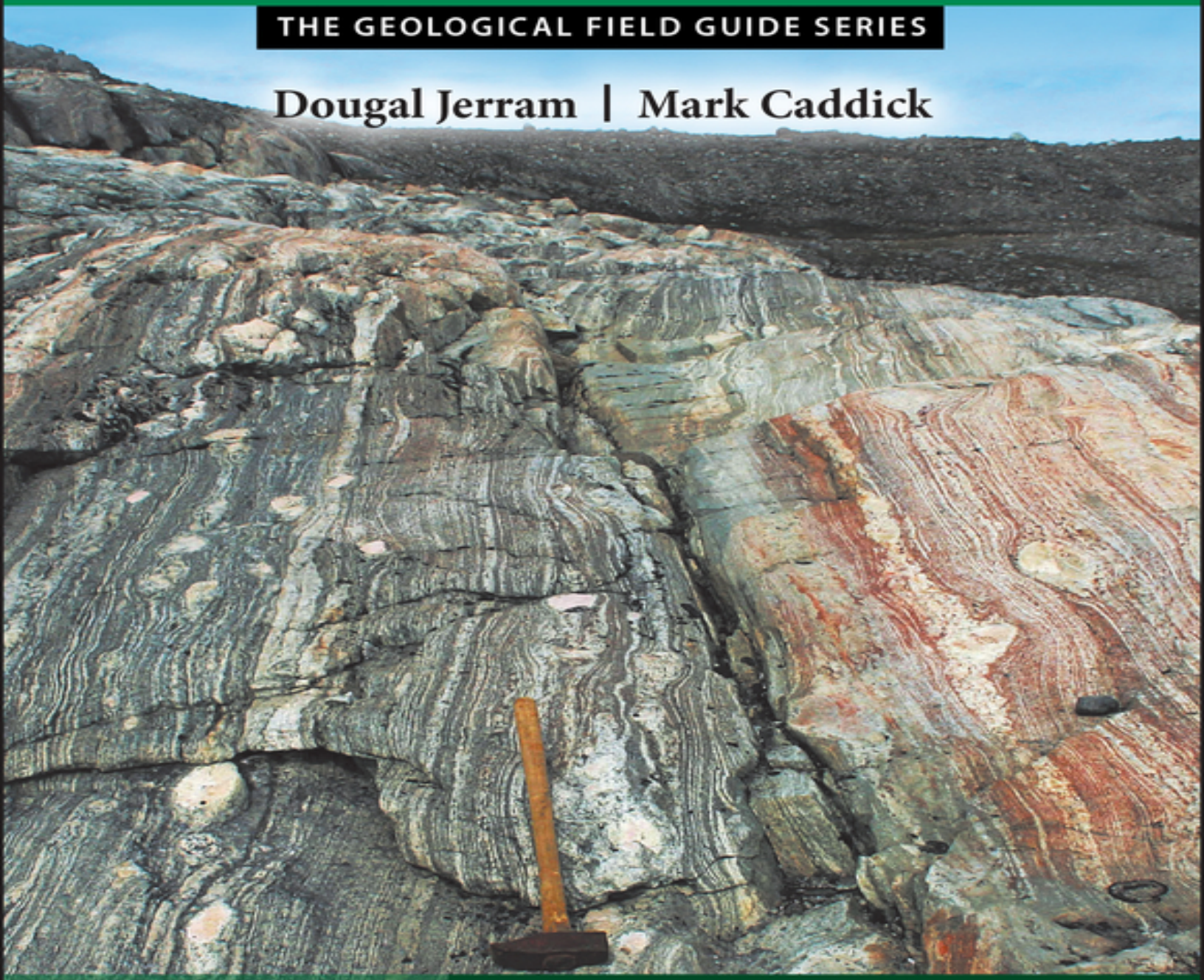
The Field Description of Metamorphic Rocks

THE GEOLOGICAL FIELD GUIDE SERIES

Dougal Jerram | Mark Caddick



SECOND EDITION

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The Field Description of Metamorphic Rocks

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PREFACE – THE FIELD DESCRIPTION OF METAMORPHIC ROCKS

In many regards, metamorphic rocks represent some of the most complicated challenges that you will find in the field. They were obviously once igneous, sedimentary, or even different metamorphic rocks, and you may be able to interpret some of this early history at the outcrop. But they have subsequently been changed through combinations of pressure, temperature, and reaction with fluid so that they might now look radically different to their original form. In order to understand these changes (the rock's metamorphosis), and to some extent the original 'parent' rock, the field description of metamorphic rocks requires careful observation and a grasp of many aspects of the broader range of the geosciences. It is not enough just to know how to identify key metamorphic minerals in the field: multidisciplinary skills borrowed from other branches of field geology, and even engineering, are increasingly essential requirements for the modern metamorphic geologist.

This concise guide is designed to give students, professionals, and keen amateur geoscientists the key tools needed to help understand and interpret the origin and evolution of complex metamorphic systems in a focused way, while in the field. This extensively revised and reorganised colour guide builds on Norman Fry's original version, published in 1984 as part of the (then) Geological Society of London Field Guide Series. Since 1984, much has changed in the scientific community's understanding of metamorphic processes and in the ways that fieldwork is conducted. Accordingly, we have tried in this first colour revision to incorporate much of this newer thinking and

methodology. At the same time, we have aimed to remain true to the original philosophy of a portable guide that concisely explains the basic concepts underpinning the field description of metamorphic rocks. Indeed, we have kept and built on some sections of Fry's original text. The original version was necessarily limited by its black and white printing, and we have enjoyed updating the figures in this version: almost every figure in the original book has been replaced here or reproduced in colour. We hope that the inclusion of the new colour images and a simple, colour-coded index system will help the reader to navigate their way through the different types, grades, and origins of metamorphic rocks. Both authors grew up with the original versions of the Geological Field Guide Series and one of us (Dougal) was even taught by Norman Fry at Cardiff University. So it has been a great pleasure, if not a long journey, to revise this field handbook, now published as part of Wiley Blackwell's 'Geological Field Guide Series'. We hope you find this new guide a great companion and an essential aid when confronted, perhaps for the first time, with metamorphic rocks in the field.

Dougal Jerram and Mark Caddick 2021

Preface – Meet the Authors

Dougal holds a 20% research professorship at the University of Oslo and is the director of DougalEARTH Ltd. He is primarily a field geologist and has undertaken fieldwork all over the world and experienced a wide range of Earth's geology and landscapes from Africa to Antarctica. He started his geological career in the UK, where he cut his teeth on the many fundamental outcrops the UK has to offer through a classic Geology degree at Cardiff and a PhD at Liverpool. His main expertise is in rock microstructure and textural analysis, 2D–3D modelling of rock textures, and understanding aspects of volcanic rifted margins from a hard rock basis. In recognition of his early significant contribution to Earth Sciences, he was awarded the Murchison Fund of the Geological Society in 2006. Dougal has written a number of other books centred

around the Earth Sciences for both adults and children. He is also keen on science outreach and has been a presenter on Discovery channel's *The Very Edge of China* (2019), *Hardest Job* (2017), BBC's *Fierce Earth* series (2013–14), *Operation Grand Canyon* (2014), as well as appearances on National Geographic, Smithsonian Channel, Eden, Channel 4, and Abandoned Engineering.

Mark is an Associate Professor at Virginia Tech. A metamorphic petrologist, his work focuses on the micro-scale processes that lead to changes in rock mineralogy and texture, and the tectonic-scale processes that these

may reveal. He has worked on metamorphic rocks from a variety of settings and with a wide range of styles, spanning from cold, deep subduction to high temperature crustal melting. Though much of his research is lab based or computational, it invariably starts in the field. He also works on high energy impacts and high temperature reactions of minerals in jet engines – which he obviously thinks of as a form of metamorphic geology! Mark was a student in the UK, at the universities of Bristol and then Cambridge, before moving to Switzerland as a research scientist at ETH Zurich. He has been in Virginia since 2012, during which time he has taught, amongst other things, an introduction to the geosciences, igneous and metamorphic petrology, thermodynamics, and field-based courses.

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First and foremost, we would like to thank Norman Fry, whose original book was an important guide for both authors as students, and he is also thanked for giving us the go ahead to update the book and to provide all the original materials that formed an invaluable framework as we planned this revised version. This book has taken a long time to mature and we must thank the support and patience of the team of people at Wiley Blackwell and associated editorial groups (both past and present) who have helped to get the book finished. We must particularly thank (and apologies if we miss anyone); Mandy Collison, Andrew Harrison, Frank Weinreich, Emma Cole, Shiji Sreejish, Priyadharshini Arumugam, Bobby Kilshaw, Athira Menon, Nithya Sechin, Vinodhini Mathiyalagan, Audrie Tan, Fiona Seymour, Ian Francis, Delia Sandford, and Rachael Ballard. Many people directly contributed figures and photographs and input to this book scientifically and these are particularly thanked for their help and open sharing of information, including (in no particular order); Isabela Carmo (with additional help from Prof. Renata S. Schimdt – UFRJ), Hans Jørgen, Nick Timms, Steve Reddy, Richard Brown, John Schumacher, John Howell, Susanne Schmid, Jim Talbot, Christoph Schrank, Bob Tracy, Claudio De Morisson Valeriano, Clayton Grove, Dave Prior, Tonje Lund, Nigel Woodcock, Victor Guevara, and Chris Clark. David Gust, Scott Bryan, Jess Trofimovs, and the Queensland University of Technology team are thanked for access to the QUT metamorphic teaching samples.

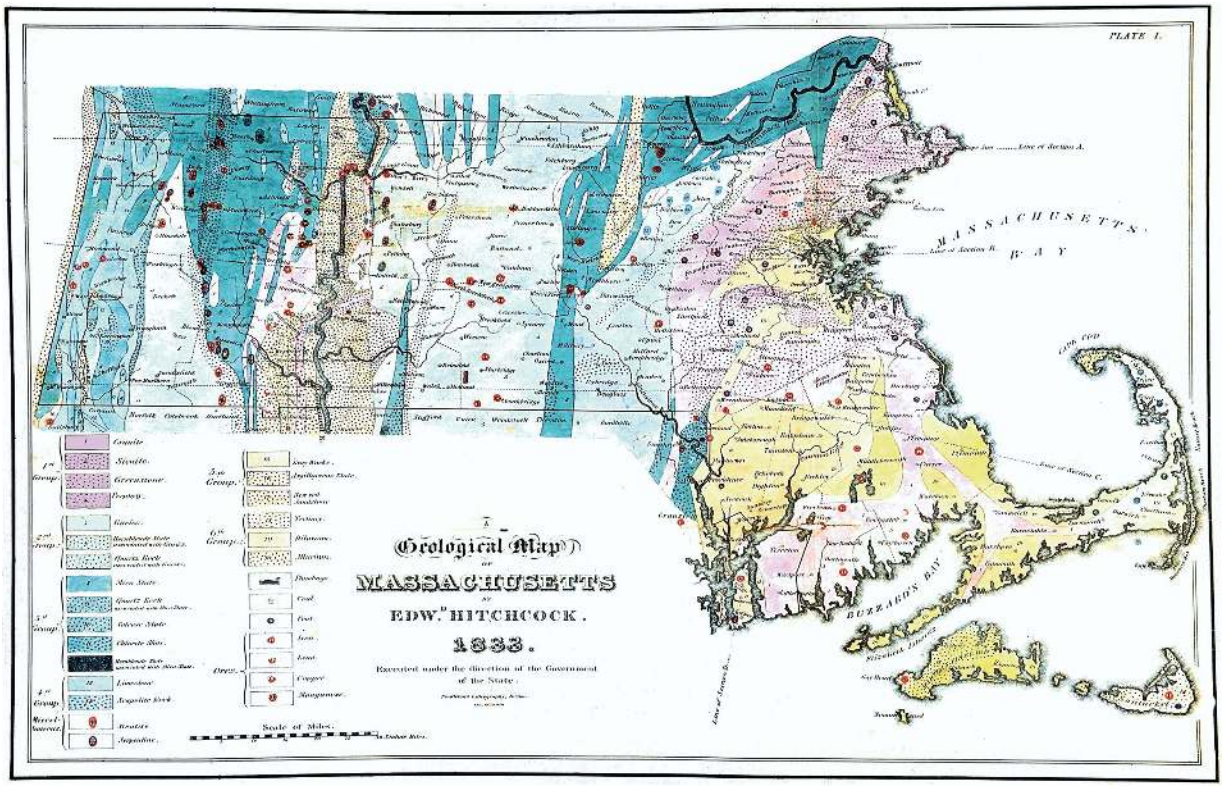
Dougal is particularly grateful to the people who showed me some of the classic metamorphic terrains, intrusive contacts, and regional geology, where I learned much about

these systems. Wes Gibbons, Dave Prior, John Wheeler, Lee Mangan, Bob Hunter, Mike Cheadle, and Henry Emeleus introduced me at the early stages of my career to some of the classic Scottish locations, and more recently the likes of John Schumacher and Torgeir Andersen introduced me to some of the more exotic and incredible metamorphic textures I have seen. My colleagues in Oslo such as Trond Torsvik, Henrik Svensen, Sverre Planke, Olivier Galland, Bjørn Jamtveit, François Renard, Stephanie Werner, Karen Mair, Brit Lisa Skjelkvåle, Bernd Etzelmüller, Carmen Gaina, and the whole of the CEED team over the last 10 years have shown great support, particularly to my book writing efforts and research collaborations, and further afield my “brother” Breno Waichel is thanked for exposing me to the South Atlantic Margins and to many Brazilian colleagues. Jo Garland and Izzy Jerram are thanked for their ongoing support, and particularly Jo for proof reading and figure commenting at various stages. Finally, I would like to personally thank all those that have helped in discussions in the field all over the world where complex hard rock relationships have been made clearer by great collaborations (you are soooo many, and you know who you are, cheers!).

Mark would like to thank Alan, Mike, Nigel, Tim, Jon, and the other great mentors he has met along the way. He only knows about many of the outcrops photographed in this book thanks to the generosity of friends and colleagues such as Eric Reusser, John Schumacher, Filippo Schenker, and Bob Tracy. The current and former members of the Metamorphic Processes group at Virginia Tech, and the students of VT’s GEOS 2024, 3704, and 4964, have always provided the best reasons to go back out and teach in the field, and I’m particularly grateful to those of you whose fingers, arms, and feet crept into some of the photos in this book – you know who you are! Thanks to Christiana Hoff for

commenting on earlier versions of some chapters. Finally, thanks to my wife, Kristie, who read parts of the text, commented on many of the figures, and had the good grace to remain patient with me throughout this whole process.

1
INTRODUCTION AND OCCURRENCE



***A** classic old metamorphic map, the 1833 map of the geology of Massachusetts, from maps associated with Edward Hitchcock's 'Report on the Geology, Mineralogy, Botany, and Zoology of Massachusetts' (Amherst, Mass.: Press of J. S. and C. Adams, 1833).*

Metamorphic rocks form a substantial proportion of the material that makes up the Earth's crust, and metamorphic processes have been almost continually occurring throughout geological time since the origin of that crust. Metamorphism can be defined simply as the process by which sedimentary or igneous rocks are transformed

(metamorphosed) by re-crystallisation due to changes in pressure, temperature, or fluid conditions. To complicate matters somewhat, metamorphism can of course also act on rocks that have already been metamorphosed previously, building layer upon layer of complexity into those rocks that record field evidence of some of Earth's most dynamic processes. Our understanding of metamorphism is somewhat limited by the fact that we are unable to directly observe it happening to the rocks. As you read this, metamorphism is in action all around the planet, in all aspects of the Earth's plate tectonic system (e.g. Figure 1.1), but we cannot directly see it (generally because it happens at depth and very slowly). In order to understand the processes and products of metamorphism and alteration in rocks, detailed fieldwork, petrography, experimental studies, and numerical modelling are required. It is important to note, however, that the very origin of metamorphic petrology (the science of understanding the distribution, structure, and origin of metamorphic rocks) is rooted in a tradition of careful and systematic field observation, and that this remains an absolute cornerstone of the discipline today. Since the late nineteenth century, Earth scientists have strived to develop an understanding of metamorphic processes by identifying the different types of key minerals, mineral assemblages, and structures present in the metamorphic rocks. Using these observations and knowledge of some fundamental principles, mineral reactions can be calculated and/or experimentally derived to help explain and understand the process by which the original rock was metamorphosed into its current state. These rocks often encode evolving conditions at tectonic plate boundaries, so deciphering their mineralogical history may be thought of as a window into the crustal-scale processes that form, modify, and stabilise Earth's crust. Underpinning all of this is the petrologist's ability to identify, describe, relate, and collect

metamorphic rocks in the field, and it is these skills which this book aims to explore and impart, by its use in the field description of metamorphic rocks.

1.1 The Importance of Fieldwork in Metamorphic Terrains

In many ways, metamorphic geology requires you to be skilful in most aspects of the Earth sciences. As metamorphic rocks can be formed from any original rock (the parent rock henceforth being called the protolith), an ability to identify and be familiar with the wide variety of minerals and textures of sedimentary and igneous rocks is a general requirement for any budding metamorphic geologist. Additionally, as the very processes involved in metamorphism are commonly associated with deformation, a keen understanding of structural geology and tectonics is also needed. *In many ways, the metamorphic scientist needs to be a jack of all trades and a master of one!*

Due to the potential complexity within metamorphic rocks, the importance of careful fieldwork cannot be overstated. The different types of observation that can be made at various scales in metamorphic terrains allow the student/researcher to build up a list of clues, like in a forensic study, which can be used to help derive the type of metamorphic rock, its protolith, and the range of processes that it has undergone to reach its present state. The map-scale distribution of metamorphic rocks can reveal the processes that formed them, but as we discuss in the following chapters, the correct interpretation of even the smallest parts of a field area are rooted in good field observations. This book aims to help build you skills in this area! Careful identification of rocks and structures is all the more important when taking samples from the field back to the laboratory for further study and analysis. The

record of structures within and around the rock mass may ultimately help you to better interpret features you subsequently see down the microscope or the data that you receive from laboratory analysis.

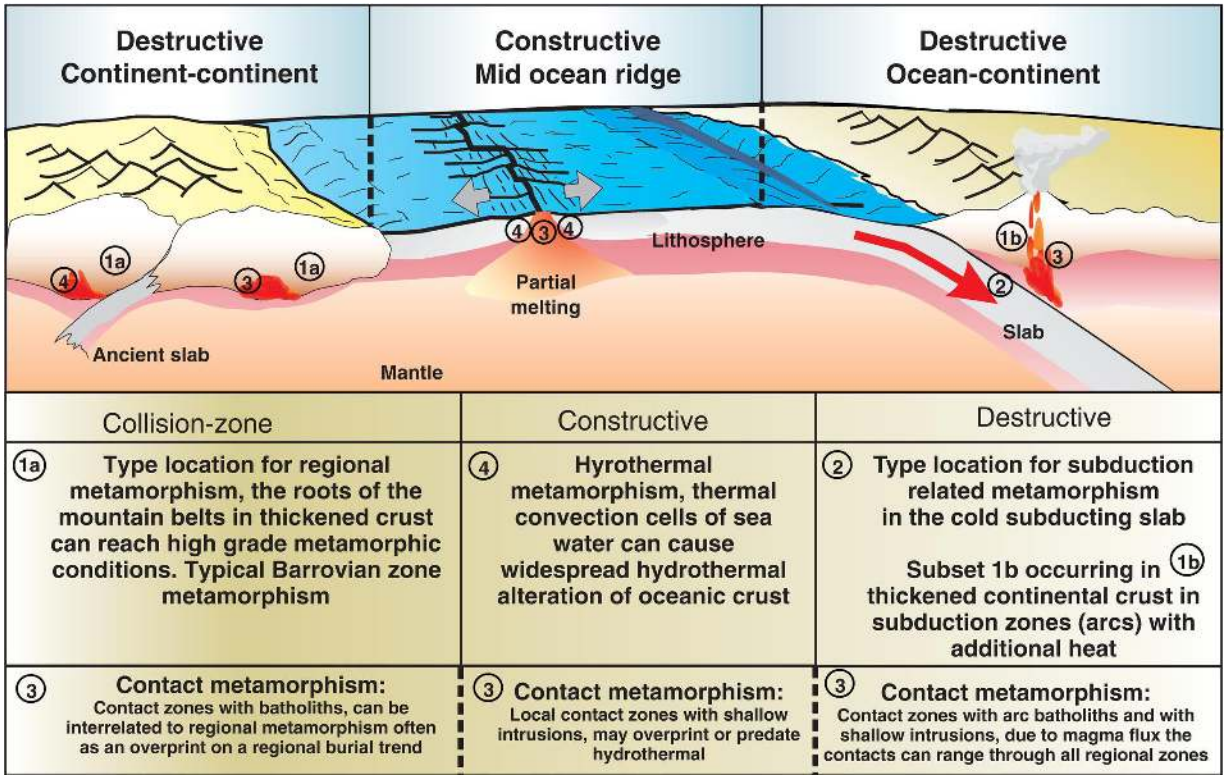


Figure 1.1 *Schematic of the plate tectonic settings where metamorphism is occurring around the world (see also Figure 1.2).*

Describable features which can be observed in metamorphic rock masses include:

1. *Pre-metamorphic* – e.g. bedding and other sedimentary features, contact relationships between batches of melt, or even fossils (though in most cases the features may be altered beyond normal recognition).
2. *Metamorphic* – relating to local mineral changes due primarily to changing temperature and pressure.

3. *Metasomatic* – involving the chemical transport and mineral change associated with fluids.
4. *Structural* – relating to and recording the rock's deformation at any point in its history.

Limitations exist as to how much information one can record regarding any of these features without the need for microscopic and chemical measurements, which is the realm of specialist study that will be touched upon within this book but is not our major theme. With good field observations of mineralogy, texture, and structure, one should still be able to adequately describe the rock masses in terms of their types and occurrence, hopefully also being able to build up an inference of the evolving conditions of their formation. Such description is particularly appropriate for the production of geological maps, logs, and recordings of outcrop structures, which will be covered in more detail in Chapter 2.

This book forms a companion to the other texts in the geological field guide series, e.g. *The Field Description of Igneous Rocks*, *Sedimentary Rocks in the Field*, and *The Mapping of Geological Structures*, and as such does not cover in detail the pre-metamorphic features of sediments and igneous bodies that may sometimes be preserved in metamorphic rocks. We do, however, show many examples of these in cases where they can either be shown to help in the identification of the protolith rock or reveal something fundamental about the metamorphism itself (e.g. that it happened in the presence or absence of deformation). There is substantial overlap between the skills required to be a metamorphic geologist in the field and those considered to be the realm of a structural geology, at least in terms of fieldwork measurements/observations, and particularly when mapping in metamorphic terrains. As such, this text will aim to provide as much help in terms of