An Introduction to Metamorphic Petrology

Second Edition

This second edition is fully updated to include new developments in the study of metamorphism as well as enhanced features to facilitate course teaching. It integrates a systematic account of the mineralogical changes accompanying metamorphism of the major rock types with discussion of the conditions and settings in which they formed. The use of textures to understand metamorphic history and links to rock deformation are also explored. Specific chapters are devoted to rates and timescales of metamorphism and to the tectonic settings in which metamorphic belts develop. These provide a strong connection to other parts of the geology curriculum. Key thermodynamic and chemical concepts are introduced through examples which demonstrate their application and relevance. Richly illustrated in colour and featuring end-of-chapter and online exercises, this textbook is a comprehensive introduction to metamorphic rocks and processes for undergraduate students of petrology, and provides a solid basis for more advanced study and research.

Bruce Yardley is Emeritus Professor at the University of Leeds. He previously taught at the Universities of Manchester and East Anglia and has spent sabbaticals at Otago, ETH Zurich and Wisconsin – Madison. He has worked on many aspects of metamorphic petrology and crustal fluid processes, and has served as Chair of the Metamorphic Studies Group (1991–3), Science Secretary of the Geological Society of London (2002–6), President of the European Association of Geochemistry (2005–6) and also President of the Mineralogical Society of Great Britain and Ireland (2019–20). He has held a Harkness Fellowship at the University of Washington (1974–6) and a Humboldt Prize at GFZ Potsdam (2009–11).

Clare Warren is a Senior Lecturer and metamorphic geologist and geochronologist at the Open University, UK, and has worked extensively on metamorphic rocks that form in subduction and continental collision zones. She has published a number of widely-cited papers, and has served as Treasurer and Secretary of the UK Metamorphic Studies Group and on the Mineralogical Society of Great Britain and Ireland Council. In 2020 she was the first recipient of the UK Metamorphic Studies Group’s Barrow Award.
An Introduction to Metamorphic Petrology

SECOND EDITION

Bruce Yardley
University of Leeds

Clare Warren
The Open University, Milton Keynes
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>ix</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>x</td>
</tr>
<tr>
<td>1 The Concept of Metamorphism</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Metamorphic Rocks</td>
<td>4</td>
</tr>
<tr>
<td>1.2 What Do Metamorphic Rocks Look Like?</td>
<td>6</td>
</tr>
<tr>
<td>1.3 Metamorphic Changes</td>
<td>11</td>
</tr>
<tr>
<td>1.4 Factors That Control Metamorphism</td>
<td>13</td>
</tr>
<tr>
<td>1.5 Types and Settings of Metamorphism</td>
<td>21</td>
</tr>
<tr>
<td>1.6 Naming Metamorphic Rocks</td>
<td>24</td>
</tr>
<tr>
<td>Summary</td>
<td>31</td>
</tr>
<tr>
<td>Exercises</td>
<td>32</td>
</tr>
<tr>
<td>Further Reading</td>
<td>32</td>
</tr>
<tr>
<td>2 Chemical Equilibrium in Metamorphism</td>
<td>34</td>
</tr>
<tr>
<td>2.1 Equilibrium</td>
<td>35</td>
</tr>
<tr>
<td>2.2 The Phase Rule</td>
<td>36</td>
</tr>
<tr>
<td>2.3 Metamorphic Phase Diagrams</td>
<td>39</td>
</tr>
<tr>
<td>2.4 Metamorphic Reactions and the Phase Rule</td>
<td>42</td>
</tr>
<tr>
<td>2.5 Application of Chemical Equilibrium to Natural Rocks: an Example</td>
<td>46</td>
</tr>
<tr>
<td>2.6 Phase Diagrams for Too Many Components: the Projection</td>
<td>50</td>
</tr>
<tr>
<td>2.7 The Influence of Fluids on Metamorphic Reactions</td>
<td>52</td>
</tr>
<tr>
<td>2.8 The Concept of Buffering</td>
<td>56</td>
</tr>
<tr>
<td>2.9 Practical Limitations to the Application of Chemical Equilibrium to Metamorphic Rocks</td>
<td>58</td>
</tr>
<tr>
<td>Summary</td>
<td>61</td>
</tr>
<tr>
<td>Exercises</td>
<td>62</td>
</tr>
<tr>
<td>Further Reading</td>
<td>63</td>
</tr>
<tr>
<td>3 The Pressure–Temperature Conditions of Metamorphism</td>
<td>64</td>
</tr>
<tr>
<td>3.1 Metamorphic Reactions: the Thermodynamic Principles</td>
<td>65</td>
</tr>
<tr>
<td>3.2 Qualitative Relationships: Metamorphic Facies</td>
<td>68</td>
</tr>
<tr>
<td>3.3 Adding Numbers: Quantitative Estimates of Pressure and Temperature</td>
<td>71</td>
</tr>
</tbody>
</table>
4 Metamorphism of Pelitic Rocks

4.1 The AFM Projection 94
4.2 Metamorphism at Moderate Pressures and Temperatures 96
4.3 Metamorphism at High Temperatures 111
4.4 Metamorphism at Low Pressures 117
4.5 Metamorphism at High Pressures 120
4.6 Summary: the Effect of Pressure on Metamorphic Zoning Patterns 125
4.7 Determining P–T Conditions for Metapelite Metamorphism 127
Summary 129
Exercises 130
Further Reading 131

5 Metamorphism of Basic Igneous Rocks

5.1 The Breakdown of Primary Igneous Mineral Assemblages 133
5.2 The Facies Classification 135
5.3 Metamorphism at Low Pressures and Temperatures 139
5.4 Metamorphism at Low to Moderate Pressures 144
5.5 Metamorphism at High Pressures 150
5.6 Fluid Flow and Chemical Change During Metamorphism of Basic Rocks 156
5.7 Determining the P–T Conditions of Metamorphism from Metabasites 159
Summary 162
Exercises 163
Further Reading 163

6 Metamorphism of Limestones – Marbles, Calc-Silicates and Skarns

6.1 Marbles 167
6.2 Calc-Silicates and Skarns 187
6.3 Final Considerations 193
Summary 194
Exercises 194
Further Reading 195
7 Mineral Growth and Textures in Metamorphic Rocks

7.1 Crystal Shapes and Alignment
7.2 How Crystals Grow
7.3 Crystallisation Textures
7.4 Disequilibrium Textures
7.5 Rates and Mechanisms of Metamorphic Mineral Growth
Summary
Exercises
Further Reading

8 Metamorphism Linked to Deformation

8.1 How Do Rocks and Minerals Deform?
8.2 Textures Produced by Deformation During Metamorphism
8.3 Determining the Relative Timing of Metamorphism and Deformation
8.4 Feedbacks Between Deformation and Metamorphism
Summary
Exercises
Further Reading

9 The Duration of Metamorphism

9.1 Indirect Estimation of Metamorphic Timescales
9.2 Minerals as Geological Clocks
9.3 Linking Age to Metamorphic History
9.4 Timescales of Metamorphism
Summary
Exercises
Further Reading

10 Metamorphism and Tectonics

10.1 Modern Tectonic Settings and their Metamorphic Implications
10.2 Linking Facies Series to Tectonic Settings
10.3 Building Orogens
10.4 How Do Tectonic Processes Drive Exhumation?
10.5 Changes in Metamorphism Through Geological Time
Summary
Exercises
Further Reading
Preface

This book is a completely new edition of *An Introduction to Metamorphic Petrology*, originally published by Longman in 1989. It is designed as a core textbook for second- and third-year undergraduate metamorphic petrology courses, and to support more-advanced teaching. Our aim is to provide the background knowledge and understanding of metamorphic rocks needed by a professional geologist who will not become a petrology specialist, and to give a thorough foundation in the basics of metamorphic petrology for future researchers in the field. We have assumed a basic knowledge of chemistry, physics, maths and mineralogy, and some familiarity with the petrological microscope. Where more-detailed knowledge is necessary, this is provided in the text or in text boxes. There are worked examples for some of the quantitative parts of the course.

The book is designed to be worked through from start to finish, with many of the later chapters building on material presented earlier. Chapters 1–3 provide background to metamorphism and the underlying theory of metamorphic mineral assemblages. Chapters 4–6 describe the metamorphism of the three main protolith types, and Chapters 7 and 8 describe the textures of metamorphic rocks and what they tell us about processes. Chapters 9 and 10 tie metamorphic petrology to the underlying tectonic processes that cause metamorphism and include applications of geochronology to metamorphic rocks. These sets of chapters could be tackled independently if required.

For this edition we have extended the sections dealing with determining the conditions of metamorphism and links between metamorphism and deformation, and added a major new section on dating of metamorphic minerals. Links between metamorphism and tectonics are completely updated. Since the text touches on many interdisciplinary topics, we have given Further Readings at the end of each chapter. The text has been rewritten throughout, making use of many new field examples, and the generous decision by Cambridge University Press to produce the book in colour has allowed us to include many photographs and produce colour figures. We have also provided questions for students at the end of each chapter, and some of these can be readily adapted to match specific materials that the instructor has been using in practical classes. Supplementary material is also available at the website [https://www.cambridge.org/IMP2e].

Bruce Yardley
Clare Warren
Acknowledgements

This book reflects an approach to metamorphic rocks that has been influenced by many mentors, colleagues and students. We owe a debt to everyone who has helped us hone our skills in teaching and research, pointed us in new directions and shown us the errors of our ways. In particular, a number of friends and colleagues have supplied us with their original photographs or published images. Our thanks to Barbara Kunz, Catherine Mottram, Alex Copley, Joe Cann, Geoff Lloyd, Neil Manktelow, Olivier Beyssac, Lucy Campbell, Becky Jamieson, Richard Taylor, Pedro Castiñeras, Jared Butler and Dave Prior. Also thanks to the many colleagues who graciously shared photos and figures that didn’t eventually make it into the text.

We are grateful for perceptive and helpful discussions and comments along the way from anonymous reviewers and from Dave Pattison, Barbara Kunz, Thomas Müller, Becky Jamieson and Catherine Mottram. The project was only possible because of the support, understanding and patience of Susan Francis, Melissa Shivers and the rest of the team at Cambridge University Press, who made it possible to deliver the sort of book we wanted.

Last but not least, Clare owes thanks to Felix for putting up with so many lost weekends, while Bruce apologises profusely to Nick for putting her through this book writing nonsense again.