# Introduction to DREFORMING PROCESSES

## LAURENCE ROBB

SECOND EDITION

WILEY Blackwell

Introduction to Ore-Forming Processes

### **Introduction to Ore-Forming Processes**

*Laurence Robb* University of Oxford Oxford, UK

Second Edition

WILEY Blackwell

This second edition first published 2021 © 2021 John Wiley & Sons Ltd.

Edition History Wiley Blackwell (1e, 2005)

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at http://www.wiley.com/go/permissions.

The right of Laurence Robb to be identified as the author of this work has been asserted in accordance with law.

Registered Offices John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office 9600 Garsington Road, Oxford, OX4 2DQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

#### Limit of Liability/Disclaimer of Warranty

The contents of this work are intended to further general scientific research, understanding, and discussion only and are not intended and should not be relied upon as recommending or promoting scientific method, diagnosis, or treatment by physicians for any particular patient. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of medicines, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each medicine, equipment, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. While the publisher and authors have used their best efforts in preparing this work, they make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials or promotional statements for this work. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

#### Library of Congress Cataloging-in-Publication Data

Name: Robb, L., author.
Title: Introduction to ore-forming processes / Laurence Robb, Department of Earth Sciences, University of Oxford, Oxford, UK.
Description: Second edition. | Hoboken, NJ : Wiley-Blackwell, 2020. | Includes index.
Identifiers: LCCN 2019058286 (print) | LCCN 2019058287 (ebook) | ISBN 9781119967507 (paperback) | ISBN 9781119232391 (adobe pdf) | ISBN 9781119232384 (epub)
Subjects: LCSH: Ores.
Classification: LCC QE390 .R32 2020 (print) | LCC QE390 (ebook) | DDC 553/.1-dc23
LC record available at https://lccn.loc.gov/2019058286
LC ebook record available at https://lccn.loc.gov/2019058287
Cover Design: Wiley
Cover Images: © Laurence Robb and Lawrence Minter

Set in 9.5/12.5pt STIXTwoText by SPi Global, Chennai, India

#### Contents

Preface to the 2nd EditionxiiiPreface to the 1st EditionxvIntroduction: Mineral Resourcesxviii

Part I Igneous Processes 1

#### **1** Igneous Ore-Forming Processes 3

- 1.1 Introduction 4
- 1.2 Magmas and Metallogeny 4
  - 1.2.1 Crustal Architecture and Mineral Wealth 4
  - 1.2.2 Magma Types and Metal Contents 7
    - 1.2.2.1 Basalt 7
    - 1.2.2.2 Andesite 9
    - 1.2.2.3 Rhyolite 10
    - 1.2.2.4 Alkaline Magmas, Carbonatite and Kimberlite 12
- 1.3 Why Are Some Magmas More Fertile than Others? The "Inheritance Factor" 13
  - 1.3.1 The "Late Veneer" Hypothesis of Siderophile Metal Concentration An Extraterrestrial Origin for Au and Pt? *14*
  - 1.3.2 Diamonds and the Story They Tell 15
  - 1.3.3 Metal Concentrations in Metasomatized Mantle and Their Transfer into the Crust 20

v

- 1.3.4 Metal Enrichment in Carbonatitic and Peralkaline Magmas 21
- 1.3.5 I- and S-Type Granite Magmas and Metal Specificity 27
- 1.4 Partial Melting and Crystal Fractionation as Ore-Forming Processes 30
  - 1.4.1 Partial Melting 31
    - 1.4.1.1 Trace Element Distribution During Partial Melting 32
  - 1.4.2 Crystallization of Magma 34
    - 1.4.2.1 The Form and Internal Zonation of Igneous Bodies 36
    - 1.4.2.2 Trace Element Distribution During Fractional Crystallization 39
  - 1.4.3 Fractional Crystallization and the Formation of Monomineralic Chromitite Layers *43* 
    - 1.4.3.1 The Irvine Model 43
    - 1.4.3.2 Other Mechanisms for the Formation of Chromitite Layers or Pods 47
  - 1.4.4 Filter Pressing as a Process of Crystal Fractionation 48
    - 1.4.4.1 Anorthosite Hosted Ti–Fe Deposits 48

#### vi Contents

- 1.5 Liquid Immiscibility as an Ore-Forming Process 49
  - 1.5.1 Silicate–Oxide Immiscibility 49
  - 1.5.2 Silicate–Sulfide Immiscibility 50
- 1.6 A More Detailed Consideration of Mineralization Processes in Mafic Magmas 52
  - 1.6.1 A Closer Look at Sulfide Solubility 52
  - 1.6.2 Sulfide–Silicate Partition Coefficients 53
  - 1.6.3 The R Factor and Concentration of Low Abundance Trace Elements 54
  - 1.6.4 Factors that Promote Sulfide Saturation 56
    - 1.6.4.1 Addition of Externally Derived Sulfur 56
    - 1.6.4.2 Fractional Crystallization 56
    - 1.6.4.3 Injection of a New Magma and Magma Mixing 58
    - 1.6.4.4 Magma Contamination 68
  - 1.6.5 Other Models for Mineralization in Layered Mafic Intrusions 69
    - 1.6.5.1 PGE Clusters 69
    - 1.6.5.2 The Role of Chromite in PGE Concentration 71
    - 1.6.5.3 Hiatus Models 72
    - 1.6.5.4 Fluid-Related Infiltration of PGE 72
- 1.7 A Model for Mineralization in Layered Mafic Intrusions 72
- 1.8 Summary 75
  - Further Reading 75

#### 2 Magmatic-Hydrothermal Ore-Forming Processes 77

- 2.1 Introduction 77
- 2.2 Some Physical and Chemical Properties of Water 78
- 2.3 Formation of a Magmatic Aqueous Phase 81
  - 2.3.1 Magmatic Water Where Does It Come from? 81
    - 2.3.2 H<sub>2</sub>O Solubility in Silicate Magmas 83
    - 2.3.3 The Burnham Model 85
      - 2.3.3.1 A Note on the Mechanical Effects of Boiling 88
- 2.4 The Composition and Characteristics of Magmatic-Hydrothermal Solutions 88
  - 2.4.1 Quartz Veins What Do They Tell Us About Fluid Compositions? 88
  - 2.4.2 Major Elements in Magmatic Aqueous Solutions 89
  - 2.4.3 Other Important Components of Magmatic Aqueous Solutions 89
    - 2.4.3.1 Magmatic Fluid Compositions from Fluid Inclusion Analysis 92
  - 2.4.4 Carbon Dioxide in Magmatic Fluids 94
  - 2.4.5 Other Important Features of Magmatic Fluids 95
- 2.5 A Note on Pegmatites and Their Significance to Granite-Related Ore-Forming Processes 97
  - 2.5.1 Early Models of Pegmatite Genesis 98
  - 2.5.2 More Recent Ideas on the Origin of Pegmatites 98
- 2.6 Fluid–Melt Trace Element Partitioning 100
  - 2.6.1 Early Experiments on Metal Solubilities in Aqueous Solution 100
  - 2.6.2 A More Detailed Look at Fluid–Melt Partitioning of Metals 102
    - 2.6.2.1 Fluid–Melt Partitioning During "First Boiling" 103
      - 2.6.2.2 Fluid–Melt Partitioning During "Second Boiling" 103
    - 2.6.2.3 Partitioning of Metals into  $H_2O$ -Vapor 104
  - 2.6.3 Partitioning of Cu, Mo, and W Between Melt and  $H_2O$ -Fluid 106

- 2.7 Water Content and Depth of Emplacement of Granites Relationships to Ore-Forming Processes 107
- 2.8 Models for the Formation of Porphyry-Type Cu, Mo, and W Deposits 110
  - 2.8.1 The Origin of Porphyry Cu–(Mo) and Porphyry Mo–(Cu) Type Deposits 110
  - 2.8.2 The Origin of Porphyry W (±Sn) Type Deposits 114
  - 2.8.3 The Role of Sulfur in the Formation of Porphyry Copper Deposits 115
    - 2.8.3.1 The Role of Sulfur in Concentrating Metals in Porphyry Systems 115
    - 2.8.3.2 The Role of Sulfur in Precipitating Ore Minerals in Porphyry Systems *116*
- 2.9 Near-Surface Magmatic-Hydrothermal Processes The "Epithermal" Family of Au–Ag–(Cu) Deposits *116* 
  - 2.9.1 Gold Precipitation Mechanisms in Epithermal Deposits 119
- 2.10 Skarn Deposits 123
  - 2.10.1 Prograde Isochemical Contact Metamorphism 126
  - 2.10.2 Prograde Metasomatism and Replacement *126*
  - 2.10.3 Retrograde Meteoric Fluid Influx and Main Metal Precipitation 127
- 2.11 Fluid Flow in and Around Granite Plutons 128
- 2.12 The Role of Hydrothermal Fluids in Mineralized Mafic Rocks 133
  - 2.12.1 The Effects of a Magmatic-Hydrothermal Fluid on PGE Mineralization in the Bushveld Complex 134
- 2.13 Summary 135 Further Reading 136

#### Part II Hydrothermal Processes 139

#### 3 Hydrothermal Ore-Forming Processes 141

3.1 Introduction 142

3.4

- 3.2 Other Fluids in the Earth's Crust and Their Origins 142
  - 3.2.1 Sea Water 144
  - 3.2.2 Meteoric Water 144
  - 3.2.3 Basinal (or Connate) Water 145
  - 3.2.4 Metamorphic Water 149
  - 3.2.5 Waters of Mixed Origin 150
- 3.3 The Movement of Hydrothermal Fluids in the Earth's Crust 152
  - 3.3.1 Factors Affecting Fluid Flow at a Crustal Scale 152
  - 3.3.2 A Note on Hydrostatic Versus Lithostatic Pressure Gradients 154
  - 3.3.3 Deformation and Hydrothermal Fluid Flow 155
  - 3.3.4 Other Factors Affecting Fluid Flow and Mineral Precipitation *158*
  - 3.3.4.1 How Do We Know that a Fluid Has Passed Through a Rock? *159* Additional Factors Affecting Metal Solubility *160*
  - 3.4.1 The Important Metal–Ligand Complexes in Hydrothermal Solutions *162* 
    - 3.4.1.1 Hard Metals 162
    - 3.4.1.2 Borderline Metals 163
    - 3.4.1.3 Soft Metals 165
    - 3.4.2 More on Metal Solubilities in the Aqueous Vapor Phase 167
    - 3.4.3 A Brief Note on Metal–Organic Complexes 167

- viii Contents
  - 3.5 Precipitation Mechanisms for Metals in Solution 169
    - 3.5.1 Physico-Chemical Factors Affecting Metal Precipitation 170
      - 3.5.1.1 Temperature 171
      - 3.5.1.2 Pressure 171
      - 3.5.1.3 Phase Separation (Boiling and Effervescence) 172
      - 3.5.1.4 Fluid Mixing/Dilution 173
      - 3.5.1.5 Fluid/Rock Reactions (pH and Eh Controls) 176
    - 3.5.2 Adsorption 176
    - 3.5.3Biologically Mediated Processes of Metal Precipitation1793.5.3.1Biomineralization180
  - 3.6 Fluid–Rock Interaction Introduction to Hydrothermal Alteration 183
    - 3.6.1 Types of Alteration and Their Ore Associations 187
      - 3.6.1.1 Potassic Alteration 187
      - 3.6.1.2 Phyllic (or Sericitic) Alteration 190
      - 3.6.1.3 Propylitic Alteration 190
      - 3.6.1.4 Argillic Alteration 190
      - 3.6.1.5 Silication 190
      - 3.6.1.6 Silicification 190
      - 3.6.1.7 Carbonatization 191
      - 3.6.1.8 Greisenization 191
      - 3.6.1.9 Hematitization 191
  - 3.7 Metal Zoning and Paragenetic Sequence 191
    - 3.7.1 Replacement Processes 194
  - 3.8 Modern Analogues of Ore-Forming Processes The VMS–SEDEX Continuum 195
    - 3.8.1 "Black Smokers" A Modern Analogue for VMS Deposit Formation 196
      - 3.8.2 The Salton Sea and Red Sea Geothermal Systems Modern Analogues for SEDEX Mineralization Processes 204
        - 3.8.2.1 Salton Sea Geothermal System 204
        - 3.8.2.2 The Red Sea and the VMS–SEDEX Continuum 206
  - 3.9 Mineral Deposits Associated with Aqueo-Carbonic Metamorphic Fluids 209
    - 3.9.1 Orogenic Gold Deposits 210
      - 3.9.1.1 Archean 210
      - 3.9.1.2 Proterozoic 211
      - 3.9.1.3 Phanerozoic 211
    - 3.9.2 Carlin-Type Gold Deposits 211
    - 3.9.3 Quartz Pebble Conglomerate Hosted Gold Deposits 214
  - 3.10 Ore Deposits Associated with Basinal Fluids 217
    - 3.10.1 Stratiform Sediment-Hosted Copper (SSC) Deposits 218
    - 3.10.2 Mississippi Valley Type (MVT) Pb–Zn Deposits 222
  - 3.11 Ore Deposits Associated with Near Surface Meteoric Fluids (Groundwater) 230
    - 3.11.1 A Brief Note on the Aqueous Transport and Deposition of Uranium 230
    - 3.11.2 Sandstone-Hosted Uranium Deposits 231
      - 3.11.2.1 Colorado Plateau (Tabular) Uranium–Vanadium Type 231
      - 3.11.2.2 Roll-Front Type 233
  - 3.12 Summary 235 Further Reading 237

#### Part III Sedimentary/Surficial Processes 239

- 4 Surficial and Supergene Ore-Forming Processes 241
- 4.1 Introduction 241
- 4.2 Principles of Chemical Weathering 242
  - 4.2.1 Dissolution and Hydration 243
  - 4.2.2 Hydrolysis and Acid Hydrolysis 244
  - 4.2.3 Oxidation 244
  - 4.2.4 Cation Exchange 245
- 4.3 Lateritic Deposits 245
  - 4.3.1 Laterite Formation 245
  - 4.3.2 Bauxite Ore Formation 246
  - 4.3.3 Nickel Laterites 251
  - 4.3.4 Gold in Laterites 253
  - 4.3.5 A Note on Platinum Group Element (PGE) Enrichment in Laterites 257
- 4.4 Clay Deposits 258
  - 4.4.1 The Kaolinite (China Clay) Deposits of Cornwall 259
  - 4.4.2 "Ion-Adsorption" Rare Earth Element (REE) Deposits in Clays 261
- 4.5 Calcrete-Hosted Deposits 265
  - 4.5.1 Calcrete-Hosted or Surficial Uranium Deposits 265
- 4.6 Supergene Enrichment of Cu and Other Metals in the Near Surface Environment 267
  - 4.6.1 Supergene Oxidation of Copper Deposits 267
    - 4.6.1.1 A Note on Supergene Enrichment of Other Metals 272
- 4.7 Summary 275 Further Reading 276

#### 5 Sedimentary Ore-Forming Processes 277

- 5.1 Introduction 277
- 5.2 Clastic Sedimentation and Heavy Mineral Concentration Placer Deposits 278
  - 5.2.1 Basic Principles 279
  - 5.2.2 Hydraulic Sorting Mechanisms Relevant to Placer Formation 281
    - 5.2.2.1 Settling 281
    - 5.2.2.2 Entrainment 283
    - 5.2.2.3 Shear Sorting 285
    - 5.2.2.4 Transport Sorting 285
  - 5.2.3 Application of Sorting Principles to Placer Deposits 288
    - 5.2.3.1 Small Scale 288
    - 5.2.3.2 Intermediate Scale 288
    - 5.2.3.3 Large Scale 288
  - 5.2.4 A Note Concerning Sediment Sorting in Beach and Eolian Environments 290
    - 5.2.4.1 Beaches 293
    - 5.2.4.2 Wind-Borne Sediment Transport 295
  - 5.2.5 Numerical Simulation of Placer Processes 296
- 5.3 Chemical Sedimentation Iron-Formations, Phosphorites, and Evaporites 298
  - 5.3.1 Iron-Formations and Ironstones 298

**x** Contents

5.4

- 5.3.1.1 Bog Iron Ores 299
- 5.3.1.2 Phanerozoic Ooidal Ironstone (POI) Deposits 300
- 5.3.1.3 Banded and Granular Iron-Formation An Enigmatic Rock Type 302
- 5.3.1.4 Mechanisms by Which BIFs Are Deposited 304
- 5.3.1.5 The Periodicity of Iron-Formation Deposition 308
- 5.3.1.6 Transformation of BIFs into Viable Iron Ore Deposits 309
- 5.3.2 Bedded Manganese Deposits 313
- 5.3.3 A Note on Ocean Floor Manganese Nodules 314
- 5.3.4 Phosphorites 316
  - 5.3.4.1 A Model for Phosphogenesis Based on Present Day Deposition 319
- 5.3.5 Black Shales 322
- 5.3.6 Evaporites 323
- Fossil Fuels Oil/Gas Formation and Coalification 330
- 5.4.1 Basic Principles 330
  - 5.4.2 Oil and Gas Formation (Conventional) 331
    - 5.4.2.1 Source Rock Considerations and Organic Maturation 335
    - 5.4.2.2 Petroleum Migration and Reservoir Considerations 337
    - 5.4.2.3 Entrapment of Oil and Gas 340
  - 5.4.3 Coalification Processes 345
    - 5.4.3.1 Coal Characteristics 349
    - 5.4.3.2 A Note Concerning Formation of Economically Viable Coals 352
  - 5.4.4 Unconventional Hydrocarbons Shale Gas, Oil Shales, and Tar Sands 354
    - 5.4.4.1 Shale Gas and Oil Shales 354
    - 5.4.4.2 Tar Sands (or Oil Sands) 354
- 5.4.5 Gas Hydrates 356
- 5.5 Summary 359
  - Further Reading 359

Sedimentology and Placer Processes 360 Chemical Sedimentation and Ore Formation 360 Fossil Fuels 360

#### Part IV Global Tectonics and Metallogeny 361

#### 6 Ore Deposits in a Global Tectonic Context 363

- 6.1 Introduction 363
- 6.2 Patterns in the Distribution of Mineral Deposits 364
- 6.3 Continental Growth and the Supercontinent Cycle 366
  - 6.3.1 Estimations of Continental Growth Rates *366* 
    - 6.3.2 Supercontinent Cycles 369
      - 6.3.2.1 Kenorland 370
      - 6.3.2.2 Nuna (also referred to as Columbia) 370
      - 6.3.2.3 Rodinia *370*
      - 6.3.2.4 Pangea 372
- 6.4 Geological Processes and Metallogenesis *375* 
  - 6.4.1 Evolution of the Hydrosphere and Atmosphere 375

Contents xi

- 6.4.2 Secular Decrease in Global Heat Production and Mantle Temperature 376
- 6.4.3 Long-Term Global Tectonic Trends and Mantle Convection 377
- 6.4.4 Eustatic Sea Level Changes and "Continental Freeboard" 379
- 6.5 Metallogeny Through Time 380
  - 6.5.1 The Archean Eon 380
    - 6.5.1.1 The Hadean (>4000 Ma) and Eoarchean (>3600 Ma) stages 381
    - 6.5.1.2 The Paleo-, Meso-, and Neoarchean stages (3600–2500 Ma) 381
    - 6.5.1.3 Shield formation (pre-3100 Ma) 382
    - 6.5.1.4 Cratonization (c. 3100–2500 Ma) 382
  - 6.5.2 The Proterozoic Eon 384
    - 6.5.2.1 The Paleoproterozoic Era (2500-1600 Ma) 385
    - 6.5.2.2 The Mesoproterozoic Era (1600–1000 Ma) 386
    - 6.5.2.3 The Neoproterozoic Era (1000–541 Ma) 386
  - 6.5.3 The Phanerozoic Eon 388
    - 6.5.3.1 Phanerozoic Tectonic Cycles and Metallogeny 392
    - 6.5.3.2 Time-Bound and Regional Aspects of Phanerozoic Metallogeny 393
- 6.6 Plate Tectonic Settings and Ore Deposits A Summary *396* 
  - 6.6.1 Extensional Settings 396
  - 6.6.2 Compressional Settings 396
- 6.7 Summary 399
  - Further Reading 400

 References
 401

 Index
 439

#### Preface to the 2nd Edition

It is now more than a decade since the first edition of this book appeared, during which time a great deal has happened in furthering the knowledge of metallogeny and earth system science. Our understanding of global tectonic processes and the nature of crustal evolution continues to influence the practice of economic geology and assists in maintaining the supply of natural resources in a responsible and sustainable way. The economies of developing nations continue to grow so that a greater proportion of people than ever before enjoy the benefits of a lifestyle that befits the twenty-first century. However, the global economy, and the natural resources industry in particular, remain cyclical in that security of supply of strategically important commodities has become a major problem - one result of this is the identification of "critical metals" whose supply cannot be regarded as sustainable in the short or medium term. Despite the fact that new metallotects are still being discovered - and even exploration for metals in the deep ocean and outer space mooted - the replenishment of depleted natural resources is becoming more difficult and environmentally demanding. In order to mitigate these problems, the responsible custodianship of natural resources is more necessary than ever before and there is a continuing need for all earth scientists to understand metallogeny and the resource cycle.

The 2nd edition of Introduction to Ore-Forming Processes has been updated to play a role in meeting these demands. The book is still introductory in nature and the basic structure and layout remain unchanged - all sections have, however, been updated and expanded with respect to research undertaken since it first appeared. My grateful thanks are to Brian Skinner, Steve Kesler, Charlie Moon, Michael Meyer, and Judith Kinnaird who provided valuable commentary on the revised content for the 2nd edition. My own development as an economic geologist has benefited over the past decade or more by collaboration with geoscientists that include Mike Searle, Dave Waters, Chris Hawkesworth, Nick Gardiner, Judith Kinnaird, and Paul Nex.

This book was originally conceived in a very different format. The 2nd edition is dedicated to Professor John Moore (1946–2011), Rhodes University, whose perceptive suggestions led to the process-related approach of the present content, and which contributed in no small measure to its success.

> Laurence Robb Oxford

#### Preface to the 1st Edition

There are many excellent texts, available at both introductory and advanced levels, that describe the Earth's mineral deposits. Several describe the deposits themselves and others do so in combination with explanations that provide an understanding of how such mineral occurrences form. Few are dedicated entirely to the multitude of processes that give rise to the ore deposits of the world. The main purpose of this book is to provide a better understanding of the processes, as well as the nature and origin, of mineral occurrences and how they fit into the Earth system. It is intended for use at a senior undergraduate level (third and fourth year levels), or graduate level (North America), and assumes a basic knowledge in a wide range of core earth science disciplines, as well as in chemistry and physics. Although meant to be introductory, it is reasonably comprehensive in its treatment of topics, and it is hoped that practicing geologists in the minerals and related industries will also find the book useful as a summary and update of ore-forming processes. To this end the text is punctuated by a number of boxed case studies in which actual ore deposits, selected as classic examples from around the world, are briefly described to give context and relevance to processes being discussed in the main text.

Metallogeny, or the study of the genesis of ore deposits in relation to the global tectonic paradigm, is a topic that traditionally has been, and should remain, a core component of the university earth science curriculum. It is also the discipline that underpins the training of professional earth scientists working in the minerals and related industries of the world. A tendency in the past has been to treat economic geology as a vocational topic and to provide instruction only to those individuals who wished to specialize in the discipline or to follow a career in the minerals industries. In more recent years, changes in earth science curricula have resulted in a trend, at least in a good many parts of the world, in which economic geology has been sidelined. A more holistic, process-orientated approach (earth systems science) has led to a wider appreciation of the Earth as a complex interrelated system. Another aim of this book, therefore, is to emphasize the range of processes responsible for the formation of the enormously diverse ore deposit types found on Earth and to integrate these into a description of Earth evolution and global tectonics. In so doing it is hoped that metallogenic studies will increasingly be reintegrated into the university earth science curricula. Teaching the processes involved in the formation of the world's diminishing resource inventory is necessary, not only because of its practical relevance to the real world, but also because such processes form an integral and informative part of the Earth system.

This book was written mainly while on a protracted sabbatical in the Department of Earth Sciences at the University of Oxford. I am very grateful to John Woodhouse and the departmental staff who accommodated me and helped to provide the combination

#### xvi Preface to the 1st Edition

of academic rigor and quietude that made writing this book such a pleasure. In particular Jenny Colls, Earth Science Librarian, was a tower of support in locating reference material. The "tea club" at the Banbury Road annexe provided both stimulation and the requisite libations to break the monotony. The staff at Blackwell managed to combine being really nice people with a truly professional attitude, and Ian Francis, Delia Sandford, Rosie Hayden, and Cee Pike were all a pleasure to work with. Dave Coles drafted all the diagrams and I am extremely grateful for his forebearance in dealing amiably with a list of figures that seemingly did not end. Several people took time to read through the manuscript for me and in so doing greatly improved both the style and content. They include John Taylor (copyediting), Judith Kinnaird and Dave Waters (Introduction), Grant Cawthorn (Chapter 1), Philip Candela (Chapter 2), Franco Pirajno (Chapter 3), Michael Meyer (Chapter 4), John Parnell and Harold Reading (Chapter 5), and

Mark Barley, Kevin Burke, and John Dewey (Chapter 6). The deficiencies that remain, though, are entirely my own. A particularly debt of gratitude is owed to David Rickard, who undertook the onerous task of reviewing the entire manuscript; his lucid comments helped to eliminate a number of flaws and omissions. Financial support for this project came from BHP Billiton in London and the Geological Society of South Africa Trust. My colleagues at Wits were extremely supportive during my long absences, and I am very grateful to Spike McCarthy, Paul Dirks, Carl Anhauesser, Johan Kruger, and Judith Kinnaird for their input in so many ways. Finally, my family, Vicki, Nicole, and Brendan, were subjected to a lifestyle that involved making personal sacrifices for the fruition of this project - there is no way of saying thank you and it is to them that I dedicate this book.

> Laurence Robb Johannesburg

#### **Introduction: Mineral Resources**

#### TOPICS

General introduction and aims of the book A simple classification scheme for mineral deposits Some important definitions metallogeny, syngenetic, epigenetic, mesothermal, epithermal, supergene, hypogene, etc. Some relevant compilations periodic table of the elements tables of the main ore and gangue minerals geological time scale Factors that make a viable mineral deposit enrichment factors required to make ore deposits how are mineral resources and ore reserves defined? Natural resources and their future exploitation sustainability environmental responsibility

#### **Introduction and Aims**

With a global population in 2019 of close to eight billion people, and this figure set to increase to some ten billion by 2050, it is apparent that the world's economies are under growing pressure to meet the demands of an increasingly materialistic lifestyle. The unprecedented growth of human population over the past century has resulted in a dramatic increase in demand for, and production of, natural resources - it is therefore evident that understanding the nature, origin, and distribution of the world's mineral deposits remains a vital and strategic topic. The discipline of "economic geology," which covers all aspects pertaining to the description and understanding of mineral resources, is, therefore, one which traditionally has been, and should remain, a core component of the university earth science curriculum. It is also the discipline that underpins the training of professional earth scientists working in the minerals and related industries of the world. Unfortunately, a tendency at many universities in the recent past has been to treat economic geology as a vocational topic, and to provide instruction only to those individuals who wished to specialize in the discipline or to follow a career in the minerals industry. There has been a trend, at least in many parts of the world, to sideline economic geology both as a taught discipline and a research topic.

Developments in the early twenty-first century have indicated how problematic institutional and governmental neglect can be when the security of supply of strategic metals is brought into question. Global demands

#### xviii Introduction: Mineral Resources

to reduce greenhouse gas emissions, and to provide a framework for the responsible and sustainable supply of natural resources, have resulted in the realization that all earth scientists need to understand the resource cycle in order to properly advise the public at large, and to manage future programs aimed at the responsible custodianship of the world's finite resources. The conceptual development of earth systems science, a feature of the latter years of the twentieth century, has led to changes in the way in which the earth sciences are taught. A more holistic, process-orientated approach has led to a much wider appreciation of the Earth as a complex, interrelated system. The understanding of feedback mechanisms has created an awareness that the solid Earth, its oceans and atmosphere, and the organic life forms that occupy niches above, at and below its surface, are intimately connected and can only be understood properly in terms of an interplay of processes. Examples include the links between global tectonics and climate patterns, and also between the evolution of unicellular organisms and the formation of certain types of ore deposits. In this context the teaching of many of the traditional geological disciplines assumes new relevance and the challenge to successfully teaching earth system science is how best to integrate the wide range of topics into a curriculum that provides understanding of the entity. Understanding the processes involved in the formation of the enormously diverse ore deposit types found on Earth is necessary, not only because of its practical relevance to the real world, but also because such processes form an integral and informative part of the Earth's evolution.

The purpose of this process-orientated book is to provide a better understanding of the nature and origin of mineral occurrences and how they fit into the Earth system. It is intended for use at a senior undergraduate level, or at a graduate level, and assumes a basic knowledge in a wide range of earth science disciplines, as well as in chemistry and physics. It is also hoped that practicing geologists in the minerals and related industries will find the book useful as a summary and update of ore-forming processes. To this end the text is punctuated by a number of boxed case studies in which actual ore deposits, selected as classic examples from around the world, are briefly described to give context and relevance to processes being discussed in the main text.

#### A Classification Scheme for Ore Deposits

There are many different ways of categorizing ore deposits. Most people who have written about and described ore deposits have either unwittingly or deliberately been involved in their classification. This is especially true of textbooks where the task of providing order and structure to a set of descriptions invariably involves some form of classification. The best classification schemes are probably those that remain as independent of genetic linkages as possible, thereby minimizing the scope for mistakes and controversy. Nevertheless, genetic classification schemes are ultimately desirable, as there is considerable advantage to having processes of ore formation reflected in a set of descriptive categories. Guilbert and Park (1986) discuss the problem of ore deposit classification at some length in chapters 1 and 9 of their seminal book on the geology of ore deposits. They show how classification schemes reflect the development of theory and techniques, as well as the level of understanding, in the discipline. Given the dramatic improvements in the level of understanding in economic geology over recent years, the Guilbert and Park (1986) classification scheme, modified after Lindgren's (1933) scheme, is both detailed and complex, and befits the comprehensive coverage of the subject matter provided by their book. In a more recent, but equally comprehensive, coverage of ore deposits, Misra (2000) has opted for a categorization based essentially on genetic type and rock association, similar to a scheme by Meyer (1981). It is the association between ore deposit and host rock that is particularly appealing for its simplicity, and that has been selected as the framework within which the processes described in this book are placed. Rocks are classified universally in terms of a threefold subdivision, namely igneous, sedimentary, and metamorphic, that reflects the fundamental processes active in the Earth's crust (Figure 1a). The scheme is universal



based on host rock type – Parts 1, 2, and 3 represent the breakdown of sections in this book. Photographs illustrate examples representing the main ore forming processes. (c) Igneous: magmatic layering and chromitite seams, Critical Zone, Bushveld Complex, South Africa. (d) Sedimentary: Au- and U-bearing conglomerate from the Witwatersrand Basin, South Africa. (e) Hydrothermal: quartz-carbonate vein network in metasedimentary host rocks of the Lily gold mine, Barberton greenstone belt, South Africa.

because rocks are recognizably either igneous or sedimentary (generally!), or, in the case of both precursors, have been substantially modified to form a metamorphic rock. Likewise, ores are rocks and can often be relatively easily attributed to an igneous or sedimentary/surficial origin, a feature that represents a good basis for classification. Such a classification also reflects the genetic process involved in ore formation, since igneous and sedimentary deposits are typically syngenetic and formed at the same time as the host rock itself. Although many ores are metamorphosed, and whereas pressure and temperature increases can substantially modify the original nature of ore deposits, it is evident that metamorphism does not itself represent a fundamental process whereby ore deposits are created. Hydrothermal processes, however, are a metallogenic analogue for metamorphism and also involve modification of pre-existing protoliths, as well as heat (and mass) transfer and pressure fluctuation. A very simple classification of ores is, therefore, achieved on the basis of igneous, sedimentary/surficial, and hydrothermal categories (Figure 1b), and this forms the basis for the structure and layout of this book. This subdivision is very similar to one used by Einaudi (2000), who stated that all mineral deposits can be classified into three types based on process, namely magmatic deposits, hydrothermal deposits, and surficial deposits formed by surface and groundwaters. One drawback of this type of classification, however, is that ore-forming processes are complex and episodic. Ore formation also involves processes that evolve, sometimes over significant periods of geologic time. For example, igneous processes become magmatic-hydrothermal as the intrusion cools and crystallizes, and sediments undergo diagenesis and metamorphism as they are progressively buried, with accompanying fluid flow and alteration. In addition, deformation of the Earth's crust introduces new conduits that also facilitate fluid flow and promote the potential for mineralization in virtually any rock type. Ore-forming processes

can, therefore, span more than one of the three categories, and there is considerable overlap between igneous and hydrothermal and between sedimentary and hydrothermal, as illustrated diagrammatically in Figure 1b.

The main part of this book is subdivided into three sections termed Igneous (Part I), Hydrothermal (Part II), and Sedimentary/Surficial (Part III) (Figure 1a-e). Part I comprises Chapters 1 and 2, which deal with igneous and magmatic-hydrothermal ore-forming processes respectively. Part II contains Chapter 3 and covers the large and diverse range of hydrothermal processes not covered in Part I. Part III comprises Chapter 4 on surficial and supergene processes, as well as Chapter 5, which covers sedimentary ore deposits, including a section on the fossil fuels. The final chapter of the book, Chapter 6, is effectively an addendum to this threefold subdivision and is an attempt to describe the distribution of ore deposits, both spatially in the context of global tectonics and temporally in terms of crustal evolution, through Earth history. This chapter is relevant because the plate tectonic paradigm, which has so pervasively influenced geological thought since the early 1970s, provides another conceptual basis within which to classify ore deposits. In fact, modern economic geology, and the scientific exploration of mineral deposits, is now firmly cast into the frame of global tectonics and crustal evolution. Although there is still a great deal to be learnt, the links between plate tectonics and ore genesis are now sufficiently well established that studies of ore deposits are starting to contribute to a better understanding of the Earth system.

## What Makes a Viable Mineral Deposit?

Ore deposits form when a useful commodity is sufficiently concentrated in an accessible part of the Earth's crust so that it can be profitably extracted. The processes by which this

	Average crustal	Typical exploitable	Approximate concentration
	abundance	grade	factor
Al	8.4%	30%	×4
Fe	5.2%	50%	×9
Cu	27 ppm	1%	×370
Ni	59 ppm	1%	×170
Zn	72 ppm	5%	×700
Sn	1.7 ppm	0.5%	×2900
Au	1.3 ppb	$2{ m g}{ m t}^{-1}$	×1500
Pt	1.5 ppb	$5  g  t^{-1}$	×3300

Table 1Average crustal abundances for selectedmetals and typical concentration factors that needto be achieved in order to produce a viable oredeposit.

*Note*: 1 ppm is the same as  $1 \text{ g t}^{-1}$ .

Source: Average crustal abundances from Rudnick and Gao (2014). Reproduced with permission of Elsevier.

concentration occurs are the topic of this book. As an introduction it is pertinent to consider the range of concentration factors that characterize the formation of different ore deposit types. Some of the strategically important metals, such as Fe, Al, Mg, Ti, and Mn, are abundantly distributed in the Earth's crust (i.e. between about 0.5% and 10%) and only require a relatively small degree of enrichment in order to make a viable deposit. Table 1 shows that Fe

and Al, for example, need to be concentrated by factors of 9 and 4 respectively, relative to average crustal abundances, in order to form potentially viable deposits.

By contrast, base metals such as Cu, Zn, and Ni are much more sparsely distributed and average crustal abundances are only in the range 30-70 parts per million (ppm). The economics of mining dictate that these metals need to be concentrated by factors in the hundreds in order to form potentially viable deposits - degrees of enrichment that are an order of magnitude higher than those applicable to the more abundant metals. The degree of concentration required for the precious metals is even more demanding, where the required enrichment factors are in the thousands. Table 1 shows that average crustal abundances for Au and Pt are in the range 1–2 parts per billion (ppb) and even though mines routinely extract these metals at grades of around  $1-5 g t^{-1}$ , the enrichment factors involved are between 1000 and 3000 times.

Another useful way to distinguish between the geochemically abundant and scarce metals is to plot average crustal abundances against production estimates. This type of analysis was first carried out by Skinner (1976), who used a plot like that in Figure 2 to confirm that



**Figure 2** Plot of global production against crustal abundances for a number of metal commodities. The line through Fe can be regarded as a datum against which the rates of production of the other metals can be compared in the context of crustal abundances. Source: After Einaudi (2000).

#### xxii Introduction: Mineral Resources

crustal abundance is a reasonable measure of the availability of a given resource. It is by design and of necessity that we use more of the geochemically abundant metals than we do the scarce ones. The nature of our technologies and the materials we use to manufacture mechanical items depend in large measure on the availability of raw materials. As an example, the technologies (geological and metallurgical) that resulted in a dramatic increase in global aluminum production over the latter part of the twentieth century, allowed iron to be replaced by aluminum in many products such as motor vehicles. More importantly, though, Figure 2 allows estimates to be made of the relative rates of depletion of certain metals relative to others. These trends are discussed again below.

#### **Mineral Resources and Ore Reserves**

Throughout this book reference is made to the term "ore deposit" with little or no consideration of whether such occurrences might be economically viable. Although such considerations might seem irrelevant in the present



context, it is necessary to emphasize that professional institutions now insist on the correct definition and usage of terminology pertaining to exploration results, mineral resources, and ore reserves. Such terminology should be widely used and applied, as it helps to reduce the incorrect, and sometimes irresponsible, usage of terminology in reports on which, for example, investment decisions might be based. Correct terminology can also assist in the description and identification of genuine ore deposits from zones of marginal economic interest or simply anomalous concentrations of a given commodity.

Although the legislation that governs the public reporting of mineral occurrences varies from one country to another, there is now reasonable agreement globally on a definition of terms. It is widely accepted that different terms should apply to mineral occurrences depending on the level of knowledge and degree of confidence that is associated with their quantification in terms of grade and mass/volume. Figure 3 is a matrix that reflects the terminology associated with an increased level of geological knowledge and confidence,

**Figure 3** Simplified scheme illustrating the conceptual difference between mineral resources and ore reserves as applied to mineral occurrences. The scheme forms the basis for a more unified description of ore deposits as now required in terms of legislation that has been passed in most major mineral producing jurisdictions.

and modifying factors such as those related to mining techniques, metallurgical extraction, marketing, and environmental reclamation. Exploration results can be translated into a mineral resource once it is clear that an occurrence of intrinsic economic interest exists in such form and quantity that there are reasonable prospects for its eventual exploitation. Such a resource can only be referred to as an ore reserve if it is a part of an economically extractable measured or indicated mineral resource. One problem with this terminology is that an economically extractable ore deposit in a developing world artisanal operation may not be viable in a technically developed economy, and vice versa. The term "ore deposit" has no significance in the professional description of a mineral occurrence and is best used simply as a descriptive or generic term.

## Some Useful Definitions and Compilations

#### **General Definitions**

This section is not intended to provide a comprehensive glossary of terms used in this book. There are, however, several terms that are used throughout the text where a definition is either useful or necessary in order to avoid ambiguity. The following definitions are consistent with those provided in the *Glossary of Geology* (Bates and Jackson 1987) and *The Encyclopedia of the Solid Earth Sciences* (Kearey 1993).

- Ore: any naturally occurring material from which a mineral or aggregate of value can be extracted at a profit. In this book the concept extends to coal (a combustible rock comprising more than 50% by weight carbonaceous material) and petroleum (naturally occurring hydrocarbon in gaseous, liquid, or solid state).
- *Syngenetic*: refers to ore deposits that form at the same time as their host rocks. In this book this includes deposits that form during the early stages of sediment diagenesis.

- *Epigenetic*: refers to ore deposits that form after their host rocks.
- *Hypogene*: refers to mineralization caused by ascending hydrothermal solutions.
- *Supergene*: refers to mineralization caused by descending solutions. The term generally refers to the enrichment processes accompanying the weathering and oxidation of sulfide and oxide ores at or near the surface.
- *Metallogeny*: the study of the genesis of mineral deposits, with emphasis on their relationships in space and time to geological features of the Earth's crust.
- *Metallotect*: any geological, tectonic, lithological, or geochemical feature that has played a role in the concentration of one or more elements in the Earth's crust.
- *Metallogenic Epoch*: a unit of geologic time favorable for the deposition of ores or characterized by a particular assemblage of deposit types.
- *Metallogenic Province*: a region characterized by a particular assemblage of mineral deposit types.
- *Epithermal*: hydrothermal ore deposits formed at shallow depths (less than 1500 m) and fairly low temperatures (50–200 °C).
- *Mesothermal*: hydrothermal ore deposits formed at intermediate depths (1500–5000 m) and temperatures (200–400 °C).
- *Hypothermal*: hydrothermal ore deposits formed at substantial depths (greater than 5000 m) and elevated temperatures (400–600 °C).

#### **Periodic Table of the Elements**

The question of the number of elements present on Earth is a difficult one to answer. There are 94 primordial nuclides present on Earth, these being the elements that formed during nucleosynthesis of the material that makes up the solar system. Most of the element compilations relevant to the earth sciences show 92 elements, the majority of which occur in readily detectable amounts in the Earth's crust. Figure 4 shows a periodic

#### xxiv Introduction: Mineral Resources

table in which these elements are presented in ascending atomic number and also categorized into groupings that are relevant to metallogenesis. There are in fact as many as 118 elements known to man, but those with atomic numbers greater than 92 (U: uranium) either occur in vanishingly small amounts as unstable isotopes that are the products of various natural radioactive decay reactions, or are synthetically created in nuclear reactors. The heaviest known element, originally called ununoctium (Uuo, atomic number 118), was only fleetingly detected in a nuclear reactor - its existence has now been confirmed and officially named "oganesson" (Symbol Og) after the Russian nuclear physicist, Yuri Oganessian. Some of the heavy, unstable elements are, however, manufactured synthetically and serve a variety of uses. Plutonium (Pu, atomic number 94), for example, is manufactured in fast breeder reactors and is used as a nuclear fuel and in weapons manufacture. Americium (Am, atomic number 95) is also extracted from spent reactor fuel and is widely used as the active agent in smoke detectors.

Of the 92 elements shown in Figure 4, almost all have some use in our modern, technologically-driven societies. Some of the elements (iron and aluminum) are required in copious quantities as raw materials for the manufacture of vehicles and in construction, whereas others (the rare earth elements, for example) are needed in very much smaller amounts for use in the alloys and electronics industries. Only two elements appear at the present time to have little or no commercial use at all (Figure 4). These are francium (Fr, atomic number 87), and protactinium (Pa, atomic number 91). Francium is radioactive and so short-lived that only some 20-30 g exists in the entire Earth's crust at any one time! Astatine (At, atomic number 85) is another very unstable element that exists in vanishingly small amounts in the crust as a decay chain by-product or is manufactured synthetically. Astatine has been manufactured in particle accelerators and is occasionally used in various nuclear medical applications.

The useful elements can be subdivided in a number of different ways. Most of the



**Figure 4** Periodic table showing the elements with atomic numbers from 1 to 92; classified on the basis of their rock and mineral associations.

elements can be classified as metals (Figure 4), with a smaller fraction being non-metals. The elements B, Si, As, Se, Te, and At have intermediate properties and are referred to as metalloids. Another classification of elements, attributed to the pioneering geochemist Goldschmidt, is based on their rock associations and forms the basis for distinguishing between lithophile (associated with silicates and concentrated in the crust), chalcophile (associated with sulfides), siderophile (occur as the native metal and concentrated in the core), and atmophile (occur as gases in the atmosphere) elements. It is also useful to consider elements in terms of their ore mineral associations, with some preferentially occurring as sulfides and others as oxides (see Figure 4). Some elements have properties that enable them to be classified in more than one way - iron is a good example, in that it occurs readily as both an oxide and sulfide.

#### **Common Ore and Gangue Minerals**

It is estimated that there are about 3800 known minerals that have been identified and classified (Battey and Pring 1997). Only a very small proportion of these make up the bulk of the rocks of the Earth's crust, as the common rock forming minerals. Likewise, a relatively small number of minerals make up most of the economically viable ore deposits of the world. The following compilation is a breakdown of the more common ore minerals in terms of chemical classes based essentially on the anionic part of the mineral formula. Also included are some of the more common "gangue" minerals, which are those that form part of the ore body, but do not contribute to the economically extractable part of the deposit. Most of these are alteration assemblages formed during hydrothermal processes. The compilation, including ideal chemical formulae, is subdivided into six sections, namely native elements, halides, sulfides and sulfosalts, oxides and hydroxides, oxysalts (such as carbonates, phosphates, tungstates, sulfates), and silicates. More detailed descriptions of both ore and gangue minerals can be found in a variety of mineralogical texts, such as Deer et al. (1982), Berry et al. (1983), Battey and Pring (1997), and Wenk and Bulakh (2017). More information on ore mineral textures and occurrences can be found in Craig and Vaughan (1994) and Ixer (1990).

#### **Native Elements**

Both metals and non-metals exist in nature in the native form, where essentially only one element exists in the structure. Metals occurring in the native form include copper, silver, gold, and platinum which are all characterized by cubic close packing of atoms, high densities, and are malleable and soft. The carbon atoms in diamond are linked in tetrahedral groups forming well cleaved, very hard, translucent crystals. Sulfur also occurs as rings of eight atoms and forms bipyramids or is amorphous.

#### Metals

Gold – Au Silver – Ag Platinum – Pt Palladium – Pd Copper – Cu

#### Non-metals

Sulfur – S Diamond – C Graphite – C

#### Halides

The halide mineral group comprises compounds made up by ionic bonding. Minerals such as halite and sylvite are cubic, have simple chemical formulae, and are highly soluble in water. Halides sometimes form as ore minerals, such as chlorargyrite and atacamite.

Halite – NaCl Sylvite – KCl Chlorargyrite – AgCl Fluorite –  $CaF_2$ Atacamite –  $Cu_2Cl(OH)_3$ 

#### **Sulfides and Sulfosalts**

This is a large group of minerals in which bonding is both ionic and covalent in character. The sulfide group has the general formula  $A_M X_P$ , where X is typically S but can be As, Sb, Te, Bi, or Se, and A is one or more of the metals. The sulfosalts, which are less common than sulfides, have the general formula  $A_M B_N X_P$ , where A is usually Ag, Cu, or Pb, B is commonly As, Sb, or Bi, and X is S. The sulfide and sulfosalt minerals are generally opaque, dense, and have a metallic to sub-metallic luster.

#### Sulfides

Chalcocite –  $Cu_2S$ Bornite - Cu<sub>5</sub>FeS<sub>4</sub> Galena - PbS Sphalerite - ZnS Chalcopyrite – CuFeS<sub>2</sub> Pyrrhotite –  $Fe_{1-x}S$ Pentlandite –  $(Fe,Ni)_9S_8$ Millerite - NiS Covellite - CuS Cinnabar - HgS Skutterudite – (Co,Ni)As<sub>3</sub> Sperrylite – PtAs<sub>2</sub> Braggite/cooperite - (Pt,Pd,Ni)S Moncheite - (Pt,Pd)(Te,Bi)<sub>2</sub> Laurite –  $RuS_2$ Cobaltite - CoAsS Gersdorffite - NiAsS Loellingite – FeAs<sub>2</sub> Arsenopyrite - FeAsS Molybdenite - MoS<sub>2</sub> Realgar - AsS Orpiment –  $As_2S_3$ Stibnite –  $Sb_2S_3$ Bismuthinite –  $Bi_2S_3$ Argentite – Ag<sub>2</sub>S Calaverite –  $AuTe_2$ Pyrite - FeS<sub>2</sub>

#### Sulfosalts

$$\label{eq:constraint} \begin{split} & \text{Tetrahedrite} - (\text{Cu},\text{Ag})_{12}\text{Sb}_4\text{S}_{13}\\ & \text{Tennantite} - (\text{Cu},\text{Ag})_{12}\text{As}_4\text{S}_{13}\\ & \text{Enargite} - \text{Cu}_3\text{AsS}_4 \end{split}$$

#### **Oxides and Hydroxides**

This group of minerals is variable in its properties but is characterized by one or more metals in combination with oxygen or a hydroxyl group. The oxides and hydroxides typically exhibit ionic bonding. The oxide minerals can be hard, dense, and refractory in nature (magnetite, cassiterite) but can also be softer and less dense, forming as products of hydrothermal alteration and weathering (hematite, anatase, pyrolusite). Hydroxides, such as goethite and gibbsite, are typically the products of extreme weathering and alteration.

#### Oxides

Cuprite –  $Cu_2O$ Hematite –  $Fe_2O_3$ Ilmenite –  $FeTiO_3$ Hercynite –  $FeAl_2O_4$ Gahnite –  $ZnAl_2O_4$ Magnetite –  $Fe_3O_4$ Chromite –  $FeCr_2O_4$ Rutile –  $TiO_2$ Anatase –  $TiO_2$ Pyrolusite –  $MnO_2$ Cassiterite –  $SnO_2$ Uraninite –  $UO_2$ Thorianite –  $ThO_2$ Columbite-tantalite –  $(Fe,Mn)(Nb,Ta)_2O_6$ 

#### Hydroxides (or Oxyhydroxides)

Goethite – FeO(OH) Gibbsite –  $Al(OH)_3$ Boehmite – AlO(OH)Manganite – MnO(OH)

#### Oxysalts

The carbonate group of minerals form when anionic carbonate groups  $(CO_3^{2-})$  are linked by intermediate cations such as Ca, Mg, and Fe. Hydroxyl bearing and hydrated carbonates can also form, usually as a result of weathering and alteration. The other oxysalts, such as the tungstates, sulfates, phosphates, and vanadates, are analogous to the carbonates, but are built around an anionic group in the form  $XO_4^{n-}$ .

#### Carbonates

 $\label{eq:calculation} \begin{array}{l} Calculate - CaCO_3 \\ Dolomite - CaMg(CO_3)_2 \\ Ankerite - CaFe(CO_3)_2 \\ Siderite - FeCO_3 \\ Rhodochrosite - MnCO_3 \\ Smithsonite - ZnCO_3 \\ Cerussite - PbCO_3 \\ Azurite - Cu_3(OH)_2(CO_3)_2 \\ Malachite - Cu_2(OH)_2CO_3 \end{array}$ 

#### Tungstates

Scheelite – CaWO<sub>4</sub> Wolframite – (Fe,Mn)WO<sub>4</sub>

#### Sulfates

Baryte(s) – BaSO<sub>4</sub> Anhydrite – CaSO<sub>4</sub> Alunite – KAl<sub>3</sub>(OH)<sub>6</sub>(SO<sub>4</sub>)<sub>2</sub> Gypsum – CaSO<sub>4</sub>·2H<sub>2</sub>O Epsomite – MgSO<sub>4</sub>·7H<sub>2</sub>O

#### Phosphates

Xenotime –  $YPO_4$ Monazite – (Ce,La,Th)PO<sub>4</sub> Apatite –  $Ca_5(PO_4)_3(F,Cl,OH)$ 

#### Vanadates

Carnotite –  $K_2(UO_2)(VO_4)_2 \cdot 3H_2O$ 

#### Silicates

The bulk of the Earth's crust and mantle is made up of silicate minerals that can be subdivided into several mineral series based on the structure and coordination of the tetrahedral  $SiO_4^{4-}$  anionic group. Silicate minerals are generally hard, refractory, and translucent. Most of them cannot be regarded as ore minerals in that they do not represent the extractable part of an ore body, and the list provided below shows only some of the silicates more commonly associated with mineral occurrences as gangue or alteration products. Some silicate minerals, such as zircon and spodumene, are ore minerals and represent important sources of metals such as zirconium and lithium, respectively. Others, such as kaolinite, are mined for their intrinsic properties (i.e. as a clay for the ceramics industry).

#### Tekto (framework)

Quartz – SiO<sub>2</sub> Orthoclase – (K,Na)AlSi<sub>3</sub>O<sub>8</sub> Albite – (Na,Ca)AlSi<sub>3</sub>O<sub>8</sub> Scapolite – (Na,Ca)<sub>4</sub>(Al,Si)<sub>4</sub>O<sub>8</sub>)<sub>3</sub> (Cl, CO<sub>3</sub>) Zeolite (analcime) – NaAlSi<sub>2</sub>O<sub>6</sub>·H<sub>2</sub>O

#### Neso (ortho)

$$\begin{split} & \operatorname{Zircon} - \operatorname{Zr}(\operatorname{SiO}_4) \\ & \operatorname{Garnet} \left( \operatorname{almandine} \right) - \operatorname{Fe}_3\operatorname{Al}_2(\operatorname{SiO}_4)_3 \\ & \operatorname{Garnet} \left( \operatorname{grossular} \right) - \operatorname{Ca}_3\operatorname{Al}_2(\operatorname{SiO}_4)_3 \\ & \operatorname{Sillimanite} - \operatorname{Al}_2\operatorname{SiO}_5 \\ & \operatorname{Topaz} - \operatorname{Al}_2\operatorname{SiO}_4(\operatorname{F},\operatorname{OH})_2 \\ & \operatorname{Chloritoid} - (\operatorname{Fe},\operatorname{Mg},\operatorname{Mn})_2(\operatorname{Al},\operatorname{Fe})\operatorname{Al}_3\operatorname{O}_2(\operatorname{SiO}_4)_2 \\ & (\operatorname{OH})_4 \end{split}$$

#### Cyclo (ring)

$$\begin{split} & Beryl-Be_{3}Al_{2}Si_{6}O_{18}\\ & Tourmaline - (Na,Ca)(Mg,Fe,Mn,Al)_{3}(Al,Mg,Fe)_{6}Si_{6}O_{18}(BO_{3})_{3}(OH,F)_{4} \end{split}$$

#### Soro (di)

Lawsonite –  $CaAl_2Si_2O_7(OH)_2 \cdot H_2O$ Epidote –  $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$ 

#### Phyllo (sheet)

 $\begin{array}{ll} \label{eq:constraint} & {\rm Kaolinite}-{\rm Al}_4{\rm Si}_4{\rm O}_{10}({\rm OH})_8 \\ & {\rm Montmorillonite}-({\rm Na},{\rm Ca})_{0.3}({\rm Al},{\rm Mg})_2{\rm Si}_4{\rm O}_{10} \\ & ({\rm OH})_2\cdot{\rm nH}_2{\rm O} \\ & {\rm Illite}-{\rm KAl}_2({\rm Si},{\rm Al})_4{\rm O}_{10}({\rm H}_2{\rm O})({\rm OH})_2 \\ & {\rm Pyrophyllite}-{\rm Al}_2{\rm Si}_4{\rm O}_{10}({\rm OH})_2 \\ & {\rm Talc}-{\rm Mg}_3{\rm Si}_4{\rm O}_{10}({\rm OH})_2 \\ & {\rm Muscovite}-{\rm KAl}_2({\rm AlSi}_3{\rm O}_{10})({\rm OH})_2 \\ & {\rm Biotite}-{\rm K}({\rm Fe},{\rm Mg})_3({\rm Al},{\rm Fe}){\rm Si}_3{\rm O}_{10}({\rm OH},{\rm F})_2 \\ & {\rm Lepidolite}-{\rm K}({\rm Li},{\rm Al})_3({\rm Si},{\rm Al})_4{\rm O}_{10}({\rm OH},{\rm F})_2 \\ & {\rm Chlorite}-({\rm Fe},{\rm Mg},{\rm Al})_{5-6}({\rm Si},{\rm Al})_4{\rm O}_{10}({\rm OH})_8 \end{array}$ 

#### Ino (chain)

$$\label{eq:constraint} \begin{split} \text{Tremolite-actinolite} &- \text{Ca}_2(\text{Fe},\text{Mg})_5\text{Si}_8\text{O}_{22}(\text{OH})_2\\ \text{Spodumene} &- \text{LiAlSi}_2\text{O}_6\\ \text{Wollastonite} &- \text{CaSiO}_3 \end{split}$$

#### **Unknown Structure**

Chrysocolla - (Cu,Al)<sub>2</sub>H<sub>2</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>·nH<sub>2</sub>O

#### **Geological Time Scale**

The development of a geological time scale has been the subject of a considerable amount of thought and research over the past few decades and continues to occupy the minds and activities of stratigraphers and geochronologists around the world. The definition of a framework within which to describe the secular evolution of rocks, and hence the Earth, has been, and continues to be, a contentious exercise. The International Commission on Stratigraphy (ICS is a working group of the International Union of Geological Sciences: IUGS) has assumed the official role of developing the geological time scale, a task that is continuously being modified and improved upon. The work of the ICS is periodically published as a book, such as Harland's (1989) seminal A Geologic Time Scale - which has now been superseded a number of times by works such as Gradstein et al. (2004 and 2012) and Ogg et al. (2016). In these books reference is made to the timing of various events and processes and the provision of a time scale to which readers can refer. Figure 5 is a time scale based on the 2018 version of the International Stratigraphic Chart, published and sanctioned by the ICS and IUGS (http://www.stratigraphy.org). In this diagram global chronostratigraphic terms are presented in terms of eons, eras, periods, and epochs, and defined by absolute ages in millions of years before present (Ma). Also shown are the approximate positions on the time scale of many of the ore deposits and metallogenic provinces referred to in the text.

#### Natural Resources, Sustainability, and the Environment

One of the major issues that characterized social and economic development toward the end of the twentieth century revolved around the widespread acceptance that the Earth's natural resources are finite, and that their exploitation should be carried out in a manner that will not detrimentally affect future generations. The concept of "sustainable development" in terms of the exploitation of mineral occurrences implies that current social and economic practice should endeavor not to deplete natural resources to the point where the needs of the future cannot be met. This would seem to be an impossible goal given the unprecedented population growth over the past century and the fact that many commodities may become depleted within the next 100 years. The challenge for commodity supply over the next century is a multifaceted one and will require a better understanding of the Earth system, improved incentives to promote more efficient recycling of existing resources, and the means to find alternative sources for commodities that are in danger of depletion.

There has been a dramatic rise in global population over the past 150 years. The number of humans on Earth has risen from one billion in 1830 to over seven billion at the start of the twenty-first century. Most predictions suggest that the populations of most countries will start to level off over the next 30 years and that global numbers will stabilize at around eleven billion people by the end of the twenty-first century. Societies in the next 100 years are, nevertheless, facing a scenario in which the demand for, and utilization of, natural resources continues to increase. and certain commodities might well become depleted in this interval. Production trends for commodities such as oil, bauxite, copper, and gold (Figure 6) confirm that demand