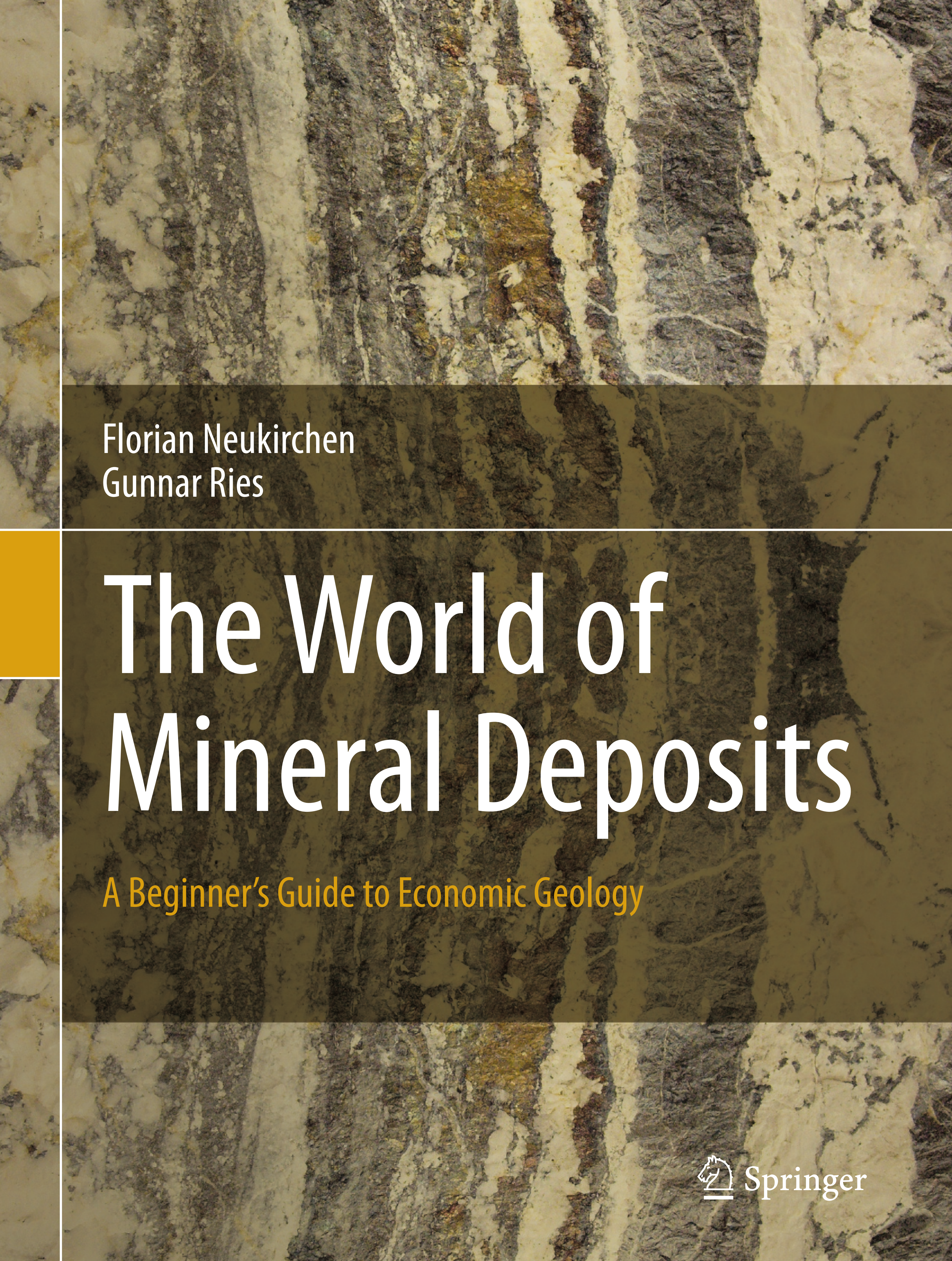

Florian Neukirchen
Gunnar Ries

The World of Mineral Deposits

A Beginner's Guide to Economic Geology

Springer

The World of Mineral Deposits

Florian Neukirchen • Gunnar Ries

The World of Mineral Deposits

A Beginner's Guide to Economic Geology

Springer

Florian Neukirchen
Berlin, Germany

Gunnar Ries
Marxen, Germany

ISBN 978-3-030-34345-3 ISBN 978-3-030-34346-0 (eBook)
https://doi.org/10.1007/978-3-030-34346-0

© Springer Nature Switzerland AG 2020
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Interest in where ore and energy resources can be found is not only relevant to geologists. This book is primarily intended for engineers, geographers, economists, chemists, mineral collectors, investors, and everyone else interested in the topic. Nevertheless, we are sure that geologists and geology students can also benefit from this book. A basic knowledge of geology is certainly helpful, although we have avoided or explained technical terms as much as possible. Background information is provided in introductory sections and boxes. Additional help is provided by a geological timescale in Sect. 1.5 and a glossary at the back of the book. Important ore minerals that are mentioned time and again throughout the book are presented in detail in Sect. 1.2, while others can be found in Chap. 2.

Our unconventional concept—a mixture of popular science, university textbook, and reference work—has obviously succeeded. The first edition of the German title quickly sold out and resulted in the authors consistently receiving very positive reviews and letters. We are pleased that the book has been translated into English and will be available to a larger audience. The translation is based on the second German edition and has been updated in a few places.

We attach particular importance to the processes that have led to the enrichment of corresponding metals. Our aim is to present them according to the current state of research in such a way that even complicated interrelationships can be understood. We show the interplay of different factors contributing to ore-forming processes. Deposits of high-tech metals such as tantalum and rare-earth elements are also explained in detail. While the main part of the book is sorted according to relevant processes, the second chapter offers an alternative starting point with an overview of individual metals. We have also explained modern applications of metals such as platinum in catalysts, which many may not think of at first glance. The chapter on fossil fuels also describes in detail increasingly important unconventional deposits including associated problems. Last but not least, non-metallic industrial rocks and minerals such as sand, gravel, limestone, and clay have not been ignored.

Some of the German deposits featured may seem exotic to readers from other continents because mining is currently pretty insignificant in Europe. However, they are well researched and serve as good examples for important deposit types found worldwide.

We thank Susanne Herting-Agthe from the Mineralogical Collections of the Technical University of Berlin for patiently digging out countless specimens from cabinets and showcases and providing us with photos from the archive. Photos of first-class mineral specimens from the Black Forest were taken with permission from a multivolume opus written by Gregor Markl. We are very happy to have been able to use them. We would like to thank Thorsten Eckardt for helping with the literature research and Lars Fischer, Walter A. Franke, Detlev Seibert, Eberhard Strehl, and Markus Hauser for helpful comments. We would also like to thank everyone who provided us with pictures, answered our questions, or otherwise supported us.

Berlin, Germany — Florian Neukirchen
Marxen, Germany — Gunnar Ries
June 2019

Contents

1 Introduction 1
- 1.1 What Is an Ore? 2
- 1.2 Selected Ore Minerals 4
  - 1.2.1 Sulfides 4
  - 1.2.2 Oxides and Hydroxides 7
  - 1.2.3 Carbonates 10
- 1.3 Resources, Reserves, and Consumption 11
- 1.4 Markets 14
- 1.5 Where to Search and How? 15
- 1.6 Remote Sensing 17
- 1.7 Geophysical Exploration 19
- 1.8 Geochemical Exploration 23
- 1.9 Drilling 24
- 1.10 Open-Pit Mining 27
- 1.11 Underground Mining 28
- 1.12 In Situ Leaching 32
- 1.13 Deep-Sea Mining 32
- 1.14 Environmental Degradation, Land Use, and Social Responsibility 33
- 1.15 Mineral Processing 35
- 1.16 Smelting 38
- 1.17 Recycling 41
- 1.18 Cast, Forged, and Chased 41
- 1.19 The Composition of the Earth 43
- 1.20 Geochemical Classification of Elements 47
- Literature 49
- Further Reading 50

2 The World of Metals 51
- 2.1 Iron and Steel Refiners 51
  - 2.1.1 Iron (Fe) 51
  - 2.1.2 Manganese (Mn) 54
  - 2.1.3 Chromium (Cr) 54
  - 2.1.4 Nickel (Ni) 55
  - 2.1.5 Cobalt (Co) 55
  - 2.1.6 Molybdenum (Mo) 55
  - 2.1.7 Vanadium (V) 57
  - 2.1.8 Tungsten (W) 57
  - 2.1.9 Tantalum (Ta) and Niobium (Nb) 57
- 2.2 Non-Ferrous Metals 59
  - 2.2.1 Copper (Cu) 59
  - 2.2.2 Lead (Pb) 60

2.2.3 Zinc (Zn) 60
2.2.4 Cadmium (Cd) 61
2.2.5 Tin (Sn) 61
2.3 Precious Metals 62
2.3.1 Gold (Au) 62
2.3.2 Silver (Ag) 63
2.3.3 Platinum-Group Elements 64
2.4 Light Metals 65
2.4.1 Aluminum (Al) 65
2.4.2 Titanium (Ti) 65
2.4.3 Magnesium (Mg) 66
2.5 Rare-Earth Elements 66
2.6 Other Metals and Metalloids 72
2.6.1 Lithium (Li) 72
2.6.2 Boron (B) 73
2.6.3 Beryllium (Be) 73
2.6.4 Germanium (Ge) 73
2.6.5 Indium (In) 74
2.6.6 Gallium (Ga) 74
2.6.7 Selenium (Se) and Tellurium (Te) 74
2.6.8 Thallium (Tl) 74
2.6.9 Mercury (Hg) 75
2.6.10 Antimony (Sb) 75
2.6.11 Arsenic (As) 75
2.6.12 Bismuth (Bi) 75
2.6.13 Uranium (U) and Thorium (Th) 76
2.6.14 Zirconium (Zr) and Hafnium (Hf) 77
2.6.15 Silicon (Si) 79
Literature 79

3 Magmatic Deposits 81
3.1 Diversification of Magmas (Introduction) 84
3.1.1 Generation of Magmas and Fractional Crystallization 84
3.1.2 Liquid Immiscibility 90
3.2 Podiform Chromite Deposits in Ophiolites 92
3.3 Layered Mafic Intrusions 95
3.3.1 Magmatic Layering and Its Causes 99
3.3.2 Chromium, Nickel, and Platinum in Basic Magmas 102
3.3.3 Bushveld Complex 105
3.3.4 Great Dyke 109
3.3.5 Sudbury Igneous Complex 109
3.4 Komatiite Hosted Deposits 113
3.5 Anorthosite-Hosted Deposits 115
3.6 Kiruna-Type Magnetite Apatite Iron Ore 116
3.7 Granite (Introduction) 116
3.7.1 Tin Granite 118
3.8 Pegmatite 119
3.9 Alkaline Rocks (Introduction) 123
3.10 Carbonatite 124
3.10.1 Phoscorite 129
3.11 Agpaitic Rocks 130
3.11.1 Ilimaussaq 133
3.11.2 Khibina and Lovozero 134

3.12 Ivigtut . . . 137
Literature . . . 138
Further Reading . . . 142

4 Hydrothermal Deposits . . . 143
4.1 Hydrothermal Veins . . . 148
4.1.1 Veins in the Black Forest . . . 151
4.1.2 Polymetallic Veins in the Ore Mountains . . . 154
4.2 Orogenic Gold Veins . . . 158
4.3 Epithermal Gold and Gold–Silver Deposits . . . 162
4.4 Porphyry Copper Deposits . . . 168
4.4.1 Porphyry Molybdenum Deposits (Climax Type) . . . 181
4.4.2 Porphyry Gold (Intrusion-Related Gold) . . . 182
4.5 Tin–Tungsten Deposits . . . 182
4.6 Greisen . . . 188
4.7 Iron Oxide Copper Gold Deposits . . . 189
4.8 Chimneys and Mantos . . . 191
4.9 Skarn . . . 192
4.10 Metasomatic Siderite Deposits . . . 194
4.11 Carlin-Type Gold . . . 195
4.12 Mississippi Valley Type . . . 196
4.13 Sandstone-Hosted Copper and Lead–Zinc Deposits . . . 201
4.14 Unconformity-Related and Sandstone-Hosted Uranium Deposits . . . 201
4.15 Hydrothermal Systems on the Seafloor (Introduction) . . . 203
4.15.1 Black Smokers . . . 203
4.15.2 Marine Brine Pools and Atlantis II Deep . . . 207
4.16 Volcanogenic Massive Sulfide Deposits . . . 208
4.16.1 Cyprus-Type Volcanogenic Massive Sulfide Deposits in the Troodos Ophiolite . . . 211
4.16.2 Besshi (Japan) . . . 214
4.16.3 Kuroko (Japan) . . . 215
4.16.4 Iberian Pyrite Belt . . . 216
4.17 Sedimentary Exhalative Deposits . . . 219
4.18 Lahn–Dill-Type Iron Deposits . . . 224
Literature . . . 224
Further Reading . . . 230

5 Deposits Formed by Sedimentation and Weathering . . . 231
5.1 Stratiform Sediment-Hosted Copper Deposits . . . 231
5.1.1 Kupferschiefer in Europe . . . 232
5.1.2 Central African Copper Belt . . . 236
5.2 Banded Iron Formation . . . 236
5.3 Iron Oolite . . . 244
5.4 Bean Ore . . . 246
5.5 Sedimentary Manganese Deposits . . . 246
5.6 Manganese Nodules . . . 246
5.7 Evaporites . . . 248
5.7.1 Marine Evaporites . . . 254
5.7.2 Salt Lakes and Salt Pans . . . 257
5.8 Phosphorite . . . 261
5.9 Placer Deposits . . . 264
5.10 Weathering (Introduction) . . . 268
5.11 Laterite and Bauxite . . . 270

5.11.1 Bauxite . . . 271
5.11.2 Lateritic Nickel Deposits . . . 273
5.11.3 Lateritic Gold Deposits . . . 275
5.11.4 Lateritic Rare-Earth Element Deposits (Ion Adsorption Clay) . . . 275
5.12 Duricrusts . . . 276
Literature . . . 277
Further Reading . . . 281

6 Fossil Fuels . . . 283
6.1 From Peat to Coal . . . 285
6.2 From Algae to Petroleum . . . 292
6.3 Petroleum and Natural Gas: Migration into Traps . . . 297
6.4 Oil from the Persian Gulf . . . 302
6.5 Production of Petroleum and Natural Gas . . . 304
6.6 Peak Oil . . . 309
6.7 Fracking: Shale Gas and Tight Oil . . . 311
6.8 Oil Shale . . . 316
6.9 Tar Sand and Heavy Crude Oil . . . 317
6.10 Methane Hydrates . . . 319
Literature . . . 321
Further Reading . . . 323

7 Industrial Minerals and Rocks . . . 325
7.1 Sand, Gravel, and Natural Stones . . . 325
7.2 Lime, Marl, and Dolomite . . . 325
7.3 Tuff, Pumice, Perlite, Pozzulan, and Trass . . . 326
7.4 Feldspar, Quartz, and Mica . . . 327
7.5 Clay and Kaolin . . . 329
7.6 Aluminium Silicates . . . 332
7.7 Wollastonite . . . 333
7.8 Garnet . . . 333
7.9 Olivine (Forsterite) . . . 333
7.10 Magnesite, Talc, and Soapstone . . . 333
7.11 Corundum . . . 335
7.12 Diamond . . . 335
7.13 Diatomite (Diatomaceous Earth) . . . 335
7.14 Fluorite and Baryte . . . 336
7.15 Zeolites . . . 337
7.16 Graphite . . . 337
7.17 Sulfur . . . 338
Literature . . . 340
Further Reading . . . 340

Glossary . . . 341

Index . . . 353

About the Authors

Florian Neukirchen is a mineralogist and non-fiction author. After his studies in Freiburg he worked on alkaline rocks at the University of Tübingen. Research trips led him to Oldoinyo Lengai in Tanzania, through the High Atlas in Morocco, and to the Ilimaussaq intrusion in Greenland. He currently lives in Berlin. He has written several books on geology in German.

Gunnar Ries studied mineralogy in Hamburg. His interest in the weathering behavior of East African carbonatites led him to Uganda and Tanzania. He works at CRB Analyse Service GmbH in Hardegsen (Germany) and in his spare time blogs about geoscientific topics at Scilogs.com.

1 Introduction

The consumption of primary raw materials has increased ever faster in recent decades, not least due to rapid economic growth in countries such as China, India, and Brazil. Petroleum and natural gas continue to be the most important energy sources driving engines and turbines worldwide, while petroleum is also the most important raw material for the production of plastics, various medicines, and other products of the chemical industry. Metals are an integral part of our world. Whether in the form of steel girders or copper wires, gold bars enclosed in safes or proudly presented silver jewelry, platinum in catalytic converters, or tantalum in electronic capacitors we use metals everywhere and in many different ways. At the same time, thanks to new high-tech applications the names of elements that until recently led a shadowy existence at the edge of the periodic table are on everyone's lips.

However, resources are limited and the effort to find and develop new mineral deposits is increasing. Questions as to how deposits formed and where they can be found are thus becoming increasingly important. Contrary to some pessimistic forecasts no commodities have yet been exhausted, although with some critical resources it may well become necessary to look for alternatives.

Fortunately, the substances that make up Earth are not homogeneously distributed. The formation of deposits involves processes that have led to economically viable enrichment of the elements concerned. The processes of fractionation are just as different as the metals being sought.

A particularly simple, yet effective means of fractionation is the deposition of gold nuggets and gold flakes by a river. In the course of a river the flow velocity changes and particles transported in the water are deposited and sorted according to size and density. Gold is preferentially deposited in certain places where it forms so-called gold placers (Sect. 5.9). With a washing pan or with chemicals we can finally separate it from the sand. Another sedimentary process is evaporation that leads to the deposition of evaporites (Sect. 5.7) such as salt and gypsum. These can also be enriched in lithium, an alkali metal that is particularly soluble as a chloride and is used in rechargeable batteries. Not only sedimentation but also weathering (Sect. 5.10) can lead to the formation of deposits. In this case we are mainly interested in those elements that are left in place by chemical weathering, while all soluble substances are leached out.

Many deposits are the result of hydrothermal processes (Chap. 4) in which certain substances are dissolved in hot water and precipitated elsewhere. This can be at a hot spring on the seabed, within the pores of a rock, in fine cracks, or along a fault. In other cases the space is created by dissolving the rock at the same time or by an exchange of substances between water and rock. In hydrothermal systems very different chemical reactions can take place and very different minerals can be formed. Hydrothermal deposits are correspondingly diverse.

Another important fractionation process is magmatism (Chap. 3) because melting and subsequent crystallization lead to strong fractionation between melt and rock. The number of different types of magmatic deposits (also called igneous-related deposits) is low, but there are some giants among them. Magmatism should also not be underestimated as the first fractionation step for the subsequent formation of hydrothermal or sedimentary deposits. This already shows that the classification of deposits is not always easy (Box 1.1).

The origin of petroleum, natural gas, and coal, on the other hand, goes back originally to living beings followed by a series of geological processes that are discussed in Chap. 6.

Of course, new deposits are still being formed today, but this is simply negligible compared with our consumption. As a rule, geology is about periods of time that are beyond human imagination as we are talking about millions of years (Fig. 1.21). That is an impossibly long period to wait for a

F. Neukirchen and G. Ries, *The World of Mineral Deposits*,
https://doi.org/10.1007/978-3-030-34346-0_1

new deposit, so we are dependent on the finite deposits that have formed over the course of the Earth's history—without disappearing again as a result of erosion.

Box 1.1 The problem with the classification of deposits

No two deposits are the same. In each case different processes took place one after the other and this happened under changing conditions. This makes classification difficult no matter how many "drawers" are used for classification. There are always some examples that don't fit or that belong best in between two drawers. Even the coarsest classification (i.e., magmatic, hydrothermal, and sedimentary deposits) is problematic since there are also transitions that flow here. Accordingly, there are countless approaches to classification and it should come as no surprise that an occurrence is pushed into a different "drawer" by different authors.

From an economic point of view it may be obvious to group deposits according to their metals. From a geological point of view, however, this has not proved successful. At most, it makes sense to indicate the economically most important metals as an additional detail. We then speak of lead–zinc veins or high-sulfidation epithermal gold–silver veins.

Of course, it is much more attractive to group deposits according to the most important processes involved in their formation. However, there are a couple of disadvantages: on the one hand, interpretation is always involved and the classification could change with further research and, on the other hand, we have to balance the importance of the processes involved.

In addition, very different types of deposits can often arise from one and the same magma or hydrothermal water. These types therefore often occur together, although they belong in different drawers. Although genetically related occurrences could be summarized, there will be some types that need to be mentioned several times. The same result would be obtained by trying to sort deposits according to how they relate to plate tectonics.

Some authors attach great importance to rock in which the ores occur (e.g., sediment bound), others more to the shape of the ore bodies (e.g., veins, breccias, disseminated in the rock), or the immediate process of precipitation (e.g., impregnation, replacement).

Another possibility is to classify on the basis of important prototypes such as Cyprus type, Carlin type, or Mississippi Valley type. Quite apart from the fact that we can define any number of prototypes it is often difficult in individual cases to decide whether a deposit corresponds more to one or the other type. The advantage is that a single keyword readily describes a complex system including the genetic model.

Dill (2010) proposes an interesting 2D scheme combining the economic enrichment of each metal with the most important processes, but of course he has to discuss each type of deposit with more than one metal correspondingly frequently.

No classification system has really established itself. Usually a mix of everything is used as in this book. In individual cases one should not worry so much about distinguishing different types, but rather about which processes have taken place during their development. A look at the similarities between different types of deposits can be helpful.

1.1 What Is an Ore?

Ore is a mineral aggregate or rock that can be mined out of economic interest—usually to extract metals. The term therefore does not only cover the ore minerals themselves such as chalcopyrite, sphalerite, and magnetite, but also the respective rocks that contain more or less high proportions of these minerals (Fig. 1.1). What is profitable naturally depends on the current situation of markets and on technological developments.

The required concentration of metal to call a rock "ore" is very different depending on the metal. Iron ore often contains more than 50% iron, while in the case of zinc and lead it is only a few percent of the respective metal. Copper and nickel contents start at 0.5% and gold at 0.0001%. If several metals are extracted from the ore the values may be correspondingly lower. The concentration of economically interesting metal in the ore is called ore grade. However, metal content is not the only consideration. Equally important is how easily the metal can be extracted from the ore by mineral processing and smelting (see Sects. 1.15 and 1.16). The size of a deposit (those with large tonnage may be worthwhile even having a low ore grade) and the cost of mining (e.g., through low-cost open-pit mining or expensive deep shafts) are also important. Cutoff grade is the minimum grade at which it is worthwhile to mine a certain deposit. Everything below it (low-grade ore or poor ore) is strictly speaking no longer ore even if metals can be extracted from it. The useless side rock is called sterile or barren.

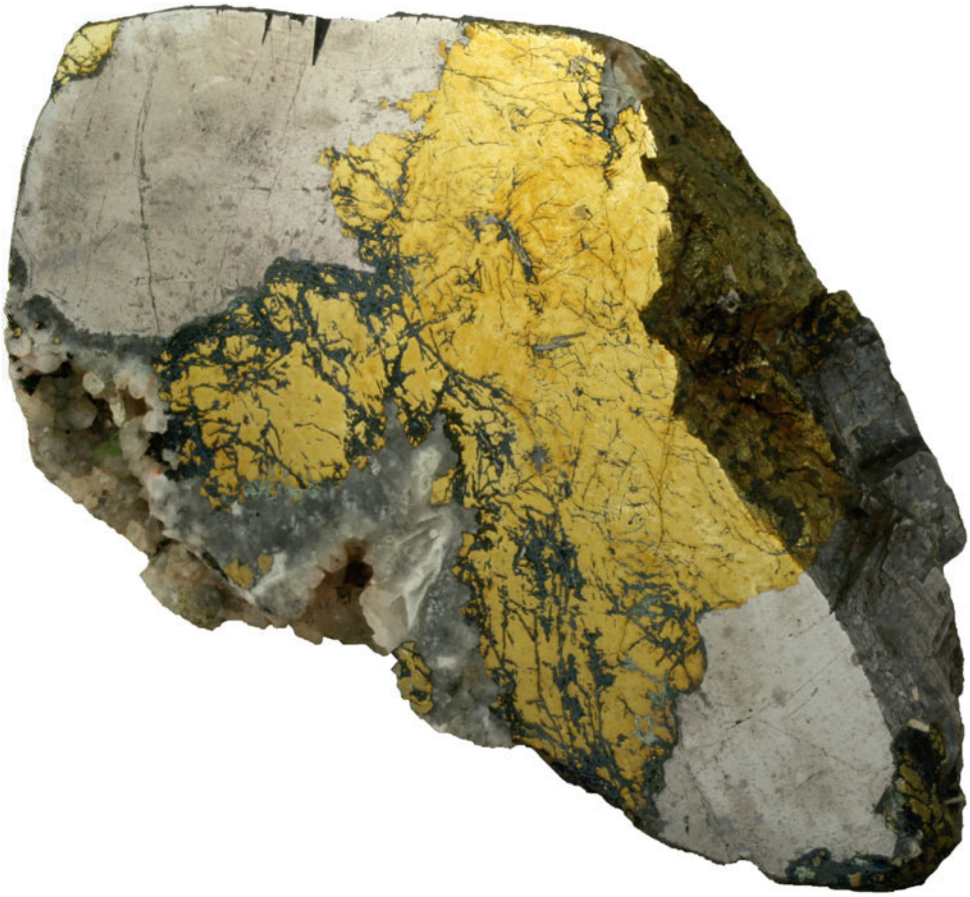

Fig. 1.1 Massive ore with galena (*gray*) and chalcopyrite (*brass*) from the Friedrich-Christian Mine in Wildschapbach, Black Forest (Germany) (*photo* © F. Neukirchen, Markl Collection/Tübingen)

Ore grade (i.e., the concentration of economically interesting metal) is expressed as a percentage by weight, with very small contents usually as grams metal per metric ton rock. The following rule applies: 1 g/t = 1 ppm = 0.0001%.

Only a few metals and metalloids occur in nature in elementary form (i.e., native) such as platinum, gold, silver, copper, mercury, antimony, arsenic, and very rarely a few others. The precious metals gold and platinum occur preferentially in elementary form, while the others usually occur in the form of compounds. Therefore, metals have to be extracted from other minerals. The most important ore minerals are sulfides for copper, zinc, lead, silver, nickel, and molybdenum and oxides or hydroxides for iron, manganese, aluminum, chromium, titanium, tin, uranium, niobium, and tantalum. Silicate minerals are, with a few exceptions (beryl, spodumene, zircon, eudialyte, garnierite, and so on), not suitable as ore because aggressive chemicals have to be used to dissolve them, while for most metals minerals that are easier to process are available. In contrast, carbonates (malachite, azurite, siderite, cerussite, smithsonite, and magnesite) are easy to process. However, they usually only occur in limited quantities and have a lower metal content than corresponding oxides or sulfides. Since carbon dioxide (CO_2) released from the ore during smelting impedes the reduction process, carbonates are usually first converted into oxides by heating in the presence of oxygen (calcination).

Ores from other mineral groups such as arsenides, arsenates, tungstates, or vanadates generally occur only in minor quantities, but can be of local importance. Rare-earth elements (REEs) represent a special case. They are mainly extracted from the minerals monazite (REE phosphate) and bastnäsite (REE fluorocarbonate). Lithium and zinc can even be obtained from specific brines, with such salt waters being regarded as liquid ore (see Sect. 5.7.2 and Box 4.29).

Ore usually contains other minerals such as quartz, feldspar, calcite, baryte, and fluorite that are separated if possible before smelting from interesting ore minerals.

Miners call them gangue. Nowadays some gangue minerals are in high demand themselves (Sect. 7.14).

Often several metals can be extracted profitably from a single ore. The economically most important metal is rarely the one with the highest content. In many sulfide deposits (e.g., pyrite, pyrrhotite, arsenopyrite, and chalcopyrite) iron is the most common metal, but it ends up in waste.

Many metals are only obtained as by-products. This applies above all to rare metals or to metals consumed in small quantities despite there being important high-tech applications. Supply and demand often vary widely resulting in highly volatile and sometimes extremely high prices.

Any occurrence of ore is called an ore deposit or a mineral deposit. Whether a deposit can be mined or not depends not only on the prices that can be achieved but also of course on the costs of mining, the development costs (infrastructure), and the size of the deposit. Box 1.2 introduces some important terms.

Box 1.2 Stratiform, syngenetic, epigenetic, stratabound …

A deposit is **syngenetic** when ores are formed simultaneously with the rock that surrounds them such as placer deposits (Sect. 5.9), banded iron formation (BIF) deposits (Sect. 5.2), and layered mafic intrusions (LMIs) (Sect. 3.3). Although sedimentary exhalative (SEDEX) deposits (Sect. 4.17) and volcanogenic massive sulfide (VMS) deposits (Sect. 4.16) are largely syngenetic, they include replacements in older rocks.

A **diagenetic** deposit is formed when unconsolidated sediment is turned into solid rock. It's almost syngenetic, so to speak. For example, copper-bearing shale (Sect. 5.1) and certain zones in SEDEX.

A deposit is **epigenetic** when ores are formed within older surrounding rocks. This applies to most hydrothermal deposits such as veins, replacements, impregnation, and metasomatism (see Chap. 4).

A **stratiform** deposit has the form of a layer that lies parallel to the rock layers (i.e., concordant). It can be syngenetic or epigenetic. For example, copper-bearing shale (Sect. 5.1), coal seams (Sect. 6.1), and massive ores in SEDEX deposits (Sect. 4.17).

A **stratabound** deposit can only be found in a certain rock layer. It can be stratiform (e.g., SEDEX; Sect. 4.17), irregular (e.g., many deposits in sandstones; Sect. 4.13), or discordant (e.g., chimneys; Sect. 4.8). It can be syngenetic, diagenetic, or epigenetic.

A deposit is **discordant** when it cuts through rock layers (in particular, veins and volcanic breccias).

1.2 Selected Ore Minerals

1.2.1 Sulfides

Chalcopyrite

$CuFeS_2$ (Fig. 1.2).

Crystal system	Tetragonal
Color	Golden to brass with a green tinge
Luster	Metallic
Streak color	Black, greenish black

The most important copper ore has a copper content of 35%. It usually forms massive aggregates and occurs in many types of sulfide deposits. In hydrothermal deposits it is often found together with bornite and pyrite (Box 1.3) and in magmatic sulfide deposits with pentlandite and pyrrhotite (FeS).

Bornite

Cu_5FeS_4 (Fig. 1.3).

Crystal system	Orthorhombic
Color	Bronze to copper, tarnishes colorfully
Luster	Metallic
Streak color	Grayish black

Fig. 1.2 Chalcopyrite on quartz. Silberwiese Mine, Oberlahr, Westerwald (Germany) (*photo* © Monika Günther/Archive Mineralogical Collections of the TU Berlin)

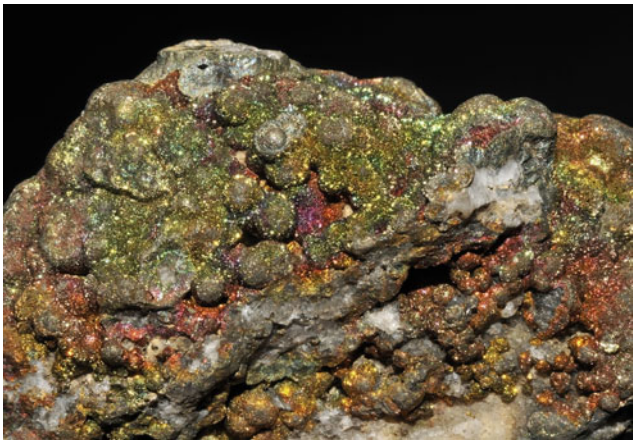

Fig. 1.3 Bornite with typical tarnish colors from Mexico (*photo* © Géry Parent, CC-BY-SA, Wikimedia Commons)

The copper content is 63%. Frequent copper ore that forms massive aggregates. Often occurs together with chalcopyrite as primary ore.

Covellite (covelline)

CuS (Fig. 1.4).

Crystal system	Hexagonal
Color	Dark blue
Luster	Semimetallic
Streak color	Bluish black

Often present in small quantities as a secondary mineral. It has a copper content of 66%.

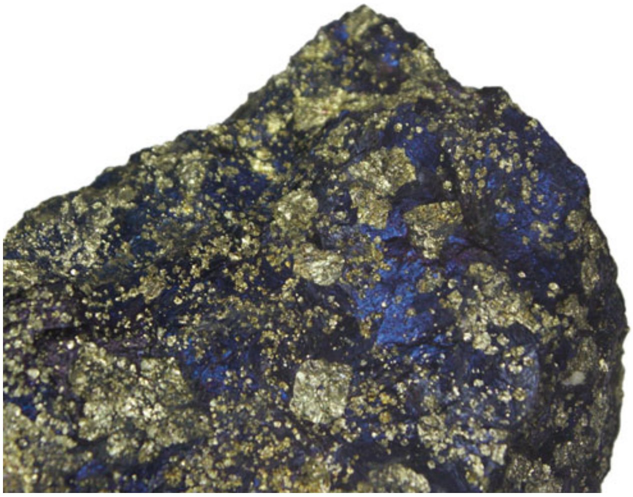

Fig. 1.4 Covellite and pyrite from Cuka Dulkan, near Bor (Serbia) (*photo* © F. Neukirchen/Mineralogical Collections of the TU Berlin)

Fig. 1.5 Chalcocite from Mammoth Mine, Mount Isa-Cloncurry Territory (Queensland, Australia) (*photo* © Rob Lavinsky/iRocks.com, CC-BY-SA, Wikimedia Commons)

Chalcocite

Cu_2S (Fig. 1.5).

Crystal system	Monoclinic
Color	Lead gray, steel gray, dull and dark tarnishing
Luster	Metallic on fresh fracture, dull tarnishing
Streak color	Grayish black

Important copper ore with a copper content of 80%. Mainly occurs in the cementation zone (Box 4.16) of copper deposits.

Tennantite and tetrahedrite (fahlore or fahlerz)

Tennantite ($Cu_{12}As_4S_{13}$) and tetrahedrite ($Cu_{12}Sb_4S_{13}$) (Fig. 1.6).

Crystal system	Cubic
Color	Steel gray, greenish to bluish
Luster	Metallic
Streak color	Gray–black, reddish gray

There is a complete series of compositions (solid solution) between antimony and arsenic endmembers. Can have high contents of Fe, Zn, Ag, and Hg. Silver content often in the percentage range. In freibergite (Ag-rich tetrahedrite) up to 18%. Important copper and silver ore.

Fig. 1.6 Tetrahedrite from Wenzel Mine in Oberwolfach, Black Forest (Germany) (*photo* © F. Neukirchen, Markl Collection/Tübingen)

Enargite

Cu_3AsS_4.

Crystal system	Orthorhombic
Color	Gray, gray–black
Luster	Metallic to dull
Streak color	Black

In hydrothermal veins (especially, in the Andes region).

Pentlandite

$(Ni,Fe)_9S_8$.

Crystal system	Cubic
Color	Bronze yellow
Luster	Metallic
Streak color	Black

Most important nickel ore. Often as segregation lamellae in pyrrhotite (FeS) or in aggregates with pyrrhotite. Often together with chalcopyrite.

Fig. 1.7 Galena on siderite and quartz from Neudorf, near Harzgerode, Harz (Germany) (*photo* © Rob Lavinsky/irocks.com, CC-BY-SA, Wikimedia Commons)

Galena

PbS (Fig. 1.7).

Crystal system	Cubic
Color	Lead gray
Luster	Metallic
Streak color	Grayish black

Most important lead ore. Usually has a silver content of 0.01–0.3%—sometimes even more—making it an important silver ore due to its frequency. Often in hydrothermal sulfide deposits together with sphalerite and often as well-formed crystals such as cubes and combinations of cubes, octahedra, and rhombic dodecahedra.

Fig. 1.8 Honey-colored sphalerite from Santander (Spain) (*photo* © F. Neukirchen/Mineralogical Collections of the TU Berlin)

Sphalerite (zincblende)

ZnS (Fig. 1.8).

Crystal system	Cubic
Color	Yellow (honey), brown, red, oil green, black
Luster	Adamantine
Streak color	Yellowish to dark brown

The edges of zinc sulfide are transparent to translucent. It often occurs in hydrothermal deposits together with galena. Crystals especially as tetrahedra and rhombic dodecahedra. Often high iron content and then dark-colored and opaque. Iron-free sphalerite is yellow and transparent (honey colored). Also brown concentric layered aggregates (colloform or botryoidal sphalerite or Schalenblende; Box 4.21) of sphalerite and wurtzite (also ZnS). Sphalerite usually also contains manganese, cadmium, and traces of indium, gallium, tellurium, and germanium.

1.2.2 Oxides and Hydroxides

Chromite

$FeCr_2O_4$ (Fig. 1.9).

Crystal system	Cubic
Color	Black, brownish black
Luster	Metallic to semimetallic
Streak color	Dark brown

Mineral of the spinel group. Most important chromium ore; see Box 3.8.

Fig. 1.9 Chromite (cockade ore) from a podiform chromium deposit (location unknown) (*photo* © Andrew Silver, USGS)

Magnetite

Fe_3O_4 (Fig. 1.10).

Crystal system	Cubic
Color	Black, gray
Luster	Metallic
Streak color	Black

Very common mineral, contained in many rocks. Important iron ore, sometimes important titanium ore due to its high titanium content. Mineral of the spinel group with both divalent and trivalent iron: $Fe^{2+}(Fe^{3+})_2O_4$. Magnetic.

Fig. 1.10 Beautiful magnetite crystals octahedral in form are found less in iron deposits than in metamorphic rocks. These crystals were collected from a serpentinite near Zermatt (Switzerland) (*photo* © F. Neukirchen)

Fig. 1.11 Hematite. Fibbia, Gotthard (Switzerland) (*photo* © Rob Lavinsky/iRocks.com, CC-BY-SA, Wikimedia Commons)

Hematite

Fe_2O_3 (Fig. 1.11).

Crystal system	Trigonal
Color	Reddish gray to black
Luster	Metallic
Streak color	Cherry red

Crystals often flaky to tabular. Frequently, there are kidney-shaped or cauliflower-shaped aggregates with a very shiny surface called kidney iron ore, fibrous red iron ore, or colloform or botryoidal hematite (Box 4.21). Important iron ore.

Ilmenite

$FeTiO_3$ (Fig. 1.12).

Crystal system	Trigonal
Color	Black, brown–black, steel gray
Luster	On fresh breaks metallic, otherwise dull
Streak color	Black, finely ground dark brown

Important titanium ore.

Pyrolusite

β-MnO_2 (Fig. 1.13).

Cystal system	Tetragonal
Color	Dark gray
Luster	Metallic
Streak color	Black

Fig. 1.12 Ilmenite from Løvjomås, Froland, near Arendal (Norway) (*photo* © F. Neukirchen/Mineralogical Collections of the TU Berlin)

Fig. 1.13 Pyrolusite from Gremmelsbach, near Triberg, Black Forest (Germany) (*photo* © F. Neukirchen, Markl Collection/Tübingen)

Most important manganese ore. Also as colloform (botryoidal) aggregates (fibrous manganese oxide; Box 4.21).

Cassiterite

SnO_2 (Fig. 1.14).

Crystal system	Tetragonal
Color	Black, black–brown, yellow–brown
Luster	adamantine to adamantine–metallic, greasy
Streak color	Yellow to almost colorless

Fig. 1.14 Cassiterite (twin crystal) from Cínovec, Erzgebirge, Ore Mountains (Czech Republic) (*photo* © Monika Günther/Archive Mineralogical Collections of the TU Berlin)

Most important tin ore. Crystals tabular, needle shaped (needle–tin ore), bipyramids. Brown colloform aggregates (wood tin). In tin granites, hydrothermal deposits, and placers.

Uraninite (pitchblende)

UO_2 to U_3O_8.

Crystal system	Cubic, crystal lattice often destroyed by radiation
Color	Black
Luster	Greasy to metallic
Streak color	Brownish black

Highly radioactive. The uranium content decreases with increasing age due to radioactive decay.

Goethite

α-FeOOH (Fig. 1.15).

Crystal system	Orthorhombic
Color	Black–brown to light yellow
Luster	Metallic, silky, earthy
Streak color	Brown, yellow–brown

Fig. 1.15 Colloform goethite from Rossbach Mine, Siegerland (Germany) (*photo* © Bernd Kleeberg/Archive Mineralogical Collections of the TU Berlin)

Often formed by the weathering of sulfide deposits. Also found as colloform (botryoidal) aggregates (fibrous brown iron ore). Earthy yellow masses consisting of different iron hydroxides are called limonite.

Gibbsite

γ-$Al(OH)_3$.

Crystal system	Monoclinic
Color	Colorless, white, gray
Luster	Vitreous, pearly
Streak color	Whitely

Together with other minerals as a component of bauxite (aluminum ore). Also included in laterite.

Diasporite (diaspore)

α-AlOOH.

Crystal system	Orthorhombic
Color	Colorless, white, gray, greenish, reddish
Luster	Vitreous, pearly
Streak color	Whitely

Together with other minerals a component of bauxite (aluminum ore). Also found in laterite.

1.2.3 Carbonates

Malachite

$Cu_2CO_3(OH)_2$ (Fig. 1.16).

Crystal system	Monoclinic
Color	Green
Luster	Vitreous, silky
Streak color	Light green

Very common in the oxidation zone (Box 4.16) of copper deposits.

Azurite

$Cu_3(CO_3)_2(OH)_2$ (Fig. 1.17).

Fig. 1.16 Malachite from Gottesehre Mine, Urberg, Black Forest (Germany) (*photo* © F. Neukirchen, Markl Collection/Tübingen)

Fig. 1.17 Azurite on dolomite from Tsumeb (Namibia) (*photo* © Bernd Kleeberg/Archive Mineralogical Collections of the TU Berlin)

Crystal system	Monoclinic
Color	Azure blue
Luster	Vitreous
Streak color	Light blue

In the oxidation zone of copper deposits.

Siderite

$FeCO_3$ (Fig. 1.18).

Crystal system	Trigonal
Color	Yellow, brown
Luster	Vitreous, pearly
Streak color	Yellowish white

Fig. 1.18 Siderite from Hoffnung und Segen Gottes Mine in Stollberg, Harz (Germany) (*photo* © Monika Günther/Archive Mineralogical Collections of the TU Berlin)

Box 1.3 Pyrite

Pyrite, the gold-colored iron sulfide with metallic luster (FeS_2; Fig. 1.19), is by far the most abundant and widespread sulfide mineral. Museums often show perfect cubes or pentagonal dodecahedra, sometimes also pyritized fossils or shales with sun-shaped aggregates. Pyrite is colloquially called fool's gold.

This mineral can be formed under very variable conditions in a variety of environments. During the solidification (diagenesis) of sediments (especially, in shales) it is formed by the action of sulfate-reducing bacteria. Under these conditions it often occurs together with marcasite that has the same composition in a different crystal lattice (orthorhombic).

Pyrite is also found in almost all hydrothermal deposit types and is often the dominant mineral (e.g., in some SEDEX deposits; Sect. 4.17 and in certain zones of VMS deposits; Sect. 4.16). Finally, pyrite can also be formed magmatically—especially, in mafic intrusions where it can occur subordinate to low-sulfur pyrrhotite (FeS).

In fact, pyrite can occur when there is sufficient Fe^{2+} and S^{2-} regardless of temperature. Accordingly, reduced conditions are the most important prerequisite. In addition, a hydrothermal fluid must be at least slightly acidic but preferably strongly acidic.

However, a fluid can be supersaturated with several metals at the same time—for example, on copper or arsenic in addition to iron so that chalcopyrite ($CuFeS_2$), arsenopyrite (FeAsS), or other minerals are formed. Depending on the ratios of the metals precipitated they occur together with pyrite or other sulfides. The result is that pyrite is often formed both very early and very late in hydrothermal systems interrupted by the crystallization of other sulfides.

Sometimes pyrite contains tiny gold grains where fool's gold in this case is actually gold ore. Pyrite is unsuitable as iron ore from today's point of view. It can only be smelted if it is first converted into iron oxide by roasting that releases large amounts of environmentally harmful SO_2. It is easier to use oxides (magnetite, hematite). Nevertheless, pyrite is mined and roasted primarily to produce sulfuric acid. However, this is no longer very important as sulfuric acid can also be produced as a by-product in the smelting of other sulfides (in particular, in copper production).

Historically, pyrite played a role in early iron production at least in some regions. Pyrite was even more important in early history because of another characteristic. If you strike another stone (e.g., a flint stone) against it, sparks are produced and a fire can be ignited. Pyrite is also to blame for acid rain. Coal and lignite contain some pyrite and other sulfur compounds that are oxidized during combustion. The SO_2 released dissolves in condensed water droplets to sulfuric acid. The weathering of pyrite and other sulfide minerals is very similar. Therefore, extremely acid mine water often accumulates in abandoned mines. In such water only specialist microorganisms can survive such as *Acidithiobacillus ferrooxidans* whose metabolism is based on the oxidation of sulfides, which accelerates weathering.

At first glance it may seem confusing that the sulfur in pyrite appears to have an oxidation state of −1 and not −2 as it should be. This is because two S^{2-} form a covalent bond. In the crystal lattice Fe^{2+} alternates with dumbbell-shaped $(S–S)^{2-}$.

Fig. 1.19 Pyrite (FeS_2) (*photo* © F. Neukirchen)

1.3 Resources, Reserves, and Consumption

Although it is well known that ores, fossil fuels, and other resources are only available in limited quantities, it is almost impossible to indicate when a particular resource might be depleted (e.g., Stürmer and Schwerhoff 2013). New deposits are discovered time and again, while in the case of known deposits estimates of the quantity of existing ore are regularly corrected upward or downward. Rising prices or new technologies can also make deposits profitable that were previously considered uneconomic. In the long term, deposits in remote areas and low-grade deposits will become increasingly important.

Well-known deposits that can be exploited profitably with current technology for the given market situation are referred to as reserves. The term resources, on the other hand, also covers deposits that are only suspected and those currently not worth exploiting. It is almost always the rule that the global reserves of a certain material correspond to the demand of only a few decades. This is no cause for concern as resources turn into reserves through rising prices, better technology, and continued exploration. Supply bottlenecks can nevertheless occur such as when sudden outages occur in politically unstable regions.

Another unknown factor is consumption. The consumption of raw materials is increasing particularly massively in emerging countries such as Brazil, India, and above all China. If a country's infrastructure is expanded quickly, this means high consumption of steel, copper, and so on. Moreover, expansion occurs in industries that consume metal and that not only supply their own market but export all over the world. China has for years been the largest consumer of many metals with still rapid growth rates. Metal consumption can be extrapolated to a certain extent into the future, but there are always unforeseeable deviations. Economic crises such as happened in the years following the 2007 financial crisis lead to a collapse in demand, falling prices, and as a result the closure of mines. Technological developments can have an equally abrupt effect (especially, if widespread high-tech components are replaced by those with a different composition).

The quantity of metal extracted (Fig. 1.20) adapts to demand as much as possible. One problem is that production reacts only very slowly to a changed market situation. A mine can be shut down relatively quickly if it is no longer profitable, but it usually takes a decade or more to open up a new mine if prices rise. Similarly, the capacity of existing plants can only be expanded with large investments and structural changes. When prices are low there is hardly any investment in the search for new deposits. If prices rise suddenly the opposite is the case. After about a decade so many new mines may go into operation at the same time that the price crashes again and some have to be closed once more. As a result reserves have increased for the time being.

Contrary to some pessimistic forecasts no resources have yet run out. The frequently quoted study titled *The Limits to Growth,* which was presented by the Club of Rome in 1972, assumed that many resources would be exhausted after a few decades at the exponential growth assumed at that time, which as is well known did not happen. However, it is relatively likely that certain materials will become significantly more expensive in the future when easily accessible deposits are depleted. The cost of production will therefore increase considerably. This can be partly offset by improvements in mining, processing, and smelting technology.

In general, it can be assumed that a certain commodity will not suddenly be completely exhausted after constant or rising production, but that from a certain point in time annual production will no longer be increased and then slowly begin to decline. Petroleum is a commodity that is already in short supply today and "peak oil" (Sect. 6.6) is already in sight. Some believe it has already been exceeded, while others are still giving us a few decades before this happens. Even the rather optimistic BGR (German Geological Survey) assumed in its 2009 energy study that no increase in oil production (including unconventional oil) will be possible after 2035. In the follow-up study of 2012 this statement is no longer to be found. This is not only because of new oil discoveries, but also because far more unconventional oil than assumed has already been produced. Nevertheless, it can be assumed that almost all oil deposits that can be extracted at favorable prices have been known for a long time and that new discoveries can only be extracted at high cost. We really are going to run out of cheap oil soon. Other fossil fuels such as natural gas and coal are available in much larger quantities. Phosphate is another scarce resource that could soon reach its peak (Sect. 5.8).

Also problematic are elements that do not form their own deposits and are only extracted as by-products from mining other metals. These include important high-tech metals such as germanium, indium, and gallium. Germanium and indium are obtained almost exclusively from zinc ore, while gallium comes almost exclusively from aluminum ore. Their production therefore depends on the production rate of the respective main metal; otherwise higher capacities can only be achieved by improving processing and refining. They are among resources currently considered critical (Box 1.4).

If ever-lower ore grades are exploited for the production of metals, then larger open-pit mines will be required to produce the same quantity of metal and at the same time larger quantities of material will have to be stored in overburden stockpiles and sludge ponds. The impact on the environment will therefore increase.

Box 1.4 Critical resources

A number of mineral resources are considered strategically important to industry because they are indispensable for high-tech applications (Elsner et al. 2010), even though the amount consumed is very small compared with the bulk metals. In addition, some are produced in only a few countries, including politically unstable regions, which can lead to unpredictable outages and supply shortages. Which resources are considered critical therefore depends not only on available deposits, but also on political developments and technological innovations. A publication by the European Union in 2010 lists 14 critical resources: antimony, beryllium, fluorite, gallium, germanium, graphite, indium, cobalt, magnesium, niobium, platinum-group elements, REEs, tantalum, and tungsten.

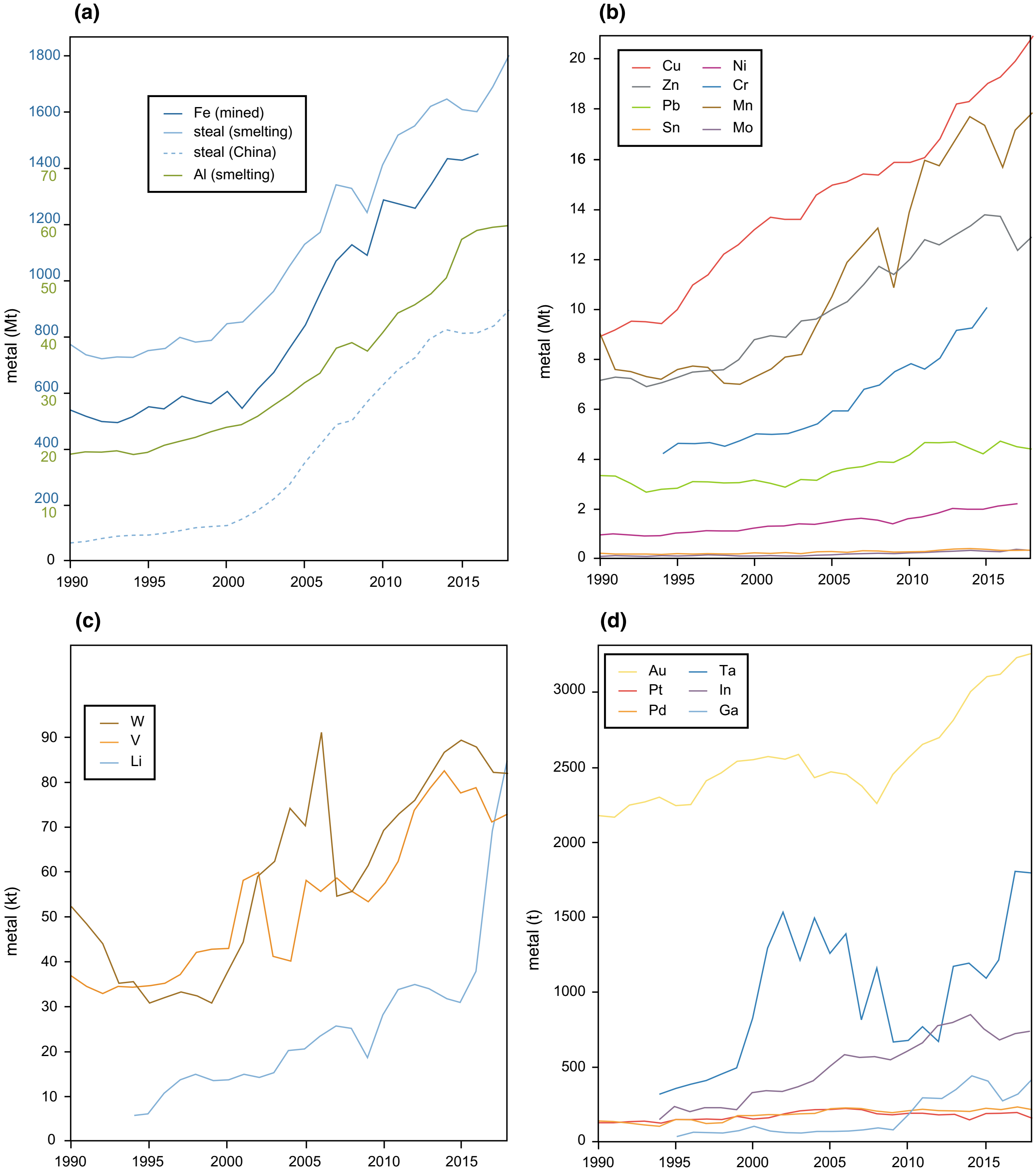

Fig. 1.20 Development of global metal 1990–2018 (note different scales). **a** Iron in mined ore, global steel production, steel production in China, and primary aluminum from smelting. Recycling is important for both metals. **b** and **c** Metal content in ore mined worldwide for copper, zinc, lead, tin, nickel, chromium, manganese, molybdenum, tungsten, vanadium, and lithium. Only part of the ore is smelted to pure metal, while other parts go into steel production or directly to the chemical industry. **d** Production of selected precious and high-tech metals. Gold, platinum, palladium, and tantalum through mine production; indium and gallium as by-products (refining). Data from *USGS Minerals Yearbooks*, USGS Commodity Summaries

1.4 Markets

A selection of commodities are traded on exchanges such as the New York Mercantile Exchange (NYMEX), the London Metal Exchange (LME), and the London ICE Futures. These commodities include petroleum, the most important industrial metals such as aluminum, copper, nickel, zinc, and tin, and precious metals such as gold, silver, platinum, and palladium. In addition to the spot market, futures are of great importance as a hedge against undesirable price developments.

Petroleum (i.e., crude oil) can be of different quality and composition, so different types of oil are traded on the exchanges. The most important varieties are Brent (from the North Sea) and WTI (West Texas Intermediate) whose prices also determine the price of other types of petroleum. While the price of oil is almost the same worldwide (apart from transport costs and subsidies), natural gas has regional markets with large differences. In some countries the price of gas is linked to the price of oil.

The most important trading places for precious metals are not the stock exchanges, but the London Bullion Market and the London Platinum and Palladium Market where such metals are traded as bars over the counter between producers, banks, traders, and consumers from all over the world. A fixed price is agreed once or twice a day at which as many transactions as possible are processed.

A large part of commodity trading takes place off-exchange through direct contracts between producers and consumers and via intermediaries with the price being based on stock exchanges. The five largest commodity traders, all based in Switzerland, have a combined turnover similar to Switzerland's national product. The largest, Glencore, is repeatedly criticized for human rights violations and corruption.

The remaining metals are not freely traded but delivered through long-term supply contracts directly from the producer or through intermediaries. Some of these are not mined in special mines but are by-products of the mining of a particular metal. The supply side is thus linked to the production conditions of another metal and changes in demand can only be responded to by optimizing the respective processing and smelting with corresponding effects on the price. Other metals such as tantalum and REEs are produced and consumed in such small quantities that just a few mines account for much of world production. Bottlenecks or overcapacities can therefore easily occur, which are reflected in sharply fluctuating prices.

The United States Geological Survey (USGS) concludes in its analysis (Papp et al. 2008) that metal prices are driven by a variety of factors such as wars and recessions, the collapse of the Soviet Union, China's economic rise, fiscal policies, exchange rates, technological developments, strikes, mine closures, and newly opened facilities. Looking at the long-term trends of different commodity prices the first thing to be noticed is that they are subject to enormous fluctuations. From time to time there are peaks brought about by a rapid rise in price followed by a rapid crash when the peak price is often a multiple of the initial price. In the middle of the twentieth century fluctuations were significantly lower than at the beginning and end of the century. It is also noticeable that the prices of most raw materials have risen in the long term. The most extreme increase was in the years before 2008 when almost all metals reached their historic price peak. Then as a result of the financial crisis the recession led to a sharp decline. Since then most prices have stabilized at a relatively high level.

The figures look somewhat different when price movements are adjusted for inflation. Although curves continue to oscillate strongly, they do so mostly on an almost constant level. Adjusted for inflation aluminum was many times more expensive at the beginning of the twentieth century than it is today; when it comes to other metals the extreme increase before 2008 remained within historical fluctuations. In interpreting these figures it is important of course to be cautious because rising prices of raw materials are passed on directly to the consumer and thus have an effect on inflation whose effect is then deducted from the nominal price. It is therefore hardly possible to tell from the prices (be they nominal or inflation adjusted) whether a commodity is becoming scarcer and how the level of necessary investment in the mining sector develops in comparison with the economy as a whole.

Gold by the way should be regarded as a normal commodity. It differs from other commodities only in that speculation has a greater impact on price fluctuations, which is mainly due to the myth that it is a safe investment.

While strongly fluctuating prices of all raw materials offer the possibility of speculation, the mining industry and the metal-processing industry are interested in price development that can be planned as far as possible. Even when there is a monopolist in the game, the monopolist usually strives to ensure that supply and demand match each other as closely as possible. Stocks can at least temporarily compensate for deviations between production and consumption. If growing demand leads to rising prices, ever-more deposits can be exploited that were previously not worthwhile. Although, as already mentioned, it takes some time for new mines to go into production, which can lead to bottlenecks.

Monopolists cannot necessarily exploit their position to their advantage. Although they may have enormous production capacity that lowers the cost of production, it may lead to oversupply on the market and thus depress prices. While booting out the competition, this does not ensure high profits either. In the case of tantalum the Wodgina Mine (Australia), which previously supplied 50% of world production, was no longer profitable in 2009 because the price of the metal crashed during the economic recession due to a lack of demand. In the following years the loss of the mine's enormous capacity naturally led to price rises; hence the mine was reopened, closed, and reopened again (the reserves are now exhausted). For more on the Chinese monopoly on REEs see Box 1.5.

An important point is that the costs involved in exploiting different deposits are very different. With some deposits high profits can be expected, but with many others the running costs can just be covered. This is of course due to geological conditions such as ore grade, size of the deposit, and depth of mining. However, there are also transport costs, wages, environmental regulations, exchange rates, and so on. In this sense price is linked not only to supply and demand, but also to the average production costs of all active mines, which together allow worldwide capacity to meet demand.

Box 1.5 Rare-earth elements and China's monopoly

With around 95% of world production China virtually has a monopoly on REEs (Braune 2008; Margonelli 2009). Apart from the huge Bayan Obo deposit (Box 3.16) other REE carbonatites (Sect. 3.10) and lateritic REE deposits (Sect. 5.11.4) are mined there. The monopoly must be regarded as problematic because these elements are just as essential for various products from entertainment to telecommunications technology as they are for the use of renewable energy sources and so-called energy transition (Sect. 2.5). Since REEs are not as rare as their name might suggest, how is it that the world has become dependent on China's monopoly for this group of commodities? Despite the minerals of REEs being not so rare there is still a problem with them because economically exploitable deposits are rare. Rare-earth minerals very often contain uranium and thorium and these radioactive ingredients cause problems. They must be separated and then stored in dumps and tailings. Moreover, there can be major problems as shown by the example of Bukit Merah (Malaysia) where 20 years ago a rare-earth refinery contaminated the soil and water. The consequences were significantly increased cancer rates in the affected region and ongoing clean-up efforts (Consumer Association of Penang 2013; Bradsher 2011).

Ores from the large Mountain Pass Mine (USA) (Sect. 3.10) are moderately radioactive. The deposit was discovered in 1949 when two geologists were searching for uranium ore with a borrowed Geiger counter (Anonymous 2013). Until 1989 this mine was the main producer of REEs in the world (Margonelli 2009). However, Deng Xiaoping had already recognized the importance of these elements in 1992 and compared China's position in REEs with that of the Middle East in terms of petroleum (Anonymous n.d.). In the 1990s China began supplying the world with cheap REE causing prices to fall sharply from USD11,700 per metric ton in 1992 to USD7430 in 1996. This led to the United States and other countries increasingly relying on imports from China and neglecting their own reserves. For mines like Mountain Pass that could not compete with the prices of Chinese suppliers such a price war would have been ruinous were it not for political support. Added to this were the rising costs of environmental regulations that were much stricter in the United States than in China. The mine was closed in 2002 after a series of accidents in 1998 involving large amounts of radioactive effluent entering Ivanpah Dry Lake.

Rare-earth prices started to rise in 2005 when China began to limit exports. In the following year and increasingly from 2010 Chinese exports were again limited (Jacoby and Jiang 2010; Anonymous 2012a, b). Other nations saw themselves cut off from the supply of important raw materials and complained to the World Trade Organization.

Reducing dependencies and resulting economic constraints resulted in frenetic activity. The Mountain Pass Mine was acquired by a newly formed consortium in 2008 under the old name of Molycorp and started production again in 2013 (Molycorp 2013). Various REE projects were also launched in other countries (particularly, those with a corresponding industry). Examples were Germany (DRAG 2013; Nestler 2013) with the deposit in Storkwitz (Box 1.8), Australia where the deposit on Mount Weld (Sect. 5.11.4) known since 1988 is probably one of the richest REE deposits in the world (Utter 2010) and where mining is already beginning, and Japan that is searching for such metals in its territorial waters (Germis and Nestler 2013).

1.5 Where to Search and How?

Every now and then geologists find a new deposit by chance often while looking for something else. The most spectacular example is the huge Olympic Dam copper–uranium deposit (Box 4.20) discovered in Australia in 1975 in an area not previously known as a mining district. However, these are exceptions and prospecting (the search for unknown deposits) is generally very expensive when it comes to replacing depleted mines and meeting increasing demand. This begs the question as to whether it is better to search in an area where many deposits are already known or where nobody has searched before.

Grassroots exploration (the second option) has a very low success rate similar to that of lotteries where there is a winner every now and then. Such exploration involves geologists and adventurers systematically roaming a large area. Some are looking for something specific such as gold grains in a river, others have their eyes open to anything conspicuous that could indicate deposits of any kind. As a rule larger companies only appear on the scene when ores have already been found and when it is a question of assessing the quantity and profitability of the ore available. At that point it is still not known whether it will actually be worth exploiting the deposit or not.

The first option is more promising. Once it is realized that respective ore-forming processes have taken place in a particular region it is reasonably safe to assume there will be more in the vicinity of a known deposit. This is the reason intensive searches are carried out in mining areas and geophysical methods are used to discover deposits that are not visible on the surface. Since such regions often already have the necessary infrastructure in place exploration and subsequent mining and processing become cheaper.

The worldwide search for areas with similar geology to corresponding known mining districts is also very promising since it is quite possible that deposits of the same type can be found there.

Whereas the Earth's surface in the past could simply be searched for ore minerals or alteration zones such easily detectable deposits hardly exist today. This obliges us to use methods that indicate hidden deposits in the depths termed blind deposits.

Successful prospecting depends on comprehensive knowledge of the type of deposit sought and use of a genetic model. This means any exploration model developed must include not just stratigraphy (Fig. 1.21) and tectonic structures but also important rock types and corresponding geophysical and geochemical parameters. Which of the methods presented in the following sections are used in the search depends not only on the type of deposit sought but also on local conditions.

During exploration—which includes prospecting and more detailed investigation of potential deposits—enormous amounts of data accumulate. Searching for the most important information in the data is so time-consuming that many geoscientists are primarily concerned with data mining: trying to obtain as much information as possible using statistical methods and sophisticated algorithms. Geoinformation systems (GIS) are used for the spatial allocation and interpretation of data and special software is used in many areas.

Remote sensing can be used in large areas to search for suitable sites (prospects) where relevant parameters apply and where more detailed investigation is worthwhile. Geophysical methods, more accurate mapping, rock sampling (see Box 1.6), and initial drilling will then be used to determine whether a site might be economically interesting (prefeasibility study). If this is the case, then more detailed investigations (evaluation) are carried out with the aim of determining as precisely as possible the spatial size and content of the ore as a planning basis for mining. The rock's mechanical properties must also be known. It is also important to decide whether only particularly rich and accordingly lucrative zones should be mined or also zones with a low ore grade, even if their exploitation is actually not profitable. In addition, experiments often have to be conducted to find out how best to process the ore. All such results are incorporated into feasibility studies together with other factors such as the market price of the commodity concerned, investments in infrastructure, and environmental requirements. Extraction will only take place if the study comes to the conclusion that it is profitable. It typically takes more than a decade from discovery of a deposit to start of mining. As to who owns the deposit see Box 1.7.

Box 1.6 Ore microscopy

Examining ores with a microscope is becoming increasingly rare, but it can be very helpful in interpreting the texture and determining the temporal sequence of mineral paragenesis. This knowledge is important not only to understand the formation of the deposit but also to find a suitable method to process it. Since almost all ores are opaque reflected light microscopes have to be used—not transmitted light microscopes. Unfortunately, most ore minerals look very similar and attention has to be paid to minimal color differences in light pastel shades.

Box 1.7 Mining law

Who owns a deposit? There are different traditions and legislations in different countries. Current German mining law goes back to the tradition of *Bergfreiheit* (freedom of mining) according to which all underground resources are unowned (i.e., belong neither to the State nor to the landowner). The State, however, regulates who may bring these resources to the surface and collects appropriate taxes that in earlier times were called tithes.

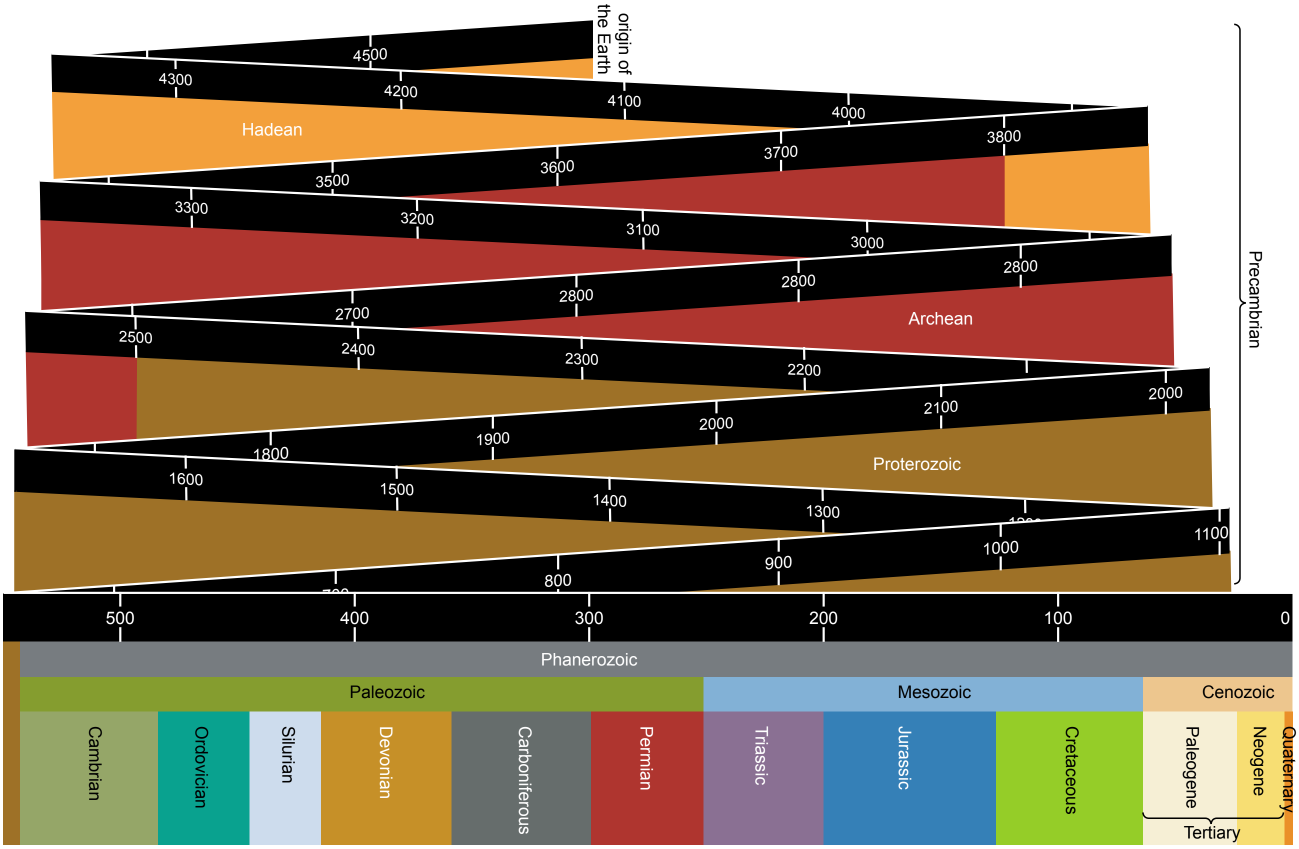

Fig. 1.21 Geological timescale in millions of years

According to a common form of mining law in the Middle Ages termed bergregal (from the German *Bergregal*) all resources were the property of the emperor, king, or sovereign. The latter was able to lend the mining rights and received tithes in return. Even today there are countries whose resources are in state ownership, which is particularly common in the case of petroleum.

In the Commonwealth countries and the United States all resources located under a piece of land are the property of the landowner with the exception of gold and silver in the Commonwealth, which are considered state property. In the United States the State reserves the right to strategically important resources. In the case of deposits on public land an annual rent can be paid for a claim.

In France and some other countries near-surface deposits belong to the landowner, while deeper ones belong to the State.

1.6 Remote Sensing

Satellites and aircraft are used to collect images and geophysical data that can be used to search vast areas for potential deposits. This works best in arid and semiarid areas, while in areas with dense vegetation the possibilities are limited. Aircraft or helicopters equipped with the appropriate equipment allow detailed investigation that is not only specially tailored to respective requirements, but is also associated with corresponding costs. Accordingly, satellites have the advantage that a large amount of existing data can already be accessed.

Tectonic structures can be mapped by simple interpretation of aerial and satellite images. Since faults and especially their intersections can serve as ascent routes for magmas or hydrothermal solutions, deposits are usually lined up along tectonic structures.

Multispectral remote sensing offers much more (Van der Meer et al. 2012; Brandmeier 2010; Rowan and Mars 2003; Yamaguchi and Naito 2003; Sabins 1999). Multispectral

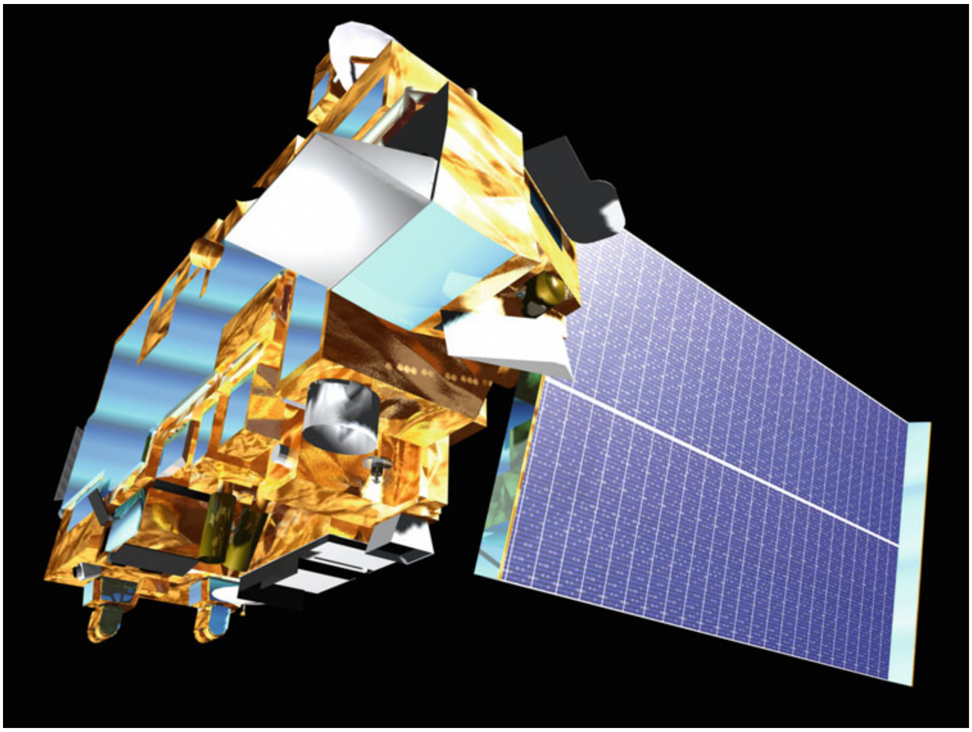

Fig. 1.22 The Terra satellite launched by NASA in late 1999 carries the Japanese instrument ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) whose data are frequently used for exploration purposes (picture © NASA)

remote sensing concerns radiation emitted by the Earth's surface made up of a mixture of reflected light and light that has penetrated a little farther into matter and lost parts of its spectrum through absorption. The Landsat satellites (mainly the Landsat Thematic Mapper) provided the corresponding data for decades, but since the launch of the Terra satellite at the end of 1999 the data of the Japan-built ASTER instrument has been used preferentially (Fig. 1.22). The way it works is in principle somewhat similar to a photo. In a digital photo each pixel consists of three channels—red, green, and blue (RGB)—whose brightness values determine the color. The three channels correspond to three wavelengths that represent only small sections of the light spectrum, but are sufficient for our eyes to perceive them as color. However, electromagnetic radiation in multispectral exploration is registered in a whole series of channels with specific wavelengths not only in the visible light range but also for infrared. ASTER has three visible and near-infrared (VNIR) channels, six shortwave infrared (SWIR) channels, and five longwave infrared (TIR) channels, the wavelengths of the channels being well chosen for our purposes. There are also devices that cover the interesting range of the spectrum more or less continuously with a large number of channels (hyperspectral). Although these have so far been mainly used from aircraft because the large amount of data and noise are still problems with satellites, they are likely to become more important in the future.

Light is absorbed differently by different minerals. In particular, transition metals such as iron and hydroxyl groups (OH^-) have an effect on this. Therefore, we can get an impression of which minerals or rocks lie on the Earth's surface from false-color images (Fig. 1.23) composed of suitable channels. The simplest possibility would be to assign one channel of the sensor to each of the RGB channels of a monitor, but better results are obtained using ratios of suitable channels (ratio images). In combination with corresponding on-site fieldwork detailed geological maps can be produced quickly.

Using mathematical methods such as principal component analysis (PCA) or the calculation of so-called mineral indices (MIs) data can even be used to create maps highlighting areas with a high content of certain minerals. The ASTER data can for example be used to distinguish pixel by pixel (with a certain degree of uncertainty) clay minerals (e.g., kaolinite and illite); mica, chlorite, various iron oxides, carbonates (e.g., calcite, dolomite); and sulfates (e.g., alunite, baryte). However, the result for each individual case should be checked on-site.

Using even more complex algorithms and corresponding calibration of the instrument the spectrum measured for each pixel can be compared with an entire database of spectra of different minerals, which in some cases even allows quantitative estimation of the mineral content. The more channels measured the better this works.

In areas covered by dense vegetation this method is unfortunately very limited. However, it is possible to map the damage to vegetation caused by heavy metals, which in turn can give indications of deposits.

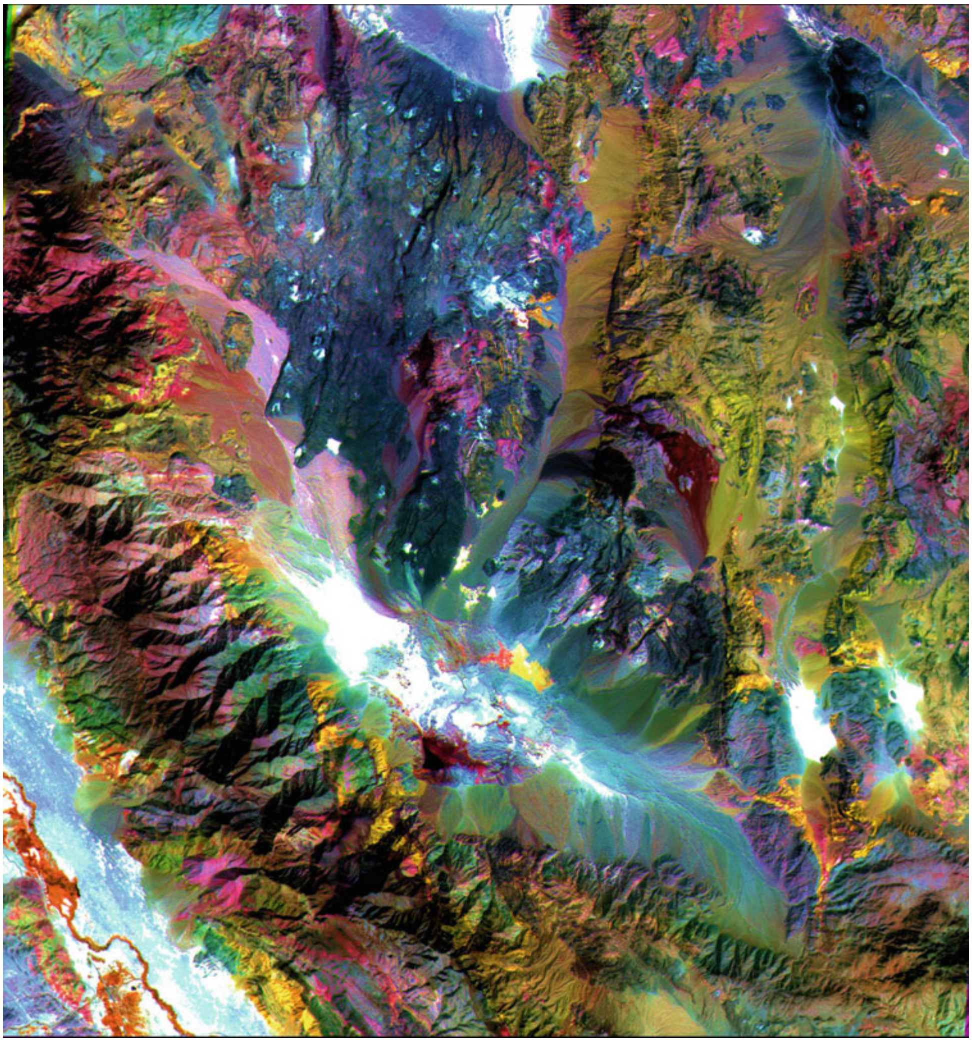

Fig. 1.23 False-color image of the edge of Saline Valley (California, USA) by ASTER. Channels 4, 6, 8 from the shortwave infrared are shown as RGB. Colors depend on contents of clay, carbonate, and sulfate minerals (*photo* © NASA, GSFC, MITI, ERSDAC, JAROS, and the US/Japanese ASTER team)

Multispectral remote sensing is particularly helpful in mapping hydrothermal alteration zones (Box 4.14) in dry regions because different types of alteration can be distinguished. Although not every alteration zone belongs to a deposit, good mapping makes it possible to decide where to look more closely. A frequently cited example is the Collahuasi copper deposit (Chile). Copper had long been mined there from hydrothermal veins. Analysis of the alteration zone at that time with Landsat data revealed that there were systematically arranged anomalies in a large area. Geophysical methods then confirmed that a huge porphyry copper deposit (Sect. 4.4) was hidden at a greater depth, now one of the most important copper mines in the world.

There are also examples where very special applications of multispectral remote sensing have been used to find and interpret natural gas and oil leaks and to map the borate content in the Salar de Uyuni (Sect. 5.7.2).

In addition to such passive systems that use natural electromagnetic waves there are active systems, which are discussed in the following section. Some geophysical methods can be performed from an aircraft or helicopter and are therefore part of remote sensing.

1.7 Geophysical Exploration

When searching for deposits a number of physical parameters can be exploited such as the magnetic field, the gravitational field, electrical conductivity, and gamma radiation. However, which methods are likely to lead to success depend on the type of deposit and various local conditions. Geophysical methods not only provide information about rocks on the surface but also about rocks at a certain depth. The search is mainly for anomalies or strong deviations from normal values. Normal values can be very different depending on the type of rocks. Usually several parameters are measured simultaneously and evaluated together. Some parameters are measured from an aircraft or helicopter (airborne geophysics) and are therefore part of remote sensing, while others use geophysical methods from ships such as the search for offshore oil and gas.

Remote sensing is usually followed by detailed measurements on the Earth's surface. Raw data can only be interpreted directly to a certain extent because the depth of an ore body, its geometry, and the rocks in between have a large impact on what is measured at the surface. Complicated algorithms can be used to create a 3D model of the subsurface capable of explaining the measured data as well as possible. This step is called inversion. A computer has to be fed with numerous other assumptions and the degree to which the local geology is more or less well known is accordingly helpful.

Finally, sensors can be placed into boreholes to measure parameters in a vertical profile and explore the surroundings of the borehole. This enables detailed 3D models that can be used to estimate the size of the deposit. There are cases where deep drilling has discovered deposits that could not be detected from data obtained on the surface.

Gravimetry is the measurement of the strength of a gravitational field. The strength of the Earth's gravitational field (Fig. 1.24a) and hence gravitational acceleration vary not only with latitude and absolute altitude but also with the relief and density of the subsurface. Since we are only interested in the latter other factors can be ignored in the data. Anomalies in corrected data (Bouguer anomalies) are due to variations in the density of the subsurface and of different rocks and their geometry in the Earth's crust and mantle. Data may indicate high-density ore or a low-density salt dome. Measurements are taken from the air, on the ground, at sea, or underground in a mine. Special satellites are also used to take such measurements.

Magnetics or magnetometry is an important method used to measure the direction, strength, or relative change of a magnetic field (Fig. 1.24b). The strength of the Earth's magnetic field varies according to latitude (31,000 nT at the equator, 63,000 nT at the poles) and fluctuates daily. It is also influenced by magnetizable minerals underground. Such minerals develop their own magnetic fields overlaying that of the Earth. This effect is strongest with magnetite (Fig. 1.25). Even a rock with a low magnetite content can have a strong influence on the magnetic field measured making a magnetite-rich iron deposit all the more noticeable (Box 5.3). Although ilmenite, hematite, pyrrhotite, and other minerals have an effect but to a lesser extent, they can also lead to strong anomalies if they are present in sufficient quantities. Magnetics is not only helpful in finding iron deposits but also in the search for other metals as long as their deposits contain magnetite or one of the other minerals

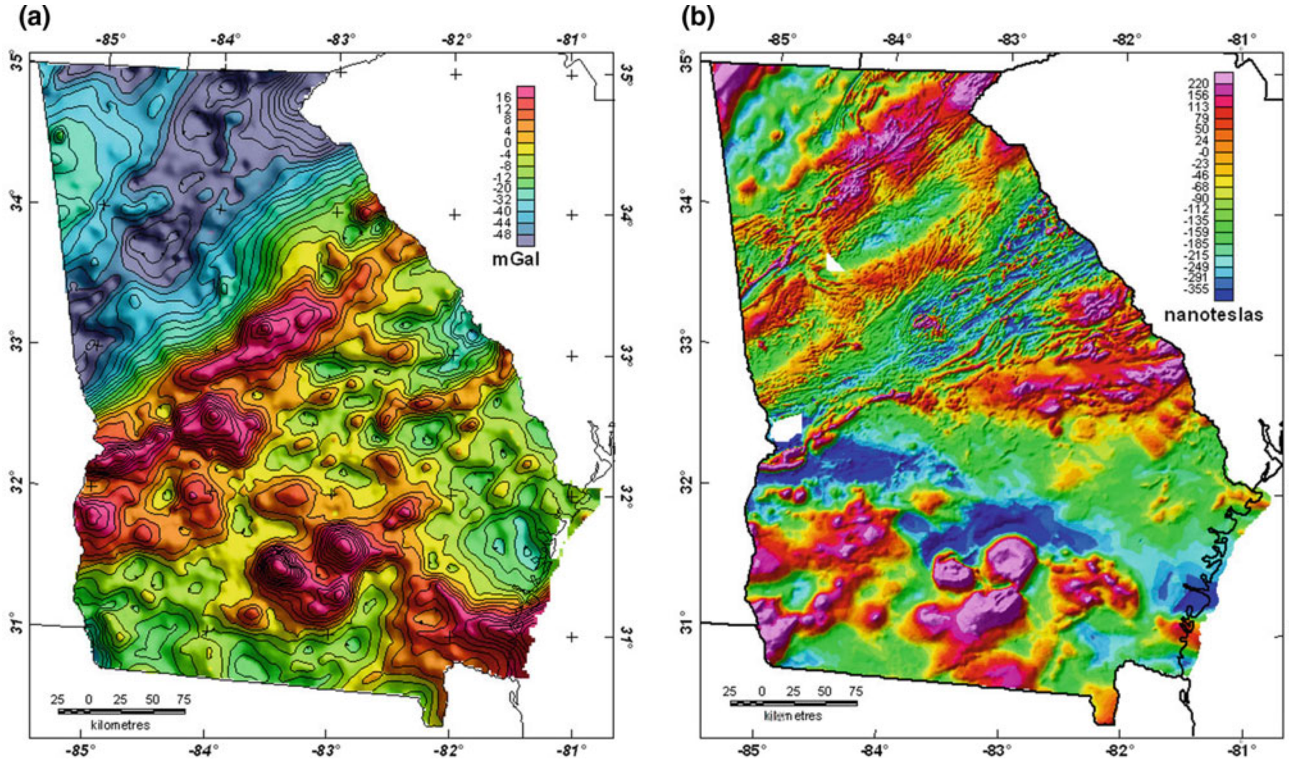

Fig. 1.24 Geophysical data of the US state of Georgia compiled by the USGS. **a** Bouguer anomalies show deviations from the Earth's normal gravity field. **b** Aeromagnetic data at a height of 305 m above the Earth's surface. The actual flight altitude was 150 m. The data were subsequently adapted to the national standard (© USGS)