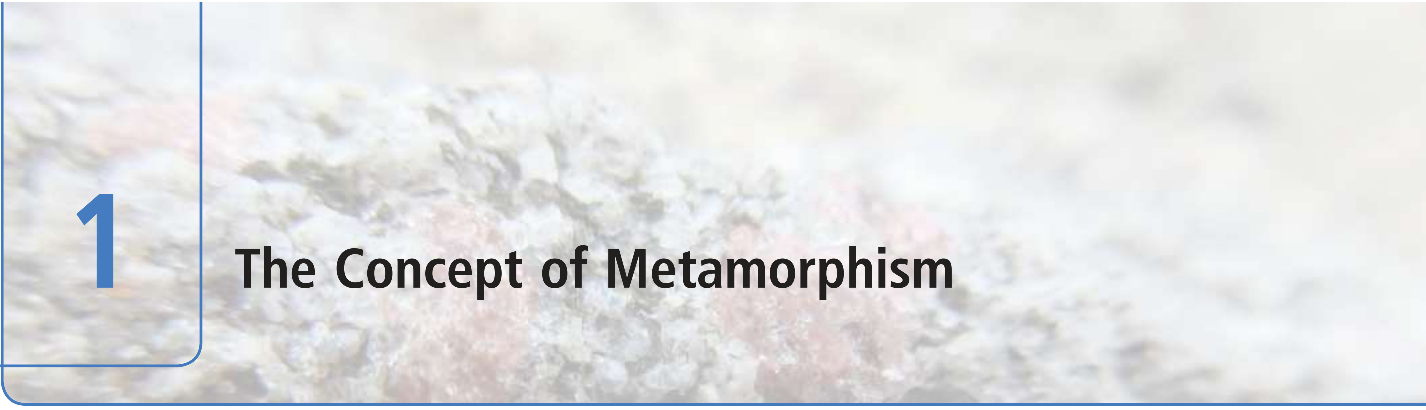

1

The Concept of Metamorphism

A **metamorphic rock** is one that has been changed from its original igneous or sedimentary form: it has grown new minerals in response to new physical or chemical conditions. A wide variety of processes can cause changes to the mineralogical composition of rocks, including heating, burial, deformation, fluid infiltration or shocks caused by meteorites hitting the Earth's surface. Most of these processes, and thus the formation of the vast majority of metamorphic rocks on Earth, take place near tectonic plate margins. As a result, metamorphic rocks provide us with a record of the ambient crustal conditions as rocks get buried, deformed, transformed into new varieties and then transported back up to the surface by a combination of tectonic and surface processes.

Many geologists tend to think that metamorphic rocks should contain large and attractive crystals. However, more objectively, a metamorphic rock can be defined as *any rock in which new mineral grains have grown in response to changed external conditions, so that it now either contains minerals which were not stable in the original sedimentary or igneous environment in which it first formed, or its original minerals have* ***recrystallised*** *to develop new textures.*

In practice, changes that take place during sediment diagenesis and those associated with ore deposit formation are conventionally excluded from the scope of metamorphism, even though some of these processes are, by this definition, metamorphic processes. The boundaries of the discipline of metamorphic geology are therefore to some extent arbitrary, and coloured by individual geologist's experience and focus.

Cambridge University Press & Assessment
978-1-108-47155-8 — An Introduction to Metamorphic Petrology
2nd Edition
Bruce Yardley , Clare Warren
Excerpt
More Information

The scientific understanding of metamorphic processes – and the rates and timescales involved – advanced more slowly than our understanding of igneous and sedimentary processes, perhaps because we cannot usually see metamorphism taking place in ‘real time’ (Box 1.1). Instead, we are reduced to inferring how and where metamorphism occurs from the rocks now exposed at the surface. However, metamorphic processes are extremely important for providing insight into how the Earth behaves, because most rocks in the Earth’s crust have experienced metamorphism of some form or other.

Recent developments in experimental, analytical and computational techniques mean that we can gain a good idea of both the depth and temperature at which a particular metamorphic rock formed, and how long the **metamorphic cycle** of heating, burial, transformation, deformation and transport back to the surface took. In favourable circumstances, we can now determine when different minerals started to crystallise, both absolutely and relative to episodes of deformation, and whether the metamorphism was episodic or relatively continuous through time.

This chapter provides an overview of what metamorphic rocks are, illustrated by some examples of metamorphic rocks in the field, and discusses simple metamorphic changes. The chapter also outlines the factors that control metamorphism and introduces some of the basic terminology that underpins the science. By the end of this chapter you should be able to distinguish a metamorphic rock from a sedimentary or igneous rock, describe some of the mineralogy and textures common in metamorphic rocks and have a basic understanding of the types of tectonic settings in which metamorphic rocks are formed. All of these subjects will be returned to in more detail in subsequent chapters.

BOX 1.1 The development of modern understanding of metamorphism

Modern ideas about how metamorphic rocks form can be traced back at least as far as James Hutton’s *Theory of the Earth* published in 1795. Hutton recognised that some of the rocks that formed the Scottish Highlands had originally been sediments and had been changed by the action of heat deep in the Earth. In the early 1800s a distinction was recognised between **contact metamorphism**, where new metamorphic minerals were found in rocks around an igneous intrusion, but generally grew without associated deformation, and **regional metamorphism**, where metamorphic minerals were present in rocks that were also affected by pervasive deformation over large areas (typically tens or hundreds of thousands of square kilometres). In both cases, studies documented variations in the mineral assemblages of metamorphic rocks which were likely to have evolved from the same starting material.

In the latter part of the nineteenth century, three main hypotheses about the cause(s) of metamorphism arose. In Britain, scientists focussed on Hutton's suggestion that *heat* was critical for forcing metamorphic changes. This idea clearly influenced George Barrow's early systematic studies of metamorphism across a region in the Scottish Highlands (Section 1.2.1); he linked the metamorphic changes to the heat from granite intrusions. In Switzerland and Germany, however, scientists more strongly emphasised the role of *pressure and deformation* over that of heat in causing regional metamorphism. A third, predominantly French, line of thought emphasised the role of *fluids*, which were considered to cause significant changes in rock chemistry during metamorphism. We are indebted to French scientists for pioneering the study of trapped bubbles of metamorphic fluids (**fluid inclusions**) in the minerals of metamorphic rocks (Chapter 2, Box 2.2).

Our present understanding of the conditions under which metamorphism takes place can be traced back to the beginning of the twentieth century, and in particular to the work of Victor Goldschmidt. He applied the then new ideas of thermodynamics to the calculation of the conditions at which certain minerals would form by reaction from others (for example, wollastonite forming from reaction between calcite and quartz). At around the same time, the Finnish geologist Pentti Eskola was studying the metamorphic changes evident in south-west Finland. He also applied the principles of chemical equilibrium to the interpretation of the different **mineral assemblages** or groups of minerals that occur together in different metamorphic rocks that he observed (discussed in Chapter 2). Comparison of his results with those of Goldschmidt led him to identify metamorphic mineral assemblages characteristic of particular pressure and temperature regimes, and to correlate assemblages formed under similar conditions in rocks formed from different original **protoliths**.

Eskola's ideas, put forward in the 1920s, were only slowly accepted. It took until the 1950s for his ideas to gain widespread acceptance, after experiments were carried out to determine the pressure and temperature conditions at which different mineral assemblages are stable. They showed that different types of metamorphic rocks could represent different temperature–depth relationships.

In the early 1960s the Japanese geologist Akiho Miyashiro recognised that metamorphic belts of a similar age, but metamorphosed under very different pressure conditions, often occurred next to each other, and coined the term **paired metamorphic belts** to describe this. The Plate Tectonics Revolution of the late 1960s provided a process-oriented framework that explained how these

Cambridge University Press & Assessment
978-1-108-47155-8 — An Introduction to Metamorphic Petrology
2nd Edition
Bruce Yardley , Clare Warren
Excerpt
More Information

different associations could all be formed. Today, information from metamorphic petrology is central to understanding the tectonic settings in which ancient metamorphic rocks formed (Chapter 10).

Since the 1960s, many metamorphic minerals and mineral assemblages have been synthesised under carefully controlled experimental conditions. Their thermodynamic properties provide additional insights into the conditions of their formation, and huge databases of mineral thermodynamic parameters now underpin modern pressure–temperature calculations (Chapter 3). The work of assembling the data and creating the software to apply it to understanding metamorphic conditions was a major focus in the last part of the twentieth century, involving groups in many countries. Thanks also to vastly improved analytical methods, different software packages now make estimating the pressures and temperatures at which many metamorphic assemblages grew something that can be done without expert knowledge of the underlying thermodynamics (Chapters 2 and 3).

Over the past few decades, the focus of metamorphic geology has progressed from determining the pressure–temperature conditions of formation of metamorphic rocks to the investigation of the rates, timescales, durations and processes of metamorphism. This information defines the origins of the terrane in which the rocks occur in a way which was inconceivable at the time the first edition of this book was published. Major developments in constraining metamorphic processes and conditions have arisen from the development of new technologies for chemical analysis. High-precision techniques for elemental and isotopic analysis of ever-smaller volumes of rocks and minerals have constrained the behaviour of fluids during metamorphism (Chapters 2, 4–6), the relationship between tectonics, deformation and metamorphism (Chapters 8 and 10) and the timescales and rates of metamorphism (Chapter 9).

1.1 Metamorphic Rocks

Metamorphic rocks exhibit new textures and/or new minerals but many also retain some characteristics of their original **protolith**, the original, un-metamorphosed rock, such as its bulk chemical composition or features such as bedding. Examples of rocks that retain some obvious protolith features but have also developed new metamorphic minerals and textures are shown in Figure 1.1. The fact that some of these rocks have been metamorphosed may be difficult to tell at a first glance: the field context of the sample is often crucial. For example, the cross-laminations of the siltstones in Figure 1.1a are still clearly preserved although the original

Figure 1.1 Examples of metamorphic rocks that retain evidence for their original nature. (a) Cross-bedded metasiltstone with coarse staurolite-bearing interbeds of metapelite, Maine, USA. (b) Metamorphosed impure limestone with bivalve fossils, Lukmanier Pass, Switzerland. (c) Metamorphosed basaltic pillow lavas, Southland, New Zealand. (d) Deformed and metamorphosed pillow lavas, Wadi Huulw, Oman.

interbedded clay-rich layers are now pelitic schists with large, metamorphic crystals of staurolite. The marble in Figure 1.1b contains clear cross-sections of bivalve (gryphaea) fossils. This rock could in theory pass as a limestone, however other rocks in the near vicinity have clearly grown new metamorphic minerals. The metabasaltic pillows in Figure 1.1c have retained the distinctive shape that demonstrates eruption of lava into water, but the original near-black minerals have been completely transformed into new blue-green varieties. The original pillow shapes in Figure 1.1d have been flattened during extensive deformation and the rock contains new metamorphic minerals that have a distinctive blue-purple colour.

Although it is not normally possible to see metamorphic changes taking place in the same way that we can watch some igneous or sedimentary rocks being formed on human timescales, there are certain types of relatively rapid metamorphic changes occurring near the surface today. For example, in high-temperature geothermal fields, such as those exploited for power in Iceland, Italy, New Zealand and

CAMBRIDGE

Cambridge University Press & Assessment
978-1-108-47155-8 — An Introduction to Metamorphic Petrology
2nd Edition
Bruce Yardley , Clare Warren
Excerpt
More Information

elsewhere, volcanic glass and minerals that originally formed in high-temperature igneous environments are being actively converted to clays, chlorite, zeolites, epidote and other minerals that are more stable in the cooler, wetter environment of the geothermal system. These metamorphic changes are taking place at depths of only tens to a few hundred metres and at rates that affect the economic exploitation of these systems (Chapter 5, Section 5.6).

1.2 What Do Metamorphic Rocks Look Like?

Before tackling some of the rather abstract concepts of how and why metamorphism takes place, it is worth having some sort of appreciation of what they actually look like in the field. Much modern metamorphic petrology is based on data collected in the laboratory. However, these data are little value unless they can be related back to the textures and field relations of natural rocks. Field studies provide the critical information that underpins the whole subject.

Metamorphic rocks may be found across regions spanning tens or even hundreds of square kilometres or may be very much more localised. Their mineral assemblages may be similar over large areas or may vary over short distances. In many cases, metamorphic rocks show clear evidence of their original rock type, but in detail there will be significant changes. Metamorphosed sedimentary rocks (**metasediments**) have very little porosity and the constituent grains no longer reflect the original sedimentary particles. Metasediments commonly have quite distinct physical properties. Metamorphosed igneous rocks may also retain the gross form of their precursors. However, instead of being made up of interlocking grains crystallised from a melt, they contain metamorphic minerals which may replace specific original crystals or demonstrate complete recrystallisation of the rock. Irrespective of the original rock type, if metamorphism was accompanied by deformation then the metamorphic minerals may be aligned in a tectonic fabric.

1.2.1 The South-East Highlands of Scotland

One of the classic examples of regional metamorphism is in the south-east Highlands of Scotland (Figure 1.2). In the late 1800s, George Barrow showed that there were systematic mineralogical changes in rocks of similar composition across this region and argued that they reflected differences in the temperature of metamorphism.

The rocks of the area were originally Neoproterozoic to Cambrian sediments with basaltic lavas and minor intrusions in parts of the succession. Original quartz-rich sandstones show relatively little mineralogical change across the area, but the **metapelitic rocks** (metamorphosed pelites, or muddy sediments originally composed predominantly of clay minerals) display new metamorphic minerals. All the rocks have fabrics of aligned minerals linked to deformation that took place during the

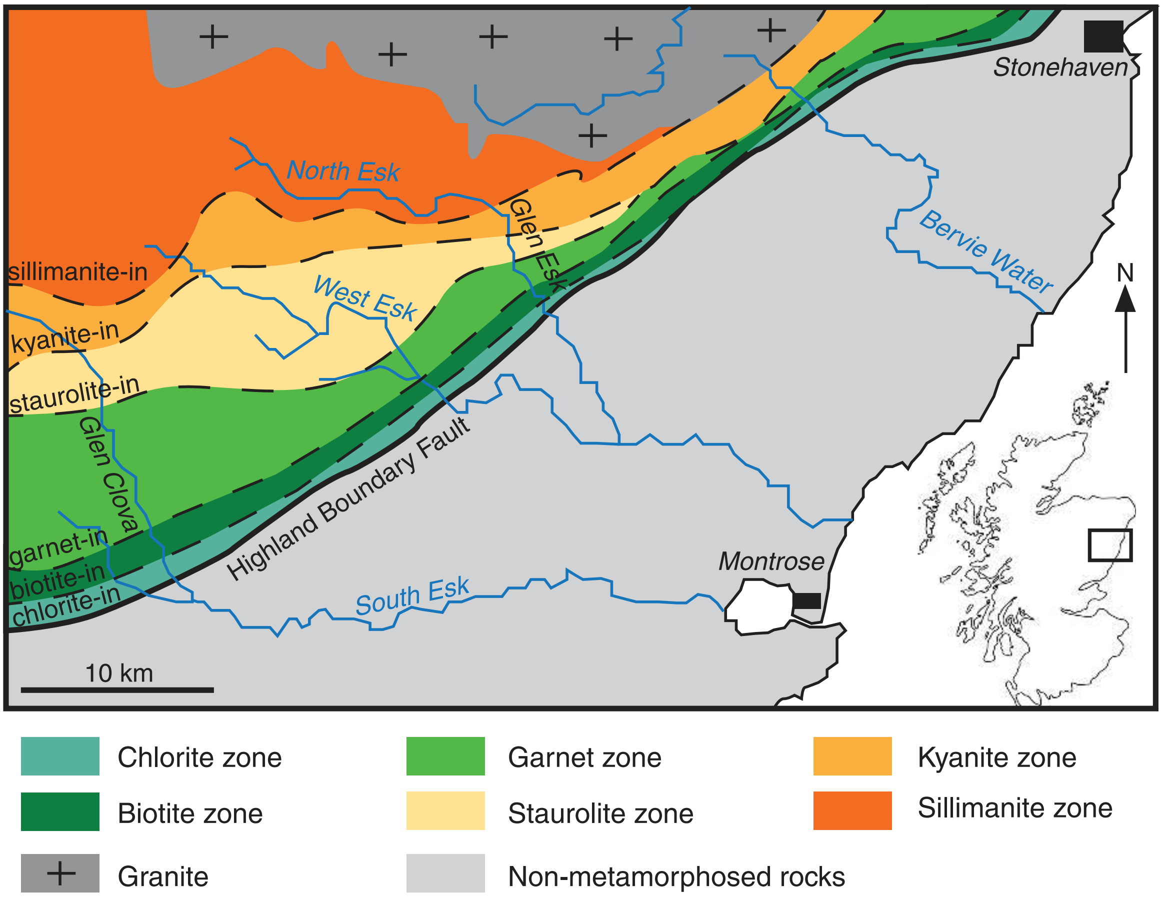

Figure 1.2 Simplified metamorphic map of index mineral zones in the Scottish Highlands, based on Tilley (1925). The Highland Boundary Fault separates older metamorphic rocks to the north and west from younger, unmetamorphosed sediments to the south and east.

metamorphism. The new minerals in the metapelites define a series of **metamorphic zones** (Figure 1.2), each with a characteristic mineralogy which reflects the conditions at which metamorphism took place.

The best-known section through the originally-mapped zones is in the valley of the River North Esk, known as Glen Esk. Immediately north of the Highland Boundary Fault, the exposed rocks are fine-grained and strongly foliated, and contain few mineral grains coarse enough to identify in the field. Under the microscope, however, fine-grained metamorphic *chlorite* can be seen, intergrown with white mica. Quartz and albite (sodic feldspar) are also present together with minerals such as pyrite and tourmaline, which are sometimes coarse enough to see in outcrop.

The next mappable metamorphic zone is marked by the appearance of visible grains of *biotite*. Not all of the rock types in the region are of the correct composition for biotite to grow, but in the metapelites, grains of biotite and muscovite are just

Cambridge University Press & Assessment
978-1-108-47155-8 — An Introduction to Metamorphic Petrology
2nd Edition
Bruce Yardley , Clare Warren
Excerpt
More Information

large enough to be visible under the hand lens. These mica grains create a 'shimmer' on the surfaces along which the rock splits.

Subsequent metamorphic zones exposed up the valley are defined by the first appearance in metapelites of the metamorphic minerals garnet, staurolite, kyanite and then sillimanite. Each grew in turn in response to increasingly higher temperatures.

The appearance of such **index minerals** often coincides with an increase in grain size, and the index minerals form **porphyroblasts**, or grains that are often much coarser than the matrix grains around them (an example of garnet porphyroblasts is shown in Figure 1.3a). Many porphyroblasts enclose **inclusions** of matrix minerals or minerals that were previously in the matrix at the time that mineral was growing. Porphyroblasts with a very high density of inclusions are termed **poikiloblasts** (Figure 1.3b).

Metamorphic geologists use the relative term **grade**, or **metamorphic grade**, to refer to the **peak** (or maximum) conditions of temperature, or more rarely peak pressure, at which a rock formed. A high-grade rock, for example, has been metamorphosed at higher peak temperatures (and usually higher peak pressures) than a low-grade rock.

Each index mineral persists to higher grades than the zone that it characterises. Whether or not a particular index mineral has developed in any rock depends on the rock composition *and* the metamorphic conditions. For example, biotite and garnet are present in a wide range of schists but staurolite only appears in metapelites whose composition is specifically rich in aluminium and poor in calcium. Each rock contains many other minerals, for example muscovite, plagioclase and quartz, which co-exist with the index minerals (Figure 1.3). These other minerals persist

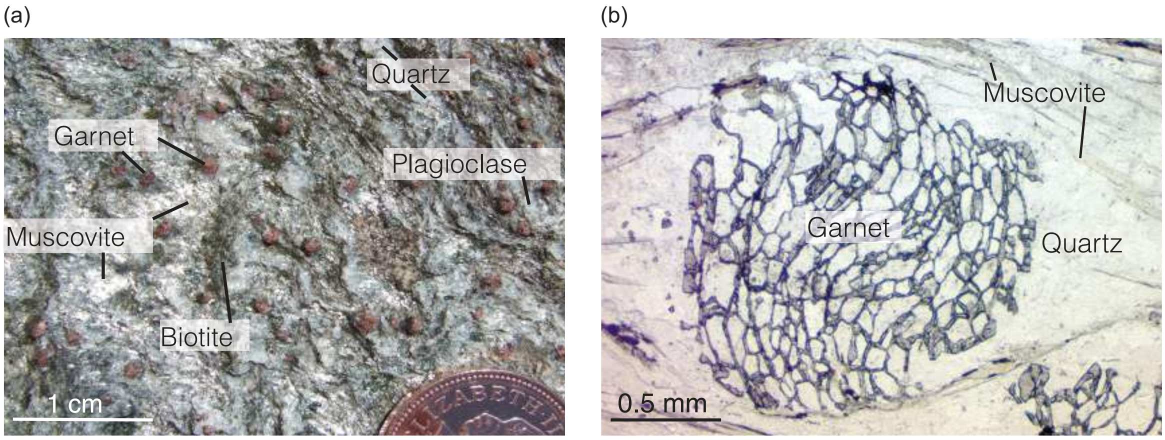

Figure 1.3 Examples of porphyroblasts and poikiloblasts. (a) Schist from Tyndrum, Scotland containing porphyroblasts of pink garnet, white crystals of plagioclase feldspar, greyish quartz, brown biotite and silvery muscovite. (b) Thin-section photomicrograph of a garnet poikiloblast in a muscovite schist (As Sifah, Oman). Note that this photomicrograph was taken in plane polarised light (PPL); unless otherwise specified, all photomicrographs in the book are taken in PPL.

across multiple zones and, despite not being useful as index minerals, they are still an important part of the mineral assemblage because they participate in the reactions by which the index minerals are created or destroyed. All of these concepts will be returned to in greater detail in Chapter 4.

The metamorphic zones in the south-east Highlands were originally defined by plotting the location of the different index minerals on a map and drawing lines through the first appearance of each index mineral in the direction of increasing grade. Index minerals may grow at somewhat different temperatures in layers of slightly different composition, and so the ‘first appearance’ method of drawing the boundaries served to smooth out the effects of random variation in rock composition. It means, for example, that some metasediments in the garnet zone will not in fact contain garnet and will be indistinguishable from biotite zone rocks (Figure 1.4). The zone boundaries are called **isograds**, meaning lines of constant metamorphic grade. Because isograds based on mineral appearance cannot be drawn accurately in areas where rock compositions vary, it is now customary to try to define isograds more rigorously by basing them on full mineral assemblages, rather than on the appearance of individual index materials.

It is generally assumed that higher-grade metamorphic rocks formerly contained the mineral assemblages of lower-grade zones, and that they progressively recrystallised and/or changed their mineralogy as metamorphism proceeded, rather than being converted directly from, say, unmetamorphosed sediment to high-grade schist. Evidence for this concept of **progressive metamorphism** includes the

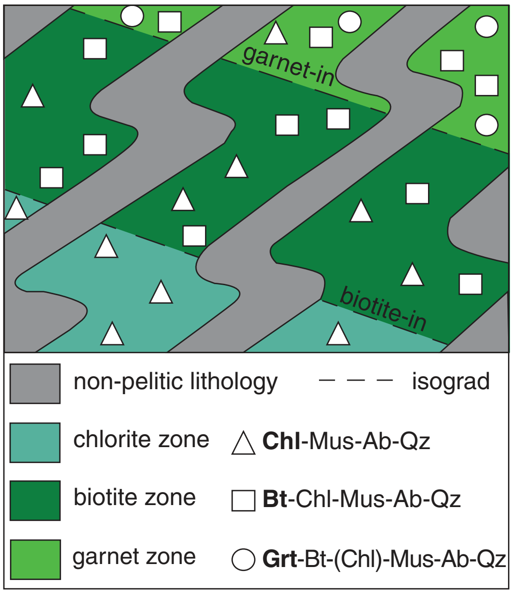

Figure 1.4 Schematic map illustrating the distribution of some index minerals and their associated typical mineral assemblages in a regionally metamorphosed metasedimentary sequence. Also shown are the isograds for the first appearance of the index minerals drawn on the basis of the assemblage information. Mineral abbreviations are detailed in Appendix 1.

CAMBRIDGE
Cambridge University Press & Assessment
978-1-108-47155-8 — An Introduction to Metamorphic Petrology
2nd Edition
Bruce Yardley , Clare Warren
Excerpt
More Information

preservation of minerals typical of lower-grade zones as **inclusions** inside larger grains of other minerals. These inclusions can persist into higher-grade zones where they would not otherwise be present. Similarly, zoned minerals, whose composition changed as they grew in response to changing pressure and temperature, preserve evidence of a history of metamorphic recrystallisation. These topics are covered in more detail in subsequent chapters.

1.2.2 Bugaboo Aureole, British Columbia, Canada

Another common type of metamorphism is developed in the **country rocks** around igneous intrusions in response to the heat given off as the magma crystallises and cools. In this situation, a **metamorphic** or **contact aureole** develops outwards from the source of heat.

In British Columbia, Canada, a granite–granodiorite magma intruded a Neoproterozoic turbidite sequence during the Late Cretaceous. The country rocks were already metamorphosed to chlorite-grade before the intrusion caused further, more-localised, metamorphism. Figure 1.5 shows the metamorphic zones and isograds that developed in the ~1 km wide metamorphic aureole around the intrusion.

You will notice that different metamorphic minerals formed in the aureole around the Bugaboo intrusion from those formed during regional metamorphism in the

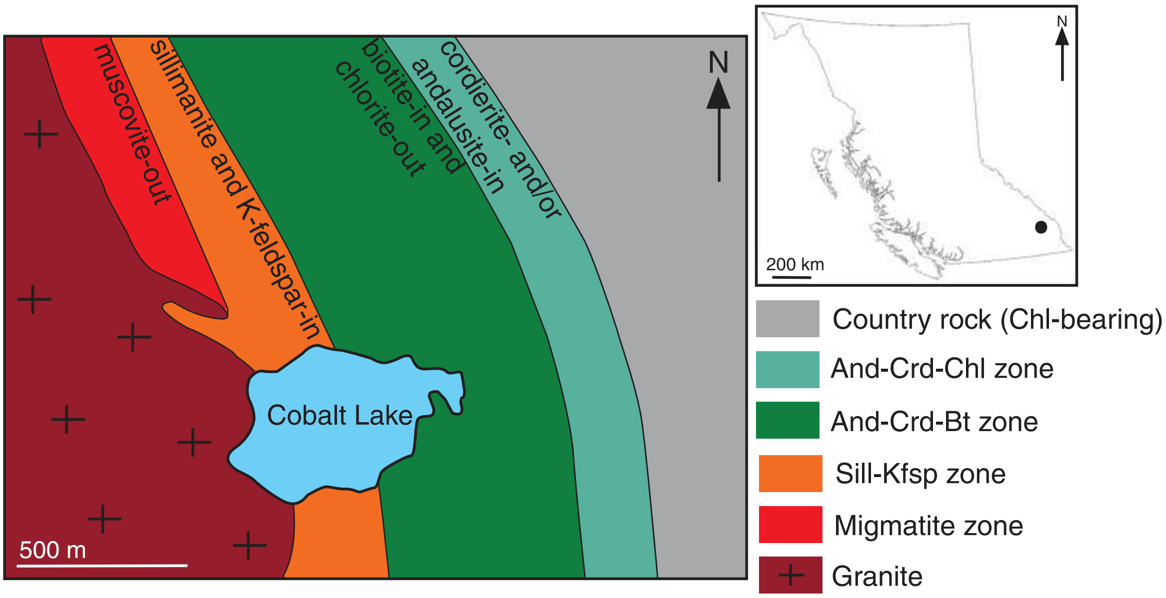

Figure 1.5 Simplified geological map of the metamorphic zones surrounding the Bugaboo batholith in British Columbia, Canada (shown in the inset). The colours of the zones are related to temperature and match those in Figure 1.2. Modified from Pattison & DeBuhr (2015).