineral Resource (Perelló *et al.*, 2001). At the time BHP Billiton was decreasing its exploration budget and the size of the resource, and large distance (>500 km) to a rail line, led the company to offer the project for joint venture. Ivanhoe Minerals (same principals involved with the Voisey's Bay Ni discovery) acquired the project and started exploration in 2000,

seeking to enlarge a shallow zone of supergene oxide Cu mineralisation. An RC hole drilled in late 2001 intersected 508 m of sulphide Cu mineralisation grading 0.8 % Cu and 1.1 g/t Au, from 70 m downhole.

A deep-penetrating IP survey was conducted to target diamond drill holes and a chargeability anomaly was identified to the north of the known deposits. Initial drilling showed the IP source to be pyrite; however, the final planned drill hole (OTD270 drilled in September 2002) that tested the anomaly's eastern margin intersected 638 m of sulphide mineralisation grading 1.6 % Cu. This led to discovery of the large deep high-grade Hugo Dummett orebody. The deposit has an estimated Indicated plus Measured Mineral Resource of 1,387 Mt grading 1.33 % Cu and 0.47 g/t Au, with an Inferred Resource of 2,367 Mt grading 0.78 % Cu and 0.33 g/t Au (at a 0.6 % Cu equiv. cut-off; Crane and Kavalieris, 2012). Rio Tinto and the Mongolian government have since acquired major stakes in the property and construction of an open pit mine began in 2010, with production starting in 2013, while the underground mine is still being constructed.

Our experience leads us to believe it is more effective to conduct exploration as a business; albeit not as taught in contemporary management courses (Wood, 2010). The business of exploration is to manufacture discovery, although this is easier said than done, as the exploration manager does not have the same control as does the manager of a factory, and the "manufacturing" is very much dependent on intangible skills of the manager and exploration team.

A crucial decision in developing tactics is the choice between conducting brownfield and greenfield (grassroots) exploration. Brownfield exploration is conducted near a mine site, but may be extended by some companies to include known mining districts occupying a much larger area than the near-mine environment. A potential issue in exploring a brownfield area might be that abandoned mines in the area have legacy liabilities with regard to reclamation, *etc.*, that transfer to a new owner. By contrast, greenfield exploration is conducted where there is little, if any, previous evidence of possible economic mineralisation (*e.g.*, old mines or major prospects) – however, there may be geological evidence, such as alteration mineralogy or minor mineral occurrences, for the presence of a possible ore environment.

The chance of discovering an orebody on a greenfield site is generally much lower than on a brownfield site, but the potential reward may be substantially greater. A prime example of major reward from greenfield exploration was the discovery in 1975 of the giant Olympic Dam Cu-U-Au orebody in South Australia (Reeve *et al.*, 1990). In the current economic cycle, exploration is increasingly concentrated in brownfield areas, not only because of the perceived greater chance of success but because a brownfield discovery usually can be developed more quickly and at a lower capital cost – due to existing infrastructure, treatment facilities, and known permitting requirements. In addition, in spite of past exploration and mining, most brownfield areas are under-explored by deep drilling, seldom below about 300-500 m, which offers the possibility of discovering new deposits at greater depth near known mines.

Part of the exploration strategy and tactics of a prudent mining company will be to risk-weight the exploration budget. In practice, so as not to rule out the chance of discovering another Olympic Dam-size orebody in a greenfield setting, the risk-weighting needs to provide opportunity for this type of very rare but high-impact discovery. The simplest way to do this is to decide a balance between brownfield and greenfield projects and maintain a discipline with this over at least a 10-year budget period. For a larger company the brownfield/greenfield ratio may be 70:30, depending on its appetite for risk. Newcrest Mining, for example, was predominantly a brownfield explorer from 1991 to 2007 and its long-term ratio was about 90:10 (D. Wood, personal observations).

The strategy for a larger company committed to growth through discovery needs to be agreed at a corporate level and recorded, along with an estimate of the amount of expenditure required over a realistic timeframe (*e.g.*, 10 years). We believe this timeframe is necessary as it takes time to build a successful team, to conduct initial exploration and to learn from unsuccessful targets, *etc*. The analogies – of non-success, costs, and length of time – to the development of drugs by the pharmaceutical industry are clear (Hall and Redwood, 2006), albeit one group works in the jungles and mountains and the other in a laboratory, with the added benefit of government support of research in universities to discover potentially useful molecules that pharmaceutical companies then investigate. Mining companies and their exploration teams, on the other hand, only have orebody models developed by researchers to guide them. However, Marlatt and Kyser (2011) note the disappointing results of model-driven U exploration, despite $3 billion expenditure worldwide over a recent 10-year period, and propose that more "innovation exploration" will help lead to discoveries.

3.5.3 Chance of success

Time has a cost in business and both time and money are inevitably in short supply in exploration, especially for junior explorers and particularly when metal prices are low. As a result, programmes have to be planned and conducted with the goal of increasing the chance of success as quickly as possible. Discovery is an unknowable outcome and impossible to predict with any degree of certainty, although there have been attempts to examine exploration success in a quantitative manner (Pretorius, 1973).

Anecdotal evidence suggests that exploration experience can contribute to increasing the chance of success, as was demonstrated by Newcrest Mining, which was judged by Metals Economics Group of Canada as "the world's most successful gold explorer, 1992-2005" (MEG, 2005). Newcrest had an experienced exploration team that added 69 Moz Au and 6.2 Mt Cu to the company's estimated mineral resources between 1991 and 2007, all through discovery rather than acquisition (Wood, 2014). Another example of where experience and corporate commitment to growth by discovery has paid off is Santiago-based Antofagasta Minerals. From 2003 to 2012, 95 % of the 7.5 Mt of Cu added to the company's reserves – twice the amount mined in the same period – resulted from exploration discovery and development by a seasoned and well-led exploration team (study by SNL MEG; J. Perelló, personal communication, 2016).

> **Box 3.9 – Exploration Success Rates** – Bailly (1967) assessed the exploration success rates of seven major mining companies and three governmental organisations in the USA over 25 years, involving 16,962 exploration programmes, mainly for base metals and U. In 2,078 cases (12 %) potential to discover a reasonable tonnage of mineralisation was indicated, but only 52 of the discoveries were potentially mineable (0.3 %, or odds of 300 to 1). Only one discovery became a Tier 1 producer.
>
> Griffis (1971) studied the exploration results of Cominco, one of Canada's largest mining companies at the time, which examined more than 1,000 properties over a period of 40 years. Only 78 properties (7 %) warranted detailed study and just 18 (1.5 %) of these projects were developed as mines, with only seven (0.5 %) of the mines being profitable over the long run.
>
> This statistical type of approach to exploration is rarely if ever applied today, but these studies convey to the reader a sense of how rarely orebody discovery occurs.

All of the evidence that we have indicates that far less than 1 % of exploration anomalies investigated will be evaluated for mining with a scoping or prefeasibility study. As a result, an exploration geologist is unable to make any promise about the likelihood of making a discovery that produces a mine, although an almost certain guarantee can be made that the project will not be successful.

Only relatively few people have the necessary fortitude to handle this almost certain outcome –that they may never be involved in a discovery. The pharmaceutical industry is similarly unsuccessful in developing new drugs (Hall and Redwood, 2006). For every 5,000 compounds that undergo early research,

only five will enter clinical trials, and only one will be successful and approved for use, with a typical time period of 15 years. Maybe chemists have another way of dealing with absence of success!

The chance of exploration success generally is better in brownfield areas, but even there it is low and depends very much on the quality of the prospect investigated and the skills of the exploration team. Rarely will discovered orebodies be world-class in size (top 10 %) and have a significant impact on world resource supply. This poor rate of success – a simple fact of Nature (Section 5, Fig. 5.4) – highlights the need to assess prospects efficiently, abandoning as quickly as possible those judged to show little or no likelihood of economic potential on the basis of available data. It is prudent to adopt the "fail quickly" saying where lack of success is the only possible outcome, but learn from these attempts at discovery. Determining the chance of success is *"primarily a judgment decision based upon experience of successes and failures"* (Lacy, 1974).

> **Box 3.10** – **Discovery Thinking** – *"People are the key to discovery and while teamwork is important, inevitably it is the individual flash of genius that sparks discovery. Discovery is not a consensus outcome; someone has to lead the way"* (Wood, 2010). It seems that inspired judgment by certain experienced geologists, rather than statistically derived prediction, is the key to discovering an orebody. Discovery requires intuitive leaps of imagination resulting from the human brain's ability to engage in lateral thinking, often by making decisions that deliberately ignore some information, and then being bold and acting on those decisions. The ability to make discoveries also benefits from the fact that humans are programmed to learn and to be selective (Pretorius, 1973), and the old adage that the "best geologist is the one who has seen the most rocks" has truth to it.

3.5.4 Risk

Inability to discover mineralisation with potential to become ore is obviously one of the major risks in exploration and is linked directly to the geology of the area being explored. However, geology is but one of several risks that need to be considered when deciding where to explore; others include political and sovereign risks, technology, economics, management, and intangible factors related to geological competence.

Technological risks are crucially important in determining whether mineralisation will ever become ore, with many of these defined by characteristics that determine the ease or difficulty of mining and recovering the resource. It is crucial to be alert to evidence of negative geological, mineralogical-metallurgical and geotechnical characteristics when drilling a potential orebody. These and other, non-geological, risks are examined in Section 4.

Much of the exploration risk equation is determined by human decision making, such as the inability to recognise a deposit or discovery opportunity when presented, and deciding when to discontinue or persist with an exploration

programme in an area. As with the chance of success, there is no accepted scientific method for making these decisions, and evaluating geological competence is difficult. However, it is essential that the best available geological talent be employed, particularly during the early area selection and appraisal stages of exploration, rather than placing only the most junior geologist in the field or core shed. Our experience suggests that the most efficient way to explore is to plan and conduct programmes as a series of relatively short-duration stages, designed to achieve a specific technical objective, with a decision point at the end of each stage.

3.5.5 Mining method

Exploration geologists need to have at least a basic knowledge of the more common mining methods (Section 4) and also be aware of mine development costs and the impact of geographic location on these. This knowledge will become increasingly important as deeper deposits are targeted for discovery.

Because deeper orebodies of the types presently mined on a large scale by open pit will be mined underground in the future, exploration geologists will need to know more than they presently do about the different available mass underground mining methods (Wood *et al.*, 2010). These mining methods place constraints on the type of deposit that can be successfully mined – one with a regular geometry, for example (Chitombo, 2011) – and knowledge of these limitations is needed to guide discovery and resource definition drilling.

Since there has been very little systematic exploration for deep orebodies (below several hundred metres in most areas), a mostly poorly explored part of the Earth's crust will be opened to exploration in the future (Section 5) to 2 km depth, the present nominal limit for mass underground mining. The deepest underground working now is the Mponeng Au mine in South Africa, albeit on a narrow reef averaging about 1 m thick, at a depth of 4 km.

3.5.6 Social considerations

If the recovery of a mineral resource (Section 4) is to be as successful as possible a mining company needs to have the support of the local community in the mining area and because the exploration team is almost always first on the scene it has a crucial role in supporting this outcome. The nature of the initial contact between the local community and the company geologist and exploration team is often critical to the long-term community-company relationship. Most exploration projects (>90 %) never move past early mapping and sampling; this work usually provides a small employment opportunity for local people, which may also produce initial (albeit limited) local support.

As soon as a community hears of interest by an exploration geologist, talk inevitably turns to mining and the exploration geologist will need to communicate and negotiate with the community from day one, rather than simply focus on

the rocks. Two of the geologist's greatest responsibilities are as an early ambassador for the mineral industry and to manage community expectations, since well over 99 % of all exploration projects fail to end up with a mine being built. It is essential that the community be made aware of this likelihood from the outset.

Some geologists are better at managing expectations than others and where the geologist in charge lacks this ability it may have negative consequences for mining, if a discovery is made.

3.6 Exploration Budget

The amount and intensity of an exploration programme is determined primarily by the size of the exploration budget, which will vary according to the amount of discretionary funding available to a company. This is determined by two factors: the profitability of the company and the availability of outside funding (equity financing and loans). Both of these sources of funding are highly dependent on economic cycles and result in funding being most readily available at the top of a cycle, when commodity prices are highest (Harris and Kesler, 1996).

Put simply, when commodity prices increase, mining investment increases and companies budget more generously for exploration; this reverses when prices fall or the economy is under financial stress for some other reason. During such downturns, even companies that have a producing mine with a positive cash flow are pressured by the market and shareholders to cut costs – including exploration, which invariably is the easiest and first cost to be reduced since it is usually considered discretionary. Conversely, the bottom of a cycle is the best time to explore, as competition from other explorers is significantly reduced and many exploration costs, including land acquisition and drilling, are lower.

While budgets are usually prepared annually, it is essential they are commensurate with achieving the long-term discovery objective and are neither too large nor too small; wildly varying budgets are detrimental to team effectiveness and efficient exploration. A well-run smaller company will need to develop a strategy and tactics and exploration budget that compensate for likely limited expenditure and a shorter timeframe for success.

3.6.1 Economic decisions in exploration

In many respects deciding whether to continue or terminate an exploration project or programme is the most difficult decision to make, because history is replete with examples of persisting and finally discovering an orebody (*e.g.*, Hemlo, Canada, Box 3.11). Often this history includes examples of companies that followed others in exploring an area (Sillitoe, 2010b), even drilling on the same prospect, if for no other reason than to drill deeper (*e.g.*, Loma Larga, Box 3.11). This is when the human psychology factor comes to the fore in exploration.

Unfortunately, there are also examples of projects where reasons for persistence did not materialise, at least during the relevant time frame (*e.g.*, overly optimistic predictions of future commodity prices, predicted increases in grade or tonnage, *etc.*), and others where location has challenged mine economics (*e.g.*, the Frieda River porphyry Cu-Au deposits in Papua New Guinea remain undeveloped almost five decades after discovery in 1968).

Since discoveries typically are not made by the first company exploring a district (Sillitoe, 2010b), all exploration information generated in some countries (*e.g.*, Canada, Australia, New Zealand, and Sweden) is required by government regulation to be reported. Government departments then make the data publicly accessible once exploration title to an area is surrendered. This ensures that the same surveys are not repeated, unless deemed necessary, when an area is reassessed during later exploration. Some government agencies also collect and store drill cores and other samples produced during company exploration, for access by future explorers.

Examples also exist of discoveries being made in jurisdictions that, for one reason or another, choose not to allow mining – exploration presumably was conducted in the (mistaken) belief that a mining permit would be negotiated if a deposit were discovered; or laws change after exploration starts. By contrast, Newmont Mining entered Peru in the 1980s at a time of instability, but the situation improved and Peru is now a strong mining country. As a result, Newmont and its partners were in a unique position to be able to define one of the world's largest Au deposits at Yanacocha in northern Peru.

Box 3.11 – Persistence in Exploration – The difficulty in deciding whether or not to persist with a programme is amply illustrated by the discovery of several ore deposits. Olympic Dam was discovered under thick cover on a greenfield site with the 9th of a nine-hole programme (Roberts and Hudson, 1983), and the main Hemlo Au orebody in Canada was discovered by the 76th hole (Muir *et al.*, 1995). The Loma Larga (Quimsacocha) epithermal Au-Cu deposit in southern Ecuador was discovered by the 40th deep hole, after 82 shallow holes had been drilled by a previous company (Jones *et al.*, 2005).

The Pampa Escondida porphyry Cu deposit, Chile, was discovered adjacent to the Escondida mine but under cover. In developing the Escondida deposit 136 shallow (mostly 250 m deep) holes had been drilled over the Pampa Escondida area years earlier to sterilise it for mine infrastructure purposes and search for oxide Cu resources. A re-examination of this old drill core and cuttings recognised bornite in the deepest of the sterilisation holes (369 m) and this led to three holes (722-1200 m deep) being drilled into the Pampa Escondida deposit (Hervé *et al.*, 2012).

Discovery of the Panguna deposit in Papua New Guinea owes much to a field decision to move the drilling rig to another part of the prospect and continue drilling, rather than stop while the programme was reviewed because of disappointing drilling results (K. Phillips, personal communication, 1976).

There are numerous examples of discovery by a hole that was drilled in the wrong place (perhaps due to the drilling rig being unable to access the planned drill site, *e.g.*, the original Escondida porphyry Cu discovery) or for the wrong reason, *i.e.* to an extent serendipitous. In addition to changing tactic by drilling deeper, discovery by a subsequent company may result from employing different exploration techniques.

3.6.2 Discovery cost

Exploring without an estimate of what will represent an acceptable discovery cost for the resource being sought can result in a company eventually going broke, unless it has exceptionally long-life mines. Even in this situation, it is likely exploration eventually will be reduced or curtailed by a company after protracted failure to discover, because of accumulated exploration expenditure.

The discovery cost target will determine the amount of money to allocate sensibly over a realistic period (*e.g.*, 10 years, given the rarity of discovery) if a company is committed to sustaining or expanding resource production through discovery. While there is no prescribed cost representing value for money, a useful rule-of-thumb is to aim for a metric representing less than 10 % of the *in situ* value of the resource to be discovered, measured as a proportion of total company exploration expenditure over time to discover and define the resource.

For example, if the target is five million ounces of Au (worth $5 billion *in situ* at a $1,000/oz Au price), the total expenditure everywhere by the company on discovery exploration and resource definition should be less than $500 million per target discovery, spent over 10 years. The time value of exploration expenditures is also an important consideration and this has the effect of significantly escalating the true cost because of the need to take into account the cost of capital (if $500 million is expended in equal amounts over 10 years, the true cost at the end of the tenth year will be $797 million at a 10 % cost of capital).

3.6.3 Discovery challenges – why discovery is rarely achieved

The reason why discovery is rarely achieved is simple – orebodies, as opposed to anomalies, are extremely uncommon (Section 5, Fig. 5.4). Moreover, they are restricted geographically and spatially on an Earth scale and there is no way presently of confidently predicting their possible locations prior to discovery. This makes choosing areas in which to explore for ore very problematic, although examining highly-endowed metallogenic provinces is one option (such as the central Andes for Cu, central Mexico for Ag, and Nevada for Au).

Faced with this uncertainty, how is a discovery to be made and what actions can be taken to improve the chance of success? As previously noted, it is becoming increasingly common for larger companies, in particular, to focus much of their exploration on known mining areas – brownfield exploration or within sight of

the "headframe" of an existing mine. Their logic is simple – the presence of a known mineral deposit or mine indicates fertility of mineralisation in a district, potentially greatly increasing the chance of further discovery.

Although area selection is usually based on technical considerations human decision making is crucial in this – when choosing which technical aspects are important in area selection, for example – and, even more so, in making a discovery. Since discovery relies heavily on intangible thinking by exploration staff and actions taken as a result of this thinking, it is not possible to manage exploration successfully at the corporate level, although belief in exploration and its leadership is essential at this level (Wood, 2014).

A question quite properly asked is – what is different about the person who facilitates discovery of an orebody as compared to everyone else? The same question can be asked about any scientist who makes breakthrough discoveries in any field. Unfortunately, in exploration there is no indication of any common attributes that clearly differentiate ore finders from their peers, although good field skills are a useful start. A characteristic often shared with other successful scientists, however, is the ability to make repeat discoveries, and it is not uncommon for a single explorer to be associated with multiple discoveries.

This aspect suggests discovery does not happen by chance, but we offer no other insight into why discoveries are made by some geologists and not others (Wood, 2010). Discovery may in some instances be due to serendipity and there is evidence for this in science (Roberts, 1989), but luck also favours the prepared mind. There are strategies which do favour discovery, however, such as outlined by Brown (2012).

3.7 Future for Discovery

Since 1950, exploration for Cu and Au has been directed largely to discovering orebodies suitable for mining by open pit. This has generally limited the search to less than 200 m below surface (Fig. 1.8; Schodde, 2014b) and has been guided mostly by surface evidence of mineralisation. Exceptions are the epithermal and deep orogenic Au, VMS, and other high-grade deposits that were sought as underground mining targets; however, open pit mining has been the dominant method of producing ore.

If >200 m of waste rock has to be removed (stripped) to access ore for mining, the deposit is typically not mined by open pit. There may be exceptions for very high-value orebodies, but even with these ~300 m of cover by waste rock will establish a limit. Since modern mass underground mining techniques now enable large regularly-shaped orebodies to be mined in bulk to a depth of 2 km, there is no mining-related reason to not explore to at least this depth for suitable deposits. The additional cost of the deep drilling required for discovery will be partly offset by the need to drill only widely spaced holes during this phase,

because of the size and regular geometry of the target deposit (*e.g.*, a porphyry Cu deposit). This mining method may also be suited to other types of large deposits with a regular geometry (Section 4).

There is a perception in the mineral industry that many developed parts of the world are mature in a discovery sense which, when combined with other issues (Section 4), has resulted in a consistent reduction over time in the amount of exploration expenditure in developed countries, replaced by an increased expenditure in developing countries (Fig. 3.10; Schodde, 2014b). However, this perception discounts the opportunity for discovery that a move to mass underground mining foreshadows and a strong argument can be made to re-explore known mining districts in developed countries for deep ore bodies.
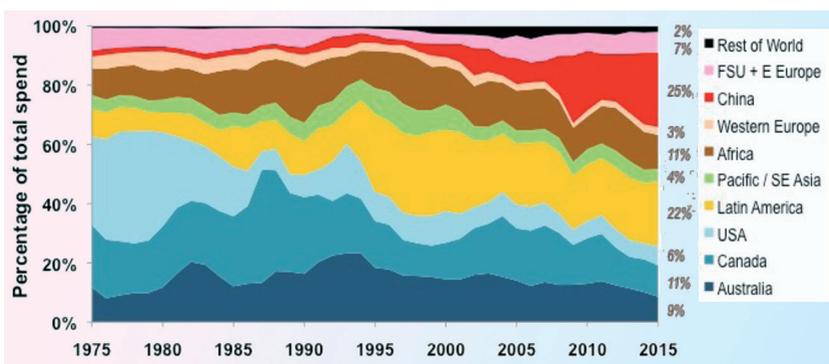

Figure 3.10   Exploration expenditures in the world on the basis of region (including that spent on bulk commodities), 1975-2015. From 1975, proportion of investment in the USA, Canada and Australia had decreased by more than half, replaced in large part by China (Schodde, 2014b; R. Schodde, personal communication, August 2016).

We predict a shift to exploring for deep orebodies – particularly in brownfield areas – for a variety of reasons. These include good potential for deep discoveries in previously discounted mineralised districts, increased prices for resources if they are in short supply, and anticipated improvements in technology and reductions in the cost of deep exploratory drilling and mass underground mining. As further deep discoveries are reported, we expect there will be a trend towards exploring deeper in presently known mineralised districts, as companies recognise the increasingly low chance of success in discovering shallow deposits in districts that have been well-explored – but only to a few hundred metres depth – and realise that the deeper ore potential has not been investigated properly in these districts (Fig. 3.11).
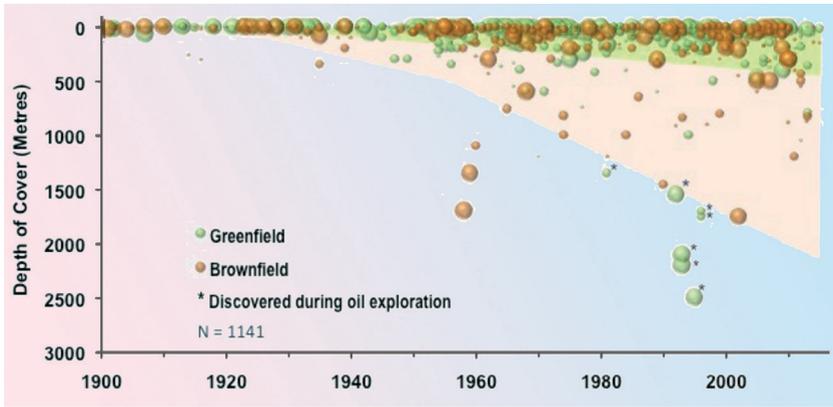
Figure 3.11 Depth to top of brownfield and greenfield discoveries of moderate to giant size base metal deposits, 1900-2015 (modified from Schodde, 2014a); the deep (>1 km) greenfield discoveries were made during exploration for oil (R. Schodde, personal communication, August 2016).

Our prediction about deep exploration and discovery requires that companies (majors in particular) reassess their general reluctance to undertake greenfield exploration and that junior company investors act upon the poorly tested discovery potential that exists at depth – in both greenfield and particularly brownfield settings. Without deeper exploration everywhere, which we confidently expect will eventuate because of society's demand for mineral resources, there will be a serious impediment to the future discovery of orebodies, as well as the identification of new mineral districts and, even, metallogenic belts or provinces.

Deeper exploration will be assisted by geological agencies of governments improving our knowledge of the Earth's crust to 3 km depth, and through the anticipated availability of much cheaper exploratory drilling methods (*e.g.*, coiled tube drilling). Although mapping of the surface geology of many parts of the world is sufficient to guide exploration for near-surface orebodies, geological knowledge below 500 m (possibly only 200 to 300 m) is mostly inadequate for the task of deep discovery. Governments that conduct regional deep-sensing geophysical surveys and drill holes sufficiently deep that they advance our fundamental understanding of the crust in regions of possible mineral resource potential – its geology, stratigraphy, structure and evolution – should attract exploration investment by forward-looking mining companies.

4. EXPLOITING MINERAL DEPOSITS

4.1 Introduction

The discovery of new resources is challenging both in well-understood geological environments and new settings (Section 3). Successful discovery does not, however, guarantee economic and socially acceptable exploitation. In this section, we review the range of mining and metallurgical processes required for economic extraction of mineral resources, along with the environmental and social constraints influencing development. Examples of major mines of different types and mining processes, discussed in this section, are shown in Figures 4.1 and 4.2.

Figure 4.1 Pictures of mines and mining equipment. **(a)** Bingham Canyon open pit mine exploiting a porphyry Cu-Mo-Au deposit. **(b)** Morenci open pit mine exploiting a supergene and hypogene porphyry Cu deposit. **(c)** Kiruna Fe mine – historical

open pits now replaced by bulk underground mining. **(d)** Hemlo underground Au mine. **(e)** Typical large shovel operating in an open pit. **(f)** Large haul trucks (200-300 tonnes capacity) typical of major open pit mines.

Figure 4.2 Examples of mining processes. **(a)** Typical grinding mill used to reduce rock to micron-scale particles. **(b)** Stacks of ore for heap leaching of Au. **(c)** Series of flotation tanks used to separate Cu minerals for gangue minerals. **(d)** Close up of bubbles in a flotation tank with Cu minerals attached to the bubble surfaces. **(e)** Earth tailings dam built in a valley to contain tailings and water. **(f)** Tailings pond with surface water that is recycled and treated.

As discussed in Sections 1 and 3, the economically extractable portion of a demonstrated (*i.e.* measured and indicated) mineral resource is an ore reserve, whose status is governed by legal codes in various jurisdictions. Selection of an economically viable extraction method is therefore a prerequisite for the definition of an ore reserve.

The approaches and technology for extracting commodities from ore reserves within mineral deposits has changed dramatically over the last hundred or more years. These changes have decreased the cost of extraction, hence lowering the long-term (inflation-adjusted) price of commodities, and have significantly improved the environmental performance of modern mining. In many cases, identified mineral resources that were not economic, and therefore contained no ore reserves, became economic as a result of technological improvements and decreasing costs of extraction. The evolution of mining and processing methods is summarised in this section, and the potential for new advances is reviewed. Given the long history of mining and associated innovation, it is reasonable to predict that new approaches and new technologies will continue to enhance effective extraction and will therefore increase resource availability.

Environmental and social concerns related to mining are an increasingly important challenge. Opposition to mining can delay new operations or stop existing ones and hence has the potential to limit future supply. This is a complex topic that includes the drive toward better practices and new mining and processing methods, an increasing focus on sustainability, and the need to engage directly with communities in the regions of proposed mine development. New practices to improve relationships, including partnerships, with communities may increase resource availability, while failure to address these issues will have the opposite effect.

As in previous sections, some of the discussion focuses on Cu as a proxy for the broader mining and extraction of metals. The history and current practices related to Cu mining illustrate many important aspects of the industry at large, but examples from other commodities will also be used to provide a broader context and to make specific points.

4.2 Historical Background

Mining has a long global history that has been the subject of books and many individual regional historical summaries (*e.g.*, Agricola, 1556; Coyle, 2010; Coulson, 2012). A comprehensive review is beyond the scope of this section, but some of the critical developments that changed mining are discussed below. Historical developments in mining paralleled and in some cases created significant changes in society, the use of metals and the resulting technologies.

4.2.1 Ancient mining to the Industrial Revolution – 40,000 BP to ~200 BP

Palaeolithic Homo Sapiens, and probably Neanderthals, mined ochre for pigment and flint and obsidian for tools 30,000-40,000 BP, *e.g.*, the Lion Cave in Swaziland and the Nile Valley in Egypt, and more recent (~5,000 BP) flint mining in England (Russell, 2000; Coulson, 2012). The presence of pits and underground workings in some areas suggest some understanding of the distribution of flint-rich layers and therefore basic geology.

Metals that were recognisable and accessible were used as ornaments and tools in the early Neolithic (more than 10,000 BP). Native Cu was clearly identified and used in some areas, but it is likely that simple roasting or smelting of attractive secondary Cu minerals (Cu hydroxycarbonates such as malachite) increased the early availability of Cu by 5,000 BP.

Smelting of Cu carbonates requires sufficiently hot fires to reduce the Cu minerals and produce molten Cu. The origin of Cu smelting is not known, but it represents the first major technological breakthrough in metal extraction and it led ultimately to bronze, Cu alloyed first with As and subsequently and more extensively with Sn. Bronze was established by 5,000 BP in Anatolia and the Balkans, around the same time across Europe and southern Asia, and later in eastern Asia (Muhly, 1985; Pernicka *et al.*, 2003; Hauptmann, 2007; Cline, 2010). Bronze is harder than Cu and therefore more useful for weapons and other purposes. Copper and tin rarely occur together in the Anatolia-Balkan region however, and therefore the onset of the Bronze Age also required trade between tin producers, Cu producers and metal workers (Figs. 4.1 and 4.2).
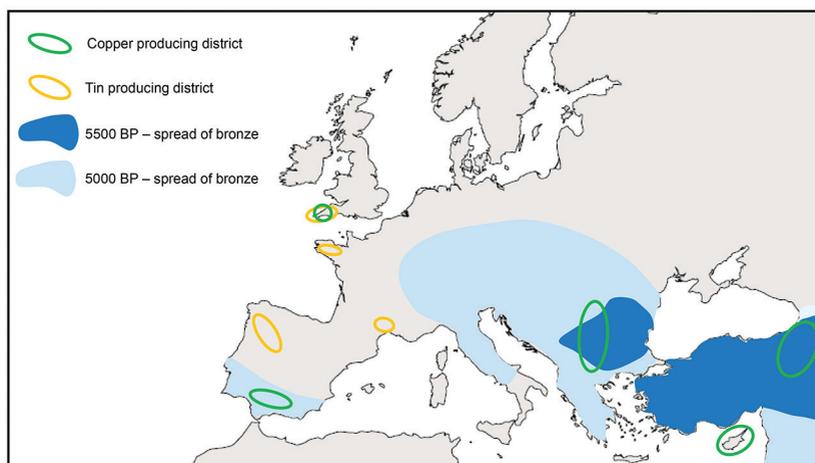
Figure 4.3   Copper and tin producing regions during the expansion of bronze use across Europe 5,500-5,000 years BP (adapted from Otte, 2007).

Although iron from meteorites was known previously, production of iron from its ores began the Iron Age approximately 3,200 BP. As with the use of bronze, increasing use of iron did not happen instantly or uniformly. The first iron tools were made from iron ore mined and smelted in charcoal fires in Anatolia by the Hittites around 3,400 BP (Muhly *et al.,* 1985). Neighbouring Assyrians adopted the technology aiding their conquests throughout the Middle East. Iron ore was easier to find and mine than relatively rare tin (for bronze), and over time the techniques to produce sponge iron, wrought iron and harder iron were developed. As a result, mining and use of iron spread and bronze decreased over several hundred years (Coulson, 2012).

Mining for metals by underground adits (tunnels; Fig. 4.4a) and shallow shafts began at least 7,000 BP (Pernicka *et al.,* 2003). Fire setting was used to break hard rocks and mine to depths of over 100 m where dry. Gold mining became more common and the Lydians started using Au (electrum) coins by 2,650 BP, mined from the Manisa (Sardis) area in western Anatolia (Akcil, 2006). The Romans expanded mining across many parts of Europe, developing water wheels to remove water from deeper mines, and using hydraulic mining to remove unconsolidated rock with Au recovery by gravity methods. The Romans employed skilled miners, presumably with some geological knowledge, in addition to slaves (Thompson, 2003).

After Roman times, mining continued but there was little change for the next 700 to 800 years. Mining expanded again from 800 BP (1200 AD) particularly in central Europe with development of the now famous Ag mines at Clausthal-Zellerfeld, Freiberg and Pribram (Lieber and Hermann, 2006), and

continued in the Eastern part of the Habsburg Empire, Scandinavia, Great Britain, Spain and Portugal, as well as in the Arab Caliphates. In the same period, mining developed in India, China and Japan (Zhang *et al.*, 2015; Akimoto, 1998).

The state of mining and metallurgy in 16th century Europe was described in detail by Agricola in his famous book, *De Re Metallica* (Fig. 4.4b; Box 4.2; Agricola, 1556). The book describes the machinery, techniques, tools and many other aspects of mining prevalent over the previous two hundred years. The Freiberg School of Mines, the oldest university of mining and metallurgy in the world, was founded (1765 AD) in Saxony.

Figure 4.4 **(a)** Early mining of sediment-hosted Cu in the Negev Desert (adit 1.3 m high). **(b)** Depiction of exploration in the 16th century (Agricola, 1556).

Box 4.2 – Georgius Agricola – Agricola (1556) wrote the first comprehensive book on exploration and mining, *De Re Metallica* (On the Nature of Metals), summarising knowledge that previously had been handed down orally. Agricola lived much of his life in the Erzgebirge (ore mountain) region of Saxony, a rich area of Europe due to its metal production. Coins minted from Erzgebirge Ag from the 16th century were known as Joachimsthaler, shortened to "Thaler" (the origin of the word "dollar"). He meticulously recorded exploration and mining techniques, even noting botanical guides for prospecting. Agricola did not argue with the art of alchemy, although he noted that the self-declared alchemists were not wealthy; rather, the wealth of the Erzgebirge was due to mining, with aristocrats being the investors. Agricola stressed the amount of knowledge that miners require to be successful, and the need for specialists. He argued that without metals, architecture and agriculture of the day would be impossible, and noted that the negative effects of mining could be offset by its benefits.

While mining expanded in countries where it already existed, the most significant change came with the exploration of the Americas driven by the desire of the Conquistadors to find Au and Ag (Hart, 2013). Mining was already underway in some areas, particularly Mexico and the central Andes, and the

Conquistadors captured these mines and developed many new ones, mostly for Ag and Au. In spite of global expansion, the approach to mining and the recovery of metals remained relatively constant through this period of expansion.

4.2.2 Industrial revolutions 1760-1910

The first phase of the Industrial Revolution in Great Britain from 1760 to 1840 included improved iron and steel making, new sources of coal-based energy, development of the steam engine and associated use in manufacturing and mining, and the organisation of factories (Coyle, 2010). In parts of Great Britain, iron ore of various types was known in close proximity to accessible coal seams and limestone. This geological coincidence allowed the rapid development of improved iron and steel making, which resulted in major expansions of coal and iron ore mining. Throughout much of this period, Great Britain supplied over 50 % of global coal and considerable amounts of steel (Coyle, 2010).

The availability of steam power led to the Cornish Engine in the early 1800s. The principal use of the engine was to pump water from mines, which allowed access to deeper zones of mineralisation below the water table. Initially applied to Cornish Sn mines, allowing mining to extend below the sea in some cases, it rapidly expanded to coal mining and then to mines around the world. Cornish miners often went along with the technology and evidence for Cornish Engines and Cornish names can still be found in historical mining camps in Australia, Brazil, Chile, Mexico, South Africa and USA. The development of large underground mines and the resulting impact on infrastructure and factories generated enormous benefits for the British economy and supported expansionist goals around the world.

As the Industrial Revolution and mine development was gaining momentum in Britain, Au rushes were happening in other parts of the world. In the United States, discovery of Au in North Carolina and Georgia caused some excitement, but discovery of Au in California in 1848 was more significant. The Californian Au rush led to a system in which individuals could stake claims and own any Au that was discovered. More than 300,000 prospectors moved into the area, causing extensive development and related damage, eventually including hydraulic mining, that polluted streams all the way to San Francisco Bay. Incredible wealth was generated for the lucky few, and California was established as an economic powerhouse. Other rushes for Au and Ag followed across western North America culminating in the Klondike, Yukon Au rush of 1896-1899 where thousands of prospectors perished during the perilous journey over Chilkoot Pass and along other routes (Berton, 2001).

The search for Au moved to other continents with the discovery of the Witwatersrand in South Africa in 1874, which went on to become the major source of the world's Au for the next 130 years – only declining in recent years. Similarly, Au prospecting and mining started in Australia in the 1820s, accelerated with the discovery of the Victorian goldfields in the 1850s, spread elsewhere

to Queensland and offshore to New Zealand in the 1860s, and culminated in the discovery of Kalgoorlie in 1893 (Coulson, 2012). Underground mining was dominant in Australia, aided by the dry conditions and the introduction of the Cornish Steam Engine. While the Au rushes supported mass migration, and created wealth and development in adjacent regions, there were limited advances in mining, and the use of traditional methods for recovering gold from ores by gravity continued.

Until the early 20th century, exploration was led by prospectors driven by greed, adventure, and desperate circumstances. The rare prospectors who were successful went on to build mines and some became wealthy. As mines grew and the industry expanded, capital requirements to build more substantial mines became prohibitively high for individuals, and industrialists and bankers became increasingly involved. Many iconic families in the US and other countries generated their initial wealth through mining, one of the most famous being the Guggenheims. Technology became increasingly important. Larger shafts, Cornish Engines to dewater deeper mines, and large mechanised dredges for placer operations developed rapidly. Mining camps changed as claims were consolidated, major operations were built and mining companies became important. Companies had to seek additional resources to support their mines and grow, leading to the start of formal mineral exploration and its development into a routine and critical part of the business.

4.3 Mining – the Past 150 Years

Over the past 100-150 years the mining industry has undergone major changes mainly in the increasing scale of operations and related technical advances. Examples of specific technical breakthroughs are summarised in Table 4.1 and a more general framework and historical overview is provided below.

Following the Industrial Revolution, the world went through successive periods of revolutionary industrial change. These included the development of low-cost mass production driven by the consumer society in the early 1900s, the introduction of the computer and its widespread availability in the 1970s, and the internet with associated digital transformation and the shared economy that is in progress today. All of these events affected society, industry in general, and inevitably the mining industry. The demand for metals and materials increased and substantial changes in mining and processing methods became necessary. Many of the changes were incremental, involving minor modifications at mine sites to solve problems or optimise processes. Efforts of this nature, "continuous improvement", are a normal part of today's mining operations. There were, however, several substantial changes to the mining industry that constituted shifts in approach, productivity, costs and performance (*e.g.*, Table 4.1).

Table 4.1	Examples of technological breakthroughs in mining and processing 1900-2015.	
Period of advance	**Technical development**	**Implications**
1905-10	Bulk mining – use of steam shovels and trucks	Use of open pit mines; significant decrease in the grade of metal that could be mined economically
1900-15	Froth flotation	Rapid separation of sulphide minerals – better recoveries and cleaner concentrates for smelting
1970-present	Hydrometallurgy	Development of technologies for extracting metals from ores and concentrates using solutions (leachates or "lixiviants") on piles, and dumps and in vats, tanks and autoclaves; in part removes the need for smelters
1940-1975	Solvent extraction (SX)	Extraction of specific metals from complex leachate ("pregnant") solutions – combined with electrowining (SX-EW), facilitated widespread use of heap leach technology for oxidised and enriched Cu deposits SX-EW; also applied to U, Zn, Ni
1970-1990	Heap leaching	Low cost method allowed economic processing of low grade ores, particularly Cu and Au
1980-present (rapidly developing)	Bulk underground caving	Several methods of relatively low cost bulk underground mining of low grade ores
1985-present	Computer modelling – GIS	Methods used to model geology and mineral resources and ore reserves, develop mine plans, and operate mines with close to real time reconciliation with the plan
1990-present	GPS, sensors and communication	GPS and laser sensors used to monitor pit slopes for improved safety; GPS monitors all vehicle movements; real-time communication with operators – surface and underground
1995-present	Automation	Initially robotic equipment driven remotely; transition to autonomous equipment; improvements in safety, performance and costs
2000-present	*In situ* leaching	Direct leaching of metal underground with processing on surface – no movement of rock – ore and waste; used for U with potential use for Cu

4.3.1 Bulk surface mining

In 1898, Daniel Jackling evaluated mineralisation in what is now the Bingham Canyon mine that exploits one of the world's major porphyry Cu-Mo-Au deposits just west of Salt Lake City. Jackling concluded that the low-grade, Cu-bearing rock could be mined economically at a large scale using steam shovels and railroad cars to transport the ore to a mill beyond the mouth of the canyon. Although few people took Jackling's ideas seriously, he was backed by Spencer Penrose, Charles Tutt and Charles MacNeill, all of whom had been involved previously in mining and stock promotion at Cripple Creek, Colorado, and elsewhere (Mining Hall of Fame Inductee Database http://www.mininghalloffame.org/inductees). Spencer Penrose solicited the advice of his brother, Richard Penrose, a geologist best known to the geological community for his subsequent financial contributions to the Geological Society of America and Society of Economic Geologists, who concluded that the idea might work.

In 1904, Jackling constructed a small-scale pilot mill, which was immediately successful, and in 1905 capital was raised to start the world's first bulk mining operation. The Guggenheims became major investors and they went on to develop the large Chuiquicamata mine in Chile using similar bulk methods. Open-pit bulk mining of low-grade Cu ores, particularly in porphyry Cu deposits, was adopted widely. Jackling's use of a pilot plant at site to demonstrate the technical and economic viability of his approach also became the accepted method of proving new technologies in the mining industry, and remains so today.

4.3.2 Concentrates – froth flotation

Many metal ores consist of metal sulphide or oxide minerals containing metals of economic interest. Base and precious metal sulphide minerals constitute 1 to 90 % of the ore, the remainder being unwanted silicate, oxide and carbonate minerals. To recover the metals, the first step is to separate the sulphides from other minerals, a process known as beneficiation. Froth flotation was developed in the early part of the 20th century for this purpose by exploiting the variable hydrophobic-hydrophilic character of minerals. It is one of the most important advances in the past 150 years of mining and the result was a dramatic decrease in processing costs, which impacted base metal prices and enabled the mining of lower grade ores. Development of the technology spanned over 50 years with contributions from workers in several countries (Furstenau *et al.*, 2007; Parekh and Miller, 1999) but widespread adoption was stalled by litigation that was eventually resolved by the US Supreme Court. Froth flotation was used extensively from the 1920s and remains the major mineral separation technology in use today.

Before undergoing flotation, ore must be crushed and ground to tens of micron to micron-scale particles to liberate ore minerals from waste (gangue) minerals. Crushing and grinding (comminution) is energy intensive, inefficient and has not changed significantly in the last hundred years. The ground material

is passed through a series of flotation cells or tanks where reagents are added: frothers (detergents) to improve the development of bubbles during aeration and agitation; collectors that adjust the surface chemistry of selected minerals to increase their hydrophobicity such that they adhere to the bubbles; and modifiers, activators, depressants and flocculants that optimise the process. The result is that the ore mineral of interest is concentrated on bubbles at the surface of the tank and is selectively skimmed off. By repeating the process, the resulting mineral concentrate captures an increasing percentage of the metal of interest, the final percentage being termed "recovery". Recoveries vary with grain size and complexity of the ore, degree of liberation, and the presence of other minerals that are not effectively suppressed. Recoveries vary from 60-70 % for complex ores, commonly precious metal-rich ores where rejected pyrite contains some of the gold, to >90 % for simple, coarse-grained base metal sulphide ores.

Optimising recovery is critical to the economics of the mining operations. The composition of the primary mineral in the concentrate determines the maximum metal content of the concentrate. For example, concentrates that are sold from Cu mines to smelters and refineries have Cu contents that vary from 20 to 50 %, depending on the dominant mineralogy: the Cu content of sulphides increases from cubanite (23.4 % Cu) to chalcopyrite (34.6 % Cu), bornite (63.3 % Cu) and chalcocite (79.8 % Cu). Smelters require "clean" concentrates with defined maximum levels of deleterious elements. Thus, if the main Cu sulphide is enargite, the resulting Cu concentrate is likely to have arsenic contents that most smelters will not accept without prior blending with an arsenic-free concentrate to reduce the arsenic content to manageable levels. Froth flotation is used to generate commercial concentrates in all base metal sulphide mining operations (Cu, Zn, Pb and Ni) as well as some precious metal mines. It has also been used to separate coal from ash, as an alternative to heavy media such as finely ground magnetite, and is one of the preferred techniques for separating bitumen from host rocks in oil sands.

4.3.3 Metallurgy and new materials

From the late 19th century, roasting and smelting were the primary methods to extract metals from ores or concentrates. Initial open-air roasting and smelting of sulphide ores released significant amounts of SO_2, causing extensive environmental damage, and some of the earliest opposition to mining (*e.g.*, the 1888 riots in Rio Tinto, Spain; Harvey, 1981).

Known as pyrometallurgy, smelting is still the method used to produce the majority of Cu, Zn and Ni from sulphide concentrates, as well as a significant proportion of precious metals, particularly Pt, Pd and other platinum group metals. Modern smelters have become increasingly efficient and now capture virtually all of the SO_2 and other noxious gaseous emissions. Blast furnaces to produce Fe were also well established in the 19th century and continue to be used today albeit with significant improvements. Blast furnaces remain the

most efficient method for the bulk reduction of Fe ore in the presence of coking (metallurgical) coal, although electric arc furnaces are used to process recycled scrap and other direct reduction methods are under development.

As metals became more widely available, metallurgical and material science research led to new products. During the First World War, the German company Krupp discovered that the addition of minor Mo to steel greatly increased the melting temperature and hardness of steel for use in armaments (Abraham, 2015). The addition of Mo and other alloy metals to improve steel became common practice. More recently, considerable effort has been made to reduce the weight of steel while maintaining its strength and performance, for example by adding small amounts of Nb. The need for lighter cars with corresponding increases in fuel efficiency and lower greenhouse gas emissions is the major incentive for decreased vehicle weight, while strength must be maintained for safety. Similar efforts are underway with Al alloys that already represent a growing substitute for steel in vehicles.

Smelters built during the mid- to late-20th century to recover metals from polymetallic sulphide concentrates (Cu-Ag-Au, Cu-Ni, Zn-Pb) are also capable of recovering minor amounts of precious and other specialty or rare metals (Fig. 4.5). These represent significant by-products, some of which add to the sale value of the concentrate, while others are only recognised and recovered by smelters or refiners that benefit from the additional revenue. In recent years, the profile of these metals has become more significant due to their use in defense, communication devices and clean technologies, and some are regarded as critical because of their specialised use and their restricted supply from one or two countries.
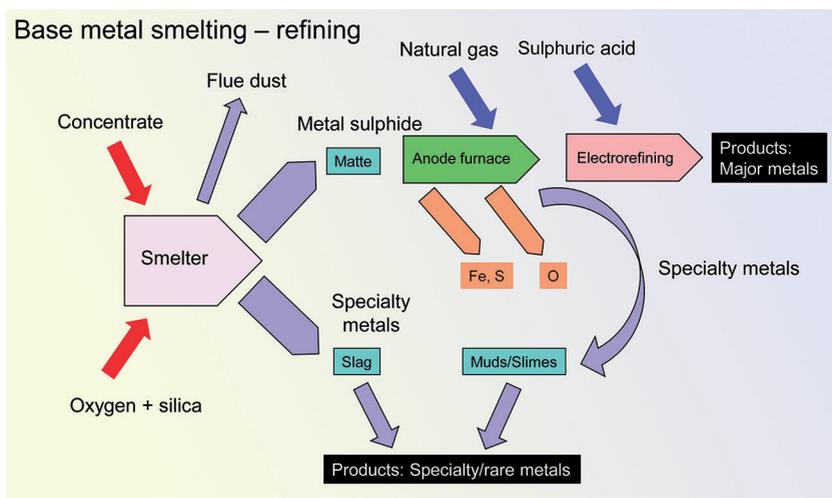

Figure 4.5   Simplified flow sheet for a base metal (Cu, Zn, Pb) smelter-refinery process producing both major commodities and minor (specialty/rare) metals.

The geological and mineralogical distribution of some of these elements and their status as minor by-products makes them dependent on the major element markets, further complicating their supply; examples include Bi, Ga, Ge, In, Se and Te. Given the importance of critical metals and materials, there is increased effort to improve the understanding of their geochemical behaviour, to find new supplies and enhance recovery from ores, and to increase recycling – all of which represent major challenges (National Science and Technology Council, 2016; US Department of Energy, 2011).

4.3.4 Hydrometallurgy – heap leaching, solvent extraction and electrowinning

Hydrometallurgy, the alternative to pyrometallurgy, was established in 1887 when Carl Bayer successfully leached bauxite with NaOH at elevated temperature and pressure to produce alumina. At the same time, Charles Hall and Paul Heroult developed a method involving electrolysis of Al_2O_3 in a molten bath of cryolite (Na_3AlF_6) to produce Al from alumina (Habashi, 2005). These discoveries transformed Al from an expensive commodity to a relatively inexpensive and widely used product.

Work on hydrometallurgy continued and by the mid-20th century researchers began to look at direct leaching of ores combined with various methods to recover the metals from the leachate, or lixiviant (Habashi, 2005). Dilute sulphuric acid was recognised as an effective leachate and was used to recover Cu from low-grade ores in the mid-1900s. Electrowinning, which was also known from the mid-1850s, was used to electroplate Cu, but it was not until 1968 that both vat and heap leaching of Cu ores were established with electrowinning of the pregnant solution used to recover Cu metal (Kordosky, 2002). The problem, however, was that the solutions were too dilute in Cu and too impure to plate pure metal (Schlesinger *et al.*, 2011).

Solvent extraction was also recognised in the late-19th century and was used extensively during the Second World War to recover U, but attempts to apply the approach to Cu failed (Kordosky, 2002). In 1965, a group working at General Mills created an organic reagent that could extract Cu at low pH. The use of this reagent for solvent extraction of Cu from pregnant solution was attempted at the Bluebird mine in Arizona in 1968, which eventually led to commercial application of solvent extraction electrowinning (SX-EW) methods to treat low-grade oxide and supergene chalcocite-enriched Cu deposits. Adoption was initially slow but gathered pace through the 1970s and '80s in the US, and was eventually used extensively in Chile by the 1990s. This technology story (Bartos, 2002), including the inability of General Mills and partners such as Ranchers to keep control of the intellectual property, and the slow adoption of the technology, particularly in Chile, illustrates the challenges related to radical innovation in the mining industry. Regardless of the slow adoption, SX-EW technology eventually allowed economic processing of low-grade Cu ores (<0.5 % Cu) and effectively decreased the average cost of Cu production across the industry in the 1990s (Fig. 4.6; Schodde, 2010).
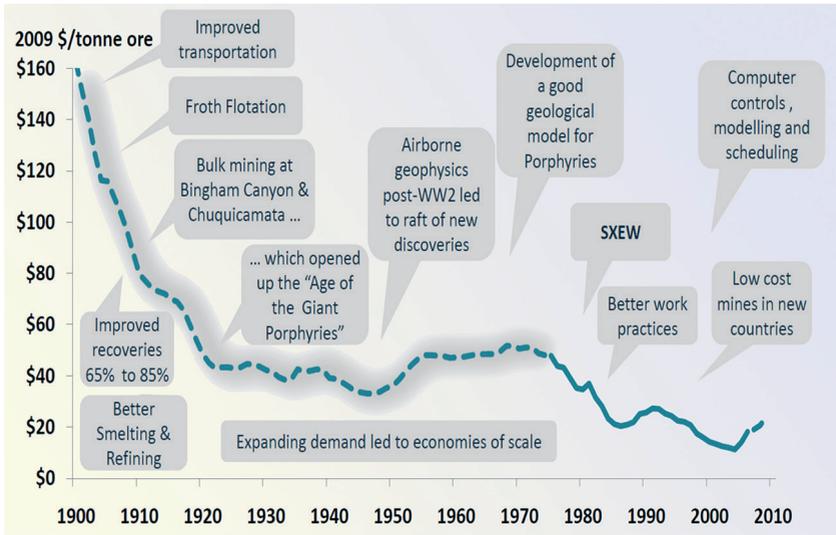
Figure 4.6 Relationship between technological developments and declining estimated average operating costs (inflation adjusted) for copper mines in the western World 1900-2009 (from Schodde, 2010). Estimates include transportation, smelting and refining costs. Sources: Minex Consultants estimates (1900-1974), and Brooke Hunt and CRU historical reports. The solid line indicates increasing availability of global data.

As SX-EW was changing the Cu industry, heap-leach extraction was also established for the recovery of low-grade Au (Marsden and House, 2006). The discovery of Au solubility in cyanide solutions was made in 1867 and patented for the extraction of Au in 1887. The technology was used extensively in the Witwatersrand goldfields of South Africa from 1888 onwards. Leaching was carried out in tanks and several methods were used to recover Au from the pregnant solution. The use of activated carbon to capture the Au through carbon-in-leach and carbon-in-pulp technologies, followed by stripping and regeneration of the carbon, was a major breakthrough. Cyanide leaching is only effective for leaching native Au or electrum, and other methods were developed to process sulphide-rich Au ores, including flotation, roasting and pressure oxidation.

The rapid increase in Au price in the 1970s (by a factor of five) provided a strong incentive to exploit low-grade Au ores (1-2 g/t Au) using dilute cyanide solutions to leach ore piles (heaps) on pads lined with rubber to prevent contamination of the environment. First used at a large scale at the Round Mountain mine, Nevada, many new mines were developed to exploit thick oxide zones, formed from deep weathering, containing native or free Au overlying deeper and more refractory, Au-bearing sulphide mineralisation. The soft oxide zones are typically mined easily and moved to heaps for leaching, the result being relatively

low capital costs and rapid start-up, aiding the economics of mine development. Nevada became one of the world's leading Au producers using this method and others soon followed, particularly in regions such as Australia and the Andes where deep supergene oxidation is common. Unlike Cu, the low operating costs of heap-leach Au operations did not affect the gold price, which has traditionally been relatively independent of production costs.

Heap leach recovery of Cu and Au has been a major source of both commodities over the past 20 years (*e.g.*, ~10-20 % of mined Cu) and has been used selectively and investigated for other commodities (*e.g.*, Zn and Ni). Processing has become more sophisticated with use of bacteria to enhance leaching, careful optimisation of leach conditions to match mineralogy, agglomeration of clay-rich ore into coherent material to maintain permeability in heaps, and controlled aeration to maximise leaching. In spite of advances, however, leaching of Au from ores containing both Cu and Au remains problematic due to competition by both metals for the cyanide in solution. Given that heap leaching can be applied only to weathered Cu and Au ores, it is likely that this process option will become less important unless new leach solutions capable of selective dissolution of a wider range of metal sulphides are developed.

4.3.5 Digital technology, automation and scale

The development of the computer and the application of digital technology resulted in major, and ongoing, changes to mining and processing. Geological, geophysical, geochemical and assay (grade) data, which are collected during exploration drilling, are routinely incorporated into 3D databases that form the basis for ore body modelling and resource estimation (Section 3). In addition, physical rock property (density, hardness), geochemical, mineralogical, and textural measurements are combined into geometallurgical models to determine process choices and performance metrics. Mines are planned, designed and optimised using these data through appropriate software, with the results used to define ore reserves, the scale of mining, scheduling, and assessment of overall economic feasibility though the life of the mine.

Once in production, the mine is operated with the assistance of GPS such that vehicle and material movement can be tracked in real time, and can be reconciled through GIS software with the 3D mine plan. Sensors and cameras are ubiquitous in modern mining operations, monitoring vehicle performance, material quality (*e.g.*, moisture content), process optimisation, and waste management. For example, cameras above flotation tanks measure the bubble size with the data being integrated through process control systems that adjust reagents to optimise recovery. Modern underground mines have Wi-Fi communication systems that provide continuous data and instructions to direct operators of equipment and to adjust mining plans in real time.

One of the more dramatic changes is the use of robotics, including remotely operated and autonomous vehicles in mines, all facilitated by digital technology. In 2015, Rio Tinto, one of the world's major Fe ore producers, announced that two of their Fe ore mines in the Pilbara of Western Australia have deployed fully automated driverless trucks (*Financial Times*, October 2015). This will become more common in the future, not only in open pit mines but in large underground mines where remotely controlled equipment is already used (*e.g.*, the Kiruna Fe mine in northern Sweden). Remote technology will be especially helpful in deeper, hotter and more geotechnically challenging underground mines.

Increasing demand for metals over the past 50 years, combined with technological improvements, have led to a significant increase in the size of mining operations. The world's largest mines now move in excess of one million tonnes of rock every day, consisting of a mixture of ore that goes to the mill and waste that is placed on dumps. Over this period, trucks have gone from a capacity of 100 tonnes to over 350 tonnes with concomitant increases in the size of shovels, crushers, mills and other equipment. The increase in size has been driven by economies of scale and the desire to maximise throughput, although over-reliance on single pieces of large equipment can increase downtime during maintenance or breakdowns. Digital technologies have supported the increasing scale of mining operations and improved equipment performance, but the fundamentals of large-scale mining has remained largely unchanged.

4.3.6 Health, safety and the environment

The mining industry has a tragic history in terms of human health and safety, similar to other heavy industries and the construction of massive infrastructure that developed during and after the Industrial Revolution. Coyle (2010) quotes Herbert Smith, then President of the Miners Federation of Great Britain, who stated that in 1923 five people died and 850 were injured every day in the UK coal industry. The environmental record was equally dismal, both as a result of poor practices and a virtual lack of concerns related to obvious impacts.

Over the last 50 years, there have been dramatic improvements in health and safety although there is still room for further improvement in some jurisdictions. Change occurred progressively through regulations, increased awareness, and significant new approaches in terms of operating and corporate cultures. In the best performing companies and jurisdictions, safety is considered a fundamental priority and nobody accepts that accidents are inevitable. A range of sensors are being deployed to monitor equipment and assist operators of heavy equipment in reducing collisions, fatigue and unsafe practices. In advanced jurisdictions, mining now has safety records that are better than other industrial sectors (*e.g.*, Canadian data from the Association of Workers' Compensation Boards of Canada (AWCBC), 2015).

In most jurisdictions, environmental performance is mandated and monitored. The industry has moved significantly to adopt sustainable practices in environmental areas such as water and biodiversity. In many cases these are governed by regulations as well as voluntary initiatives developed by industry associations, non-governmental organisations and individual companies. As with health and safety, sensors are used to monitor environmental issues such as vibration, dust, and effluent. In some cases, data are live and available to local communities.

Changes to environmental performance have affected mining and processing at operations, and downstream facilities such as smelters and refineries. The latter, in particular, have advanced significantly to reduce emissions and effluent while producing an increased range of major and minor metal products. Solid waste, including rock and tailings at mines, and residues and slag from smelters and refineries, still represent a significant challenge for safe long-term storage in terms of volumes, acid-rock drainage, and the potential release of toxic elements. Regulators and the industry continue to seek improvements in waste storage, treatment of run-off and reclamation (*e.g.*, 2016 changes to the mining code in British Columbia in response to the Mt. Polley tailings spill in 2014; http://www2.gov.bc.ca/gov/content/industry/mineral-exploration-mining/health-safety/health-safety-and-reclamation-code-for-mines-in-british-columbia/codereview). Similarly, spills of cyanide solution related to Au mining operations have caused considerable concern although fortunately the effects are short term. The Au mining industry has supported efforts to reduce the risk of such spills (*e.g.*, the ICMM International Cyanide Management Code; http://www.cyanidecode.org/).

4.4 Modern Mining and Processing Methods – Importance of Deposit Types

The mining and processing methods used to recover metals in the form of concentrate, bulk materials, or semi-pure metals at mine sites depend significantly on the geology of the ore deposit (Section 2). Critical factors include geometry, depth below surface, size, grade (concentration) of the commodity of interest, mineralogy, and the physical and chemical properties of the ore and waste. Table 4.2 summaries the major mining and processing methods and their relationship to commodities, ore deposit types and mineralogy. Critical features of four major types of mining and related processing are illustrated schematically in Figure 4.7.

Large surface mining operations with open pits are used for bulk commodities such as coal and Fe ore, where mining is carried out at massive scales (>one million tonnes/day). Both commodities were mined dominantly by underground methods in the past. The health and safety challenges related to underground coal mines are severe but have been mitigated by new mechanised methods such as longwall mining. International thermal and metallurgical coal (for Fe

blast furnaces) markets are supplied largely by open pit operations in Australia, western Canada, Colombia and the western United States. Similarly, internationally traded Fe ore is dominated by high-grade, hematite-rich ores (62-66 % Fe) mined by open pit methods in the Carajás region of Brazil and the Pilbara of Western Australia. Magnetite-rich Fe ores are also mined, usually by open pit but also underground (*e.g.*, the giant Kiruna mine, northern Sweden).
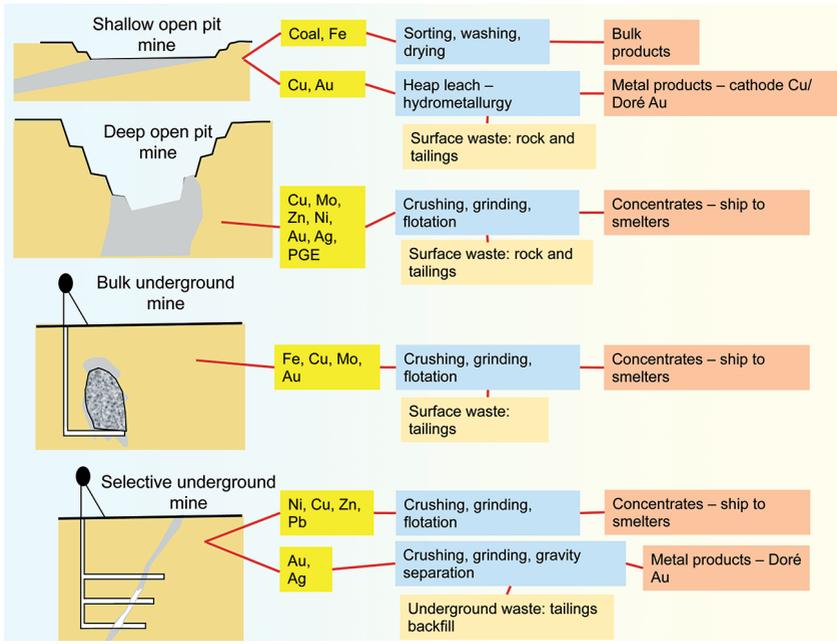

Figure 4.7   Simplified schematic examples of four deposits with different ore body geometries (in grey) and hence different mining methods. The commodities (yellow highlight), processing method (blue highlight), waste (tan highlight) and products (brown highlight) are shown.

Modern bauxite and Ni laterite mining are surface mining processes. Nickel laterite deposits formed from tropical weathering of nickel-rich protoliths during the last 20-30 Ma and therefore are close to the current land surface, but older palaeolaterites are also mined in some areas, including deposits where the lateritic land surface has been tilted and covered by younger sediment. The secondary mineralogy in nickel laterites determines the processing method, pyrometallurgical or hydrometallurgical, and in both bauxites and laterites, the presence of clay-rich weathered rock can present a significant challenge in terms of material handling.

Table 4.2	Major types of mining and processing methods as determined by deposit types, mineralogical characteristics and products.		
Deposit character	**Commodity**	**Mining method**	**Processing**
Near-surface, laterally continuous, relatively flat layer of valuable rock/ore	Coal, iron ore, bauxite (alumina), lateritic nickel, aggregates	Large shallow open pit (typically <50 m in depth) mined with shovels, trucks and conveyers; or, long strip mines using drag lines advancing perpendicular to the strip followed by reclamation	Products may be ready to ship with limited crushing and washing, or may require processing at or close to site (bauxite, nickel laterite)
Near-surface, disseminated low grade (<1 % of the metal of interest in sulphide)	Base and/ or precious metals, most commonly porphyry copper deposits	Open pit (typically 100->1000 m in depth) with large-scale drilling and blasting and material movement: shovels, trucks and conveyers	Crushing, grinding, and flotation to separate the "ore mineral(s)" from gangue (waste) minerals – concentrate with 15-60 % metal grade shipped to smelter; precious metals may be recovered at mine site by gravity, roasting, leaching or included in concentrate
Below ~200 m – as above	As above	Underground caving – variety of methods (sublevel, panel and block caving) that mine large volumes of ore from below to be transported to surface; significantly less waste and surface disturbance than open pits	As above
Near-surface, disseminated low grade, <0.5 % of the main metal in soluble ore mineral	Copper, zinc or gold	Open pit with large scale material movement: shovels, trucks and conveyers	Put in pile (heap) or vat and leached to dissolve metal, followed by recovery (SX-EW for copper and zinc), or cyanide-carbon recovery for gold

Deposit character	Commodity	Mining method	Processing
High grade polymetallic sulphide typically with discrete ore-waste contacts	Base metals and precious metals, most commonly in SEDEX or VMS deposit	Small open pit at surface or underground to 3000 m or more (decline near surface, shaft for greater depth)	Underground crushing, surface grinding and flotation to produce concentrate
Narrow high grade mineralised structure (vein) or layer	Precious metals, most commonly epithermal or orogenic gold vein	Selective underground mining in small stopes using small mechanised or handheld equipment; typically backfilled with paste from tailings and waste; design dependent on geometry	Underground or surface crushing, surface grinding and flotation (base+/-precious metals) or gravity, roasting' leaching (precious metals)
Disseminated ore in a permeable sandstone horizon or distinct bed	Uranium, potash and some copper	*In situ* leaching of low-grade ore to recover metal (U, Cu) or solution mining of the complete bed for potash	Hydrometallurgical recovery (solvent extraction) or precipitation of potash
Active or paleo river beds and offshore equivalents (placers)	Gold, diamonds, platinum-palladium, rutile, ilmenite and aggregate	Dredging of gravels at small to large scales	Concentration through size separation (*e.g.,* screens) and gravity

Unlike the bulk commodities, base and precious metals are concentrated in a wide variety of geological environments and deposit types. As a result, a number of mining methods are used for different deposit types, and similarly several processing options are tailored to individual deposits. Near-surface deposits are mined using open pits, and given the typically higher value of the ore, strip ratios (the volume of waste rock removed relative to the volume of ore during the life of the mine) can be much higher than for typical bulk commodities. Deeper deposits are mined using underground mining methods, which can be highly selective for valuable ores or less selective using bulk underground methods. Depth, geometry, grade and size determine specific mining methods.

Base and precious metal mines each have distinctive flow sheets (Fig. 4.8) with some unique aspects being designed to optimise the economic recovery of the specific minerals that host the metal, or metals, of interest at an appropriate scale. There are also several types of products, ranging from concentrates of various types (15-60 % of the metal of interest) to virtually pure metal, and this

influences the infrastructure needed to ship products to specific customers. For example, Au mines typically produce Au-Ag (Doré) bars at the mine site, greatly reducing infrastructure requirements for shipping products and allowing some high-value Au mines to operate in extremely remote locations.
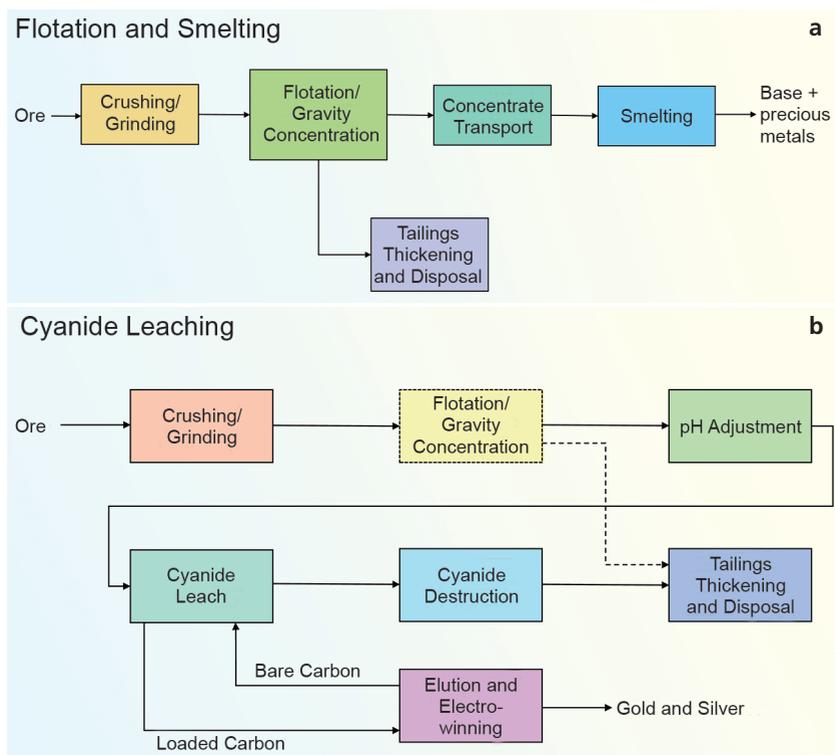

Figure 4.8 **(a)** Simplified flow sheet for the mining, mineral processing and smelting of base metal sulphide ores that may also contain precious metals. **(b)** Simplified flow sheet for the mining and processing of Au ores using gravity or cyanide leaching for extraction of Au.

Some commodities are amenable to *in situ* or solution mining (*e.g.*, potash and U). This has significant appeal due to greatly reduced development and infrastructure costs. It is, however, only possible where (i) the mineralogy allows the material hosting the metal or commodity of interest to be dissolved, (ii) good permeability allows the leachate to contact all ore minerals (no channeling of the fluid), and (iii) leachate flow can be controlled to remove the risk of contaminating local aquifers. The potential for *in situ* leaching of Cu has been considered for years and is currently being pursued in Arizona (Sinclair and Thompson, 2015).

The Au rushes of the 19th century were driven at least initially by the search for placer deposits containing fine particles and nuggets in active, or recently active, stream beds. These operations dredged large volumes of sand and gravel and concentrated Au *via* gravity methods, often with disruptive consequences for the stream. Commercial placer mining continues today, generally at relatively small scales with better management in jurisdictions with clear mining codes. Offshore placer mining for alluvial diamonds is active off the coast of Namibia in shallow to moderately deep water.

In developing countries, artisanal placer and residual Au mining is still active and although it accounts for only 20 % of global Au production, the environmental damage is significant. Major artisanal mining districts involve thousands of workers (including children) with little or no regulatory control of run-off, health and safety, or the use of Hg to amalgamate Au. Much of the Hg used in artisanal mining is dispersed during burning of Hg-Au amalgam, resulting in significant emissions and widespread impacts. Efforts to reduce and control artisanal placer mining and related pollution are underway (*e.g.*, work by the United States Environmental Protection Agency; https://www.epa.gov/international-cooperation/reducing-mercury-pollution-artisanal-and-small-scale-gold-mining).

4.5 Copper Deposits, Mining and Processing

The types of Cu deposit and related mining and processing methods are discussed below and summarised in Table 4.3. Copper is a diverse metal and forms deposits in at least six different geological environments (Table 4.3). Mining methods vary among, as well as within, these types of deposits. Processing is focused on two major methods and products; concentrate for smelters and cathode Cu sold directly to the market.

Table 4.3	Types of Cu deposit and applicable mining and processing methods.

Deposit type	Mining and processing	Resource opportunities/risks
Porphyry – sulphide (hypogene) Cu+/-Mo+/-Au + skarn deposits in some cases	Bulk open pit or underground caving, grinding and flotation to produce concentrate	Open pits becoming increasing large and deep – increasing cost, plus more waste, and potential environmental and geotechnical concerns. Increasing development of underground caving operations – new deep resources with low waste, high initial capital but low operating costs and lower cut-off grade.

Table 4.3   Cont.

Deposit type	Mining and processing	Resource opportunities/risks
Porphyry – secondary oxide or sulphide (supergene) Cu	Near-surface deposits – shallow pits; ore placed on large leach pads, leached by dilute sulfuric acid (bacterially assisted), with SX-EW recovery	Significant increase of leach operations (1985-2000), but near surface leachable resources in decline; potential for more efficient leaching of low grade dumps and development of subsurface *in situ* leaching, and new approaches to leaching transition (partially oxidised) and hypogene (primary sulphide) zones; – success of these approaches could result in significant new low cost resources.
Sediment-hosted Cu+/-Co+/-Ag	Well-defined ore layer mined underground or in shallow open pits for near-surface ore; most mines using grinding and flotation to produce concentrate – rare hydrometallurgical treatment at mine sites	Increased resources at depth – shallow-dipping thin layers are difficult to mine efficiently. New discoveries (*e.g.*, Kamoa) – laterally extensive resource. Potential for improved technologies (sorting, leaching) to enhance economics.
Volcanogenic massive sulphide (VMS) Cu+/-Zn+/-Pb+/-Ag+/-Au	Zones of massive sulphide mined selectively underground (historical open pits but few now operating); flotation to produce one or more concentrates of different metals	Value of VMS deposits enhanced by relatively high grade and polymetallic character – not as reliant on price as single commodity deposits; many deposits found (1960-80) using geophysics and emerging seafloor geological model; considerable potential remains below geophysical penetration depths; complex ores can be problematic – hydrometallurgical treatment of bulk concentrates may be possible.
Iron-oxide copper-gold (IOCG) Cu-Au+/-U+/-Mo+/-REE+/-Re	Overall similar geometry and grade to porphyry deposits – bulk mineable open pits – plus smaller high grade zones suitable to selective underground mining; processing similar to porphyry deposits	Poorly understood class of deposits with complex geometry and metallurgy (*e.g.*, high F and U) that hinders formation of clean Cu concentrate; additional potential with large scale mining (Olympic Dam) and more selective mining of high-grade zones (Candelaria) plus recovery of magnetite.
Magmatic sulphide Cu-Ni+/-PGE	Low- to high-grade deposits mineable by bulk and selective methods; grinding and flotation for separate Cu and Ni concentrates (or bulk Cu-Ni); challenge to optimise recovery of PGE if present	Very significant low-grade resources (*e.g.*, Duluth, USA) but with metallurgical challenges; potential for hydrometallurgical methods to unlock value at mines sites.

4.5.1 Porphyry – Cu ± Mo, Au

Porphyry Cu deposits account for approximately 65 % of annual global Cu production. Deposits are associated with porphyritic intrusions and consist of large volumes of rock, typically including the porphyritic intrusions, with low grade Cu (0.2-1.5 %) in irregular pipe-like bodies on the order of 1 x 1 km in cross-section and up to 3 km in depth (Section 2). Given the volume and grade, the majority of these deposits are mined by open pits that are commonly roughly circular and can be over 1 km deep. Increasing amounts of waste must be removed to allow the pits to access mineralised material at depth, and when this is no longer economic, the deposit must be mined by underground bulk mining that has become increasingly efficient in recent years. It is now economic to mine ore underground with relatively low Cu grades around 0.5 % Cu ± Au-Mo, especially once capital cost is recovered from mining higher-grade material initially (*e.g.*, Cadia in New South Wales; Wood *et al.*, 2010). Table 4.4 provides a comparison of the site and mining costs for Cu-Au mining operations relative to their mining rate based on indicative numbers (2002 data; Wood *et al.*, 2010). In this analysis, the costs and Cu/Au cut-off grades are comparable for open pit and underground panel and block caving. The challenge for underground caving operations, however, is a combination of the significant capital required prior to production and risks regarding how well the process will work. Efforts to minimise risks are becoming increasingly sophisticated and effective. Copper-rich skarn deposits associated with some porphyry deposits are mined by similar methods, although geometrical complexity related to structural and stratigraphic controls may necessitate more selective underground mining to minimise dilution (*e.g.*, Bingham Canyon, Grasberg-Ertsberg). Complex mineralogical variation resulting from multiple overlapping skarn hydrothermal events requires careful geometallurgy with definition of ore types, separate or batch processing, and the sale of different concentrates (*e.g.*, the Antamina Cu-Zn mine, Peru).

Table 4.4	Indicative production rates, site and mining costs, and equivalents cut-off grades for four types of mass mining in 2002. Costs to indicate relative economics of different mining methods, with panel and block caving being the least expensive (Wood *et al.*, 2010; A.S. Logan, personal communication, 2002).

	Open pit, 5:1 strip ratio	Panel and block caving	Sub-level caving	Stoping
Mining rates (Mt/y)	17	16 (5 to 50)	5 (1 to 25)	3 (1 to 14)
Site costs ($/t ore)	11	9 (7 to 12+)	16 (13 to 20+)	15 (14 to 20+)
Mining costs ($/t)	7 to 8	4 (3 to 6)	8 (6 to 12+)	13 (10 to 20+)
Cut-off grades Au (g/t equivalent) Cu (% equivalent)	0.75 0.6	0.65 0.55	1.15 0.85	1.45 1.05

The scale of mining for porphyry Cu deposits requires efficient material handling *via* large shovels, trucks, conveyor belts, crushers and grinding circuits, all of which consume large amounts of energy. The ground ore is typically treated by flotation to recover a Cu concentrate (Fig. 4.8a); if Au is present, it usually reports to the Cu concentrate, but if some of the Au occurs as discrete grains, it may be recovered directly by a separate gravity-based circuit. Molybdenum, if present as a by-product, requires a separate recovery process to produce a Mo concentrate. Other trace elements of economic interest may be recovered from the concentrate (*e.g.*, Ag, Pd, Pt, Te, Se).

Copper grade varies within porphyry deposits. Access to higher-grade material in the early years of mining reduces the time to pay off the capital cost and therefore improves economics. Similarly, the presence of recoverable concentrations of other elements (*e.g.*, Mo, Au and Ag) increases revenue. Many porphyry deposits exhibit extensive low-grade halos (<0.2 % Cu), which may become economic if Cu prices increase, particularly once infrastructure is established and capital costs are paid off. In some mines, this material is retained in low-grade stockpiles during stripping to reach material with more economic grades. Low-grade stockpiles represent a modest but easily accessible resource for the future.
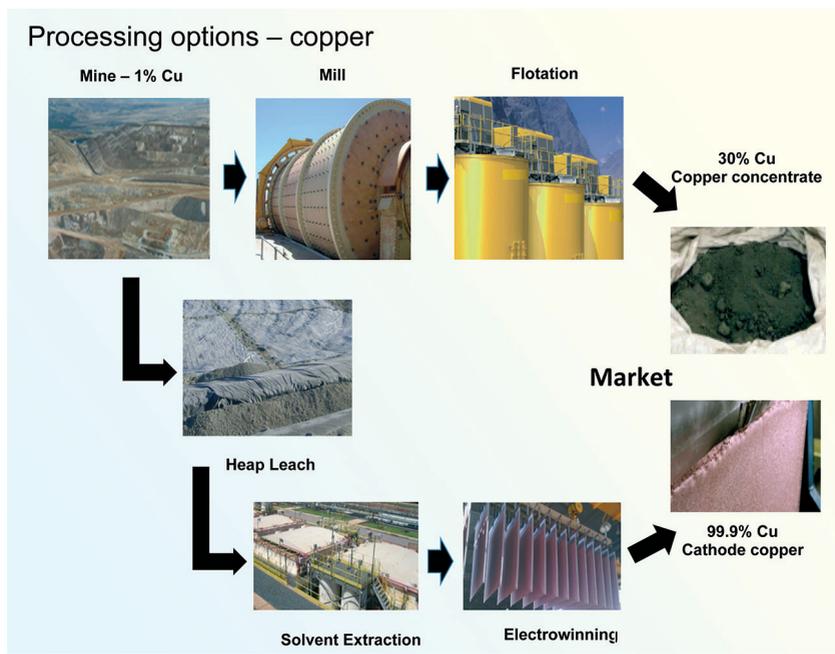

Processing options – copper

Mine – 1% Cu   Mill   Flotation

30% Cu
Copper concentrate

Market

Heap Leach

99.9% Cu
Cathode copper

Solvent Extraction   Electrowinning

Figure 4.9   Schematic diagram illustrating the two different processing routes and product options for Cu deposits.

4.5.2 Supergene oxide and sulphide-enriched porphyry Cu

Some porphyry deposits have undergone weathering that created oxide Cu ore and/or supergene enrichment blankets dominated by secondary chalcocite (Section 2). In some cases, the Cu moved a considerable distance (1-5 km) away from the source porphyry deposit before re-precipitating with Fe and Mn as "exotic" deposits in gravels. Since these deposits all formed relatively close to the surface, due to surface weathering processes, shallow open pit mining is used. The ore is crushed and placed on large, gently sloping pads built on impermeable liners (Fig. 4.9). Dilute sulphuric acid is added by drip feeders at the top while air is fed from below. Most Cu oxides and related supergene minerals dissolve and the Cu-bearing pregnant solution is recovered at the base of the pad. Chalcocite-rich supergene ores typically require bacteria to enhance oxidation and dissolution of Cu, and managing the leach pad temperature, acid flux, and air flow are critical to success. Copper is recovered from the pregnant solution by SX-EW, with >99 % pure Cu cathode being the sole product (Fig. 4.9).

4.5.3 Sediment-hosted – Cu ± Ag, Co

Sediment-hosted Cu deposits comprise high-grade (1-5 % Cu), thin (5-25 m) layers in sedimentary sequences at the interface between reduced units above and extensive oxidised units below (Section 2). In some sedimentary basins the economic layer is flat lying or gently dipping (*e.g.*, Kupferschiefer of north-central Europe and the newly discovered Kamoa and Kakola deposits in the Democratic Republic of Congo, but in other areas deformation has tilted, folded and thickened the economic interval (most of the deposits in the Central African Copperbelt of Zambia and the DRC). Near-surface deposits have been mined by open pits, but the bulk of production has come from underground mines developed to exploit thin mineralised intervals typically with some dilution from barren rocks above the ore. The ore is usually crushed underground and taken to surface *via* shafts or declines (tunnels), where it is ground and Cu concentrate is recovered by flotation. Some of the near-surface oxidised and mixed sulphide-oxide supergene ores in Zambia and the DRC are treated by heap leaching and SX-EW as well as flotation.

4.5.4 Volcanogenic massive sulphide (VMS) – Cu ± Zn, Pb, Au, Ag

VMS deposits represent a family of deposit types that vary in tectonic setting, association with different volcanic rocks, and the concentration of several metals (Cu, Zn, Pb, Au, and Ag) (Section 2). The mining methods for VMS deposits are generally selective and commonly underground, but processing methods to produce concentrates may be complex. VMS deposits have relatively high-grade ore, massive to semi-massive (>75 %) sulphide and, in some deposits, lower-grade, footwall sulphide-rich stringers and stockwork veins. Selective mining of high-grade deposits can be economic to considerable depths (*e.g.*, >3000 m at Kidd Creek, Ontario), but a key issue can be dilution by unmineralised

wall rocks. Fine-grained and complexly intergrown sulphides (*e.g.,* chalcopyrite and sphalerite) can hinder production of separate clean (marketable) Cu and Zn concentrates (*e.g.,* Wills and Finch, 2016). Recovery of precious metals can also be an issue, with Au being retained in pyrite, which is intentionally suppressed during flotation and is therefore sent to tailings. These complexities have hampered development of some deposits.

In the past ten years there have been efforts to find, evaluate and potentially mine recently formed seafloor massive sulphide (SMS) deposits (*e.g.,* Nautilus Minerals' work in the Bismark Sea, Papua New Guinea). This effort had to overcome technical challenges related to deep sea mining, and the ore may also exhibit the same mineralogical complexity to that in ancient, now on-land VMS deposits. There has been opposition to mining on the seafloor, but the Bismark Sea is within the national waters of Papua New Guinea who control the permitting process.

4.5.5 Iron oxide Cu-gold (IOCG) – Cu-Au ± U, REEs

Although mined for many years (*e.g.,* in the coastal belt of Chile and the Cloncurry area of Queensland, Australia), IOCG deposits grew quickly in importance following the discovery of Olympic Dam in South Australia in 1975 (Haynes, 2006). This class of deposit is complex, highly variable and its exact origin remains uncertain. In terms of size and geometry, large IOCG deposits are similar to porphyry Cu deposits, although smaller deposits are more confined and exhibit strong structural control. In addition to Cu, IOCG deposits can be enriched in other elements (*e.g.,* Au, U, F, and REE) that can be important economic by-products for some mines or deleterious elements for others. Abundant magnetite and/or hematite are recovered in a few deposits. Large, near-surface IOCG deposits are mined in open pits, but the geometry and grades for some deposits are more suitable for selective underground mining. For example, Olympic Dam is located beneath 350 m of post-mineral cover rocks and has been mined underground from the beginning. In recent years, BHP Billiton, the owner, has considered the development of an enormous open pit that would access a significantly larger proportion of the mineral resource (Ehrig *et al.,* 2012).

4.5.6 Magmatic Cu-Ni ± PGEs

Magmatic sulphide deposits are major sources of Ni and PGE production (Section 2) but are also an important source of Cu. Deposits vary from relatively small, high-grade lenses of massive sulphide suitable for underground mining to large, low-grade, disseminated deposits that are mined by open pits. Mining and processing methods are similar to those for VMS deposits, with the challenge in the case of magmatic deposits being to produce clean (marketable) Ni and Cu concentrates that also capture the PGEs if present. Sulphide mineralogy and complex textures can hinder processing and some mines produce bulk Ni-Cu concentrates, or low-grade concentrates (*e.g.,* <25 % Cu) which decreases their

value. These problems have limited the development of the significant Cu-Ni-PGE resources in the Duluth complex in Minnesota, USA (*e.g.*, Dreisinger *et al.*, 2005).

4.6 Current Issues and Challenges

The mining and metal industries are strongly affected by economic cycles and associated changes in commodity prices. To some extent, the industry itself contributes to, and exacerbates, the price cycles by building too much capacity when metal prices are high, at least some of which comes into production when prices are declining, and failing to adjust production during the low-price part of the cycles (*e.g.*, Harris and Kesler, 1996). Any effort to influence prices directly is prohibited by anti-trust legislation, and companies are reluctant to reduce production or close mines for financial, labour and other logistical reasons. As a result, the industry is effectively a price taker rather than a price maker, and medium- to long-term variation of metal prices typically represents the most significant variable and risk when developing new mines.

The markets for most major metals are relatively well balanced between supply and demand, and hence small changes in either can influence metal prices. In the last 10 to 15 years, however, the industry experienced an extreme commodity price and demand cycle driven by Chinese demand; rapid development (the boom of 2003-2012) followed by declining rates of growth (2013 to present). The mining industry responded to high prices by ramping up production to meet the demand, and by building new operations. The costs of new operations increased rapidly due to the escalating cost of raw materials (steel and concrete) and labour. As prices declined post-2012, operations were encumbered with high costs and reduced margins, and for the new operations, considerable debt. The industry addressed these issues by cost-cutting and improvements in productivity with some success, but many of the underlying issues remain. Financial constraints within the mining industry led to a significant decrease in exploration for and evaluation of new resources for most commodities, as well as limited construction of new mines or expansion of existing operations (*e.g.*, Jennings and Schodde, 2016). This will eventually translate into a supply deficit, assuming continued demand, and that deficit will lead to another cycle of higher prices.

Commodity cycles can influence other critical aspects of the mining industry, particularly the ability to deliver resources in a timely, efficient and responsible manner. During the down part of the price cycle, the focus is on cost-cutting, improved productivity and maintaining margins. Driven by necessity, the resulting pressure translates into a focus on continuous improvement. Major changes requiring substantial investments, however, are challenging because of lack of capital. In the high-price part of the cycle, capital is available but there is typically less focus on small changes that improve performance, and major technological changes remain challenging due to fear of disruption from new unproven technologies and potential loss of revenue.

In addition to cyclical effects, other challenges can slow the conversion of mineral resources to ore reserves and the subsequent development of mines. Some are global and influence metal markets, some are the result of jurisdictional politics, and others reflect changing societal attitudes at the global, regional or local scales. Four major issues are summarised below in the context of their impact on resource availability.

4.6.1 Jurisdictional issues

Many countries benefit financially from mining and some are largely dependent on it (*e.g.*, Bolivia, Chile, Peru, Mongolia, South Africa, and Zambia). During the boom that ended in 2012, some countries used the high metal prices to justify increased taxation on mining while others sought to increase ownership positions in existing or new mines, so-called resource nationalisation. Declining commodity prices made some of these policy changes problematic due to loss of revenue and closure of some mines, and related reduction in capital budgets to improve technical or environmental performance. For companies, the level of ownership and taxation is not necessarily a problem as long as the mine remains economic; the challenge occurs when there are sudden changes in policy and taxation during development or early production, with the resultant uncertainty affecting multi-billion dollar investments.

Some jurisdictions also made policy changes to increase local employment and to obtain added value from the production of downstream products; for example, in 2014, Indonesia introduced policies to reduce the export of concentrates and encourage the development of smelters to produce metals in country. Others have used environmental concerns to place restrictions on mining, such as banning open pit mines or cyanide usage. Large open pit mines have a significant footprint, and if not managed well, there is potential for tailings dam failures, acid-rock drainage, and release of toxic elements on a scale considerably larger than for most underground mines. The countries that have banned open pit mining generally have limited or no mining activity and related revenue, although the recent ban in the Philippines is an exception.

In general, the perception (not necessarily correct) that developed countries have been well explored and do not welcome mining has driven exploration and mine development increasingly to developing countries. Some of these countries lack effective environmental controls increasing the potential for environmental or social incidents even if the majority of mining companies observe international standards. A single company that acts irresponsibly can do immense harm to the host country, and given global connectivity, significant damage to the industry as a whole.

4.6.2 Community issues

Mining operations cannot proceed without a "social license to operate" from local communities, indigenous and non-indigenous. The process by which companies seek community approval is integral to "Corporate Social Responsibility" (CSR)

and it requires extensive engagement in order to understand the aspirations and needs of local people, manage their expectations, and provide real and lasting benefits. If communities oppose the development of a mine, significant delays and even termination of the project are possible. Furthermore, once relations with communities have soured as a result of ineffective engagement at the earliest stage (Section 3), whether by the current or a previous explorer, there is little chance of recovery. This is one of the most important reasons why some resources become permanently (or at least for decades) alienated. Efforts by the mining industry to adopt the United Nations Sustainable Development Goals is one of several initiatives to improve relationships between communities and the mining industry, and to seek broader understanding of the role that the mining industry plays in global development (*e.g.*, the UNDP-CCSI-WEF, 2016).

4.6.3 Environmental issues

Increasing environmental awareness, including the damage done by past mining, places mining under considerable scrutiny both locally and internationally. Most jurisdictions now have strict regulations and permitting processes, although some companies strive to meet more rigorous international standards driven by management, boards and, in some cases, activist shareholders, and industry- or NGO-driven voluntary initiatives (*e.g.*, World Economic Forum Report, 2016). Permitting delays are common, even when all prerequisites are met, in large part because mines are exceedingly complicated and some jurisdictions may not have the capacity to review all aspects of the proposed development in a reasonable timeframe. Increasingly there is a need to address cumulative impacts, the added effects of multiple operations in one area, and historical mining legacy issues such as acid drainage from old waste dumps or open adits.

Environmental incidents at existing operations not only cause major problems for the mine in question, but also cast a shadow over the industry in general, and this can delay approvals for new projects globally. The most damaging of these are tailings spills that result in major physical, chemical and biological damage in drainages below the tailings dam, and in the worst cases, loss of life. Breaches of tailings dams at Mt Polley, B.C., King Mine, Colorado, and Samarco, Minas Gerais, all during 2015-16, illustrate the extent of the problem. Reducing tailings, new methods to store tailings, and technologies to improve the safety of tailings dams are being pursued actively by the mining industry.

4.6.4 New materials, substitution and recycling

Metal prices have an important impact on new materials and uses. Significant price escalation increases the incentive to seek substitutes for existing uses as well as new materials that may improve performance. A good example is the effort to decrease or eliminate Nd from magnets (*e.g.*, in hybrid cars; http://www.greencarcongress.com/2016/07/20160712-honda.html). The result can be disruptive to segments of the metal market most exposed to the loss of such customers.

In spite of changing use, the overall demand for most major metals has increased steadily over the last hundred years mainly because of the growing global population and increased affluence among an expanding middle class. The growth in metal flow is expected to continue for the foreseeable future (Graedel and Cao, 2010) but the potential for significant substitution of some metals is also likely (Graedel *et al.*, 2013). Rapid technological developments are most disruptive to metal markets with relatively small volumes; for example, the effect of more electric cars on lithium demand. Recycling is also becoming more important due to societal pressures and the benefits of adding metal produced with less energy and at lower cost compared to mining. Recycling is well established for several major commodities, *e.g.*, Pb and Al and to a lesser extent Fe and Cu (*e.g.*, Section 1; World Economic Forum Report, 2015), but is much more challenging for specialty metals that are used in minor amounts, usually as complex alloys, in consumer goods (Reck and Graedel, 2012).

The combination of jurisdictional, societal, environmental and technical factors may influence the timely development of new mines that will be needed to meet increasing demand. These issues may become more important to the long-term supply of metals than the overall geological availability. Based on an analysis of these issues, the different perspectives used to assess resource availability were evaluated in a World Economic Forum Report (2014).

4.7 Future Developments in Mining and Processing – Implications for Resources

Over the past 25 years or so, the mining industry has increasingly recognised the need for change if it is to continue to deliver commodities that improve the lives of billions of impoverished people (*e.g.*, Thompson, 2015; Bouw, 2016). Critical challenges and potential changes are summarised in Table 4.5. For mining operations, change is driven by productivity, safety and efforts to meet the sustainable development goals defined by the United Nations in 2015 (*e.g.*, the UNDP-CCSI-WEF, 2016).

Resource extraction is a competitive business and most companies seek mining operations with revenue and costs that place them in the first quartile of equivalent operations worldwide. Not only do top quartile operations generate the most revenue for the least cost, they weather down-cycles with comparative ease, are highly regarded for technical, environmental and social performance, and provide the maximum benefit to the parent company, shareholders and other stakeholders. The value of the asset also enables the company to raise additional financing and pursue new opportunities.

Efforts are underway to improve operations on a continuous basis, such as energy reduction and preventive maintenance of equipment; however, these do not address fundamental problems. To meet increasing demand the industry has tended to increase production by mining lower grade ore at higher rates

Table 4.5	Examples of some current challenges facing the mining industry, potential technical and business solutions, and implications for future resources.

Challenge	Solution(s)	Resource implications
Discovery of new quality deposits	Multiple new and existing approaches to exploration with greater focus and more drilling – especially for deep targets.	Discovery of resources for the future; better quality – lower impact.
Ore and waste characterisation – geometallurgy	Improved understanding facilitates optimised mine design, increased operating efficiency, and potential use of more selective technologies.	More efficient mines can exploit lower grade resources and manage waste more effectively.
Declining grade	Discovery of better grade deposits; new selective extraction technologies to increase the amount of metal recovered per unit of rock.	Offsetting grade decline will improve efficiency and energy management; increased mining and processing selectively may make resources economic even where bulk grades are not viable.
Energy consumption	Grind less rock (remove more waste ahead of grinding); new lower energy grinding technology; *in situ* leaching.	Reduced energy and costs may allow mining of lower grade resources.
Water management	Reduce volume and maximise recycling; use seawater, brine or other non-potable water; integrate plans with communities.	Better water management will increase efficiency but more importantly it may increase confidence and acceptance among communities.
Tailings – volume and management (prevent dam failures)	Reduce tailings (more selective technologies above); move to more consolidated paste or dry tailings in arid climates or with sulphide-poor tailings; other approaches needed to avoid acid rock drainage in sulphide-rich tailings.	Similar issue to water; tailings volumes and dam failures highlight mining problems, and may be a major obstacle for permitting and community approval in new mines; solutions will improve mining's reputation and development time lines.
Mine development	Optimise scheduling of ore and waste types to maximise efficiency and minimse impact; improve flexibility – modular design.	As above, permitting issues and delays hinder development and may alienate resources; improved design may alleviate these issues.
Community opposition	Seek new partnership models with communities – involve in design and share benefits.	More investment in time and money up front could unlock resources and accelerate development.

– processing more rock and using more energy for less metal. This works during the peaks of the price cycle but is challenging at lower prices. The focus is shifting toward different approaches that significantly improve efficiency and allow more selective mining, effectively producing more metal from less rock. Major improvements in efficiency and reduced environmental impact are challenging given the scale of large mines, and may require fundamental organisational as well as technical changes. If successful, however, the result may be an increase in the mineral resources that are available for conversion to ore reserves and subsequent mining in the mid- to long-term. Some of the critical technical features associated with these developments are summarised below.

1. New methods have been developed to quantify ore and waste characteristics directly or through proxies and hence define variability in ore bodies at a range of scales. The resulting data are incorporated into geometallurgical models that improve mine plans by anticipating the nature of the rock to be blasted, crushed and ground. Integrated operations can then schedule mining and blending of ore types to reduce energy across the mine and mill, and hence maximise the recovery of the metals or minerals of interest.

2. Data on rock characterisation assembled during evaluation can be augmented by sensors that improve safety and provide real time data on material movement, grade, and the mechanical reliability of equipment. Sensor-based data can be used to update mine plans in real time with critical information relayed to operators so that adjustments can be made. Effective use of big data will align modern mines with manufacturing and production facilities in other industries.

3. Effective use of autonomous trucks and shovels, facilitated by the mine data and sensors discussed above, offers improved safety and performance, reduced numbers of mine site employees and related travel impacts in remote fly-in fly-out operations. Widespread use of automation may generate cultural, employee and community concerns that will need to be addressed during implementation.

4. The combination of exploration and evaluation data and sensors will facilitate more selective mining. Removing waste from ore, and capturing ore in waste will reduce the unintended processing of waste and hence increase the average grade of ore that is processed. The earlier this is done, the more energy is saved. Repeated sorting steps may be used to maximise results, similar to the multiple banks of flotation tanks required to produce high-quality concentrates.

5. Bulk underground caving removes the need for an open pit and related long-term storage of the waste, significantly reducing the mining footprint relative to surface mining at an equivalent scale. Bulk underground mining is an area of considerable research (Chitombo, 2011; Wood *et al.*, 2010) with potential improvements including the use of sorting technologies (above) to remove waste accidently included during

caving, locating processing facilities underground with only concentrate going to surface, and using cemented tailings to backfill panels as they are drawn down, hence removing the need for surface tailings storage. Bulk underground mining provides the economic means to exploit new deposits discovered at depth, and hence increase global resources for base and precious metals (Section 3). These methods will not influence commodities that only occur near-surface and therefore have to be mined by open pits (*e.g.*, bauxite, Ni laterites, supergene Cu and Au ores, limestone and other industrial minerals and aggregates).

6. The ultimate selective approach for the extraction of metals is direct *in situ* extraction, such as, for example, bulk dissolution of halite or sylvite-bearing layers. For metal deposits in which the ore mineral is disseminated throughout the rock, selective *in situ* leaching is needed. This is already used to recover U and has been tested at the pilot scale for Cu. Use of effective leachates, permeability and access to ore minerals, plus hydrologic management are major challenges. Improved hydraulic fracturing technologies, modified for hard rocks, and methods to impose permeability barriers that isolate the leachate (*e.g.*, cryogenic curtains) may be required.

7. Energy consumption and sources are major issues for mining. In particular, grinding is a major energy consumer in many mines. Sorting to increase the amount of metal recovered per unit rock and new grinding technologies are needed to reduce energy consumption. Renewable energy is being introduced at mines, particularly in remote locations that rely on diesel which is costly to purchase and transport to site (*e.g.*, Hamilton, 2016). Power storage, pumped hydro, flywheels or batteries will be required to help renewable energy sources meet the continuous power needs in mines.

8. Continuous efforts are already being made to minimise and recycle water, but further innovation is critical. Seawater or subsurface brines are used directly for processing in some operations with complete or partial desalination to improve performance in some cases. However, desalination requires significant energy and alternatives are needed. Water is commonly the greatest source of concern for local communities and integrated community-operation water management plans may help by providing lasting benefits to communities.

9. In low-grade operations, tailings represent >99 % of the ore that was mined, with a net volume increase due to reduced density after crushing and grinding. In most cases, tailings are mixed with water and are contained behind earth dams that are located to take advantage of topography or existing lakes. The tailings spills mentioned previously demonstrate the pressing need to find new long-term sustainable solutions to tailings management. Options in arid climates and for tailings with low sulphide contents include removing most of the

water before making tailings piles (*e.g.*, dry stacking), or thickening to produce extensive paste layers that dry over time. In selective underground mining, tailings are used to fill the mined-out areas and similar approaches may be developed for bulk underground mining.

10. The two-stage process for producing metals, mining followed by smelting and refining in a different location, is inefficient and isolates mines from product development, new technologies, and customers. Closing the gap between mines and final customers might create benefits. Some mines already produce metals at site (Au and cathode Cu), and in some cases these mines directly supply customers (*e.g.*, some Au and diamond mines) as a certified clean, conflict-free source. Emerging hydrometallurgical technologies can produce metal from concentrate at the mine site (*e.g.*, Dreisinger, 2006), with the advantage that metal production can be integrated with mining and processing, allowing complete optimisation of the mine to metal process. The net benefit may be to decrease cut-off grades, hence making lower grade ores economic and increasing global resources. Environmental benefits include decreased shipping of products (metal instead of concentrate), lower emissions relative to smelters, and easier verification of metal sources.

11. Once built, mines are relatively inflexible and mistakes made at the outset can be extremely costly. Designing mines is challenging because of the many factors that control the success of a project, including ore quality and heterogeneity, metal prices over the mine life, jurisdictional costs and taxes. Many trade-offs need to be considered in terms of scale, capital *versus* operating expenses, location of employees, power and water sources, and location of waste storage. Increased flexibility using modular designs and phased ramp-ups are options for consideration. Building large-scale equipment off-site and shipping by barge, if near tidewater, or perhaps by large airships may increase flexibility and reduce costs.

12. Many jurisdictions require closure plans and, in most cases, bonds to guarantee completion. In reality, many mines increase ore reserves during their life and exceed their original mine life, which then require new closure plans. The task, therefore, is to plan for closure without alienating existing or potential new resources, and expansion plans that may become economically viable during mining, either because of increasing metal prices or new technologies that decrease costs. Many older operating and historical mines have no closure plans and the resulting negative legacy issues are a constant reminder of past bad practices in mining. Remediation inevitably falls to the jurisdiction and taxpayers adding to negative perceptions. New ways to manage and remediate legacy sites are desperately needed, ideally including ways to recover any remaining mineral resources.

13. New sources of the metals to meet future demand will be needed, including frontiers such as the seafloor, metal-rich brines and seawater, or even asteroids (to support space travel). Regardless of the source, having a means to extract these resources physically, chemically and biologically is equally important. For example, although metal-rich nodules and crusts on the abyssal plains of the deep oceans have been known for many years, and a legal framework for exploiting these resources has been established, none of the potential processing methods developed in the past (Agarwal *et al.*, 1976; Fuerstenau and Han, 1983), or more recent alternatives, have been shown to be economically viable. Research to unlock the metals that we will need in the future is vital. The modern world is focused on new materials for emerging technologies but more effort is needed to address education and research in extractive metallurgy. The interface with microbiology offers new potential ways to process existing and new complex ores in addition to current use in the remediation of polluted groundwater.

14. The technologies developed for processing complex ores will aid ongoing efforts to increase recycling, particularly to unlock minor metals from the complex materials that we have created. The links between the materials and the consumer goods that contain them, and our ability to recover individual metals and materials, requires a fundamental shift in design. Emerging research in this area may provide ways to produce some of the metals that we need from recycled "urban ore" more efficiently than from the natural ore.

Much of the discussion in this section has focused on the technological development of mining and related processing over the past 5,000 years or more. Technology continues to play a vital role in producing metals, supporting the identification of mineral resources, and converting these resources to ore reserves that can be mined cleanly and economically. It is clear, however, that technology alone will not provide solutions to resource demand and availability. A complex array of non-technical issues such as politics, societal expectations, and a poor understanding of the connection between mining as the source of metals and global standards of living must be addressed. Even at the local scale, cultural issues among employees and the support of local communities are as important to success as the technologies that have the potential to increase the availability of resources in the future.

5. ESTIMATING ULTIMATE RESOURCES

5.1 Estimating Global Mineral Resources

Our continuing global mineral needs must come from reserves and resources. Recall from Section 1 that the term "resources" refers to Earth's entire inventory of the mineral of interest, whereas "reserves" refer to that part of the resources that have been identified and quantified and can be exploited economically. In general, reserves are of greater interest to producers and industrial consumers, who tend to look forward for only a few years or decades, while resources are of greater interest to governments and scientists who are concerned about long-term mineral supplies. Unlike reserves, as discussed in Section 3, there is no widely accepted method for estimating resources, especially when the estimate is supposed to include the entire global resource to undefined depths. Also, much of the global resource consists of material that has not yet been found or recognised, and thus cannot be quantified by direct observation and measurement. If resources have not been observed, how can we estimate them? We have to do this if we are to have some idea of the long-term mineral potential of the planet. This is the conundrum we address in this section.

Global mineral resources have been estimated by two main methods, one based on production data and the other on geological observations. In both cases, the available data are extrapolated into the future or into unknown areas to generate an estimate. Much of the variation in predicted lifetimes of mineral supplies comes from uncertainty in these estimates, and for this reason we will review them in detail.

5.1.1 Production-based estimates

Production-based estimates use present and past production patterns to estimate future production. The best known of these approaches – the so-called Hubbert "peak oil" approach – was originally applied to petroleum resources in the United States, but has had a wider impact extending to all raw materials.

> **Box 5.1 – *The Hubbert Peak Method*** – M. King Hubbert, a Shell Oil geophysicist, developed this method, inspired by D.F. Hewett's (1929) work on cycles of metal production in Europe. Hubbert extended this thinking to oil production in the United States. His method involved several observations and assumptions. First, it was assumed that oil production, when plotted against time, would follow a curve that increased to a peak and then declined symmetrically (because the ultimate resource of oil was assumed to be finite and consumption would eventually start to deplete the resource). Second, in reviewing data for the contiguous 48 U.S. states, Hubbert noted that curves showing the amount of oil discovered and the amount of oil that was actually produced were similar in shape, but the production curve lagged the

discovery curve by about 10 years. Thus, recognition of a peak in the discovery curve led to prediction of a corresponding peak in production in the period 1965 to 1970 (Hubbert, 1956, 1962, 1982; St. Pierre, 1978). The curve for the production of oil could be fitted using a logistic function,

$$Q(t) = \frac{Q_{max}}{1 + ae^{-bt}}$$

where $Q(t)$ is the cumulative production of crude oil, Q_{max} is the ultimate recoverable resource and a and b are constants. The peak, *i.e.* the year of maximum production is given by:

$$T_{max} = \frac{1}{b}\ln(a)$$

Note that the year and the size of the peak depend on the constants a and b as well as Q_{max}, the estimate of ultimate recoverable resource.

Figure 5.1 shows that Hubbert's original intuitive approach was generally correct; production in the United States did indeed reach a peak in the 1970s. With the passage of time, however, two complications became apparent. First, the large North Slope discoveries in Alaska in the 1980s added a secondary peak to the overall conventional U.S. production curve. Second, in 2007 the U.S. oil production curve turned steeply upward and departed from the simple Hubbert-type curve, raising serious questions about the method.
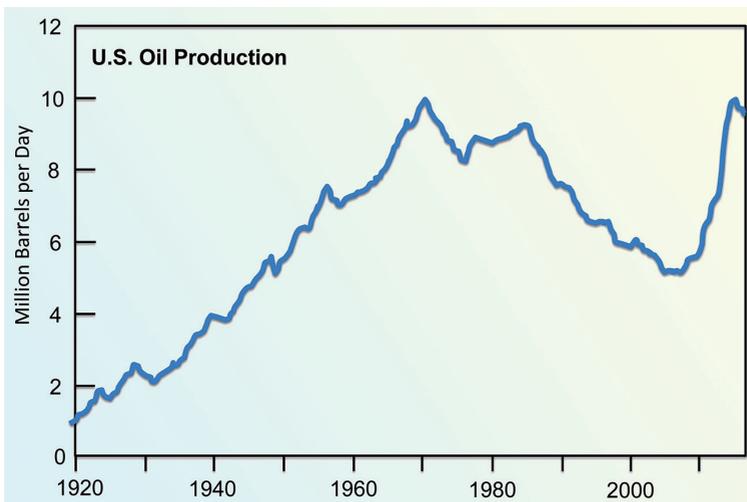
Figure 5.1   U.S. oil production. Prior to 2007, production came almost entirely from conventional deposits. The large increase after that came largely from shale sources (data from U.S. Energy Information Administration).

The abrupt increase in 2007 represents the contribution from shale-oil deposits, which started to be developed at that time because of technological advances. The production curve in Figure 5.1 is actually a composite for two different types of oil deposits. The first part represents conventional oil deposits, and even though it consists of two peaks (one for production in the lower 48 and the other for new discoveries in Alaska), it is still sufficiently symmetrical to allow a relatively good estimate of conventional oil reserves. The last part, however, consists of production from shale oil, an entirely different type of deposit, which obviously cannot be combined with conventional deposits into a simple model. This illustrates that the geologically accurate way to apply the peak curve method to mineral resources is to confine it to production from a *specific deposit type* for a commodity rather than to total production of the commodity, and possibly to focus on a single country or geological province. As you can see in Figure 5.2, application of the method to global resources has not yet converged on a single estimate.
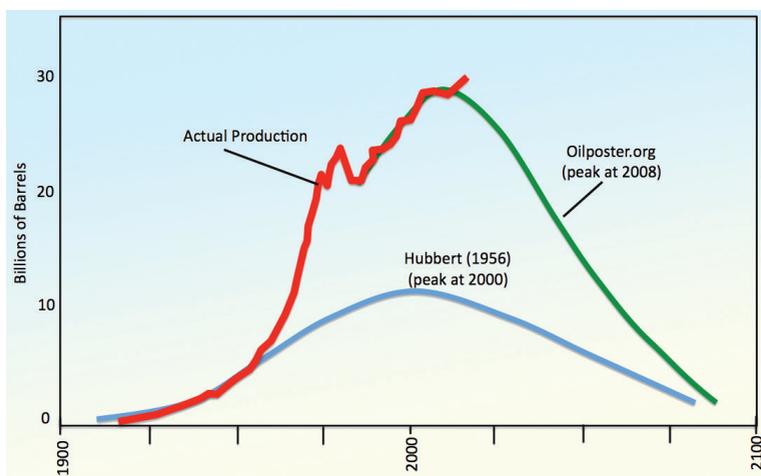
Figure 5.2   World oil production compared to Hubbert's (1956) prediction of a peak at 2000. A more recent prediction from http://oilposter.org/ has the peak slightly later, at 2008, but this also in inconsistent with the latest production data.

Figure 5.2 illustrates the difficulty of using the Hubert method to estimate global oil production in the future. In order for the curve to be symmetrical, a requirement of the method, the ultimate resource must be fixed and production must follow a specific pattern, accelerating initially then declining as the resource becomes depleted. From a mathematical standpoint, estimation of the peak requires a knowledge of the parameters Q_{max}, a and b in the equations above, which are poorly constrained (Deffeyes, 2001, 2005; Aleklett and Campbell,

2003; Claerbout and Muir, 2008; Sorrell *et al.*, 2009; Kerr, 2011; May *et al*, 2012). In addition, there are potential economic complications. Rather than geology, supply and demand, and consequent fluctuations in price, can control the shape of the production curve. For example, coal production in the United States and Australia has declined sharply in the last few years, partly because of the avail-ability of abundant, relatively cheap natural gas but also in response to efforts to use fuels with lower CO_2 emissions to generate electricity. Brandt *et al.* (2013) have suggested that similar market factors, combined with pressure to reduce the consumption of fossil fuels, might cause a decrease in global oil consumption as increases in fuel efficiency and the development of renewables provide alternative energy sources. In the two cases, oil and coal, any future decline in production will result from a decrease in demand, not progressive exhaustion of the resource. These factors illustrate the need to plan as well as possible for future changes in supply and demand, as discussed by Mason *et al.* (2011).

5.1.2 Peak Cu?

The peak-curve method has been used to estimate future supply and consump-tion of global metal resources, with mixed results. The main problems are that few, if any, commodities show a well-defined peak in global production and there is no widely accepted way to predict when a peak might occur. In the case of Cu, peak production was predicted in about 2020 by Laherrère (2010), in 2040 by Northey *et al.* (2014) and in 2050 by Sverdrup and Ragnarsdóttir (2014), while Mudd *et al.* (2013) indicated that *"….it is clear that Cu is far from a peak in known resources or production…."*.

Recognising a peak in production for a metal resource is more difficult than for oil because there are so many different deposit types for each metal, and many regions remain poorly explored and unevaluated. Oil exploration has been much more complete than metal exploration, both on land and offshore, and to greater depths because oil consumption is so much greater than the consumption of Cu or any other metal and because oil is readily recovered from depths far greater than those of most operating mines. In addition, individual oil discoveries are generally well explored and quantified before production begins (although some oil fields increase in size as production proceeds; Cook, 2013), even if the life of the field will be many decades. Knowledge of identified metal deposits is far less complete and many of these known deposits remain under explored simply because preliminary information suggests that they are not as attractive as deposits currently in production. As a result, production data are less likely to reflect the entire population of deposits. May *et al.* (2012) present a good overview of these factors and Giurco *et al.* (2009) emphasise the changing challenges, both economic and environmental, that affect the development of a resource over its lifetime.

Box 5.2 – Global Resource Estimates for Lithium – Lithium, like the rare earth elements, has received increased attention because of its role in low-carbon energy production and storage. The history of resource estimates for lithium illustrates the widely different results that can be derived from a relatively small data set. Prior to its battery-related fame, lithium consumption was limited; applications such as pyroceramics, low-temperature greases, alloys, metallurgical processes and pharmaceuticals consumed only a few thousand tonnes annually (Bradley and Jaskula, 2014). The opening of large markets for new types of batteries stimulated exploration, beginning in the 2000s and continuing today. Exploration focused on the two main types of economic lithium deposits, granitic pegmatites and lacustrine brines, and has extended into previously uneconomic deposits such as oil field brines and lacustrine sediments (Goonan, 2012; Kesler *et al.*, 2012). As more deposits were located, resource estimates grew considerably (Table 5.1). In general, the increase reflects the identification of a greater number of lacustrine evaporite deposits, known as salars (Munk *et al.*, 2016). However, inadequate or incomplete information on most of these deposits has led to widely different results, including the Yaksic and Tilton (2009) high estimate that stems from an unusually optimistic assessment of the Atacama salar. Estimated demand also varies because of different assumptions about the level of electric car production and the amount of recycling; estimates range from a high of about 40 Mt (Tahil, 2008) to lows of about 3 to 5 Mt (Gaines and Nelson, 2009; Gruber *et al.*, 2011) through the year 2100. The wide ranges, for both supply and demand, demonstrate the large uncertainties inherent to such long-term estimates.

Table 5.1	Estimates of world lithium resources.
Li Resource (millions of tonnes)	**Reference**
13.8	USGS (2009)
19.2	Tahil (2008)
23.6	Mohr *et al.* (2012)
29.9	Evans (2008)
31.1	Kesler *et al.* (2012)
34.5	Evans (2010)
39.0	Gruber *et al.* (2011)
39.5	USGS (2016)
64.0	Yaksic and Tilton (2009)

Meinert *et al.* (2016) discussed this issue with reference to Cu and concluded that "*forecasts of imminent peak production due to resource exhaustion in the next 20-30 years are not valid*". They based this assertion on geologic evaluations of the total amount of Cu that might be extracted, thereby providing an introduction to the other important method that is used to assess global mineral resources, geology-based estimations, as outlined below.

5.2 Geology-Based Methods

Resource estimates based on geologic factors focus on individual deposit types and the geologic environments that are most favourable for their formation. This pattern of evaluation has been practiced for many decades and forms the basis for most regional mineral exploration programmes. Allais (1957) was one of the first to use the method in an evaluation of mineral potential in Algeria, and Harris (1984) showed how the approach could be expanded through use of computer-based and other methods. The USGS developed a systematic version of this approach that was used in regional mineral evaluations of Federal lands, including those of the Wilderness Act of 1964 and the Alaska Native Claims Settlement Act of 1971. Singer and Menzie (2010) described a multi-step process involving development of deposit models including tonnage-grade data for known deposits, identification of favourable terranes, and estimation of the number of undiscovered deposits in these areas, based on information from deposit densities in well-known areas.

Johnson *et al.* (2014) used the USGS approach to estimate global Cu resources in deposits with Cu grades like those mined today. The study divided the continents into 175 favourable tracts for porphyry deposits, of which 114 contain at least one deposit, as well as 50 favourable tracts for sediment-hosted deposits, of which 27 contain at least one deposit. Evaluations were made to depths of 1 km in the case of porphyry Cu deposits and 2.5 km for sediment-hosted Cu deposits. The final resource estimate is 3.5×10^9 tonnes; 3.1×10^9 tonnes in porphyry Cu deposits and 0.4×10^9 tonnes in sediment-hosted deposits (Table 5.2). When added to known reserves of 2.1×10^9 tonnes, a total of 5.6×10^9 tonnes of Cu is obtained (some studies have used only the 3.5×10^9 tonnes estimate rather than the 5.6×10^9 tonne total, *e.g.*, Sverdrup and Ragnarsdóttir, 2014).

This resource estimate applies only to the continental crust and only to porphyry and sediment hosted Cu deposits. As discussed in Section 2, other deposit types contain Cu, especially IOCG (iron-oxide Cu-Au) and VMS (volcanogenic massive sulphide). According to Mudd *et al.* (2013), about 83 % of the current global Cu reserve is in porphyry and sediment-hosted Cu deposits. If we use this proportion, another 1.1×10^9 tonnes of Cu might be present in other types of deposits, including IOCG, which brings the global continental Cu resource estimate to about 6.7×10^9 tonnes.

This estimate does not include deposits with lower grades than those exploited presently nor ocean basins and extensions of the continents in the shelf areas. Hannington (2011) estimated that 1×10^9 tonnes of Cu is present in sea-floor VMS deposits and Hein *et al.* (2013) adds an additional 0.2×10^9 tonnes in polymetallic nodules. Adding this to the USGS estimate yields an estimated global Cu resource in ore deposits of known types of about 7.5×10^9 tonnes.

Table 5.2	Assessment results for identified and undiscovered porphyry and sediment-hosted Cu deposits (from Johnson *et al.*, 2014). Shaded areas were not evaluated because they lack evidence of the deposit type. Columns labelled 90, 50, 10 and Mean reflect statistical certainty of the estimate. Estimates fall between the 10th and 90th percentile of probability.

Region	Deposit type	Tract extent (km²)	Undiscovered resources (Mt)				Identified resources (Mt)
			90	50	10	Mean	
South America	Porphyry	1,200,000	500	730	1,000	750	810
	Sediment-hosted	99,000					0.51
Central America and the Caribbean	Porphyry	540,000	78	150	280	170	42
North America	Porphyry	3,200,000	250	370	540	400	470
	Sediment-hosted	450,000	15	48	110	57	18
Northeast Asia	Porphyry	2,300,000	76	220	500	260	8.8
North Central Asia	Porphyry	3,200,000	210	360	590	440	130
	Sediment-hosted	180,000	22	49	90	53	48
South Central Asia and Indochina	Porphyry	3,800,000	280	490	770	510	63
	Sediment-hosted	29,000					4.5
Southeast Asia Archipelagos	Porphyry	850,000	180	290	430	300	130
Australia	Porphyry	580,000	1.9	14	54	21	15
Eastern Europe ans Southwestern Asia	Porphyry	1,200,000	130	220	370	240	110
	Sediment-hosted	4,800	0.052	4.8	36	13	6.4
Western Europe	Porphyry	73,000					1.6
	Sediment-hosted	190,000	38	110	230	120	77
Africa and the Middle East	Sediment-hosted	200,000	81	150	260	160	160
Total copper						**3,500**	**2,100**

5.3 Extending Geologic Estimates

5.3.1 Deposit-model based estimates

The 7.5×10^9 tonnes global Cu resource estimated for deposits of known types is obviously much larger than the 1.4 to 2.6×10^9 tonnes resource normally adopted in peak-curve methods (Table 1.1). However, even this estimate is far from the ultimate resource that might be available to us. One important factor is that porphyry Cu deposits below 1 km and sediment-hosted deposits below 2.5 km were not counted. As mentioned in Section 1, we know that many porphyry Cu deposits form below 2 km (Singer *et al.*, 2008) and there must be a large number of deposits below 1 km in terranes that have not been brought to the surface. Kesler and Wilkinson (2008) estimated the number of deposits of this type using a tectonic diffusion numerical model that mimics the movement of deposits through the crust in response to burial and uplift (Fig. 5.3). Their results suggest that 48,000 porphyry Cu deposits containing ~1.7×10^{11} tonnes of Cu remained
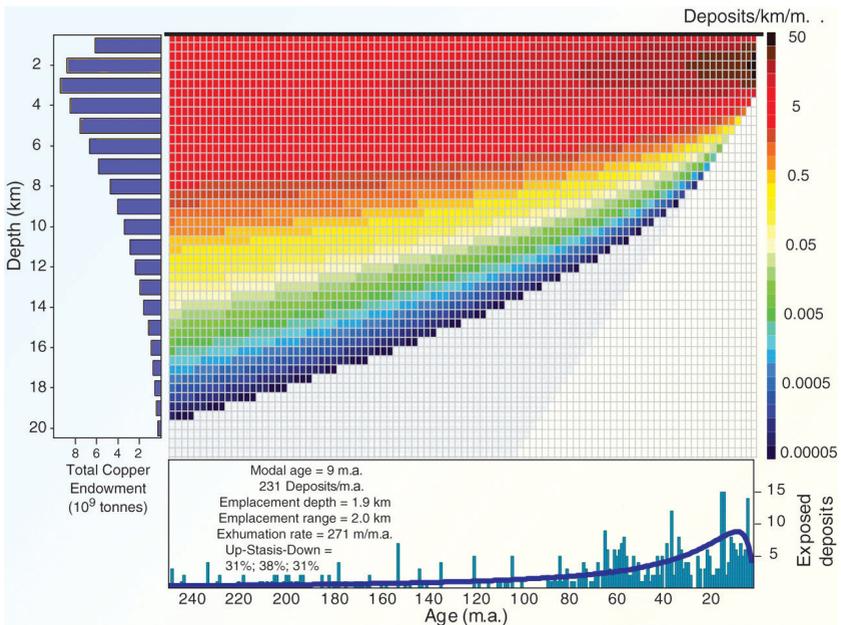
Figure 5.3   Distribution of porphyry Cu deposits in the crust through time and space based on results of tectonic diffusion modelling (from Kesler and Wilkinson, 2008). In the model calculation, deposits form at a depth of 2 km on the right side of the main panel and migrate through time (X axis) and depth (Y axis). The

at all levels in the crust. Because exploration and mining depths are limited, as explained in Sections 3 and 4, a depth of 3.3 km was used as a limit for deposits that might contribute to the global Cu resource. For this depth limit in the continental crust, Cu deposits with grades similar to those exploited today were estimated to contain about 8.9×10^{10} tonnes of Cu, about 10 times larger than the more restrictive estimate outlined above.

A similar resource estimate has not been made for the ocean crust. However, Cathles (2010) has used heat and fluid flow to make a highly speculative resource estimate of about 5.9×10^{11} tonnes of metal for VMS mineralisation at mid-ocean ridge and back-arc spreading centres. Based on the average Cu:Zn ratio of black smoker fluids, copper in these deposits would amount to about 1.1×10^{11} tonnes, more than doubling the amount estimated for the continental crust. Combining the continental and ocean estimates suggests that the planet might contain as much as 2×10^{11} tonnes of Cu in metal deposits that are beyond the limits of conventional geologic estimates.

This amount dwarfs our adjusted USGS estimate of 7.5×10^{9} tonnes of Cu, by a margin large enough to induce scepticism. However, there is ample evidence that we have failed to find numerous even shallowly buried deposits in the continental crust. In plots of discoveries *versus* depth (Figs. 1.8 and 3.11), almost all discoveries are very close to the surface; a few near-mine discoveries extend to a depth of 2 km, and most are at much shallower depths. Thus, it is inescapable that many deposits remain to be discovered at even these relatively shallow depths in the continental crust. Much of the ocean crust remains unexplored, which further expands the potential resource. In addition, it should be remembered that these estimates are based on grades similar to those of deposits exploited today. If lower grades become feasible to mine, as has occurred over the past century, the resource size will increase significantly.

5.3.2 Distribution of copper in the crust – The role of low-grade, anomalous, mineralised rock

Even the 2×10^{11} tonnes Cu resource estimated above is likely only the tip of the iceberg in the upper crust. The main part consists of geochemically anomalous rocks that are enriched in Cu relative to average crust, but have Cu contents well below those mined at present. These rocks almost certainly attained their Cu enrichment by some mineralising process, and we refer to them here as "low-grade mineralised rocks". How large is this population and can its Cu be recovered in the future?

The nature and size of this population depends on the distribution of Cu in the crust. Figure 5.4 shows the two possibilities. In a unimodal distribution (Fig. 5.4a), ore deposits are the high-concentration tail of a skewed distribution

of Cu values that extends continuously from a major peak for common rocks through lower grade material to the richest ore deposits. In a bimodal distribution (Fig. 5.4b), ore deposits form a separate population distinct from that of common rocks (Skinner, 1976). From the standpoint of long-term Cu resources, it is important to understand which of these distributions is correct for Cu and other metals because a continuous distribution would probably yield a larger low-grade resource (Fig. 5.4c).
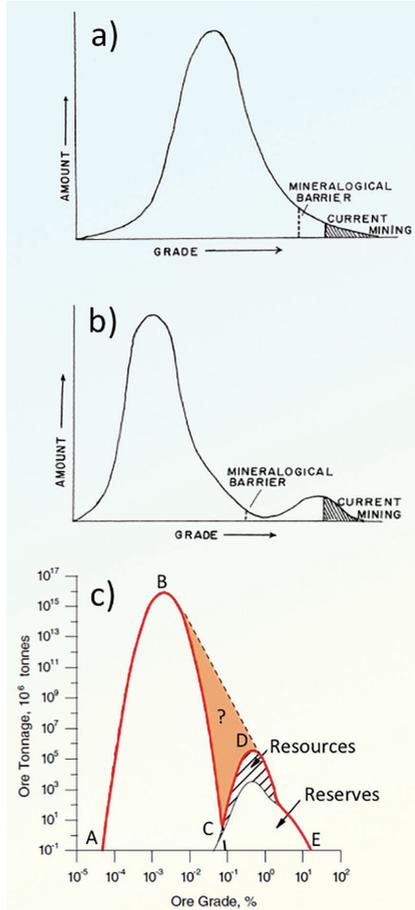
Figure 5.4   **(a)** and **(b)** Alternative possibilities for the distribution of Cu in the continental crust and ore deposits (modified from Skinner, 1976). The "mineralogical barrier" is discussed in the next section. **(c)** Distribution of Cu in average rocks and ore deposits (modified from Gerst, 2008). Curve A-B-C-D-E represents the bimodal distribution and curve A-B-D-E represents the unimodal, skewed

distribution. The labelled Reserves and Resources represent the Cu picture for a bimodal distribution. In the case of a unimodal distribution, the area shown by the question mark (?) would include a large but unquantified amount of low-grade mineralised rock that would add to the resource.

The distribution of Cu in ore deposits and in the continental crust can be explored from both the low-Cu and high-Cu ends of the spectrum (Fig. 5.4c). At the high-Cu end, studies of many ore deposits have shown that the volume of ore increases exponentially as the grade decreases arithmetically (Lasky, 1945, 1949, 1950a, 1950b; Gerst, 2008). Figure 5.5 shows how the tonnage of Cu varies with cut-off grade for several porphyry Cu deposits. Although slopes vary, the tonnage increases by a factor of 2 to 3 as the cut-off decreases from 0.5 to 0.3 %, and where data are available there is a smaller increase as the cut-off goes from 0.3 to 0.2 %. This relationship comes about because the volume (and mass) of rock increases exponentially with distance from the centre of the deposit. Geological and mathematical constraints complicate the extrapolation of this relation to rocks with grades considerably below that of ore (DeYoung, 1981), impeding direct estimation of the volume of low-grade material in the crust. Most exploration drilling does not extend into adjacent country rock with low metal grades, and data for rock with sub-ore grades are rarely reported in the financial or research literature.
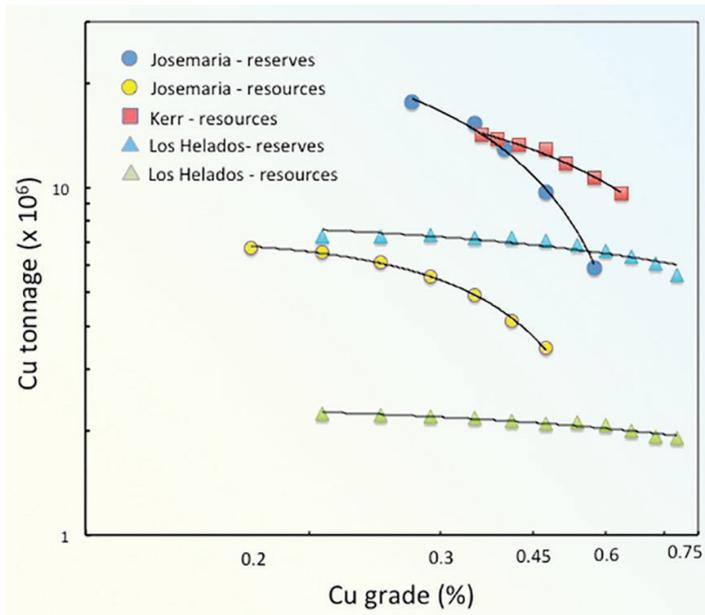
Figure 5.5 Variation of Cu (Mt metal) as a function of cut-off grade in several porphyry Cu deposits (data from http://www.ngexresources.com/s/Technical_Reports.asp).

In view of the paucity of data for low-grade samples around ore deposits, we have sought insights into the size and nature of the low-grade mineralised rock population from the low-Cu end (Fig. 5.4c) using data for a large number of samples of upper crustal rocks, soils and stream sediments. We used three databases: 1) a compilation of ~5,631 analyses from GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/), 2) the National Uranium Resource Evaluation (NURE) database (http://pubs.usgs.gov/of/1997/ofr-97-0492/nurehist.htm), and 3) 5,840 analyses from the Rock Geochemical Database of the Geological Survey of Finland (http://hakku.gtk.fi/en/locations/search).

The three databases contain analyses of different types of samples. The GEOROC samples are mainly of volcanic rocks with a smaller number of plutonic and metamorphic samples that were collected to represent the compositions of the original magmas; altered rocks of the type that might contain hydrothermal ore minerals are normally avoided by petrologists. The Finnish samples, on the other hand, were collected over a grid and comprise all types of rock that crop out in that part of the continental crust, whether altered or fresh. Material analysed in the NURE programme comprised soils that formed by weathering, and stream sediments that formed by erosion and fluvial transport of rock material.

Figure 5.6 shows the distribution of Cu estimated for these three databases. The concentration-frequency plots on the left do not show a log-normal distribution but instead a progressive decrease in frequency with increasing Cu content. In the diagrams on the right, "mass" represents the number of analyses within the sampling interval (5 ppm, 10 ppm and 100 ppm, depending on the concentration) multiplied by the concentration. This procedure provides an approximate and non-scaled estimate of the mass of Cu in the sampled rocks and stream sediments. Peaks are apparent in all three curves, near 30 ppm in the rocks and a little lower in the soils and sediments. These values are similar to Rudnick and Gao's (2003) recommended value (28 ppm) for the average Cu content of the upper continental crust. The high-Cu end of all three curves show irregularities reflecting the small number of Cu-rich samples, and the NURE curve shows a longer tail towards high-Cu values. These curves do not show bimodality because they do not include samples of ores.

Figure 5.7 also shows our estimate of how the mass of Cu in the upper 3 km of the crust varies with Cu concentration. In this diagram, we grouped data from the GEOROC and Finland suites and plotted them as the curve labelled "Cu in rocks", with the NURE data plotted separately ("Cu in stream sediments and soils"). To do this we assumed that the distribution of Cu contents in each sample suite reflected that of Cu in the continental crust. We divided the suite into 5 ppm intervals then calculated the mass of Cu using the following equation:

$$M = N \times C \times F$$

where M is the mass of Cu in each interval, N is the number of samples in the interval, C is the concentration, and F the fraction of the mass of the upper 3 km of the crust represented by each interval; for the NURE suite, F = M/No, where M = the mass of the upper 3 km of the crust (1.32×10^{18} tonnes) and No is the
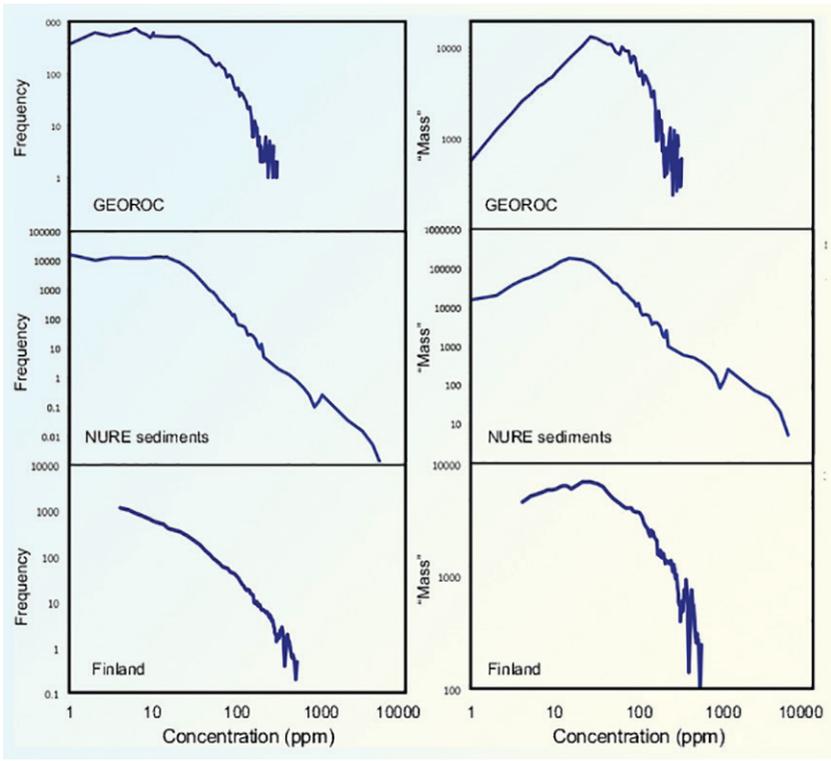
Figure 5.6 Graphs of frequency and "mass" of Cu *versus* concentration in rocks of the continental crust for data from the GEOROC, NURE and Finland databases as discussed in the text. "Mass" represents the number of analyses within the sampling interval (5 ppm, 10 ppm and 100 ppm, depending on the concentration) multiplied by the concentration. This procedure provides an approximate and non-scaled estimate of the mass of copper in the sampled rocks and stream sediments.

number of samples in the suite (17,500). In the figure, both the "rock" and "stream sediment-soil" curves in Figure 5.7b extend across the trough in Figure 5.7a. In other words, data on low-grade mineralised rocks appear to fill the trough, making a unimodal distribution much more likely. There is a large uncertainty about the exact form and position of the rock and stream sediment-soil curves but the difference in Cu contents between those curves and the trough between modes in Figure 5.7a is many orders of magnitude. The dashed blue curve shows the probable distribution; a skewed log-normal curve passes continuously from the rock-stream sediment-soil data to the ore data.

A unimodal distribution for Cu is very encouraging for long-term resource outlook because it indicates that there is a large amount of rock in the upper crust with Cu values intermediate between ore and average rocks, without a trough separating the two. However, before we add this material to the long-term global Cu resource, we need to know just how difficult – energy-intensive – it might be to recover the Cu from low-grade material of this type, and this depends on the mineralogical setting of the Cu.
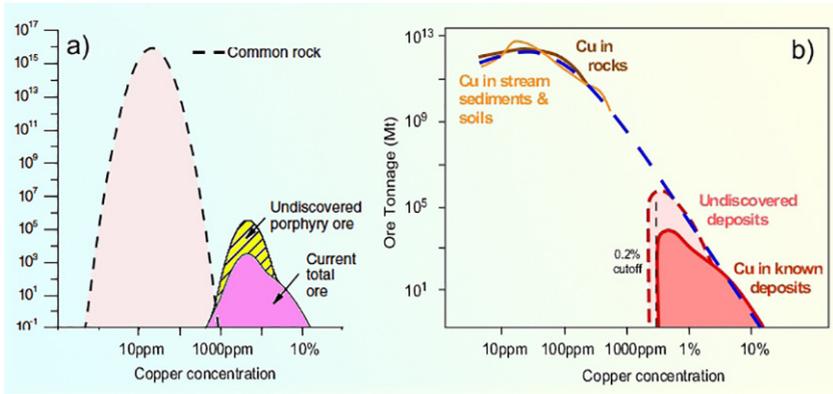
Figure 5.7 **(a)** Bimodal distribution of Cu in rocks and ores (modified from Gerst, 2008). **(b)** The same diagram including our estimates of the distribution of Cu in crustal rocks (from the NURE, GEOROC and Finland databases). The dashed blue curve is our estimate of the probable unimodal distribution of Cu, which extends continuously from rocks to ores. The curve for ores is modified to take into account the absence of data for rocks around ore deposits in which the grade is below a cut-off grade of 0.2 % Cu.

5.3.3 Mineralogical setting of copper in low-grade, mineralised rocks

The possibility that mineralised but low-grade rocks might constitute a resource for Cu depends in part on the energy needed to remove the contained Cu. This, in turn, depends on the type of mineral that contains the Cu. If hosted by sulphide minerals like those in most ore deposits, it will be relatively easy to release from the rock. On the other hand, if the metal substitutes for other elements in rock-forming silicates or oxides, its release will require much more energy. This is the basis of Skinner's (1976) "mineralogical barrier" between ores and normal crustal rocks (Fig. 5.4b): he proposed that most of the Cu in normal rocks is unattainable because it is hosted by rock-forming minerals, not sulphides.

Growing evidence indicates, however, that sulphides are the main host for Cu in almost all rocks, including those with very low Cu contents. This point was not recognised in early studies that detected geochemically anomalous Cu in silicate and oxide minerals (particularly biotite) in igneous rocks (Al-Hashimi

and Brownlow, 1970; Lovering *et al.*, 1970; Graybeal, 1973). An absence of ore minerals and hydrothermal alteration led to suggestions that the silicate minerals might host most or all of the Cu in normal rocks. However, more accurate electron microprobe and synchrotron analyses on smaller sample sizes showed that unaltered silicates and oxides do not contain significant amounts of Cu. Much of the Cu is indeed hosted by magmatic sulphides (Mathez, 1976), or by native Cu and Cu sulphide minerals that had been introduced during hydrothermal alteration or weathering (Ilton and Veblen, 1988, 1993; Core *et al.*, 2006).

Copper in sulphide form is relatively common in unaltered igneous rocks. Primary Cu-Fe sulphides have been reported in low quantities in unaltered mafic and silicic volcanic rocks from a wide range of settings, including MORB, Reunion, Mount Pinatubo, El Chichon, Galeras, Katmai, Kawah Ijen and Satsuma Iwo-Jima (Mathez, 1976; Lowenstern, 1993; Stimac and Hickmott, 1995; Fournelle, 1996; Hattori, 1996; Collins *et al.*, 2012; Patten *et al.*, 2013; Berlo *et al.*, 2014). Primary Cu-Fe sulphides have also been observed in felsic intrusive rocks from the Bingham-Wasatch trend and Arizona (Banks, 1982; Borrok *et al.*, 1999; Core *et al.*, 2005). Stavast *et al.* (2006) pointed out that, in felsic rocks, these sulphides are most abundant in rapidly quenched volcanic and intrusive rocks and proposed that they are commonly leached from intrusive rocks by later magmatic fluids.

These observations indicate that sulphides host a significant proportion of the Cu in unaltered igneous rocks. Information on the form of Cu in metamorphic and sedimentary rocks is lacking, although their Cu mineralogy is probably similar to that of igneous rocks simply because alternative mineral hosts for Cu are scarce. Thus, most of the Cu in unaltered and especially low-grade, mineralised rock is probably hosted by sulphides, which is relatively easy to recover. This could make low-grade mineralised rocks a potential low-grade resource.

5.3.4 Estimating the global low-grade mineralised rock resource for copper

The maximum size of this potential resource can be estimated from the proportion of samples with Cu contents greater than 150 ppm in the three datasets. Such rocks contain far more Cu than average upper continental crust (~30 ppm) and have almost certainly undergone some Cu concentrating process and can therefore be classed as low-grade, mineralised rocks. Table 5.3 summarises the results for the upper 3.3 km of the crust. The low-grade mineralised rock population designated in this way (>150 ppm Cu) comprises about 1.5 % of the GEOROC data, 3.3 % of the NURE data, and 4.6 % of the Finland data. Average Cu contents of the three populations are 346, 338 and 243 ppm, respectively. These values are less than one magnitude lower than the ore grade of the Aitik porphyry Cu deposit, Sweden, which is mined profitably at a grade of 0.22 % Cu (http://www.boliden.com/operations/mines/boliden-aitik/). These values indicate an average of about 1×10^{13} tonnes Cu in the upper 3.3 km of the continental crust, a figure that is nearly two orders of magnitude larger than the 2×10^{11} tonnes estimate made above for model ore deposits in the continental and oceanic crust (Fig. 5.8).

Comparison of the relative sizes of the three main estimates discussed here: red – Cu content of low-grade, mineralised rocks; blue – model-based estimates for the continental crust to 3.3 km depth (Kesler and Wilkinson, 2008); and green – USGS estimate of Johnson *et al.* (2014) plus estimates of Cu in seafloor deposits (Cathles, 2010). Black dot shows size of resource estimates used in many studies of future Cu resources (Table 1.1).
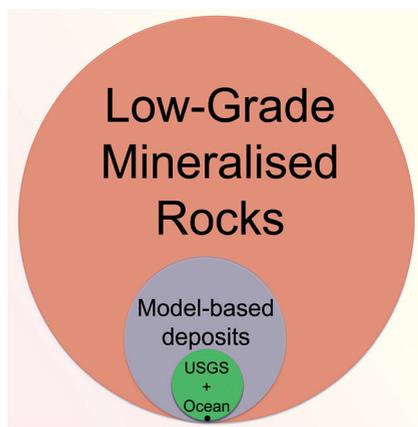
5.4 Conclusions

It should be obvious from the previous sections, as well as the estimates and speculations outlined in this section, that Earth contains a truly enormous amount of Cu. Just how much of this material might be mined now or in the future is not known, but it is definitely much larger than currently available estimates of reserves and resources. The long-term resource picture for most other mineral commodities, especially the metals, is probably similar. How long these might last depends not only on their supply, and our ability to find the deposits, but also on the rate at which we consume and recycle the commodities, plus on technological advances in mining and mineral processing as well as efficiencies of use and alternatives. These topics are far beyond the scope of this volume, but are obviously just as important.

For the moment, we hope we have demonstrated that mineral resources are much more abundant than simple reserve estimates indicate. It is our challenge, as geoscientists, to find and help mine them. We trust that our picture of an evolving resources industry will encourage geochemists, and geoscientists in general, to think about and find ways to make significant contributions to the discovery, production and environmental challenges that the mining industry will face in the future. Below, we suggest a few of these challenges.

Box 5.3 – The Future of Open-pit Mining – Some environmental groups advocate a total ban on open pit mines. They applauded the remark made in 2016 by the incoming Philippines Environment and Natural Resources Secretary, in charge of mining, who proclaimed that open pit mining is "madness". According to another group "In a bold and precedent-setting move, Costa Rica has prohibited all future open-pit metal mining! Environmentalists are celebrating the passage of the new law,

which – approved unanimously by the Costa Rican Congress – establishes Costa Rica as a country that is 'free from open-pit metal mining.' Earthjustice and its partners are thrilled with this development …". How realistic are these actions?

As mentioned in Section 4, many types of deposits can be exploited only by surface mines; for many others, an underground mine would cost so much more that the operation would not be viable. All of the world's Al and half its Ni come from laterites that form as laterally extensive but relatively thin deposits at or close to the surface. Resources of these metals are sufficient to meet demand to well into the next century and, for all of this period, the deposits will be developed in open pit mines. When done properly, this type of operation has only a temporary impact on the environment. The layer of topsoil at the surface is removed and conserved, and is replaced once the underlying ore has been removed. Examples of successful remediation can be found in regions south of Perth in Western Australia where the endemic jarrah forest is progressively restored after bauxite mining is completed (*e.g.*, Gardner, 2001).

Most other high-volume bulk commodities like Fe, Mn, aggregates, limestone (for cement) and industrial minerals (including gravel and sand) are mined in open pits. There are some exceptions, such as Kiruna in northern Sweden, a steeply dipping sheet-like Fe deposit that has been mined underground since the 1960s, but well over 90 % of Fe is recovered in vast open pits like those in the Hamersley region of Australia or the Carajás Mine in Brazil. Stringent procedures are now imposed to help assure the mine site is properly rehabilitated following mine closure, but total restoration of the large holes left after mining is impossible. The bottom line is that if modern society continues to consume Fe and steel for cars (electric or conventional), bridges and wind turbines, plus the rest of the infrastructure needed for the production of renewable energy, a large proportion of the raw materials will be recovered in open-pit mines, at least for several decades in the future.

For the base and precious metals, mining is and will continue to be divided between open pits and underground mines, depending on the nature of the deposit, its location, and other factors. There is a well-developed trend towards large-scale underground mining of Cu as the introduction of new and improved caving practices increase the efficiency of the process. Other factors that will favour underground mines are the exhaustion of near-surface deposits. Examples like the Mittersill tungsten mine in Austria illustrate the advantages of modern underground mines. The mine operates near a National Park and Nature Reserve but the operation is highly automated and the ore is transported to the ore-dressing plant through a 3-km long tunnel with the consequence that the mine is barely visible at the surface.

Finally, the development of *in situ* leaching techniques, whereby metals are extracted in fluids then transported to the surface, may eventually eliminate the need for traditional mines.

5.5 Looking Ahead – Challenges for Geoscientists Who Will Supply Resources for Future Generations

When it comes to future supplies of Cu and other minerals, we can look at the problem in two time frames – the short-term – over 30 to 50 years – and a longer term of centuries, when demand is expected to level out or even decrease for

some commodities. Obviously, the short term is most important and here the challenge is to generate reserves at a rate that keeps up with production. The technical challenges to doing this have been discussed in Sections 3 and 4. Below we focus on broader issues, particularly those related to us as geologists, geochemists and citizens.

1. *Apply geochemical research to ores*. Geochemistry, together with geology and geophysics, are the main tools used to understand ore-forming processes and find new ore deposits. In recent decades, many economic geologists converted to other disciplines, emptying research centres in universities, government surveys and industry. Only in the last few years has the trend reversed. Geochemical research such as the analysis and interpretation of the compositions of rocks and ores, mineralogical and geometallurgical studies of metal deportment and processing, and experimental examination of phase relations and element partitioning, have been crucial to our understanding of how ores form and how to process them. This research must continue, both at the theoretical and analytical level.

2. *Improve exploration*. To find new mineral resources, we must improve our success rate in exploration. To do this, we need better information on ore deposits, their characteristics, their origin and their geochemical and geophysical expression. This is a job for research in which academics and industry work as a team. It should also lead to the recognition of completely new types of ore deposits. In addition, the mining industry must explore more efficiently, supporting and guiding the research that is required to produce improved deposit models and exploration tools.

3. *Improve personnel*. The recent economic decline has deprived the mineral industry of experienced scientists who can guide complex exploration projects and mentor new hires. Industry and universities need to find ways to keep senior people active in the business and maintain contact with students and young exploration geoscientists.

4. *Educate economic geologists*. The number of university courses and more dedicated programmes that focus on ore deposits and the mineral industry has declined seriously during the last decades. We need to reverse this trend and educate students about the resources industry, so that they can take up essential positions in the minerals sector and better represent the industry to the public at large. Major challenges will be faced, and will need to be overcome, by the next generation of exploration geoscientists. These challenges – to identify, assess and develop mineral resources while helping to minimise the environmental and social impact – are far greater than those faced by present and past generations of economic geologists.

5. **Educate the public**. We need to educate all students, regardless of their main study programme, and the public at large, on the following issues: 1) the need for minerals and the fact that, even if recycling is optimised, the metals needed for industry cannot be supplied without exploration and mining; 2) the wealth produced by mining mineral deposits is far above that of most alternative uses for land; 3) most land can be reused after mineral extraction; 4) mining contributes directly to quality of life for people in most regions where the activity continues. The industry has made major strides in improving its performance, by improving the efficiency of mining and reducing its footprint and environmental impact. By publicising the initiatives that have been taken (Box 5.4) we can improve our ability to convince society of the need for minerals and the value of the mineral industry.

Box 5.4 – Initiatives for Responsible Mining – The following sources illustrate some of the articles, organisations and initiatives that encourage the minerals industry to act in a responsible and sustainable manner.

Ali, S. (2010) Treasures of the Earth: Need, Greed and a Sustainable Future. Yale University Press, New Haven and London.

Cheshire, L., Everingham, J.A., Lawrence, G. (2014) Governing the impacts of mining and the impacts of mining governance: Challenges for rural and regional local governments in Australia. *Journal of Rural Studies* 36, 330-339.

Extractive Industries Transparency Initiative https://eiti.org/

Giurco, D., McLellan, B., Franks, D.M., Nansai, K., Prior, T. (2014) Responsible mineral and energy futures: views at the nexus. *Journal of Cleaner Production* 84, 322-338.

Initiative for Responsible Mining Assurance http://www.responsiblemining.net/

International Council on Mining & Metals (2015) Research on company-community conflict. In brief http://www.icmm.com/document/8515

International Institute on Environment and Development (IIED) and World Business Council for Sustainable Development (WBCSD) (2002) Breaking New Ground; Mining minerals and sustainable development. The report of the MMSD project. Earthscan, London, 419 pp.

Owen, J.R., Kemp, D. (2014) 'Free prior and informed consent', social complexity and the mining industry: Establishing a knowledge base. *Resources Policy* 41, 91-100.

Resourcing Future Generations Mineral Resources and Future Supply. International Union of Geological Sciences (2014) http://iugs.org/index.php?page=resourcing-the-future-initiative

Söderholm, P., Svahn, N. (2015) Mining, regional development and benefit sharing in developed countries. *Resources Policy* 45, 78-91.

UNDP-CCSI-WEF Report (2016) Mapping mining to the sustainable development goals http://unsdsn.org/resources/publications/mapping-mining-to-the-sustainable-development-goals-an-atlas/

World Economic Forum Report (2014) The future availability of natural resources http://www3.weforum.org/docs/WEF_FutureAvailabilityNaturalResources_Report_2014.pdf

World Economic Forum Report (2015) Mining and metals in a sustainable world 2050 http://www3.weforum.org/docs/WEF_MM_Sustainable_World_2050_report_2015.pdf

World Economic Forum Report (2016) Voluntary responsible mining initiatives – A review http://www3.weforum.org/docs/Voluntary_Responsible_Mining_Initiatives_2016.pdf

6. ***Improve our game and become better communicators****.* The general public has a negative impression of mining and the mineral industry, stemming largely from poor mining practices in the past and fuelled by more recent incidents like the Samarco spill in Brazil. Members of the public also do not appreciate the major contribution that mining makes to society's present standard of living, and the risk to society if new ore bodies are not discovered and mined in the future. The long-term deleterious impact of reduced greenfield exploration over the past few years, and potentially for years to come, is not widely understood, even by corporate managers in the mineral industry. This not only deprives the industry and society of the opportunity to benefit from new reserves that are potentially higher grade than those currently available, but also seriously reduces the chances of discovering new mineral districts and metallogenic provinces: the ultimate suppliers of resources and wealth creators.

While there is no doubt that Earth contains the necessary resources for future society, they cannot be identified and developed without the collective will of the exploration and mining community, technical input and developments from the scientific community, the necessary funding from investors, and the understanding and support from the general public.

The issues and challenges summarised above are daunting but the failure to deliver resources cleanly and effectively will result in declining living standards for many, and loss of any opportunity for simple improvements in the quality of life for billions of people. The challenges of miners are poorly understood by the industry's detractors, who readily accept all of the benefits of mining while decrying its existence. On the positive side, solutions are appearing and may in some cases be available already. The mining industry has proven to be innovative and resilient in the past, and there is every reason to be optimistic that it can expand our resources for the future.

REFERENCES

ABRAHAM, D.S. (2015) The elements of power. Yale University Press, 336 pp.

AGARWAL, J.C., BEECHER, N., DAVIS, D.S., HUBRED, G.L., KAKARIA, V.K., KUST, R.N. (1976) Processing of ocean nodules: a technical and economic review. *Journal of the Minerals, Metals, and Materials Society* 28, 24–31.

AGRICOLA, G. (1556) De Re Metallica. Translated by H.C. Hoover and L.H. Hoover in 1912. Published by Dover Publications, Inc., New York (1950).

AKCIL, A. (2006) Mining history in Anatolia (Part 2). *Canadian Institute of Mining, Metallurgy and Petroleum CIM Magazine* March/April 2006.

AKIMOTO, Y. (1998) The History of Mining in Japan and its Prospects for the 21st Century. *Shigen-to-Sozai* 114, 389–396.

ALEKLETT, K., CAMPBELL, C.J. (2003) The peak and decline of world oil and gas production. *Minerals & Energy* 18, 5–20.

AL-HASHIMI, A.R.K., BROWNLOW, A.H. (1970) Copper content of biotites from the Boulder Batholith, Montana. *Economic Geology* 65, 985–992.

ALLAIS, M. (1957) Method of appraising economic prospects of mining exploration over large territories – Algerian Sahara case study. *Management Science* 3, 285–347.

ASSOCIATION OF WORKERS' COMPENSATION BOARDS OF CANADA (AWCBC) (2015) http://awcbc.org/

AUCI, S., VIGNANI, D. (2013) Environmental Kuznets curve and domestic material consumption indicator: a European analysis. MPRA Paper No. 52882. https://mpra.ub.uni-muenchen.de/52882/1/MPRA_paper_52882.pdf

AUDÉTAT, A., SIMON, A.C. (2012) Magmatic controls on porphyry copper genesis. In: Hedenquist, J.W., Harris, M., Camus, F. (Eds.) *Geology and genesis of major copper deposits and districts of the world – A tribute to Richard H. Sillitoe. Society of Economic Geologists Special Publication* 16, 553–572.

BAILLY, P.A. (1967) Mineral Exploration and Mine Developing Problems. Statement presented to the Public Lands Law Conference, University of Idaho, Boise, Idaho, 44 pp.

BANKS, N.G. (1982) Sulfur and copper in magma and rocks: Ray porphyry copper deposit, Pinal County, Arizona. In: Titley, S.R. (Ed.) *Advances in Geology of Porphyry Copper Deposits, Southwestern North America*. University of Arizona Press, Tucson, 227–257.

BARNES, S.-J., LIGHTFOOT, P.C. (2005) Formation of magmatic nickel sulfide deposits and processes affecting their copper and platinum group element content. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 179–213.

BARNES, S.J., CRUDEN, A.R., ARNDT, N.T., SAUMUR, B.-M. (2016) The mineral system approach applied to magmatic Ni-Cu-PGE sulphide systems. *Ore Geology Reviews* 76, 296-316.

BARTON, M.D., JOHNSON, D.A. (1996) Evaporitic source model for igneous-related Fe oxide-(REE-Cu-Au-Au) mineralization. *Geology* 24, 259–262.

BARTOS, P.J. (2002) SX-EW copper and the technology cycle. *Resources Policy* 28, 85–94.

BEGG, G.C., HRONSKY, J.A.M., ARNDT, N.T., GRIFFIN, W.L., O'REILLY, S.Y., HAYWARD, N. (2011). Lithospheric, cratonic, and geodynamic setting of Ni-Cu-PGE sulfide deposits. *Economic Geology* 105, 1057–1070.

BEKKER, A., SLACK, J.F., PANAVSKY, N. KRAPEZ, B., HOFMANN, A. KONHAUSER, K.O., ROUXEL, O.H. (2010) Iron formation: The sedimentary product of a complex interplay among mantle, tectonic, oceanic and biospheric processes. *Economic Geology* 105, 467–508.

BERLO, K., van HINSBERG, V.J., VIGOUROUX, N., GAGNON, J.E., WILLIAMS-JONES, A.J. (2014) Sulfide breakdown controls metal signature in volcanic gas at Kawah Ijen volcano, Indonesia. *Chemical Geology* 371, 115–127.

BERTON, P. (2001) Klondike: the last great gold rush 1896-1899. Anchor, Toronto, 472 pp.

BEUKES, N.J., GUTZMER, J., MUKHOPADHYAY, J. (2003) The geology and origin of high-grade hematite iron ore deposits. *Applied Earth Science* 112, 18–25.

BLANCHARD, R. (1968) Interpretation of leached outcrops. Nevada Bureau of Mines, Bulletin 66.

BORROK, D., KESLER, S.E., VOGEL, T.A. (1999) Sulfide minerals in intrusive and volcanic rocks of the Bingham-Park City belt, Utah. *Economic Geology* 94, 1213–1230.

BOUW, B. (2016) The future of mining. *Corporate Knights* 15, 38–43.

BRADLEY, D., JASKULA, B. (2014) Lithium—For harnessing renewable energy. U.S. Geological Survey Fact Sheet 2014–3035, doi: 10.3133/fs20143035.

BRANDT, A.R., MILLARD-BALL, A., GANSER, M., GORELICK, S.M. (2013) Peak oil demand: The role of fuel efficiency and alternative fuels in a global oil production decline. *Environmental Science and Technology* 47, 8031–8041.

BRODKIN, E., COPES, R., MATTMAN, A., KENNEDY, J., KLING, R., YASSI, A. (2007) Lead and mercury exposures: Interpretation and action. *CMAJ* 176, 59–63.

BROWN, G. (2012) Sustainable exploration: A major's perspective. *Society of Economic Geologists Newsletter* 91, 7–9.

BUCKLEY, S.J., HOWELL, J.A., ENGE, H.D., KURZ, T.H. (2008) Terrestrial laser scanning in geology: data acquisition, processing and accuracy considerations. *Journal of the Geological Society* 165, 625–638.

BUTLER, D.K. (Ed.) (2005) Near-surface Geophysics. Society of Exploration Geophysicists, Tulsa, 758 pp.

CAMUS, J. (2011) Value creation in the mining business. *Mining Engineering Magazine* March, 43–52.

CANFIELD, D.E. (2005) The early history of atmospheric oxygen: Homage to Robert M. Garrels. *Annual Review of Earth and Planetary Sciences* 33, 1–36.

CATHLES, L.M. (2010) What processes at mid-ocean ridges tell us about volcanogenic massive sulfide deposits. *Mineralium Deposita* 46, 639–657.

CATHLES, L.M. (2013) Future Rx: optimism, preparation, acceptance of risk. In: Jenkin, G.R.T., Lusty, P.A.J., Mcdonald, I., Smith, M.P., Boyce, A.J., Wilkinson, J.J. (Eds.) *Ore Deposits in an Evolving Earth. Geological Society of London Special Publications* 393, doi: 10.1144/SP393.6.

CAWOOD, P.A., HAWKESWORTH, C.W. (2015) Temporal relations between mineral deposits and global tectonic cycles. In: Jenkin, G.R.T., Lusty, P.A. J., Mcdonald, I., Smith, M.P., Boyce, A.J., Wilkinson, J.J. (Eds.) *Ore Deposits in an Evolving Earth. Geological Society of London Special Publications 393*, doi: 10.1144/SP393.6.

CHITOMBO, G. (2011) Total deposit knowledge – geology, underground mass mining and the future – a mining engineer's perspective. Eighth International Mining Geology Conference, Queenstown, New Zealand, 22-24 August 2011, Proceedings, 11–14.

CLAERBOUT, J., MUIR, F. (2008) Hubberts math. http://sepwww.stanford.edu/sep/jon/hubbert.pdf

CLARKE, F.W. (1889) The relative abundance of the chemical elements. *Bulletin of the Philosophical Society of Washington* 11, 135–143.

CLINE, E.H. (Ed.) (2010) Oxford Handbook of the Bronze Age Aegean. Oxford University Press, Oxford, 930 pp.

CLOUT, J.M.F., SIMONSON, B.F. (2005) Precambrian iron formations and iron formations-hosted iron deposits. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 643–672.

COLLINS, S.J., MACLENNAN, J., PYLE, D.M., BARNES, S.J., UPTON, B.G.J. (2012) Two phases of sulfide saturation in Réunion magmas: Evidence from cumulates. *Earth and Planetary Science Letters* 337-338, 104–113.

CONDIE, K.C. (2014) Growth of continental crust: a balance between preservation and recycling. *Mineralogical Magazine* 78, 623–637.

CONDIE, K.C., ASTER, R.C. (2010) Episodic zircon age spectra of orogenic granitoids: The supercontinent connection and continental growth. *Precambrian Research* 180, 227–236.

COOK, T.A. (2013) Reserve growth of oil and gas fields – Investigations and applications. U.S. Geological Survey Scientific Investigations Report 2013-5063, 29 pp.

COOKE, D.R., BAKER, M., HOLLINGS, P., SWEET, G., CHANG, Z., DANYUSHEVSKY, L., GILBERT, S., ZHOU, T., WHITE, N.C., GEMMELL, J.B., INGLIS, S. (2014) Advances in detecting the distal geochemical footprints of porphyry systems— Epidote mineral chemistry as a tool for vectoring and fertility assessments. *Society of Economic Geologists Special Publication* 18, 127–152.

COPPER DEVELOPMENT ASSOCIATION (2016) Copper – the world's most reusable resource. http://www.copper.org/environment/lifecycle/g_recycl.html

CORE, D.P., KESLER, S.E., ESSENE, E.J., DUFRESNE, E.B., CLARKE, R., ARMS, D.A., WALKO, K. (2005) Copper and zinc in silicate and oxide minerals in igneous rocks from the Bingham-Park City belt, Utah: Synchrotron X-ray fluorescence data. *Canadian Mineralogist* 43, 1781–1796.

CORE, D.P., KESLER, S.E., ESSENE, E.J. (2006) Unusually Cu-rich magmas associated with giant porphyry copper deposits. Evidence from Bingham, Utah. *Geology* 34, 41-44.

COULSON, M. (2012) The history of mining. Harriman House, Petersfield, 488 pp.

COYLE, G. (2010) The riches beneath our feet. Oxford University Press, Oxford, 267 pp.

COX, D.P. (1979) The distribution of copper in common rocks and ore deposits. In: Nriagu, J.O. (Ed.) *Copper in the environment – Part I*. Wiley, New York, 1011 pp.

COX, D.P., SINGER, D.A. (Eds.) (1986) Mineral deposit models. U.S. Geological Survey Bulletin 1693, 379 pp.

CRANE, D., KAVALIERIS, I. (2012) Geologic Overview of the Oyu Tolgoi Porphyry Cu-Au-Mo Deposits, Mongolia, In: Hedenquist, J.W., Harris, M., Camus, F. (Eds.) *Geology and genesis of major copper deposits and districts of the world – A tribute to Richard H. Sillitoe. Society of Economic Geologists Special Publication* 16, 187–213.

CROWSON, P. (2008) Mining unearthed. Aspermont, London, 423 pp.

CUNEY, M., KYSER, K. (2009) Recent and not-so-recent developments in uranium deposits and implications for exploration. Mineralogical Association of Canada, Short Course Series Volume 39, 257 pp.

DAVIS, J.R. (2000) Corrosion: Understanding the basics. ASM International, Ohio, 563 pp.

DEFFEYES, K.S. (2001) Hubbert's peak: The impending world oil shortage. Princeton University Press, Princeton, 232 pp.

DEFFEYES, K.S. (2005) Beyond Oil—The View from Hubbert's Peak. Farrar, Straus and Giroux, New York.

DENTITH, M., MUDGE, S. (2014) Geophysics for the mineral exploration geoscientist. Cambridge University Press, Cambridge, 454 pp.

DEYOUNG, J.H. (1981) The Lasky cumulative tonnage-grade relationship – a re-examination. *Economic Geology* 76, 1067–1080.

DE RONDE, C.E.J., WALKER, S.L., DITCHBURN, R.G., MERLE, S.G. (2014) The Anatomy of a buried submarine hydrothermal system, Clark Volcano, Kermadec Arc, New Zealand *Economic Geology* 109, 2261–2292.

DICKINSON, W.R. (1980) Plate tectonics and key petrologic associations. In: Strangway, D.W. (Ed.) *The continental crust and its mineral deposits. Geological Association of Canada Special Paper* 20, 341–360.

DREISINGER, D. (2006) Copper leaching from primary sulphides: Options for biological and chemical extraction of copper. *Hydrometallurgy* 83, 10–20.

DREISINGER, D., MURRAY, W., HUNTER, D., BAXTER, K., FERRON, J., FLEMING, C. (2005) The Application of the Platsol™ process to copper-nickel-cobalt-PGE/PGM concentrates from Polymet Mining's Northmet deposit. In: *Proceedings of the ALTA World Forum on Nickel and Cobalt Hydrometallurgy, Perth, Australia,* 16.

DUCLAUX, G., SALLES, T., RAMANAIDOU, E.R. (2013) Alluvial iron deposits exploration using surface processes modelling – a case study in the Hamersley Province (Western Australia). Iron Ore Conference – Perth, WA, 12-14 August 2013, 75–80.

DUTTA, T., KIM, K.H., UCHIMIYA, M., KWON, E.E., JEON, B.H., DEEP, A., YUN, S.T. (2016) Global demand for rare earth resources and strategies for green mining. *Environmental Research* 150, 182-190, doi: 10.1016/j.envres.2016.05.052.

EHRIG, K., MCPHIE, J., KAMANETSKY, V. (2012) Geology and mineralogical zonation of the Olympic Dam Iron Oxide Cu-U-Au-Ag Deposit, South Australia. In: Hedenquist, J.W., Harris, M., Camus, F. (Eds.) *Geology and genesis of major copper deposits and districts of the world – A tribute to Richard H. Sillitoe. Society of Economic Geologists Special Publication* 16, 237–268.

ERICSSON, M. (2008) Trends in Mining, Present & Future. UNCTAD Secretary-General's High-Level Multi-Stakeholder Dialogue on Commodities in the context of UNCTAD XII 28-29 January 2008. http://unctad.org/sections/wcmu/docs/ditc_comb_05ericsson_en.pdf

EVANS, R.K. (2008) An abundance of lithium: Part two. http://www.evworld.com/library/KEvans_LithiumAbunance_pt2.pdf

EVANS, K.A., O'NEILL, H.ST.C., MAVROGENES, J.A. (2008) Sulphur solubility and sulphide immiscibility in silicate melts as a function of the concentration of manganese, nickel, tungsten, and copper at 1 atm and 1400C. *Chemical Geology* 255, 236–249.

EVANS, R.K. (2010) The lithium-brine reserve conundrum. *The Northern Miner* 96, 2–6.

FOURNELLE, J., CARMODY, R.W., DAAG, A.S. (1996) Anhydrite-bearing pumices from the June 15, 1991, eruption of Mount Pinatubo; geochemical, mineralogy and petrology. In: Newhall, C.G., Punongbayan, R.S. (Eds.) *Fire and mud. Eruptions and lahars of Mt. Pinatubo, Philippines*. University of Washington Press, Seattle, 845–863.

FRANKLIN, J.M., GIBSON, H.L., JONASSON, I.R., GALLEY, A.G. (2005) Volcanogenic massive sulphide deposits. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 523–560.

FREYSSINET, P., BUTT, C.R.M., MORRIS, R.C., PIANTONE, P. (2005) Ore-forming processes related to lateritic weathering. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 681–722.

FRIMMEL, H.E., GROVES, D.I., KIRK, J., RUIZ, J., CHESLEY, J., MINTER, W.E.L. (2005) The formation and preservation of the Witwatersrand goldfields, the world's largest gold province. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 769–797.

FUERSTENAU, D.W., HAN, K.N. (1983) Metallurgy and processing of marine manganese nodules. *Mineral Processing and Technology Review* 1, 1–83.

FURSTENAU, M.C., JAMESON, G., HOON, R-H. (2007) Froth flotation, a century of innovation. Society of Mining, Metallurgy, and Exploration Inc. (SME), Englewood, 891 pp.

GAINES, L., NELSON, P. (2009) Lithium-ion batteries—Possible materials issues. U.S. Department of Transportation, 16 pp. http://www.transportation.anl.gov/pdfs/B/583.PDF

GALLEY, A.G., HANNINGTON, M.D., JONASSON, I.R. (2007) Volcanogenic massive sulphide deposits. In: Goodfellow, W.D. (Ed.) *Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods*. *Geological Association of Canada Special Publication* 5, 141–161.

GARDNER, J.H. (2001) Rehabilitating mines to meet land use objectives: bauxite mining in the jarrah forest of Western Australia. *Unasylva* 207, 3–8.

GARLICK, W.G. (1961) Structural evolution of the Copperbelt. In: Mendelsohn, F. (Ed.) *The Geology of the Northern Rhodesian Copperbelt*. MacDonald, London, 89–105.

GARNETT, R.H.T., BASSETT, N.C. (2005) Placer deposits. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 813–843.

GARWIN, S. (2002) Ore geology setting of intrusion-related hydrothermal systems near Batu Hijau porphyry copper-gold deposit, Sumbawa, Indonesia. In: Goldfarb, R.J., Nielsen, R.L. (Eds.) *Integrated method for discovery: Global exploration in the twenty-first century*. *Society of Economic Geologists Special Publication* 9, 333–366.

GERST, M.D. (2008) Revisiting the cumulative grade-tonnage relationship for major copper ore types. *Economic Geology* 103, 615–628.

GILES, D., HILLIS, R., CLEVERLEY, J. (2014) Deep exploration technologies provide the pathway to deep discovery. *Society of Economic Geologists Newsletter* 97, April, 1, 23–27.

GINZBURG, I.I. (1960) Principles of geochemical prospecting (translation from Russian by V. P. Sokoloff). Pergamon, New York and London, 311 pp. (original published by Gosgeotekhizdat, Moscow, 1957, 298 pp.)

GIURCO, D., PRIOR, T., MUDD, G., MASON, L., BEHRISCH, J. (2009) Peak minerals in Australia: a review of changing impacts and benefits. Prepared for CSIRO Minerals Down Under Flagship, by the Institute for Sustainable Futures (University of Technology, Sydney) and Department of Civil Engineering (Monash University), March 2010.

GLACKEN, I.M., SNOWDEN, D.V. (2001) Mineral resource estimation. In: Edwards, A.C. (Ed.) *Mineral resource and ore reserve estimation – The AusIMM Guide to Good Practice: (Monograph 23)*, 189–197.

Goldfarb, R.J., Baker, T., Dube, B., Groves, D.I., Hart, C.J.R., Gosselin, P. (2005) Distribution, character and genesis of gold deposits in metamorphic terranes. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 407–450.

Goodfellow, W.D., Lydon, J.W. (2007) Sedimentary exhalative (SEDEX) deposits. In: Goodfellow, W.D. (Ed.) *Mineral deposits of Canada: a synthesis of major deposit types, district metallogeny, the evolution of geological provinces, and exploration methods. Geological Association of Canada Special Publication* 5, 163–183.

Goold, D., Willis, A. (1997) *The Bre-X Fraud*. McClelland and Stewart, 272 pp.

Goonan, T.G. (2012) Lithium use in batteries. U.S. Geological Survey Circular 1371, 14 pp. http://pubs.usgs.gov/circ/1371/

Graedel, T.E., Cao, J. (2010) Metal spectra as indicators of development. *Proceedings of the National Academy of Sciences of the United States* 107, 49, 20905–20910.

Graedel, T.E., Harper, E.M., Nasser, N.T., Reck, B.K. (2013) On the materials basis of modern society. *Proceedings of the National Academy of Sciences of the United States,* doi: 10.1073/pnas.1312752110.

Graedel, T.E., Gunn, G., Espinoza, L.T. (2014) Metal resources, use and criticality. In: Gunn, G. (Ed.) *Critical Metals Handbook*. Wiley, New York, 1–19.

Graybeal, F.T. (1973) Copper, manganese, and zinc in coexisting mafic minerals from Laramide intrusive rocks in Arizona. *Economic Geology* 68, 785–798.

Griffis, A.T. (1971) Exploration: Changing techniques and new theories will find new mines. *World Mining* 24, 54–60.

Groves, D.I., Vielreicher, R.M., Goldfarb, R.J., Condie, K.C. (2005) Controls on the heterogeneous distribution of mineral deposits through time. *Geological Society of London Special Publications* 248, 71–101.

Groves, D.I., Bierlein, F.P., Meinert, L.D., Hitzman, M.W. (2010) Iron oxide copper-gold (IOCG) deposits through earth history: implications for origin, lithospheric setting and distinction from other epigenetic iron oxide deposits: *Economic Geology* 105, 641–654.

Gruber, P.W., Medina, P.A., Keoleian, G.A., Kesler, S.E., Everson, M.P., Wallington, T.J. (2011) Global lithium availability: A constraint for electric vehicles? *Journal of Industrial Ecology* 15, 760–775.

Gupta, V., Gautam, O. (2004) Royal Dutch/Shell 'oil reserves' controversy. IBS Center for Management Research, Reference Number 704-049-1. http://www.thecasecentre.org/educators/products/view?id=20533

Gurney, J.J., Helmstaedt, H.H., le Roex, A.P., Nowicki, T.E., Richardson, S.H., Westerlund, K.J. (2005) Diamonds: crustal distribution and formation processes in time and space and an integrated deposit model. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 143–177.

Habashi, F. (2005) A short history of hydrometallurgy. *Hydrometallurgy* 79, 15–22.

Hack, A.C., Mavrogenes, J.A. (2006) A synthetic fluid inclusion study of copper solubility in hydrothermal brines from 525 to 725C and 0.3 to 1.7 Gpa. *Geochimica et Cosmochimica Acta* 70, 3970–3985.

Hall, D.J., Redwood, S.D. (2006) The mineral exploration business: Innovation required. *Society of Economic Geologists Newsletter* 65, April, 1, 9–15.

Hamilton, T. (2016) Mining industry starts to dig renewables. *Corporate Knights* 15, 44–47.

Hannington, M. (2011) Comments on "What processes at mid-ocean ridges tell us about volcanogenic massive sulfide deposits" by L.M. Cathles. *Mineralium Deposita* 46, 659–663.

HARLAN, J.B., JONES, M.L., SUTOPO, B., HOSCHKE, T. (2005) Discovery and characterization of the Martabe epithermal gold deposits, North Sumatra, Indonesia. In: Rhoden, H.N., Steininger, R.C., Vikre, P.G. (Eds.) *Geological Society of Nevada Symposium 2005, Window to the World*. Reno, Nevada, May 2005, 917–942.

HARRIS, D.P. (1984) Mineral resources appraisal – mineral endowment, resources and potential supply – concepts, methods and cases. Oxford University Press, Oxford, 464 pp.

HARRIS, J.H., KESLER, S.E. (1996) BLASH vs GF: Theory in mining investment. *Society of Economic Geologists Newsletter* 26, 23–24.

HART, M. (2013) Gold: the race for the world's most seductive metal. Simon and Schuster, New York, 304 pp.

HARVEY, C.E. (1981) The Rio Tinto Company: An Economic History of a Leading International Mining Concern 1873 – 1954. Alison Hodge, Gwennap, 390 pp.

HATTON, C. (1995) Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces. *Journal of African Earth Sciences* 21, 571–577.

HATTORI, K. (1996) Occurrence and origin of sulphide and sulphate in the 1991 Mount Pinatubo eruption products. In: Newhall, C.G., Punongbayan, R.S. (Eds.) *Fire and mud. Eruptions and lahars of Mt. Pinatubo, Philippines*. University of Washington Press, Seattle, 807–824.

HAUPTMANN, A. (2007) The archaeometallurgy of copper: evidence from Faynan, Jordan. Springer Science and Business Media, Berlin, 388 pp.

HAWKES, H.E. (1957) Principles of geochemical prospecting. U.S. Geological Survey Bulletin 1000-F, 225–355.

HAYNES, D. (2006) The Olympic Dam ore deposit discovery–A personal view. *Society of Economic Geologists Newsletter* 66, 1–15.

HEDENQUIST, J.W., SIMMONS, S.F., GIGGENBACH, W.F., ELDRIDGE, C.S. (1993) White Island, New Zealand, volcanic hydrothermal system represents the geochemical environment of high sulfidation Cu and Au ore deposition. *Geology* 21, 731–734.

HEDENQUIST, J.W., THOMPSON, J.F.H., GOLDFARB, R.J., RICHARDS, J.P. (Eds.) (2005) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 1136 pp.

HEIN, J.R., MIZELL, K., KOSCHINSKY, A., CONRAD, T.A. (2013) Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. *Ore Geology Reviews* 51, 1–14.

HERVÉ, M., SILLITOE, R.H., WONG, C., FERNÁNDEZ, P., CRIGNOLA, F., IPINZA, M., URZÚA, F. (2012) Geologic overview of the Escondida porphyry copper district, northern Chile, In: Hedenquist, J.W., Harris, M., Camus, F. (Eds.) *Geology and genesis of major copper deposits and districts of the world – A tribute to Richard H. Sillitoe. Society of Economic Geologists Special Publication* 16, 55–78.

HERZBERG, C., CONDIE, K., KORENAGA, J. (2010) Thermal history of the Earth and its petrological expression. *Earth and Planetary Science Letters* 292, 79–88.

HEWETT, D.F. (1929) Cycles in metal production. AIME Technical Publication 183, 31 pp. (also AIME Transactions, 65–93; Discussion 93–98).

HITZMAN, M.W., KIRKHAM, R., BROUGHTON, D., THORSON, J., SELLEY, D. (2005) The sediment-hosted stratiform copper ore system. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 609–642.

HITZMAN, M.W., SELLEY, D., BULL, S. (2010) Formation of sediment-hosted stratiform copper deposits through Earth history. *Economic Geology* 1045, 627–640.

HOPE, A.R. (2011) The Hope Factor – mineral discoveries Australia, Papua New Guinea and the Philippines. Self-published, 536 pp.

HUBBERT, M.K. (1956) Nuclear energy and the fossil fuels. American Petroleum Institute Drilling & Production Practice, Proceedings, Spring Meeting, San Antonio, Texas, 7–25 [#187].

HUBBERT, M.K. (1962) Energy resources, a report to the Committee on Natural Resources. National Academy Sciences USA. Publication 1000D, 141 pp.

HUBBERT, M.K. (1982) Techniques of prediction as applied to the production of oil and gas. Oil and gas supply modeling; proceedings of a symposium. Washington, DC, United States, June 18-20, 1980, 631, 16–141.

ILTON, E.S., VEBLEN, D.R. (1988) Copper inclusions in sheet silicates from porphyry Cu deposits. *Nature* 334, 516–518.

ILTON, E.S., VEBLEN, D.R. (1993) Origin and mode of copper enrichment in biotite from rocks associated with porphyry copper deposits: a transmission electron microscopy investigation. *Economic Geology* 88, 885–900.

IRARRAZAVAL, V., SILLITOE, R.H., WILSON, A.J., TORO, J.C., ROBLES, W., LYALL, G.D. (2010) Discovery history of a giant, high-grade, hypogene porphyry copper-molybdenum deposit at Los Sulfatos, Los Bronces-Río Blanco district, central Chile, In: Goldfarb, R.J., Marsh, E.E., Monecke, T. (Eds.) *The challenge of finding new mineral resources: Global metallogeny, innovative exploration, and new discoveries. Society of Economic Geologists Special Publication* 15, 253–269.

ISHIHARI, S. (1981) The granitoid series and mineralization. In: Skinner, B.J. (Ed.) *Economic Geology Seventy-Fifth Anniversary Volume*. The Economic Geology Publishing Company, Texas, 458–484.

JÉBRAK, M., MARCOUX, E. (2015) Geology of Mineral Resources. Geological Association of Canada, Mineral Deposits Division, 668 pp.

JENNINGS, K., SCHODDE, R. (2016) From mineral discovery to project delivery. *Society of Economic Geologists Newsletter* 105, 20–24.

JOHNSON, K.M., HAMMARSTROM, J.M., ZIENTEK, M.L., DICKEN, C.L. (2014) Estimate of undiscovered copper resource of the world, 2013. U.S. Geological Survey Fact Sheet, 2014-3004. http://pubs.usgs.gov/fs/2014/3004/

JONES, D., BARRENO, J.E., PEREZ, P., NARANJO, G., VIERA, F., CAMINO, M. (2005) The high sulphidation Quimsacocha deposit, Ecuador. Boart Longyear, NewGenGold 2005, Perth, Western Australia, November 2005, Proceedings, 117–134.

KELLEY, D.L., KELLEY, K.D., COKER, W.B., CAUGHLIN, B., DOHERTY, M.E. (2006) Beyond the obvious limits of ore deposits: The use of mineralogical, geochemical, and biological features for the remote detection of mineralization. *Economic Geology* 101, 729–752.

KERR, A. (2003) Voisey's Bay and the nickel potential of Labrador: A summary for the nonspecialist. Newfoundland Department of Mines and Energy Geological Survey, Report 03-1, 231–239.

KERR, R.A. (2011) Peak oil production may already be here. *Science* 331, 1510–1511.

KERRICH, R., GOLDFARB, R.J., RICHARDS, J.P. (2005) Metallogenic provinces in an evolving geodynamic framework. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 1097–1136.

KESLER, S.E., SIMON, A.C. (2015) Mineral resources, economics and the environment. Second Edition, Cambridge University Press, Cambridge, 356 pp.

KESLER, S.E., WILKINSON, B.H. (2006) The role of exhumation in the temporal distribution of ore deposits. *Economic Geology* 101, 919–922.

KESLER, S.E., WILKINSON, B.H. (2008) Earth's copper resources estimated from tectonic diffusion of porphyry copper deposits. *Geology* 36, 255–258.

KESLER, S.E., GRUBER, P.W., MEDINA, P.A., KEOLEIAN, G.A., EVERSON, M.P. (2012) Global lithium resources; relative importance of pegmatite, brine and other deposits. *Ore Geology Reviews* 48, 55–69.

KORDOSKY, G.A. (2002) Copper recovery using leach/solvent extraction/electrowinning technology: Forty years of innovation, 2.2 million tonnes of copper annually. *Journal of the South African Institute of Mining and Metallurgy* 102, 445–450.

KOUZMANOV, K., POKROVSKI, G.S. (2012) Hydrothermal controls on metal distribution in porphyry Cu (-Mo-Au) systems. In: Hedenquist, J.W., Harris, M., Camus, F. (Eds.) *Geology and genesis of major copper deposits and districts of the world – A tribute to Richard H. Sillitoe. Society of Economic Geologists Special Publication* 16, 573–618.

KYSER, K., BARR, J., IHLENFELD, C. (2015) Applied geochemistry in mineral exploration and mining. *Elements* 11, 241–246.

LACY, W.C. (1974) Porphyry copper deposits. Australian Mineral Foundation Inc. Workshop course.

LAHERRÈRE, J. (2010) Copper peak. http://europe.theoildrum.com/node/6307

LARGE, R.R., BULL, S.W., McGOLDRICK, P.J., DERRICK, G., CARR, G., WALTERS, S. (2005) Stratiform and stratabound Zn-Pb-Ag deposits of the Proterozoic sedimentary basins of northern Australia. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 931–963.

LASKY, S.G. (1945) The concept of ore reserves. *Mining Metallurgy* 26, 466, 471–474.

LASKY, S.G. (1949) National mineral resource appraisal. *Mining Congress Journal* 35, 35–37.

LASKY, S.G. (1950a) Mineral-resource appraisal by the U.S. Geological Survey. *Colorado School of Mines Quarterly* 45, 1–27.

LASKY, S.G. (1950b) How tonnage and grade relationships help predict ore reserves. *Engineering and Mining Journal* 151, 81–85.

LEACH, D.L., SANGSTER, D.F. KELLEY, K.D., LARGE, R.R., GARVEN, G., ALLEN, C.R., GUTZMER, J., WALTERS, S. (2005) Sediment-hosted lead-zinc deposits: A global perspective. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 561–608.

LEACH, D.L., BRADLEY, D.C., HUSTON, D., PISAREVSKY, S.A., TAYLOR, R.D. AND GARDOLL, S.J., (2010) Sediment-hosted lead-zinc deposits in Earth history. *Economic Geology* 105, 593–625.

LEARNED, R.E., CHAO, T.T., SANZOLONE, R.F. (1985) A comparative study of stream water and stream sediment as geochemical exploration media in the Rio Tanama porphyry copper district, Puerto Rico. *Journal of Geochemical Exploration* 24, 175-195.

LESHER, C.M., BARNES, S.J. (2008) Komatiite-associated Ni-Cu-PGE deposits. In: Arndt, N.T., Barnes, S.J., Lesher, C.M. (Eds.) *Komatiites*. Cambridge University Press, Cambridge, 295–327.

LESHER, C.M., ARNDT, N.T., GROVES, D.I. (1984) Genesis of komatiite-associated nickel suphide deposits at Kambalda, Western Australia: a distal volcanic model. In: Buchanan, D.L., Jones, M.J. (Eds.) *Sulphide deposits in mafic and ultramafic rocks*. Institute of Mining and Metallurgy, London, 70–80.

LIEBER, W., HERMANN L. (2006) German silver: An historical perspective on silver mining in Germany. *The Mineralogical Record* 17, 3–17.

LIGHTFOOT, P.C., NALDRETT, A.J. (Eds.) (1994) *Proceedings of the Sudbury-Noril'sk Symposium*. Sudbury: Ministry of Northern Development and Mines.

LINDGREN, W. (1933) Ore Deposits. Fourth Edition. McGraw Hill, New York, 930 pp.

LIU, W., McPHAIL, C.D.C., BRUGGER, J. (2001) An experimental study of copper(I)-chloride and copper(I)-acetate complexing in hydrothermal solutions between 50°C and 250°C and vapor-saturated pressure. *Geochimica et Cosmochimica Acta* 65, 2937–2948.

LOVERING, T.G., COOPER, J.R. DREWES, H.D., CONE, G.C. (1970) Copper in biotite from igneous rocks in southern Arizona as an ore indicator. U. S. Geological Survey Professional Paper 700-B, 1–8.

Lowenstern, J.B. (1993) Evidence for a copper-bearing fluid in magma erupted at the Valley of Ten Thousand Smokes, Alaska. *Contributions to Mineralogy and Petrology* 114, 409–421.

Maier, W.D., Barnes, S.-J., Groves, D.I. (2013) The Bushveld Complex, South Africa: formation of platinum–palladium, chrome-and vanadium-rich layers via hydrodynamic sorting of a mobilized cumulate slurry in a large, relatively slowly cooling, subsiding magma chamber. *Mineralium Deposita* 48, 1–56.

Malehmir, A., Durrheim, R., Bellefleur, G., Urosevic, M., Juhlin, C., White, D.J. (2012) Seismic methods in mineral exploration and mine planning: A general overview of past and present case histories and a look into the future. *Geophysics* 77, 173–190.

Malone, E. (2011) The Cadia Valley Mines – a mining success story. The AusIMM Spectrum Series 19, 252 pp.

Manske, S., Paul, A. (2002) Geology of a major new porphyry copper center in the Superior (Pioneer) district, Arizona. *Economic Geology* 97, 197–220.

Marlatt, J.L., Kyser, T.K. (2011) Paradigmatic shifts in the uranium exploration process: Knowledge brokers and the Athabasca Basin learning curve. *Society of Economic Geologists Newsletter* 84, January, 1, 17–23.

Marsh, E., Anderson, E. (2011) Ni-Co laterites – a deposit model. U.S. Geological Survey Open-File Report 2011-1259.

Marsden, J.O., House, C.I. (2006) The chemistry of gold extraction. Second Edition, Society for Mining, Metallurgy, and Exploration Inc., 651 pp.

Marshall, D., Anglin, C.D., Mumin, H. (2004) Ore mineral atlas. Geological Association of Canada, Mineral Deposits Division, 112 pp.

Mason, L., Prior, T., Mudd, G., Giurco, D. (2011). Availability, addiction and alternatives: three criteria for assessing the impact of peak minerals on society. *Journal of Cleaner Production* 19, 958–966.

Matheron, G. (1963) Principles of geostatistics. *Economic Geology* 58, 1246–1266.

Mathez, E.A. (1976) Sulfur solubility and magmatic sulphides in submarine basalt glass. *Journal of Geophysical Research* 81, 4277–4284.

May, D., Prior, T., Cordell, D., Giurco, D. (2012) Peak minerals: Theoretical foundations and practical application. *Natural Resources Research* 21, 43–60.

McCarthy, J.H., Vaughn, W.W., Learned, R.E., Meuschke, J.L. (1969) Mercury in soil gas and air – a potential tool in mineral exploration. U.S. Geological Survey Circular 609, 16 pp.

Meadows, D.H., Meadows, D., Randers, J., Behrens III, W.W. (1972) Limits to growth. New American Library, New York, 205 pp.

Meinert, L.D., Dipple, G.M., Nicolescu, S. (2005) World skarn deposits. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 299–336.

Meinert, L.D., Robinson, G.R. Jr., Nassar, N.T. (2016) Mineral resources: Reserves, peak production and the future. *Resources* 14, 5–14.

Menzies, M.A. (1990) Archaean, Proterozoic and Phanerozoic lithospheres. In: Menzies, M. A. (Ed.) *Continental Mantle*. Clarendon, Oxford, 67–86.

MEG Metals Economics Group (2005) Strategies for gold reserves replacement. Metals Economics Group, Halifax, Nova Scotia.

MEG Metals Economics Group (2012) World expenditure trends 2012. Special MEG report for the PDAC International Convention, Canada, March 2012.

Meyer, C. (1981) Ore-forming processes in geologic history. In: Skinner, B.J. (Ed.) *Economic Geology Seventy-fifth Anniversary Volume*, 6–41.

Meyer, C., Hemley, J.J. (1967) Wall-rock alteration. In Barnes, H.L. (Ed.) Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart and Winston, 166–235.

MOHR, S.H., MUDD, G.M., GIURCO, D. (2012) Lithium resources and production: Critical assessment and global projections. *Minerals* 2, 65–84.

MOLE, D.R., FIORENTINI, M.L., THEBAUD, N., CASSIDY, K.F., MCCUAIG, T.C., KIKLAND, C.L., ROMANO, S.S., DOUBLIER, M.P., BELOUSOVA, E.A., BARNES, S.J., MILLER, J. (2014) Archean komatiite volcanism controlled by the evolution of early continents. *Proceedings of the National Academy of Sciences USA* 111, 10083–10088.

MOORHEAD, C.F., DUNHAM, P.B., EASTWOOD, G.J., LECKIE, J.F. (2001) Cadia Hill: from discovery to a measured resource – a case study. In: Edwards, A.C. (Ed.) *Mineral resource and ore reserve estimation – The AusIMM Guide to Good Practice (Monograph 23),* 97–108.

MUDD, G.M. (2013) The limits to growth and 'finite' mineral resources: re-visiting that assumption and drinking from that half-capacity glass. *International Journal of Sustainable Development* 16, 204–215.

MUDD, G.M., WENG, Z., JOWITT, S.M. (2013) A detailed assessment of global Cu resource trends and endowments. *Economic Geology* 108, 1163–1183.

MUHLY, J.D. (1985) The sources of tin and the beginnings of bronze metallurgy. *American Journal of Archaeology* 89, 275–291.

MUHLY, J.D., MADDIN, R., STECH, T., ÖZGEN, E. (1985) Iron in Anatolia and the nature of the Hittite iron industry. *Anatolian Studies* 35, 67–84.

MUIR, T.L., SCHNIEDERS, B.R., SMYK, M.C. (Compilers and Editors) (1995) Geology and gold deposits of the Hemlo area. Hemlo Fieldtrip Guidebook. Geological Association of Canada–Toronto'91, 120 pp.

MUKHERJEE, I., LARGE, R.R. (2016) Application of pyrite trace element chemistry to exploration for SEDEX style Zn-Pb deposits: McArthur Basin, Northern Territory, Australia. *Ore Geology Reviews,* doi: 10.1016/j.oregeorev.2016.08.004.

MUNK, L.A., HYNEK, S.A., BRADLEY, D., JOCHENS, H. (2016) Lithium brines: A global perspective. *Reviews in Economic Geology* 18, 339–365.

MUNTEAN, J.L., CLINE, J.S., SIMON, A.C., LONGO, A.A. (2011*)* Magmatic-hydrothermal origin of Nevada's Carlin-type gold deposits*. Nature Geoscience* 4*,* 122–127*,* doi: 10.1038/ngeo1064.

NALDRETT, A.J. (2004) *Magmatic Sulphide Deposits: Geology, Geochemistry and Exploration*. Springer Verlag, Heidelberg, Berlin, 728pp.

NALDRETT, A.J., WILSON, A., KINNAIRD, J., YUDOVSKAYA, M., CHUNNETT, G. (2011) The origin of chromitites and related PGE mineralization in the Bushveld Complex: new mineralogical and petrological constraints. *Mineralium Deposita* 47, 209–232.

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL (2016) Assessment of critical minerals: Screening methodology and initial application. https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/csmsc_assessment_of_critical_minerals_report_2016-03-16_final.pdf

NOBLE, J.A. (1955) The classification of ore deposits. In: Bateman, A.M. (Ed.) *Economic Geology Fiftieth Anniversary Volume.* The Economic Geology Publishing House, Urbana, 155–169.

NORTHEY, S., MOHR, S., MUDD, G.M., WENG, Z., GIURCO, D. (2014) Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resources, Conservation and Recycling* 83, 190–201.

OTTE, M. (2007) Vers la préhistoire : une initiation. De Boeck Supérieur, Brussels, 432 pp.

PAREKH, B.K., MILLER, J.D. (1999) Advances in flotation technology. Society of Mining, Metallurgy, and Exploration Inc., 463 pp.

PATTEN, C., BARNES, S.-J., MATHEZ, E.A., JENNER, F.E. (2013) Partition coefficients of chalcophile elements between sulfide and silicate melts and the early crystallization history of sulfide liquid: LA-ICP-MS analysis of MORB sulfide droplets. *Chemical Geology* 358, 170–188.

PERELLÓ, J., COX, D., GARAMJAV, D., SANJDORJ, S., DIAKOV, S., SCHISSEL, D., MUNKHBAT, T.-O., GONCHIG, O. (2001) Oyu Tolgoi, Mongolia: Siluro-Devonian porphyry Cu-Au-(Mo) and high-sulfidation Cu mineralization with a Cretaceous chalcocite blanket. *Economic Geology* 96, 1407–1438.

PERNICKA, E, EIBNER, C., ÖZTUNALI, O., WAGNER, G.A. (2003) Early Bronze Age Metallurgy in the North-East Aegean. In: Wagner, G.A., Pernicka, E., Uerpmann, H.-P. (Eds.) *Troia and the Troad*. Springer, Berlin Heidelberg, 143–172.

POHL, W.L. (2011) Economic Geology Principles and Practice: Metals, Minerals, Coal and Hydrocarbons – Introduction to Formation and Sustainable Exploitation of Mineral Deposits. Wiley Online Library. http://onlinelibrary.wiley.com/book/10.1002/9781444394870

PORTER, M.E. (1985) Competitive advantage: creating and sustaining superior performance. Free Press, New York, 592 pp.

PRETORIUS, D.A. (1973) The role of EGRU in mineral exploration in South Africa. Information Circular No. 77, Economic Geology Research Unit, University of the Witwatersrand, Johannesburg, 19 pp.

PUFAHL, P.K, GROAT, L.M. (2017) Invited paper: Sedimentary and igneous phosphate deposits: Ore formation and exploration. *Economic Geology* 112, 483-516.

RADETZKI, M. (2009) Seven thousand years in service of humanity – the history of copper, the red metal. *Resources Policy* 34, 176–184.

RECK, B.K., GRAEDEL, T.E. (2012) Challenges in metal recycling. *Science* 337, 690–695.

REEVE, J.S., CROSS, K.C., SMITH, R.N., ORESKES, N. (1990) Olympic Dam copper-uranium-gold-silver deposit, In: Hughes, F.E. (Ed.) *Geology of the mineral deposits of Australia and Papua New Guinea.* Australian Institute of Mining and Metallurgy Monograph Series 14, 1009–1035.

RENFREW, C. (1990) Before civilization: the radiocarbon revolution and prehistoric Europe. Penguin Books Ltd., Harmondsworth, 320 pp.

RETALLACK, G.J. (2010) Lateritization and bauxitization events. *Economic Geology* 105, 655–667.

RICHARDS, J.P. (2011) Magmatic to hydrothermal metal fluxes in convergent and collided margins. *Ore Geology Reviews* 40, 1-26.

RICHARDS, J.P. (2014) Making faults run backwards: the Wilson Cycle and ore deposits. *Canadian Journal of Earth Sciences* 51, 266–271.

RIDLEY, J. (2013) Ore deposit geology. Cambridge University Press, Cambridge, 409 pp.

ROBB, L. (2004) Introduction to Ore-Forming Processes. Wiley-Blackwell, New York, 384 pp.

ROBERTS, R.M. (1989) Serendipity, accidental discoveries in science. John Wiley & Sons, Inc., New York, 270 pp.

ROBERTS, D.E., HUDSON, G.R.T. (1983) The Olympic Dam copper-uranium-gold deposit, Roxby Downs, South Australia. *Economic Geology* 78, 799–822.

RUDNICK, R.L., GAO, S. (2003) Composition of the continental crust. *Treatise on Geochemistry* 3, 1–64.

RUSSELL, M. (2000) Flint Mines in Neolithic Britain. Tempus Publications Limited, Dublin, 160 pp.

SABINS, F. (1999) Remote sensing for mineral exploration. *Ore Geology Review* 14, 157–183.

SAUNDERS, A.D., ENGLAND, R.W., REICHOW, M.K., WHITE, R.V. (2005) A mantle plume origin for the Siberian Traps: Uplift and extension in the West Siberian Basin, Russia. *Lithos* 79, 407–424.

SAWKINS, F.J. (1984) Metal deposits in relation to plate tectonics. Springer-Verlag, Berlin, 325 pp.

SCHLESINGER, M.E., KING, M.J., SOLE, K.C., DAVENPORT, W.G. (2011) Extractive metallurgy of copper. Fifth Edition, Elsevier, Oxford, 472 pp.

SCHODDE, R. (2010) The key drivers behind resource growth: an analysis of the copper industry over the last 100 years. Minex Consulting. http://minexconsulting.com/publications/Growth%20Factors%20for%20Copper%20SME-MEMS%20March%202010.pdf

SCHODDE, R. (2014a) The global shift to undercover exploration – How fast? How effective? SEG 2014 Conference, Keystone, Colorado, 30 September 2014. http://www.minexconsulting.com/publications/sep2014b.html

SCHODDE, R. (2014b) Uncovering exploration trends and the future: Where's exploration going? International Mining and Resources (IMARC) Conference, Melbourne, Victoria, 22 September 2014. http://www.minexconsulting.com/publications/sep2014.html

SEEDORFF, E., DILLES, J.H., PROFFETT, J.M. Jr., EINAUDI, M.T., ZURCHER, L., STAVAST, W.J.A., JOHNSON, D.A., BARTON, M.D. (2005) Porphyry deposits: Characteristics and origin of hypogene features. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume.* Society of Economic Geologists, Inc., Littleton, 251–298.

SILLITOE, R.H. (2005) Supergene oxidized and enriched porphyry copper deposits. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume.* Society of Economic Geologists, Inc., Littleton, 723–768.

SILLITOE, R.H. (2008) Major gold deposits and belts in the North and South American Cordillera: Distribution, tectonomagmatic settings, and metallogenic considerations. *Economic Geology* 103, 663–687.

SILLITOE, R.H. (2010a) Porphyry copper systems. *Economic Geology* 105, 1–21.

SILLITOE, R.H. (2010b) Exploration and discovery of base- and precious-metal deposits in the circum-Pacific region – A 2010 perspective. *Resource Geology Special Issue* 22, 139 pp.

SILLITOE, R.H. (2012) Copper provinces. In: Hedenquist, J.W., Harris, M., Camus, F. (Eds.) *Geology and genesis of major copper deposits and districts of the world – A tribute to Richard H. Sillitoe. Society of Economic Geologists Special Publication* 16, 1–18.

SILLITOE, R.H., HEDENQUIST, J.W. (2003) Linkages between volcanotectonic settings, ore-fluid compositions, and epithermal precious-metal deposits. *Society of Economic Geologists Special Publication* 10, 315–343.

SIMMONS, S.F., BROWNE, P.R.L. (2000) Hydrothermal minerals and precious metals in the Broadlands-Ohaaki geothermal system: Implications for understanding low-sulfidation epithermal environments. *Economic Geology* 95, 971–999.

SIMMONS, S.F., WHITE, N.C., JOHN, D. (2005) Geological characteristics of epithermal precious and base metal deposits. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume.* Society of Economic Geologists, Inc., Littleton, 485–522.

SIMON, A.C., PETTKE, T., CANDELA, P.A., PICCOLI, P.M., HEINRICH, C.A. (2006) Copper partitioning in a melt-vapor-brine-magnetite-pyrrhotite assemblage. *Geochimica et Cosmochimica Acta* 70, 5583–5600.

SINCLAIR, L., THOMPSON, J.F.H. (2015) In situ leaching of copper: challenges and future prospects. *Hydrometallurgy* 157, 306–324.

SINGER, D.A. (2017) Future copper resources. *Ore Geology Reviews* 86, 271-279.

SINGER, D.A., DREW, L.J. (1976) The area of influence of an exploratory hole. *Economic Geology* 71, 642–647.

SINGER, D.A., MENZIE, W.D. (2010) Quantitative mineral resource assessments—An integrated approach. Oxford University Press, Oxford, 219 pp.

SINGER, D.A., BERGER, V.I., MORING, B.C. (2008) Porphyry copper deposits of the world: Database and grade and tonnage models. U.S. Geological Survey Open File Report 1155-2008, 44 pp.

SINCLAIR, L., THOMPSON, J.F.H. (2015) In situ leaching of copper: challenges and future prospects. *Hydrometallurgy* 157, 306–324.

SKINNER, B.J. (1976) A second Iron Age ahead? *American Scientist* 64, 258–269.

Smith, B.W. (2015) 60 centuries of copper. Copper Development Association. http://www.copper.org/education/history/60centuries/

Sorrell, S., Speirs, J., Bentley, R., Brandt, A., Miller, R. (2009) Global oil depletion. A report produced by the Technology and Policy Assessment function of the UK Energy Research Centre. U.K. Energy Research Centre. http://www.ukerc.ac.uk/publications/global-oil-depletion-an-assessment-of-the-evidence-for-a-near-term-peak-in-global-oil-production.html

St. Pierre, L.E. (Ed.) (1978) Resources of Organic Matter for the Future: Perspectives and Recommendations. Multiscience Publications Ltd., Montreal, 184 pp.

Stavast, W.J.A., Keith, J.D., Christiansen, E.H., Dorais, M.J., Tingey, D., Larocque, A., Evans, N. (2006) The fate of magmatic sulfides during intrusion or eruption, Bingham and Tintic districts, Utah. *Economic Geology* 101, 329–345.

Stimac, J., Hickmott, D. (1994) Trace-element partition coefficients for ilmenite, orthopyroxene and pyrrhotite in rhyolite determined by micro-PIXE analysis. *Chemical Geology* 117, 313–330.

Sutopo, B., Jones, M.L., Levet, B.K. (2003) The Martabe gold discovery: A high sulphidation epithermal gold-silver deposit, North Sumatra, Indonesia. In: Proceedings NewGenGold 2003 Conference, Louthen Media, Perth, Australia, 147–158.

Sverdrup, H., Ragnarsdóttir, K.V. (2014) Natural Resources in a Planetary Perspective. *Geochemical Perspectives* 3, 129–341.

Tahil, W. (2008) The trouble with lithium 2: Under the microscope. Meridian International Research, Martainville, France. http://www.meridian-int-res.com/Projects/Lithium_Microscope.pdf

Thompson, F.H. (2003) The Archaeology of Greek and Roman slavery. The Society of Antiquaries, London, 331 pp.

Thompson, J.F.H. (2015) The need for innovation in mining and exploration. *AusIMM Bulletin.* https://www.ausimmbulletin.com/opinion/the-need-for-innovation-in-exploration-and-mining/

Thompson, A.J.B., Thompson, J.F.H. (Eds.) (1996) Atlas of alteration: A field and petrographic guide to hydrothermal alteration minerals. Geological Association of Canada, Mineral Deposits Division, St. John's, 128 pp.

UNDP-CCSI-WEF Report (2016) Mapping mining to the sustainable development goals. http://unsdsn.org/wp-content/uploads/2016/01/160115-Atlas_full.pdf

U.S. Department of Energy (2011) Critical Materials Strategy. http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

U.S. Geological Survey (2009) Mineral commodity summaries 2009, Lithium. U.S. Geological Survey, 94-95.

U.S. Geological Survey (2016) Mineral commodity summaries 2016. U.S. Geological Survey, 202 pp., doi: 10.3133/70140094.

Warren, J.K. (2016) Evaporites: A Geological Compendium. Second Edition, Springer International Publishing, Berlin, 1813 pp.

White, M.E. (2001) Feasibility studies – Scope and accuracy. In: Edwards, A.C. (Ed.) *Mineral resource and ore reserve estimation – The AusIMM Guide to Good Practice: (Monograph 23)*, 421–434.

Wilkinson, B.H., Kesler, S.E. (2009) Quantitative identification of metallogenic epochs and provinces: Application to Phanerozoic porphyry copper deposits. *Economic Geology* 104, 607–622.

Wilkinson, J.J., Chang, Z., Cooke, D.R., Baker, M.J., Wilkinson, C.C., Inglis, S., Chen, H., Gemmell, J.B. (2015) The chlorite proximitor: A new tool for detecting porphyry ore deposits. *Journal of Geochemical Exploration* 152, 10–26.

Williams, P.J., Barton, M.D., Johnson, D.A., Fontbote, L., de Haller, A., Mark, G., Oliver, N.H.S., Marschik, R. (2005) Iron oxide copper-gold deposits: Geology, space-time distribution, and possible modes of origin. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*. Society of Economic Geologists, Inc., Littleton, 371–406.

WILLS, B.A., FINCH, J.A. (2016) Wills' mineral processing technology: an introduction to the practical aspects of ore treatment and mineral recovery. Eighth Edition, Butterworth-Heinemann, Oxford, 512 pp.

WILSON, A. (2012). A chill sequence to the Bushveld Complex: Insight into the first stage of emplacement and implications for the parental magmas. *Journal of Petrology* 53, 1123–1168.

WOOD, D. (2010) Mineral resource discovery – science, art and business. *Society of Economic Geologists Newsletter* 80, January, 12–17.

WOOD, D. (2012) Discovery of the Cadia Deposits, NSW, Australia (Part 2). *Society of Economic Geologists Newsletter* 89, April, 1, 17–22.

WOOD, D. (2013) Discovering deeper porphyry ore bodies – is there a role for geophysics? 23rd International Geophysical Conference and Exhibition, 11-14 August 2013, Melbourne, Australia.

WOOD, D. (2014) Creating wealth and avoiding gambler's ruin: Newcrest Mining exploration, 1991-2006. *Society of Economic Geologists Newsletter* 96, January, 1, 12–17.

WOOD, S.A., SAMSON, I.M. (1998) Solubility of ore minerals and complexation of ore metals in hydrothermal solutions. In: Richards, J.P., Larson, P.B. (Eds.) *Reviews in Economic Geology v. 10. Techniques in Hydrothermal Ore Deposit Geology.* Society of Economic Geologists, Inc., Littleton, 33–80.

WOOD, D., CHITOMBO, G., BRYAN, S. (2010) Mass underground mining and the role of the exploration geologist. *Society of Economic Geologists Newsletter* 83, October, 1, 22–24.

WORLD COPPER FACTBOOK (2015) International Copper Study Group, 59 pp.

WORLD ECONOMIC FORUM REPORT (2014) The future availability of natural resources. http://www3.weforum.org/docs/WEF_FutureAvailabilityNaturalResources_Report_2014.pdf

WORLD ECONOMIC FORUM REPORT (2015) Mining and metals in a sustainable world 2050. http://www3.weforum.org/docs/WEF_MM_Sustainable_World_2050_report_2015.pdf

WORLD ECONOMIC FORUM REPORT (2016) Voluntary responsible mining initiatives – A review. http://www3.weforum.org/docs/Voluntary_Responsible_Mining_Initiatives_2016.pdf

YAKSIC, A., TILTON, J. (2009) Using the cumulative availability curve to assess the threat of mineral depletion: The case of lithium. *Resources Policy* 34, 185–194.

YARDLEY, B.W.D., CLEVERLEY, J.S. (2013) The role of metamorphic fluids in the formation of ore deposits. In: Jenkin, G.R.T., Lusty, P.A.J., McDonald, I., Smith, M.P., Boyce, A.J., Wilkinson, J.J. (Eds.) *Ore Deposits in an Evolving Earth. Geological Society of London Special Publications* 393, doi: 10.1144/SP393.5.

ZHANG., R., PLAN, H., SANTOSH, M., ZHANG, S. (2015) The history and economics of gold mining in China. *Ore Geology Reviews* 65, 718–727.

APPENDIX TO SECTION 3: EXPLORATION METHODS

GEOLOGY

Launch of the Landsat 1 satellite in 1972 initiated acquisition of moderate resolution imagery of Earth from space, with significant application to geological mapping at regional scale. The seven satellites that were launched between 1972 and 1999 incorporated improved imaging instruments that progressed from a multispectral scanner (MSS) to include a thematic mapper (TM) and, finally, a new enhanced thematic mapper (ETM+) sensor. Satellites launched after 1999 enabled collection of image data with a resolution that had reduced from 0.82 m to 0.41 m by 2007. Launch of the ASTER (Advanced Spaceborne Thermal Emission and Reflectance Radiometer) imaging system in 1999 provided Visible and Near Infrared (VNIR), Shortwave Infrared (SWIR), and Thermal Infrared (TIR) measurements at resolutions of 15, 30 and 90 m, respectively. The World View 3 satellite that was launched in 2014 has 31 cm panchromatic resolution, eight VNIR bands with 1.24 m multispectral resolution, and a further eight bands of 3.7 m SWIR resolution. In addition, the availability of high-accuracy Global Positioning System (GPS) data since 2000 has substantially improved the efficiency and location accuracy for regional- to local-scale geological mapping and other exploration activities.

Drainage surveys are an extension of panning stream sediments used by the Ancients, old-time prospectors and present-day geologists to trace resistant ore minerals dispersed mechanically into drainages by weathering of ore. Panning to register the presence of alluvial gold or cassiterite was used traditionally to discover gold and tin sources, and is still used in modern stream-sediment surveys as an adjunct to collection and chemical analysis of fine-grained sediment fractions.

Modern drainage surveys typically collect a sample by sieving sediment to produce one, or several, fine fractions (typically 180 μm, and finer) for quantitative chemical analysis of a range of elements. The 2+ orders of magnitude reductions in detection limits that have been achieved using Inductively-Coupled Plasma Mass Spectrometry (ICP-MS), and analysis of sediment fractions <75 μm in size, offer scope for previously explored areas to be re-evaluated, since sub-cropping or shallowly buried deposits may produce low-level geochemical anomalism that was not detected by older surveys. Analysis of water collected from flowing streams also has been employed as a drainage geochemical technique (*e.g.*, Learned *et al.*, 1985), in effect reproducing an old prospecting technique reported by Agricola, along with other details of Late Medieval stream sediment geochemistry, as well as increasing groundwater sampling.

Soil surveys involve chemical analysis of soil samples collected on a grid or section line at a sample spacing of 100s to 10s of m. They are used to detect deposits located at depth within the weathering profile, or to identify a halo of lower grade mineralisation around an ore body. As with drainage surveys, advances in the effectiveness of soil surveys owe much to development, from the mid-1960s onwards, of increasingly sophisticated analytical techniques, initially Atomic-Absorption Spectrophotometry, since surpassed by ICP-MS technology, which has progressively lowered detection limits for a wide range of elements, now measured in parts per billion (ppb) or less.

Specialised sampling and analytical techniques were developed over the past 50 years to assist in detecting particular types of mineralisation and ultra-low levels of enrichment. The bulk leach extractable gold (BLEG) technique was developed in the 1980s to detect extremely low-level gold abundances (ppb) in stream sediment and soil samples. Airborne and ground detection of mercury as a vapour associated with mineralisation was tested in the 1960s (McCarthy *et al.*, 1969), but was never widely adopted. A range of other, usually proprietary, geochemical prospecting techniques, commonly with partial or selective leach techniques, have been used to search for deep mineralisation, often under thick transported recent cover, but with uncertain success. The most effective geochemical techniques are based on careful collection of sample media followed by sample preparation and analysis using continually improving analytical tools (Kyser *et al.*, 2015).

Discovery of the Martabe Deposit – Regional exploration in 1995-96 on the west side of Sumatra followed up base metal anomalies identified in the 1980s by the British Geological Survey (Sutopo *et al.*, 2003; Harlan *et al.*, 2005). A 120 km-long portion of a Miocene volcanic arc was initially explored using a BLEG survey (Fig. A3.1a). A 14 ppb Au anomaly was identified in the Aek Pahu river (Fig. A3.1b), surrounded by regional samples that contained largely <5 ppb Au (Fig. A3.1a). Follow-up identified several secondary drainages with anomalies of 58 to 157 ppb Au. Samples of Au-anomalous rocks in streams (float) were traced to a series of prominent north-trending siliceous ridges, and subsequent tape and compass geological mapping, ridge and spur auger soil, grid soil and rock sampling plus ground and airborne geophysical methods identified seven Au prospects (Fig. A3.1b). In late 1998, hole APSD022 was drilled at an angle of –45°, to the east from the base of the steep cliff of Purnama hill. The drill hole intersected an interval of 61 m containing 0.95 g/t Au. This hole was followed up by a second phase of drilling in May 1999, during which the Purnama discovery hole, APSD029, intercepted 81 m grading 2.43 g/t Au from collar. Production at this multi-million ounce Au mine started in 2012.

Rock sampling and analysis is a standard technique for detecting the presence of geochemical anomalies in outcrop, complemented by mineralogical studies to identify hydrothermal alteration products, although weathering and associated leaching of mobile metals may affect the geochemical results. Often the most representative sample comes from compositing a large number of chips across an outcrop. By contrast to a soil anomaly, which may be dispersed some distance from related mineralisation, a rock sample reflects a localised anomaly.

Historically, prospectors used oxidised outcrops of sulphide mineralisation (gossan) as a surface guide to the presence of underlying ore. Gossan is a Cornish word used to describe cellular masses of limonitic iron-oxide and gangue – unreactive silicates and other minerals; characteristic types and colours of limonite are produced by the oxidation of pyrite and various metal sulphides (Blanchard, 1968).

Vegetation geochemistry, or biogeochemistry (Kyser *et al.*, 2015), in the form of visual observation of plants occurring close to ore, may have been used as much by old-time prospectors to make discoveries as were visible signs of ore in rock and soil. Chemical analysis of plants, known as biogeochemical prospecting, was first used in 1936 to explore for tin, tungsten, lead and zinc in Cornwall and Wales, with Harry Warren pioneering the technique in Canada. Between 1948 and 1956, the U.S. Geological Survey used biogeochemistry in the search for uranium in western USA. Groundwater sampling is now employed in some settings, for example to identify the signatures of kimberlite pipes that may host diamonds below the glacial till of northern Canada, to distinguish geophysical anomalies.

Figure showing BLEG Geochemistry Gold (ppb) distribution map with legend:
- △ < 5
- ■ 5 - 10
- ● 10 - 50
- ✶ > 50

Map labels: Martabe District, Sibolga CoW, INDIAN OCEAN

Figure A3.1   **(a)** Regional BLEG results from western Sumatra (from Harlan *et al.*, 2005). **(b)** Prospect results from the Martabe district, consisting of the Purnama and several other ore bodies (modified from Sutopo *et al.*, 2003).

GEOPHYSICS
(Dentith and Mudge, 2014)

Gravity is used to identify sedimentary basins in search of oil and gas accumulations and coal deposits, as well as in delineating major structures, igneous intrusions, and some types of ore body with significant variations in density due to mineralogical differences. Early gravity surveys were used in 1917 and 1924 to locate salt domes in northern Germany and the Gulf Coast region of Texas, in search of oil. An airborne gravity technique was developed by BHP and successfully used to identify kimberlite pipes under glacial sediments in Canada in the 1990s, some found to be diamond-bearing. The technique has broad application as a geological mapping tool; for example, airborne gravity coupled with other airborne geophysical surveys has been conducted over northern Chile and southern Peru to support an exploration programme for porphyry copper deposits. Its greatest advantage is in reducing the high cost of conventional gravity data collection by enabling rapid data acquisition.

Seismic reflection is the primary geophysical technique used in searching for oil and gas accumulations, using two-way travel time of P waves to record data in 3D seismic surveys and on 2D seismic lines. Seismic data require sophisticated processing, but when combined with other geological information obtained from drilling can provide an interpretation of sedimentary sequences to >10 km depth. Smaller seismic arrays are now being developed that are more applicable to mineral exploration at shallow depths, less than 3 km. A limitation is the effect of reflectors (lava flows, intrusions) that are stronger than the deposit itself. The costs are still greater than other geophysical methods, but many of the latter only collect data to depths of several 100 m (Malehmir *et al.*, 2012). Further research on the petrophysical properties of rocks may allow seismic interpretation to be confidently extended from sedimentary basins to igneous rock.

Magnetic intensity has several applications – detecting mineralisation with a related magnetic signature and aiding geological mapping. Magnetic surveys were first used to detect iron ore deposits and are still a primary technique for locating iron ore, particularly in areas of poor outcrop and where forest cover has a masking effect. Magnetic susceptibility is a basic technique, from aerial, ground or hand-held surveys, to distinguish between magnetite- and ilmenite-type intrusions, which are known to be associated with more oxidised (copper-gold) *versus* reduced (tin-tungsten-molybdenum) metal suites, respectively (Ishihara, 1981).

The magnetic signature of mineralisation may be due to an increase or decrease in the content of magnetic minerals, typically magnetite or pyrrhotite. Hydrothermal alteration during mineralisation may cause an increase in the magnetite content during the potassic alteration stage in porphyry copper deposits, but the phyllic alteration overprint results in magnetite destruction.

Magnetic intensity is measured at a regional to prospect scale, using the differences in magnetic intensity related to rock type and alteration. The airborne magnetometer was developed during World War 2 to detect submarines from low-flying aircraft. Increasingly, regional- and prospect-scale surveys are making use of evolving drone technology, to reduce cost and increase resolution by permitting very low altitude surveying.

Radiometric geophysics developed from the search for uranium deposits immediately following World War 2 and initially employed simple Geiger counters to record radioactivity from decaying uranium. Subsequent exploration application of scintillometers in the 1960s enabled potassium and thorium to also be recorded and expanded a wider geological mapping application for radiometry, enabling discrimination between different igneous and sedimentary rock types, and hydrothermal alteration effects associated with some types of mineralisation. The fluorescent property of some minerals under short-wave ultraviolet light is employed in the search for scheelite, a tungsten ore mineral, and other fluorescent minerals such as fluorite.

Remote sensing by satellite or aircraft is used to gather data covering the electromagnetic spectrum. In exploration (Sabins, 1999) this method has two main applications, which depend on the wavelength of radiation being measured – geological mapping, and recognising hydrothermal alteration from mineral spectral signatures. Initially, only a relatively small number of visible and infrared spectra bands were measured, but technology now permits multiple visible, shortwave infrared (SWIR), and thermal infrared (TIR) bands to be recorded and processed (as discussed above).

Hand-held spectrometers have been developed for field use to analyse for major and trace elements using XRF technology and to identify minerals using SWIR spectra. The earliest field-portable commercially available SWIR equipment was the Portable Infrared Mineral Analyser (PIMA), with newer generation solid-state equipment now available. Detailed recording of alteration minerals in drill cuttings and core is conducted using automated, hyperspectral core scanners (*e.g.*, Hylogger, Corescan) which provide information on mineralogy, structure and other geological properties by measuring in VNIR, SWIR and TIR wavelengths.

LIDAR (Light Detection and Ranging) is a high-resolution surveying technology developed in the early 1960s. It can be very useful during exploration, especially over heavily forested terrain from an airborne platform. The ability to penetrate vegetation canopy, record elevation to cm accuracy and produce high-resolution digital elevation maps of engineering quality provides an excellent controlled topographic base for geological mapping (Buckley *et al.*, 2008), geochemical surveys, engineering design, *etc*.

Electrical geophysical techniques include induced polarisation (**IP**) and several electromagnetic (**EM**) technologies. Their development can be traced back to the exploration for copper vein deposits in Cornwall and observation of self potential (SP) in 1830. Major improvements in equipment between 1960 and 1980 permitted recording of higher-quality data and digital data processing and interpretation, which are ongoing.

IP (chargeability-resistivity) is a controlled-source geophysical method, used particularly in searching for porphyry copper, bedded lead-zinc and sulphide-related gold ore bodies, as well as in geothermal and hydrocarbon exploration, and for environmental studies. Unlike other methods, which make use of mineral or rock physical properties, the IP effect is due to an interface electrochemical phenomenon and is greatly enhanced by the presence of disseminated, rather than massive, sulphides. The effect is due to slow, rather than instant, decay of voltages in the Earth produced when a direct electrical current is applied and then interrupted abruptly. Besides identifying the presence (or absence) of chargeable sulphides, the resistivity of the rock (low if clays, high if a siliceous residue or fresh rock) can be determined.

EM (electromagnetic induction) methods are used to measure electrical resistivity of the Earth by making use of Faraday's Law of Induction. A primary magnetic field generated by electric current flowing through a transmitter loop induces secondary electric currents in a conductor (ore body), which generate

a secondary magnetic field recorded by a receiver loop. The transmitter and receiver loops may be located on the ground or on an airborne platform. There are a number of different EM methods used in exploration, including VLF (very long frequency), MT (magnetotellurics), CSAMT (controlled source audio MT), airborne EM and borehole EM. They work best with large conductor bodies, such as massive sulphide deposits, and have had a major impact on exploration for volcanogenic massive sulphide and nickel ore bodies from the 1960s onwards, using both airborne and ground EM techniques.

Although many, if not most, geophysicists see geophysics as a direct ore finding technique, in practice its greatest application is often in detecting physical property anomalism, spatially associated with ore in the Earth's crust. For example, as illustrated with the Ridgeway discovery and originally used in Arizona, IP is an excellent technique for indicating the presence of disseminated sulphides (Wood, 2013). Typically in porphyry copper deposits, barren pyrite-bearing phyllic alteration that may be a halo to copper sulphides will give a large IP chargeability response and may be a guide to associated ore that is in fact offset from the largest IP anomaly. Advances in processing and interpreting geophysical data are resulting from digital data acquisition, inversion modelling and improved integration of geophysical and geological data.

DRILLING

Diamond core drilling provides the highest quality sample of all the drilling methods, by use of an annular, diamond-impregnated drill bit attached to the penetrating end of a core barrel, which houses core until it is recovered after the end of each, relatively short (<3 m), core run. It is used to collect high-quality continuous samples of rock for grade determination, metallurgical characterisation, mechanical testing of the rock and, by using orientated core, of spatially located samples of ore and waste rock for measurement of structural orientations and rock properties. In some cases, such as supergene oxidised gold mineralisation, the circulation fluid may wash out some coarse gold and result in assays that are lower than the real values, which is why a core barrel with an inner-tube is used where this effect is anticipated. The inner-tube prevents the circulation fluid from contacting the core. Core holes can be drilled at any angle from vertical to horizontal.

Percussion drilling uses high-pressure air introduced through drill rods to drive a "hammer" (pneumatic reciprocating piston) with an attached tungsten-steel bit, which in turn produces drill cuttings recovered through return air movement to the surface, either outside (RAB) or inside (RC) the drill rods. These percussion-drilling methods have the advantage of providing fast penetration at lower costs than diamond core, but they have limitations with respect to sample quality. RC drilling provides a more representative sample than RAB because

sample recovery through RC drill rods reduces wall rock contamination that may occur with RAB drilling. Cable tool drilling, an early-developed method, is used in many developing countries with low labour costs to drill for water, and is still used to evaluate alluvial deposits (*e.g.*, tin and gold) to sample unconsolidated material reliably. Auger drilling is used to quickly collect geochemical samples, along with RAB and air core drilling.

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