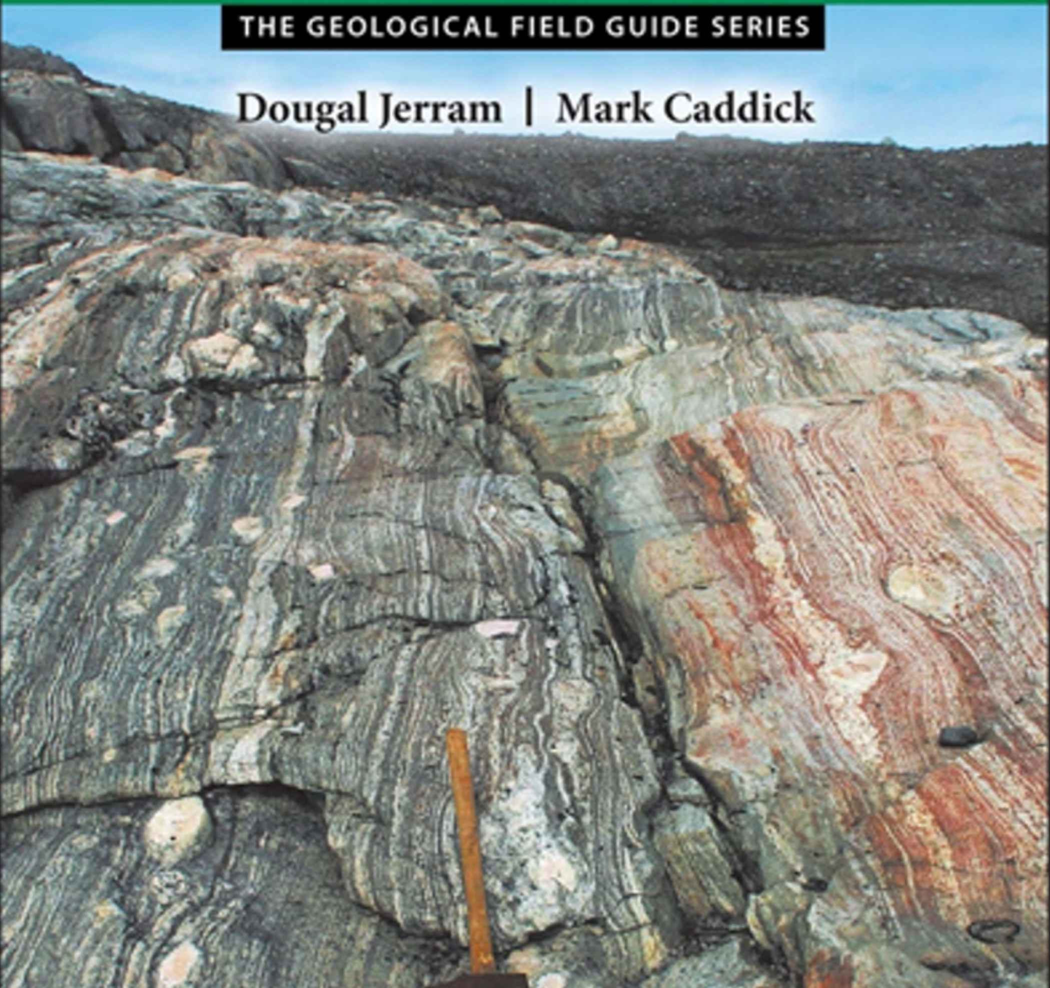
The Field Description of Metamorphic Rocks

THE GEOLOGICAL FIELD GUIDE SERIES



Dougal Jerram | Mark Caddick

SECOND EDITION

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This edition first published 2022

Edition History
John Wiley & Sons Ltd (1e, 2013)

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

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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.

Library of Congress Cataloging-in-Publication Data

Names: Jerram, Dougal, author.
Title: The field description of metamorphic rocks / Dougal Jerram, Centre for Earth Evolution & Dynamics, University of Oslo, Norway, DougalEARTH Ltd, Solihull, UK, Mark Caddick, Virginia Tech, Blacksburg, VA.
Description: Second edition. | Hoboken, NJ : Wiley, 2022. | Series: The geological field guide series | Revised edition of: The field description of metamorphic rocks / Norman Fry. 1984. | Includes bibliographical references and index.
Identifiers: LCCN 2021052480 (print) | LCCN 2021052481 (ebook) | ISBN 9781118618752 (paperback) | ISBN 9781118618691 (adobe pdf) | ISBN 9781118618677 (epub)
Subjects: LCSH: Metamorphic rocks–Handbooks, manuals, etc.
Classification: LCC QE475.A2 F79 2022 (print) | LCC QE475.A2 (ebook) | DDC 552/.4–dc23/eng/20211204
LC record available at https://lccn.loc.gov/2021052480
LC ebook record available at https://lccn.loc.gov/2021052481

Cover Design: Wiley
Cover Image: Courtesy of Susanne Schmid

Set in 8.5/10.5pt TimesLTStd by Straive, Pondicherry, India

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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.

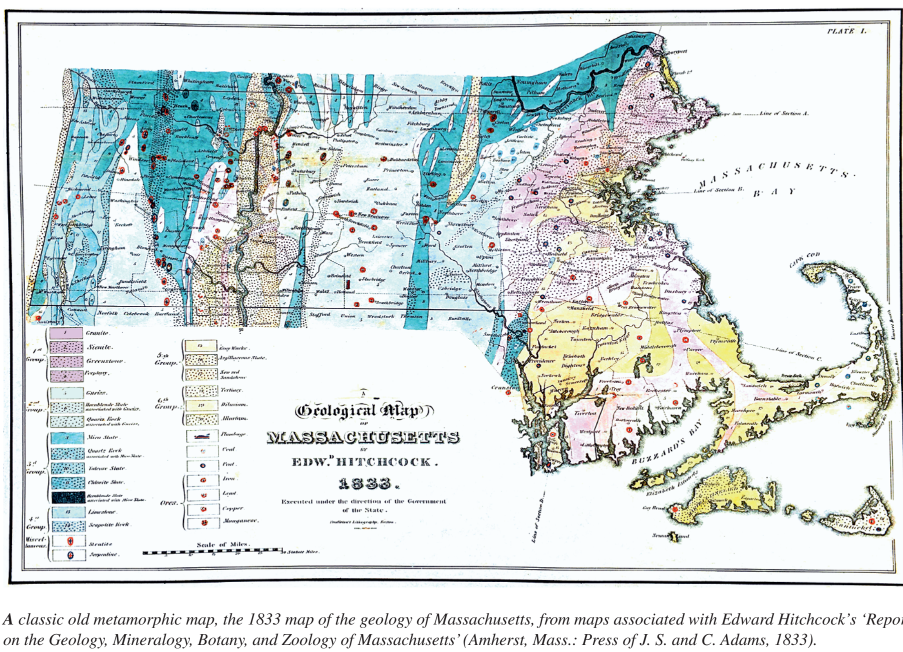
ACKNOWLEDGMENTS

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.

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).*

1
INTRODUCTION AND OCCURRENCE

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,

The Field Description of Metamorphic Rocks, Second Edition. Dougal Jerram and Mark Caddick.

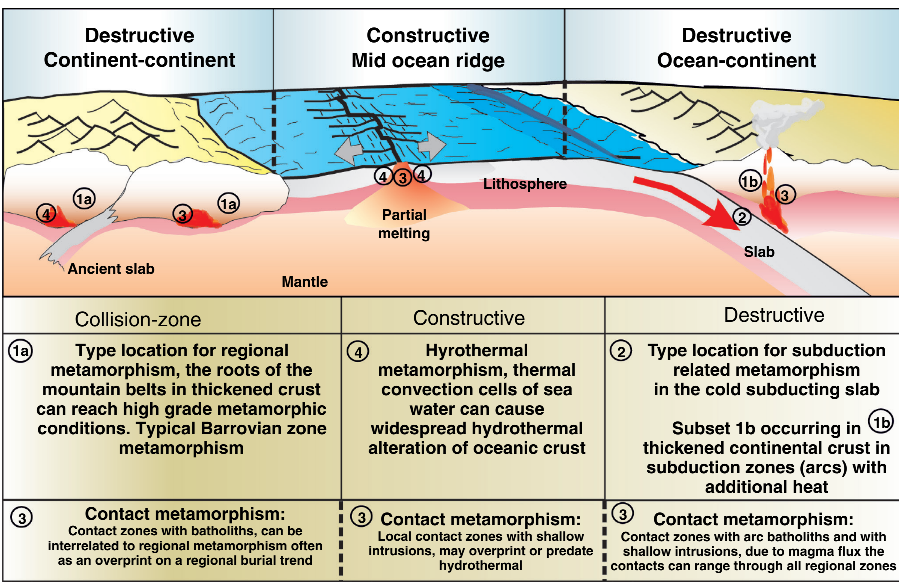


Figure 1.1 *Schematic of the plate tectonic settings where metamorphism is occurring around the world (see also Figure 1.2).*

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.

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 structural description, as will be necessary to get the most out of your metamorphic rocks. The reader will need to make an assessment as to what level of understanding of sedimentary, igneous, and structural geology might be best suited for the problem at hand, and where needed can supplement this guide with an appropriate partner guide. For example, if you are mapping a metamorphically altered igneous region, then additional help from *The Field Description of Igneous Rocks* may be useful. In a thrust zone, the structural guide may provide some vital additional assistance, and so on. However, we have tried, wherever possible, for this book to be a stand-alone guide to achieve success in the field description of metamorphic rocks. Ultimately, we aim for this handbook to provide the required information on how to observe metamorphic rocks in the field, from the outcrop to the hand specimen scale, and to tie these observations into basic interpretations of how the metamorphic rocks formed. This also necessitates comments on sampling strategies for projects in which fieldwork is the start of a wide-reaching study. As such, before we take on metamorphic rocks in the field it is useful to consider how metamorphism relates to regional and global tectonics and the main occurrence of metamorphic rocks.

1.2 Understanding Metamorphism; Pressure/Temperature Relationships

Rocks undergo metamorphic and metasomatic changes as they are subjected to different pressure and temperature conditions, or are infiltrated by chemically reactive fluids. Indeed, a fundamental building block to a deeper understanding of metamorphism is a good grasp of pressure, temperature, and time (it takes time for metamorphic reactions to take place, evidence of which may be preserved in the field in the form of incomplete reactions). In this sense, it is very useful from the onset of your training as a metamorphic Earth scientist to become familiar with the ranges of pressure and temperature experienced in the Earth and the key metamorphic mineral associations (assemblages) that are found within these ranges. One of the main ways in which we consider this is through what is known as a *P*/*T* diagram, in which changing aspects of a rock are plotted as a function of pressure (*P*) and temperature (*T*). This allows one to highlight various aspects of metamorphism and question how they might be represented in the field. *P*/*T* diagrams will appear throughout this text to help understand the types and styles of metamorphism, and will feature specifically in Chapter 3 in relation to the main classification of metamorphic rocks, and in associated tables within the reference Chapter 8.

At this introductory stage it is useful to consider the basic *P*/*T* diagram in relation to the relative intensity of metamorphism, as this forms a good basis for understanding under what conditions the different types of metamorphic rocks are formed. Figure 1.2 shows a *P*/*T* diagram (with approximate depths included) that expands on the key 'facies' concept (originally described by Pentti Eskola in 1915), namely that rocks of a similar composition will, when subjected to the same *P*/*T* conditions, form the same mineral assemblages. You can also see how this relates to the main tectonic settings by referring the numbers on the trends to the locations on Figure 1.1. The fields in Figure 1.2 thus map out the *P*/*T* stabilities of major mineral assemblages that could form in a metamorphosed mafic rock (e.g. a basalt) as a general reference. A far more detailed and subtle record of mineral reactions almost certainly occurs in most rocks and will be discussed in subsequent chapters, but the reactions at the boundaries of these fields are significant enough that the metamorphic facies (and thus approximate metamorphic *P*/*T* conditions) of a mafic rock can generally *be identified in the field*. Generally speaking, Figure 1.2 suggests that low grade metamorphism starts around 150–200 °C and ~3 kbar (300 MPa, or ~10 km depth). As temperature and pressure increase, the grade of metamorphism progressively increases accordingly until, at temperatures of 600–800 °C (or greater), the rocks themselves begin to melt and we start to enter the realm of igneous petrogenesis. These fields and the main ways in which we classify metamorphic rocks will be discussed in detail in Chapter 3, and as you go along you will see that the *P/T* of the rocks can be displayed in a variety of diagrammatic forms.

1.3 Mode of Occurrence of Metamorphic Bodies

Because metamorphism is a response of pre-existing rocks to changes in temperature and pressure, it may be expected that metamorphism is restricted to major zones of deformation in the Earth, such as convergent (destructive) tectonic plate margins. Clearly where major tectonic forces act, such as at subduction/collision zones, the crust undergoes deformation, and rocks will experience changing pressure and temperature upon burial as the crust is thickened. However, metamorphism is not restricted to these environments of the Earth. Extreme temperature changes can be achieved through the contact of molten igneous bodies (sills, dykes, magmas chambers) with country rocks. Also, in certain settings, the wholesale circulation of fluids through the crust can lead to alteration and metamorphism (such as at mid-ocean ridges). Rocks that are metamorphosed in subduction/collision zones undergo metamorphic changes over broad zones, and can record evidence of passage from one metamorphic grade to another as they journey through different depths. These form the most common types of metamorphic rocks, termed the Regional Metamorphic Rocks. Where rocks are metamorphosed due to contact with hot igneous bodies they are referred to as Contact Metamorphic Rocks.

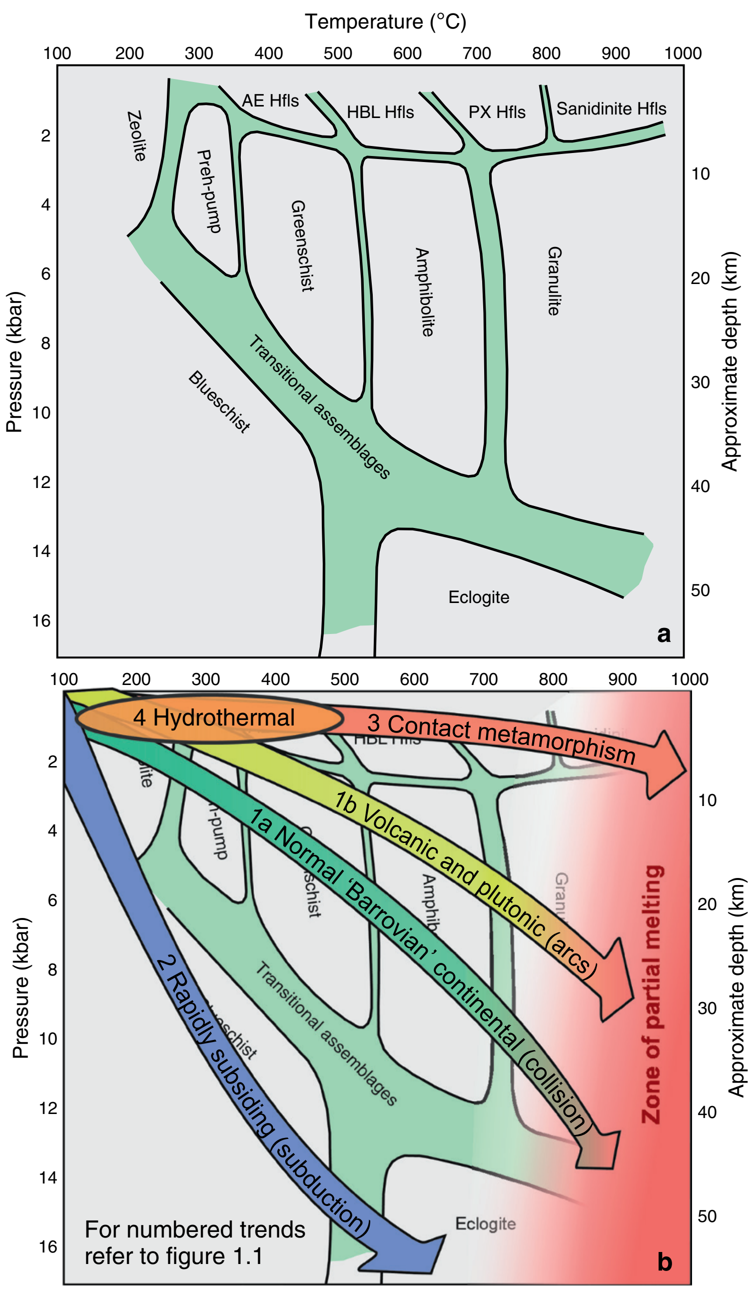


Figure 1.2 *The P/T diagram: (a) the classic fields of metamorphism of mafic rocks (the so-called metamorphic facies) in P/T space, and (b) the routes that certain tectonic systems take through the P/T space which give rise to different metamorphic rocks. This will be expanded on in more detail in Chapter 3.*

1. Introduction and Occurrence
2. Field Skills and Mapping Outcrop Structures
3. Metamorphic Minerals, Rock Types, and Classification
4. Understanding Textures and Fabrics 1: Banding, Cleavage, Schistosity, and Lineations

Finally, where alteration and metamorphism occur due to fluids, the rocks are called Hydrothermally Altered Metamorphic Rocks. Some more exotic and rare examples of metamorphic rocks include those specific to fault zones (Cataclastic Metamorphism) occurring as a result of mechanical deformation when two bodies of rock move past one another, and Shock Metamorphism (Impact Metamorphism), where rocks are metamorphosed due to impact from an extraterrestrial body, such as a meteorite or comet.

1.3.1 Regional metamorphic rocks

The most common of the metamorphic styles, regional metamorphism, occurs in zones defined by key pressure and temperature environments found at certain burial depths in the Earth's crust. The regional metamorphic zones are also restricted by certain tectonic settings that are generally related to subduction and continental collision zones, defining two broad groups of regional metamorphic rocks: those related to mountain building events, where two continents collide, and those formed at subduction zone settings where oceanic crust is subducted. As continent–continent collision is preceded by subduction, both styles of regional metamorphism can sometimes be found in the same location, occasionally with strong evidence of high-pressure, low-temperature mineral growth in a subduction zone overprinted by higher temperature mineral growth upon and after collision.

Regional metamorphic zones typically occur due to thickening and/or burial of the crust, so pressure is a very important parameter that drives reactions to progressively change the original rock (protolith) into its different metamorphic types. Certain reactions are strongly pressure-dependent, and thus the occurrence of specific minerals or mineral assemblages is indicative of ranges of pressure conditions (the most well-known of which is that diamond typically only forms at pressures greater than the base of normal continental crust). The pressure at which metamorphism occurred is often linked directly with depth, by considering the force applied by the overlying mass of rock. Temperature generally increases with pressure, known as the geothermal gradient (the rate at which temperature increases with depth), but the specifics of this gradient can vary dramatically with tectonic setting. Again, there is generally a mineralogical response to changing temperature, so unravelling the metamorphic history of a series of outcrops in the field can yield important information about the style of regional metamorphism and, thus, tectonic setting and evolution.

A classic study by G. Barrow in the late nineteenth and early twentieth century examined a suite of metamorphic rocks from the Scottish Highlands. The rocks here were formed as part of a mountain building event, the Caledonian orogeny, and show progressively increasing grades of metamorphism depicting the different depths of burial and temperatures attained during the mountain building event. This was unknown at the time of Barrow, whose work was subsequently expanded on by people such as C.E. Tilley in the 1920s, and the concept of exposure of the roots of an ancient mountain belt was yet to be developed. Barrow, however, recognised that specific metamorphic minerals occur in certain groupings, and that the order of their occurrence was predictable (if he walked north in one valley and first found rocks containing garnet, then found rocks containing staurolite, he would be able to find the same succession in a parallel valley several kilometres away). These minerals, termed 'index minerals', were thus used to define different zones of metamorphism in the Scottish highlands, and have since been termed the Barrovian sequence. Based on a concept called isograds (planes of constant metamorphic grade), in which the first appearance of a key metamorphic index mineral is mapped, six 'Barrovian' zones were thus defined (Figure 1.3). These will be touched on in more detail in Chapter 3, but can be considered as the background to many of the main metamorphic rocks recognised in unroofed collision zones. As such, a systematic view of metamorphism as formulated by Barrow would state that if the protolith was an aluminous sedimentary rock (e.g. a shale) a typical sequence from low to high grade would exhibit the indicator minerals (which are the mapped isograds in Figure 1.3):

Chlorite > Biotite > Garnet > Staurolite > Kyanite > Sillimante > Melt

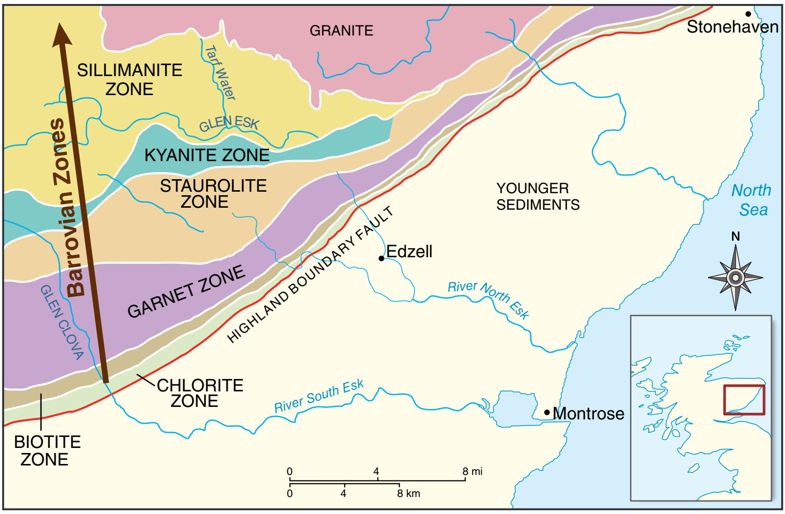


Figure 1.3 *The classic Barrovian Zones of regional metamorphism first described from Scotland.*

This mineralogical change with increasing grade would be mirrored in a maturation of the rock texture as follows:

Sedimentary Rock > Shale > Slate > Phyllite > Schist > Gneiss > Migmatite

If the starting material was an igneous rock, such as basalt, the sequence would be:

Basalt > Greenschist > Ambibolite > Granulite

This is highlighted by the ‘normal continental (collision)’ arrow in Figure 1.2. Examples of low intermediate and high grade regional metamorphic rocks are given in Figure 1.4. Chapter 3 provides a more detailed and systematic overview of how rock texture and mineralogy change in rocks of various compositions as metamorphic grade increases.

1.3.2 Subduction zone rocks

In a subduction zone setting (see Figure 1.1), the relatively fast burial of one of the cold plates leaves insufficient time for it to heat up substantially until it is at significant depth. It takes time for the subducted rocks to heat up (generally by conduction from the hotter rocks around them at depth), but application of pressure during burial is instantaneous. Thus in subduction zones the conditions of high pressure – low/moderate temperature metamorphism occur (e.g. the numbered trend 2 in Figure 1.2), and rocks exhumed from these settings record evidence for having been in the blueschist facies. Again, these rocks are characterised by certain indicator minerals and mineral assemblages, and blueschist rocks often appear blue (hence their name) because of the prevalence of a blue amphibole mineral called glaucophane. Exposures of blueschist facies rocks are relatively rare, most obviously because it is difficult to exhume them from the subduction zone to the Earth’s surface, but they are an important record of plate tectonics on Earth and will be described in more detail in Chapter 3. An example of a blueschist is given in Figure 1.5a. When the most extreme pressures and moderate