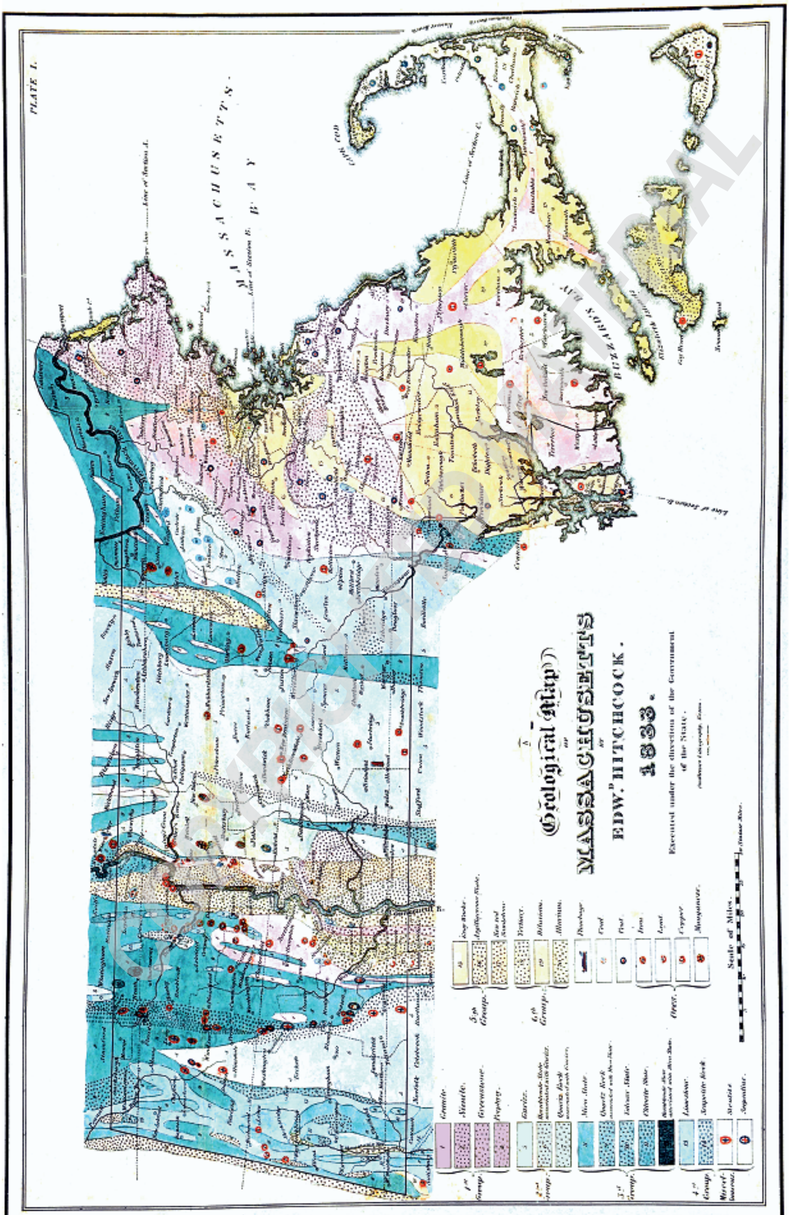
INTRODUCTION AND OCCURRENCE



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).

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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,

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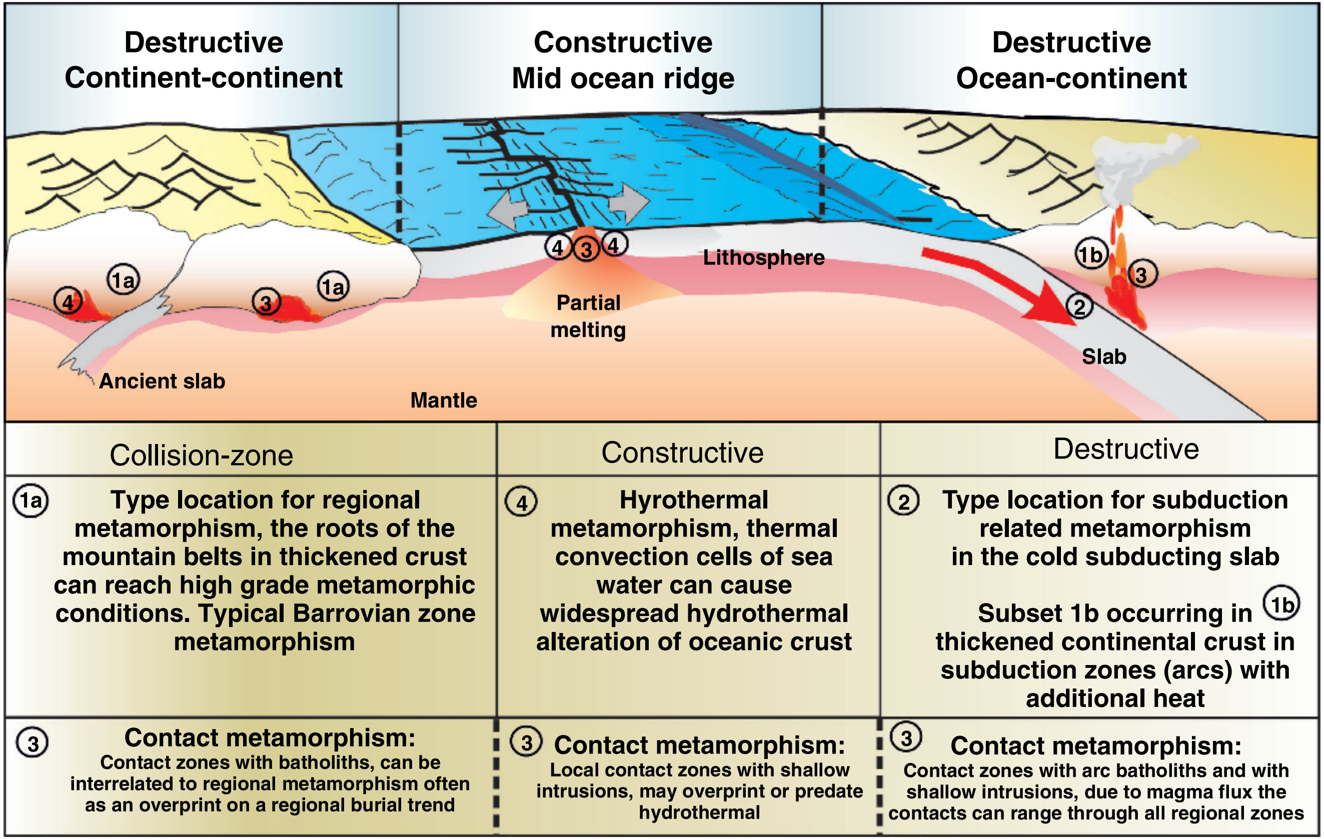
The Field Description of Metamorphic Rocks, Second Edition. Dougal Jerram and Mark Caddick.



Collision-zone	Constructive	Destructive
(1a) Type location for regional metamorphism, the roots of the mountain belts in thickened crust can reach high grade metamorphic conditions. Typical Barrovian zone metamorphism	④ Hyrothermal metamorphism, thermal convection cells of sea water can cause widespread hydrothermal alteration of oceanic crust	② Type location for subduction related metamorphism in the cold subducting slab (1b) Subset 1b occurring in thickened continental crust in subduction zones (arcs) with additional heat
③ **Contact metamorphism:** Contact zones with batholiths, can be interrelated to regional metamorphism often as an overprint on a regional burial trend	③ **Contact metamorphism:** Local contact zones with shallow intrusions, may overprint or predate hydrothermal	③ **Contact metamorphism:** Contact zones with arc batholiths and with shallow intrusions, due to magma flux the contacts can range through all regional zones

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.

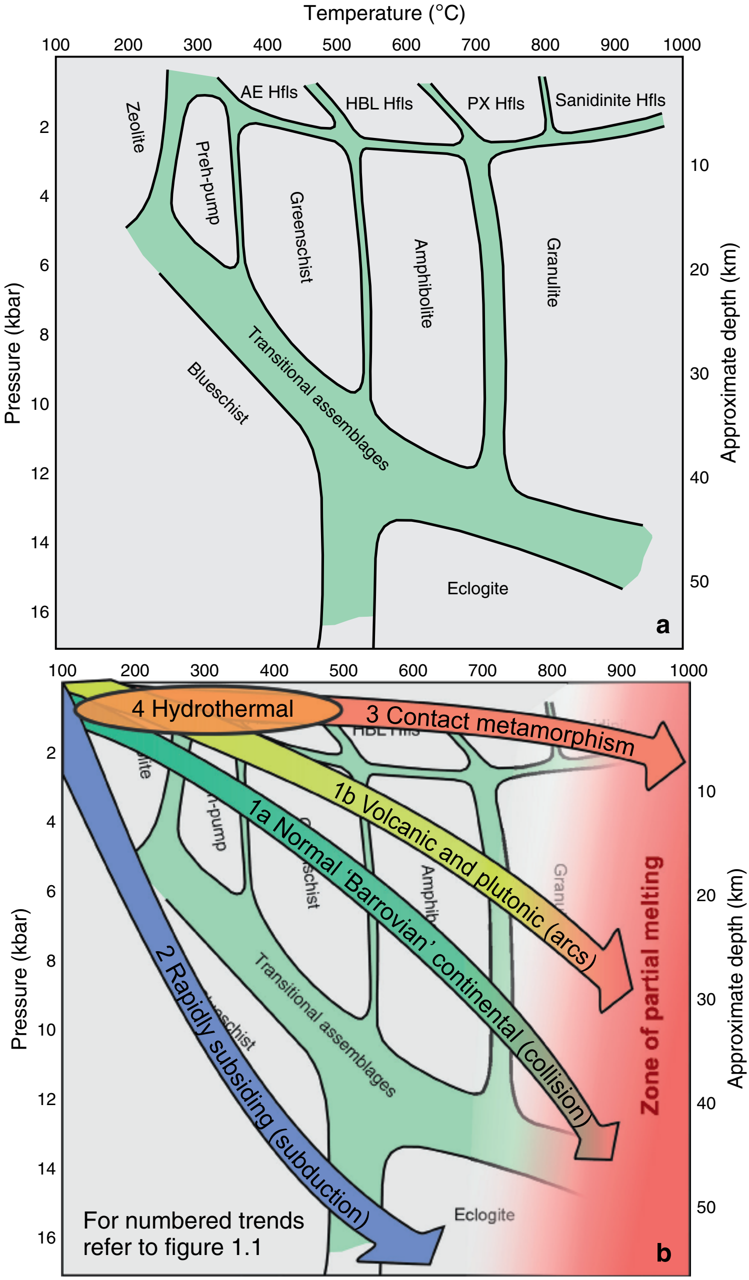


Figure 1.2 *The P/T diagram: (a) the classic fields of metamorphism of mafic rocks (the so-called metamorphic facies) in P/T space, and (b) the routes that certain tectonic systems take through the P/T space which give rise to different metamorphic rocks. This will be expanded on in more detail in Chapter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

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

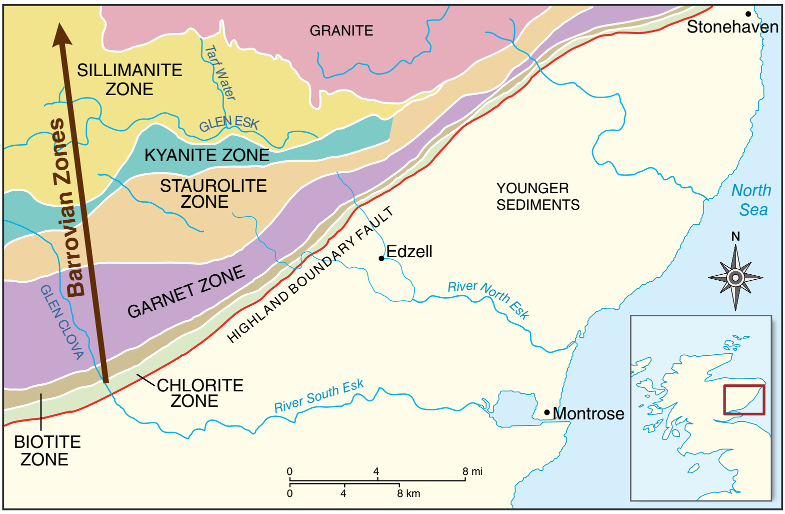


Figure 1.3 *The classic Barrovian Zones of regional metamorphism first described from Scotland.*

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

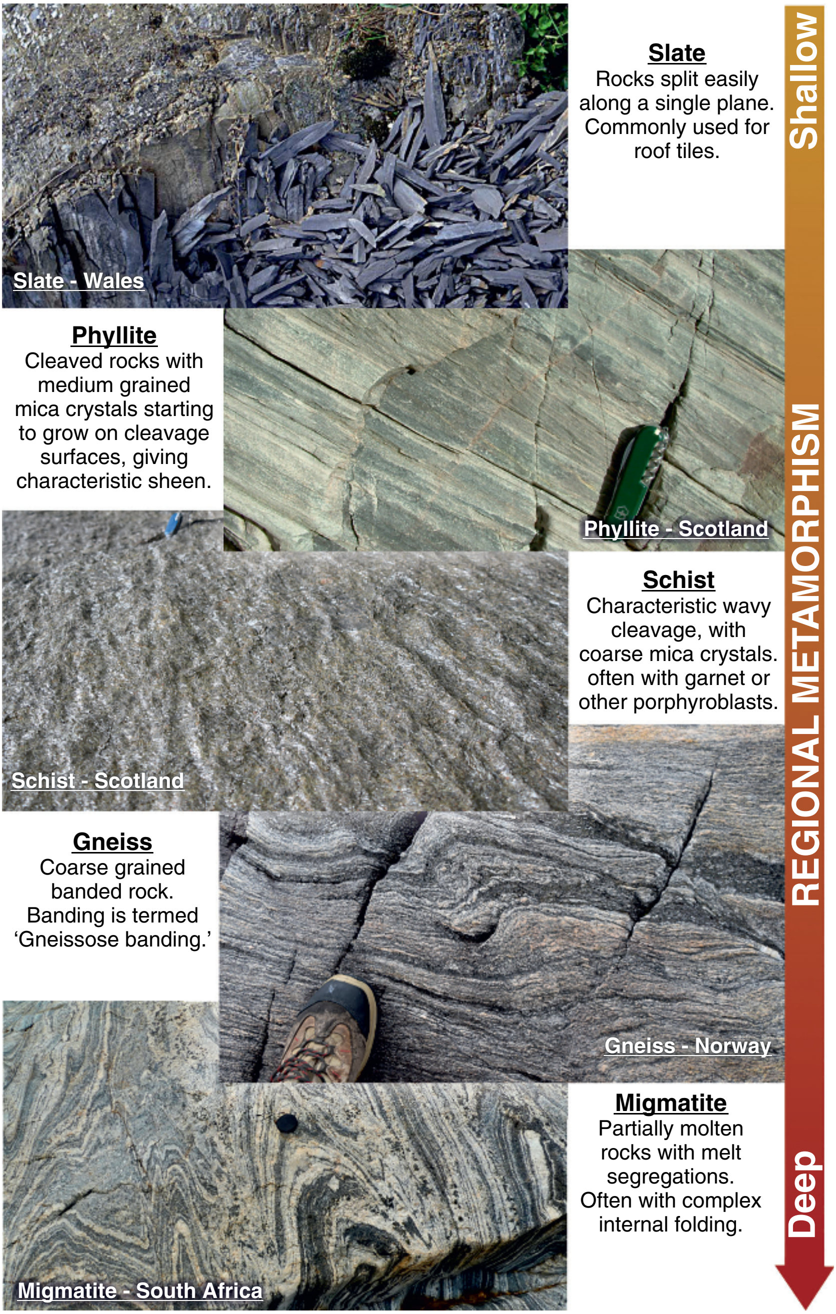
If the starting material was an igneous rock, such as basalt, the sequence would be:

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



Slate
Rocks split easily along a single plane. Commonly used for roof tiles.

Phyllite
Cleaved rocks with medium grained mica crystals starting to grow on cleavage surfaces, giving characteristic sheen.

Schist
Characteristic wavy cleavage, with coarse mica crystals. often with garnet or other porphyroblasts.

Gneiss
Coarse grained banded rock. Banding is termed ‘Gneissose banding.’

Migmatite
Partially molten rocks with melt segregations. Often with complex internal folding.

Figure 1.4 *Examples of classic (Barrovian) regional metamorphic rocks (slate photo Jim Talbot, phillite, schist, and gneiss photos Dougal Jerram, migmatite photo Mark Caddick).*

Figure 1.5 *(a) Blueschist facies, Syros, Greece (Mark Caddick for scale) with inset figure highlighting lawsonite porphyroblasts, (b) Eclogite facies, Alps (photo a Mark Caddick, photo b Hans Jørgen).*

to high temperatures are reached, a group of rocks termed the eclogite facies form. Exposure of these on Earth's surface is again relatively rare, but they are generally easily identified, characterised by a pale green pyroxene (sodic rich called omphacite) and a deep red garnet (almandine-pyrope), an example of which is given in Figure 1.5b (see Chapter 3 for more detail).

The regionally metamorphosed rocks are often also characterised by having many structures associated with deformation. The rocks are put under pressure from all sides, but often this pressure is not the same from all sides. This leads to asymmetry in the pressure distribution and the alignment of new metamorphic minerals, rotation of existing and newly growing ones, and faulting and folding of the rocks during their metamorphism. These textures will be touched on in detail in Chapters 4 and 5, but banding, cleavage, folding, and dislocation structures are commonplace in regional metamorphic areas (e.g. Figure 1.6).

1.3.3 Contact metamorphic rocks

Igneous rocks can be emplaced into the crust at exceedingly high temperatures. Granites will crystallise at around 700+ °C, and basic rocks such as gabbro may intrude around 1200 °C, establishing a marked temperature gradient between the molten rocks and the host into which they intrude (commonly termed the 'country rocks'). Along the contact zones between the igneous bodies and their host rock, metamorphic reactions are commonly driven by heat from the cooling magma. This leads to a group of rocks called the contact metamorphic rocks. The contact or 'baked' zone around the igneous body can contain a variety of different metamorphic grades that are typically only seen over a relatively short distance as the effects of the hot igneous body diminish rapidly with distance from the magma. This zone of contact metamorphism is called the 'aureole' and is typically meters to tens of meters in thickness. Pressure tends to have little effect in contact metamorphism, as it is the act of

Figure 1.6 *Highly folded metamorphic carbonate turbidites, Namibia (photo Dougal Jerram).*

emplacing the hot igneous body and not a change in burial that makes the metamorphic aureole. Fluid flow during the metamorphism can substantially modify the wall rock composition, a process called metasomatism that is described more in Section 1.3.4, and can increase the footprint of the metamorphic effects by carrying heat further from the magmatic source (a process known as advection).

As with regional metamorphic rocks, different assemblages of minerals occur depending on the grade (mainly defined by the amount of heat) that the country rock reached, and depending on the type of country rock. With silliciclastic sediments like sandstones and shales the sequence may consist of chlorite, andalusite, and corderite hornfels, with silimanite and K-feldspar at very high temperature, and garnet if the crust was at sufficient depth during intrusion (e.g. a contact metamorphic overprint in a regional metamorphic setting). In limestone host rocks, marble is commonly formed, with tremolite, diopside, wollastonite, and forsterite as common minerals if the original carbonate was 'impure' (e.g. contained some Si). A schematic contact aureole with some examples is given in Figure 1.7 (further detail can be found in Chapter 6).

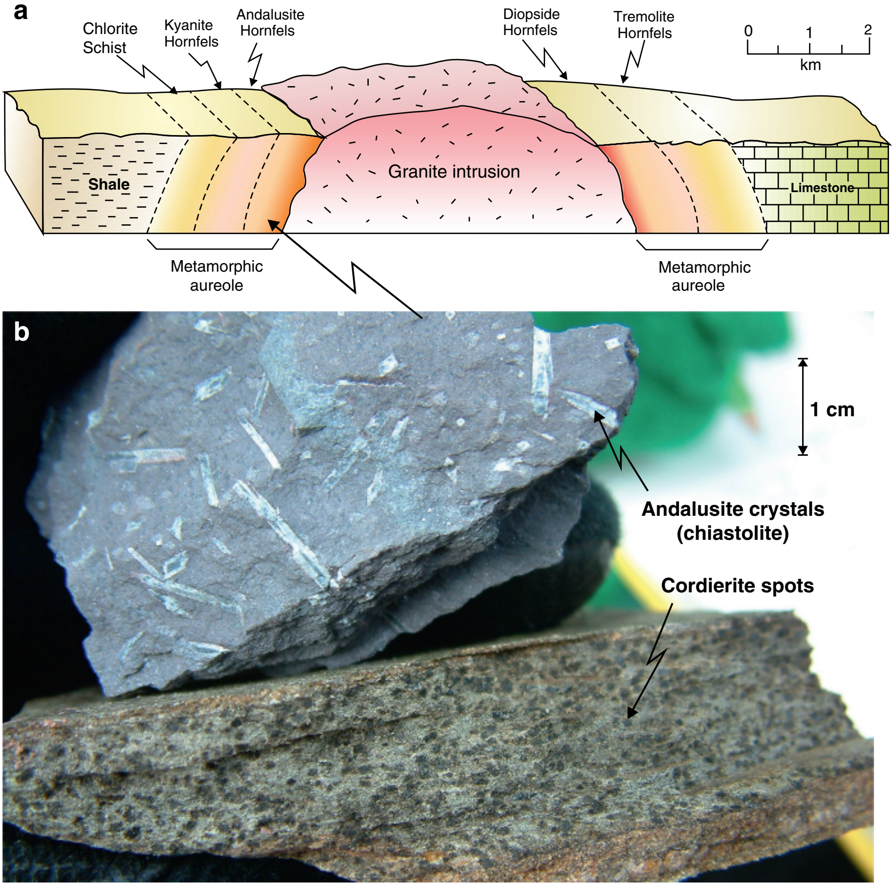


Figure 1.7 *Contact metamorphism. (a) schematic of contacts around a granite body. (b) Examples of Andalusite (chiastolite form with graphite intergrowths) and cordierite hornfels from the Lake District, UK (photo Dougal Jerram).*

A major difference between contact metamorphic rocks and the regional metamorphism discussed here is that contact metamorphism is generally quite static, with far less deformation during mineral growth. This means that the newly formed minerals are not typically as strongly aligned as they are in regional metamorphism, and an irregular orientation of fine grained minerals is typical of a 'hornfels', a classically diagnostic rock of relatively high temperatures of contact metamorphism.

1.3.4 Hydrothermal metamorphic rocks

The third major set of metamorphic rocks are formed through hydrothermal circulation of fluids. In hydrothermal alteration/metamorphism, the host rocks can be involved in wholesale chemical changes upon interaction with chemically reactive fluids. There exist large parts of the Earth's oceanic crust and upper mantle that are almost entirely made of hydrothermally metamorphosed rocks, formed as oceanic rocks interacts with large hydrothermal cells that circulate seawater and initiate mineral reaction. Depending on the temperature of the crust during this circulation and on the availability of water, the result can vary from almost pristine basalt with a little carbonate veining, through to highly 'serpentinised' rocks in which primary olivine in a mantle rock is thoroughly replaced by serpentine group minerals (see Figure 1.8).

The metamorphic rocks exhibit considerable chemical changes that are often termed 'metasomatic', with the loss of calcium and silica, and the relative gain of magnesium and sodium. In modern settings the occurrence of 'black smokers' and 'white smokers' on the sea floor are direct evidence of the hydrothermal cells in action. In the rock record, examples of obducted oceanic crust in the form of ophiolites display this hydrothermal metamorphism and they can also be associated with rich economic metal sulphide mineralisation.

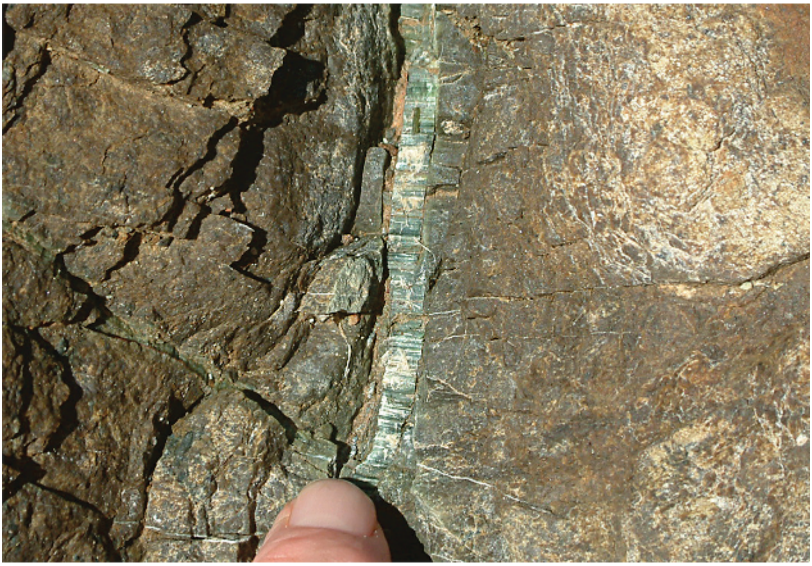


Figure 1.8 *Serpentinised ocean crust from the Troodos Ophiolite, Cyprus. A fibrous serpentine vein is visible in the centre of the photo (photo Dougal Jerram).*

1.4 Summary

As we have introduced, a number of key settings exist that lead to the wide variety of metamorphic rocks and metamorphic associations that we find in the field (summarised in Figure 1.9; see also Figure 1.1). This field descriptions book is organised and laid out such that it introduces metamorphic rocks in terms of how they may be recorded in the field, making comments about sample collection and how work might be followed up in the lab and through additional studies (e.g. under the microscope). It is important to understand the various classification schemes and the different

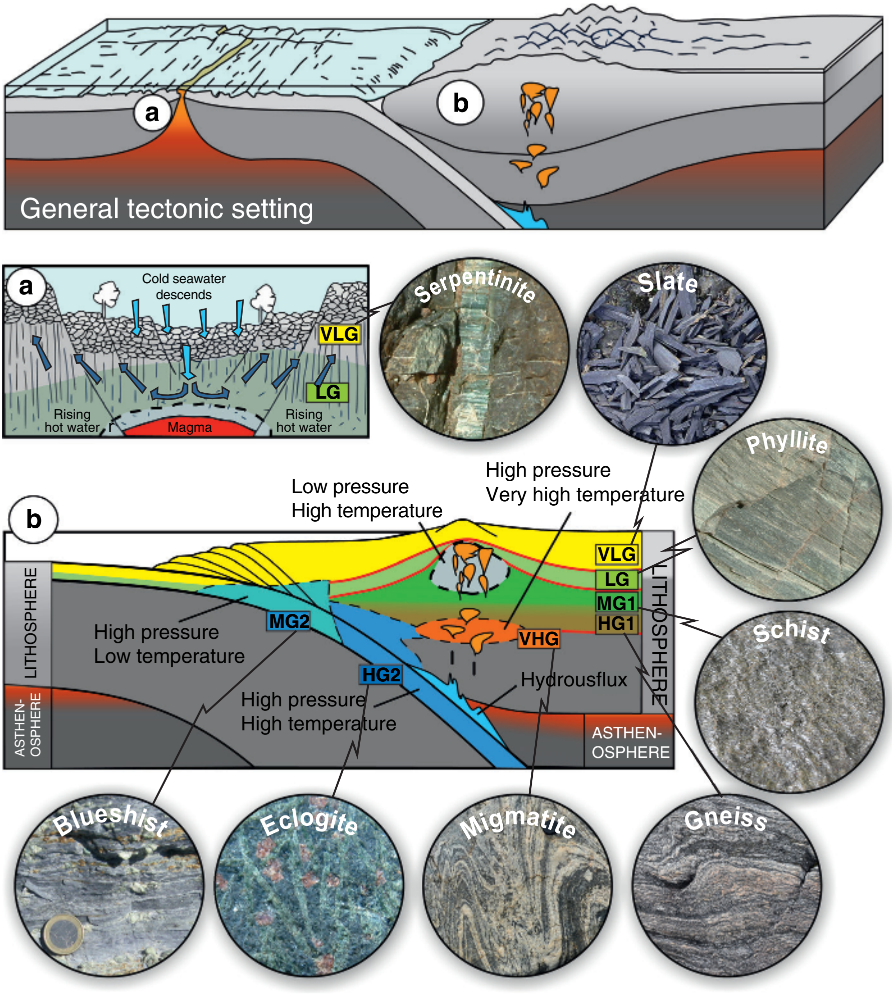


Figure 1.9 *Summary of the two main types of tectonic settings with an outline of the metamorphic grades (Source: partly redrawn from Hefferan and O'Brien (2010)). The metamorphic grades: Very Low Grade VLG, Low Grade LG, Medium Grade MG/MG2, High Grade HG/HG2 and Very High Grade VHG, are indicated on panels (a) and (b) (also refer to Table 3.1 and Chapters 3 and 8) (Source: Rock picture inserts from the figures in this chapter).*

grades of metamorphism that can affect the rocks, but it is also equally important to be aware of the many difficulties often faced in identifying metamorphic rock textures and assemblages. Chapters 2 and 3 provide advice and information on some of the key field skills and metamorphic outcrop description (Chapter 2), as well the main classification criteria (Chapter 3). Chapters 4 and 5 focus in more detail at key structures in metamorphic rocks such as cleavage, shistosity, and isolated bodies such as boudains, augen, and sheared entities. Chapter 6 looks at contacts with igneous rocks, veins, and reaction zones. Chapter 7 looks at the structural control of faults and fault zones in metamorphic rocks and shear zones including shear sense indicators. In Chapter 8, there are key tables and details for reference by way of a summary, as well as some advice for those who are undertaking a more detailed mapping dissertation or project.