Grade and Facies of Metamorphic rocks

Grade of Metamorphism

Metamorphic Grade is a term used in a relative sense to refer to the conditions of temperature (or sometimes pressure) to which a rock has been subjected.

The intensity of metamorphism can vary substantially from one environment to another.

As the temperature and/or pressure increases on a body of rock we say the rock undergoes prograde metamorphism or that the grade of metamorphism increases.

For example, in low-grade metamorphic environments, the common sedimentary rock shale becomes the more compact metamorphic rock slate.

Hand samples of these rocks are sometimes difficult to distinguish.

Metamorphic grade is a general term for describing the relative temperature and pressure conditions under which metamorphic rocks form.

In more extreme environments, metamorphism causes a transformation so complete that the identity of the parent rock cannot be determined.

In high-grade metamorphism, such features as bedding planes, fossils, that existed in the parent rock are obliterated.

In the most extreme metamorphic environments, the temp approach those at which rocks melt.

However, during metamorphism the rock remains essentially solid.

But partial melting is usually found under such conditions.

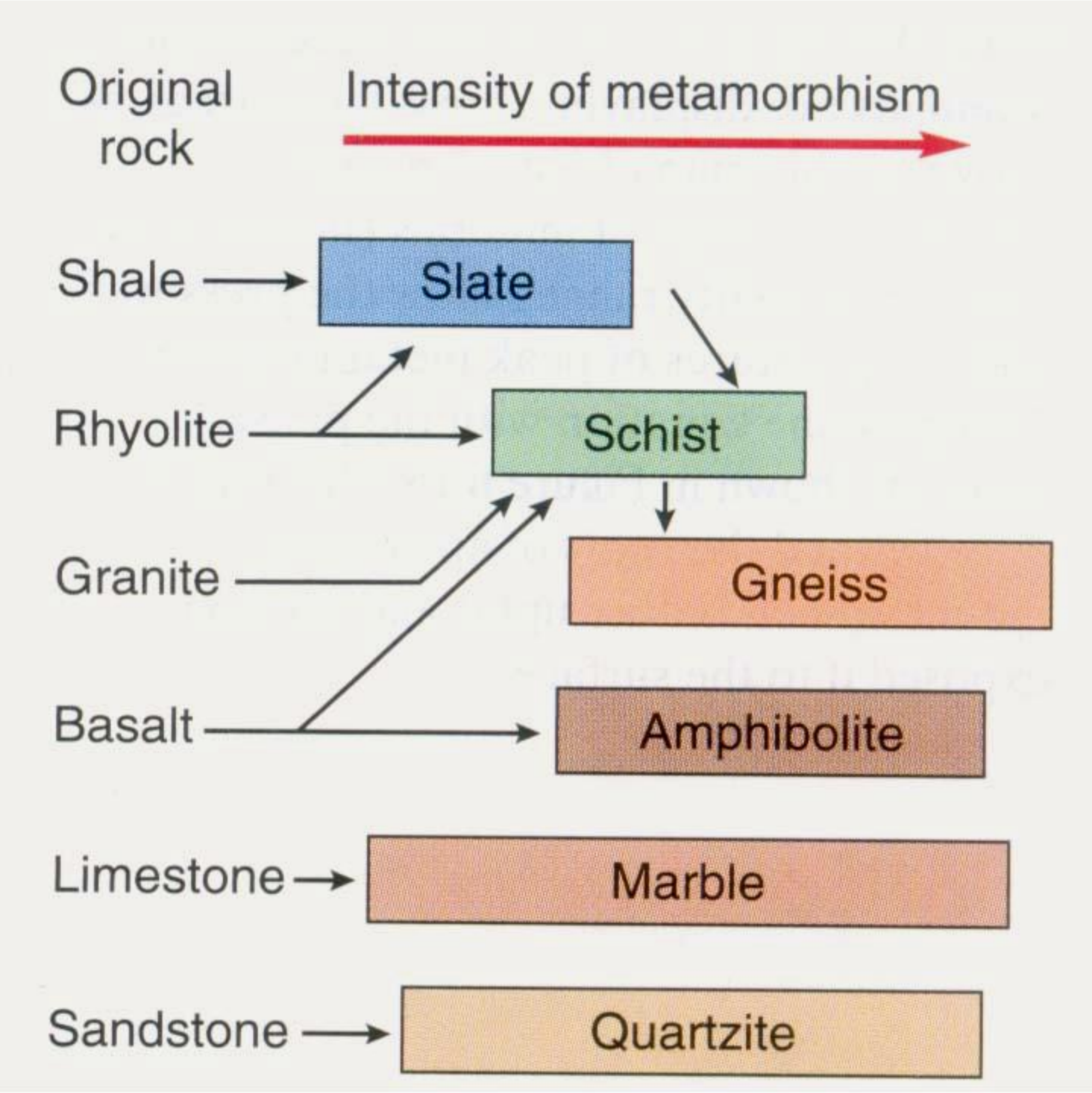


Fig. 6.12: The source rocks for common metamorphic rocks are varied. In some cases, such as quartzite, marble, and meta-conglomerate (not shown in diagram), the nature of the original rocks is easily determined. In other cases, such as schist and gneiss, it is difficult and sometimes impossible to determine the type of source rock. This simplified flow chart shows the origin of some of the common metamorphic rocks

Low-grade metamorphism takes place at temperatures between about 200 to 320^{o}C, and relatively low pressure.

Low grade metamorphic rocks are generally characterized by an abundance of hydrous minerals.

With increasing grade of metamorphism, the hydrous minerals begin to react with other minerals and/or break down to less hydrous minerals.

High-grade metamorphism takes place at temperatures greater than 320°C and relatively high pressure.

As grade of metamorphism increases, hydrous minerals become less hydrous, by losing H_2O, and non-hydrous minerals become more common.

Index Minerals and Metamorphic Grade

In addition to textural changes, we encounter corresponding changes in mineralogy as we shift from regions of low-grade metamorphism to regions of high-grade metamorphism.

An idealized transition in mineralogy that results from the regional metamorphism of shale is shown in Fig 8.27.

The first new mineral to form as shale changes to slate is chlorite.

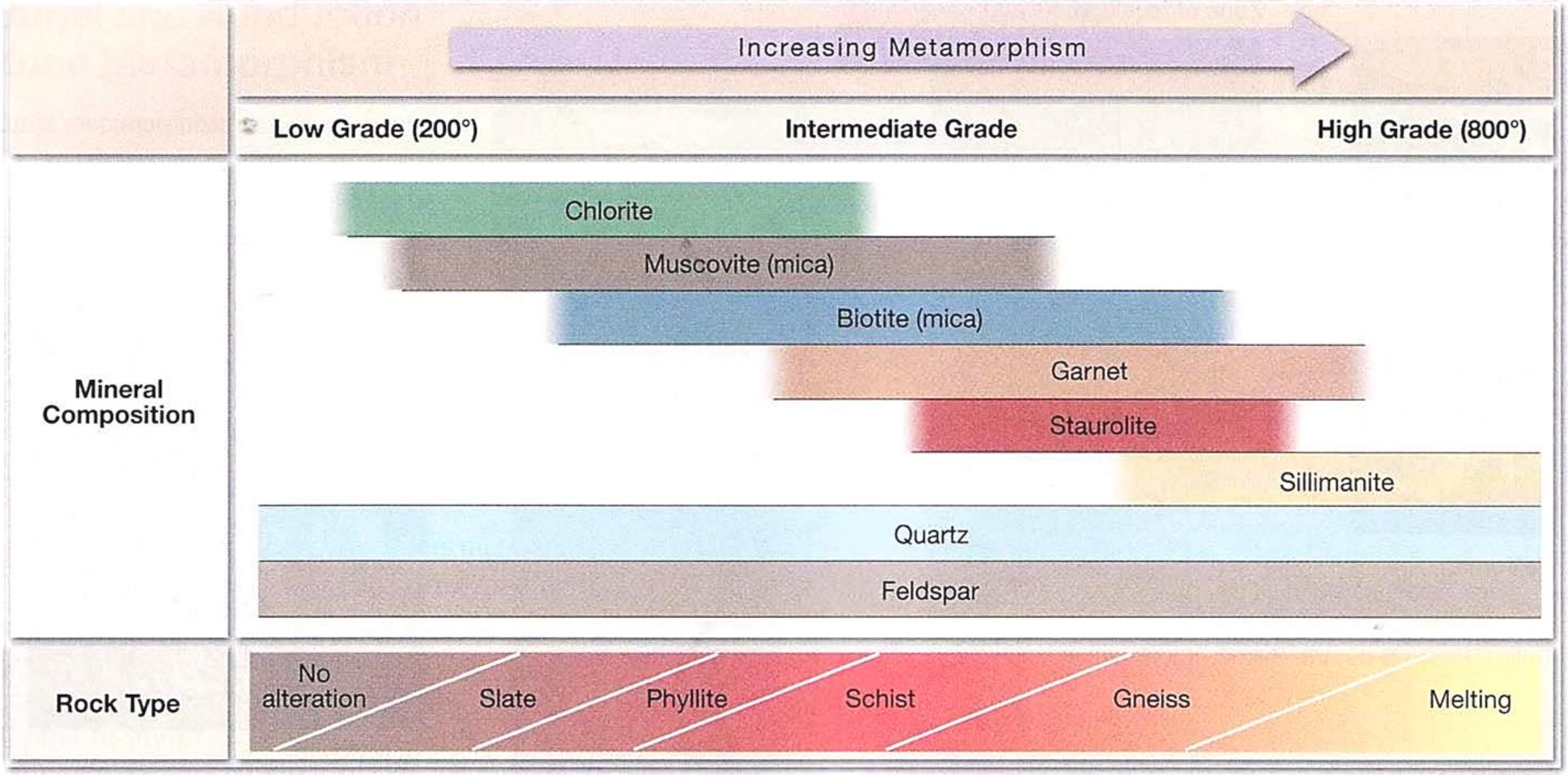


FIGURE 8.27 The typical transition in mineralogy that results from the progressive metamorphism of shale.

At higher temperatures flakes of muscovite and biotite begin to dominate.

Under more extreme conditions, metamorphic rocks may contain garnet and staurolite crystals.

At temperature, approaching the melting point of rock, Sillimanite forms. Sillimanite is a high-temperature metamorphic mineral used to make refractory porcelains such as those used in spark plugs.

Through the study of metamorphic rocks in their natural settings (called field studies) and through experimental studies,

we know that certain minerals (Fig 8.27) are good indicators of the metamorphic environment in which they formed.

Using these index minerals, we distinguish among different zones of regional metamorphism.

For example, the mineral chlorite begins to form when temperatures are low, less than 200 °C.

Thus, rocks that contain chlorite (usually slates) are referred to as low-grade. By contrast, the mineral sillimanite only forms in extreme environments where temperatures exceed 600^{o}C, and rocks containing it are considered high-grade.

By mapping the occurrences of index minerals, we are mapping zones of varying metamorphic grade.

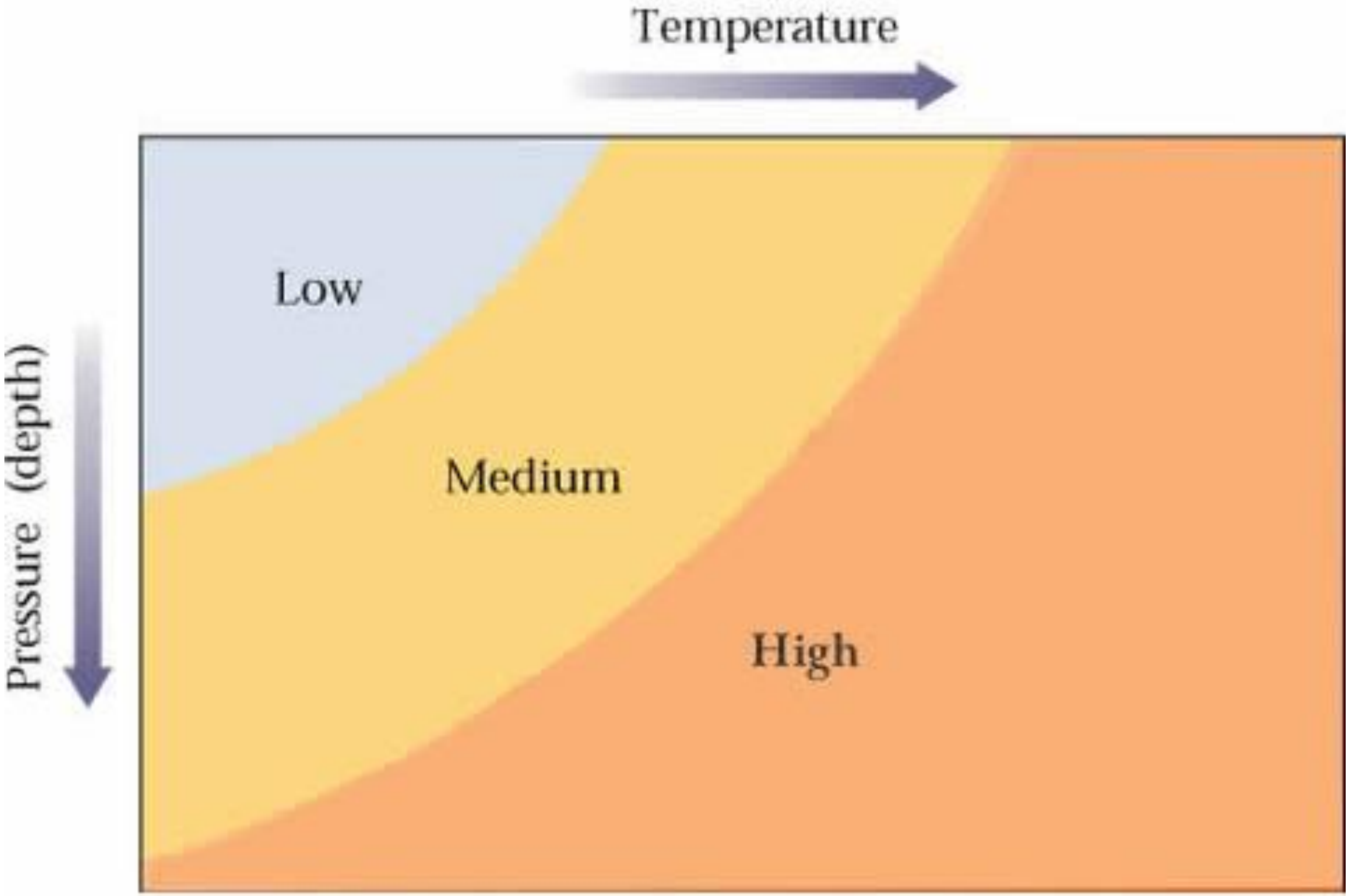
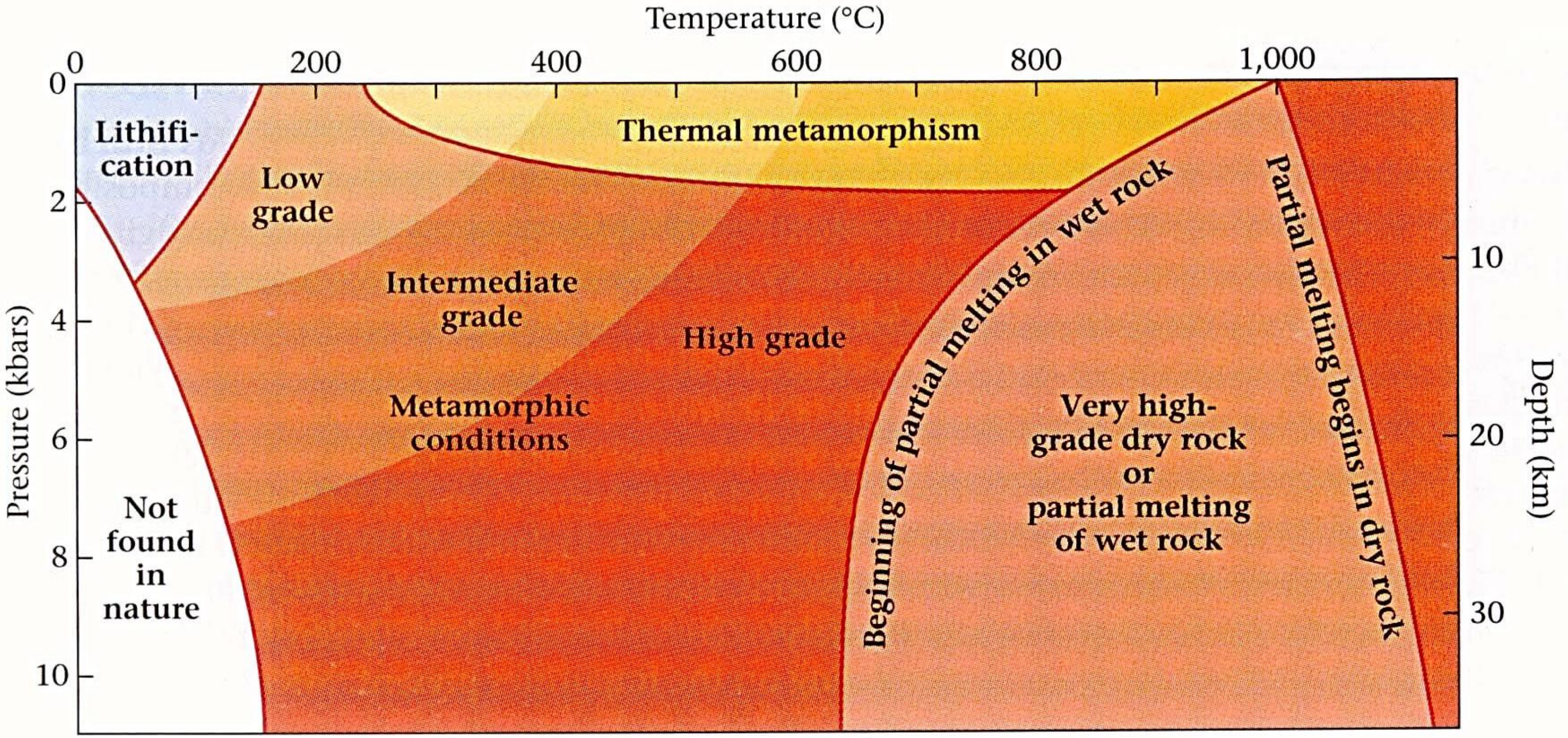

Temperature
Pressure (depth)
Low
Medium
High

FIGURE 8.18 The conditions of pressure and temperature under which metamorphism occurs. At low pressures and temperatures, only lithification takes place. At progressively higher pressures and temperatures, a rock passes from low to medium to high grade. If the temperature increases but the pressure stays low, we call the metamorphism "thermal." If the rock contains water, it begins to melt at the upper limit of high-grade metamorphism, but if it does not contain water, melting doesn't begin until higher temperatures.



Migmatites

In the most extreme environments, even the highest-grade metamorphic rocks undergo change.

For example, gneissic rocks may be heated sufficiently to cause melting to begin. Note different minerals melt at different temperatures.

The light-colored silicates, usually quartz and potassium feldspar, have the lowest melting temperatures and begin to melt first, whereas the mafic silicates, such as amphibole and biotite remain solid.

When this partially melted rock cools, the light bands will be composed of igneous, or igneous-appearing components while the dark bands will consists of unmelted metamorphic material.

Rocks of this type are called **migmatites** (migma= Mixture. ite = a stone) (Fig 8.29).

The light-colored bands in migmatites often forms tortuous folds and many contain inclusions of the dark components.

Migmatites serve to illustrate the fact that some rocks are transitional and do not clearly belong to any one of the three basic rock groups.

But still we generally include migmatites as special kind of metamorphic rocks and do not include as igneous rock.

FIGURE 8.29 Migmatite. The lightest-colored layers are igneous rock composed of quartz and feldspar, whereas the darker layers have a metamorphic origin. (Photo by Stephen Trimble)

Metamorphic Facies

(From Klein and Philpotts)

Metamorphic grade and facies

When discussing metamorphic rocks we commonly refer to their metamorphic grade, which loosely expresses the intensity of metamorphism, with increasing grade being thought to relate mainly to increasing temperatures.

One of the first attempts to map the grade of metamorphism was the study by Barrow (1893) in the southeastern Scottish Highlands.

He noted that mudrocks (pelites) in this region become progressively more metamorphosed toward the north.

He mapped the increasing metamorphic grade by recording the first appearance of particular metamorphic index minerals, which included chlorite, biotite, garnet, staurolite, kyanite, and sillimanite.

This sequence of minerals, though extremely common and found in metamorphic terranes worldwide, is not the only sequence that can occur.

The fact that other sequences are found indicates that metamorphism is not a simple phenomenon and must involve numerous factors that can differ from region to region.

Later, the boundaries between Barrow's index mineral zones were termed isograds, which implies that points along these lines underwent equal intensities of metamorphism.

When examined in detail, however, such lines cannot truly represent equal intensities of metamorphism, because the first appearance of an index mineral is strongly dependent on a rock's bulk composition or fluid compositions.

Although isograds are not rigorous lines of equal metamorphic intensity, they are still mapped and provide a useful general measure of metamorphic grade.

The big advance in measuring metamorphic intensity came when thermodynamics was first applied to the study of metamorphic rocks.

In 1911, Goldschmidt, noted that contact metamorphic rocks around igneous intrusions near Oslo, Norway, rarely contained more than four or five minerals and that the mineral assemblages were consistent with the Gibbs phase rule, which implied that the assemblages approached thermodynamic equilibrium.

He emphasized that it was the mineral assemblage rather than the first appearance of a single mineral that was a measure of metamorphic grade.

In 1920, Eskola, carrying out similar studies of contact metamorphic rocks around bodies of granite at Orijarvi in Finland, noted that rocks contain small numbers of minerals that are consistent with the Gibbs phase rule but that the mineral assemblages are different from those around the Oslo intrusions.

He concluded that metamorphic rocks in both areas had approached thermodynamic equilibrium but under different conditions.

This led him to propose the metamorphic facies concept.

He defined a metamorphic mineral facies as comprising all rocks that have originated under temperature and pressure conditions so similar that a definite bulk rock chemical composition results in the same set of minerals.

The metamorphic facies concept has two very important consequences.

1. If two rocks of identical bulk composition have different mineral assemblages, they must have been metamorphosed under different conditions.
2. Conversely, if two rocks that have been exposed to the same metamorphism (e.g., found side by side in the field) contain different minerals, they must have different bulk compositions.

Eskola's facies approach used the entire mineral assemblage and avoided the problems associated with different bulk compositions, which plagued the application of Barrow's index minerals.

Eskola originally proposed five different metamorphic facies to which a few extra were added subsequently.

He showed the relative positions of these facies on a pressure-temperature diagram.

Modern experimental studies allow us to give approximate pressure and temperature ranges for these facies (Fig. 14.4).

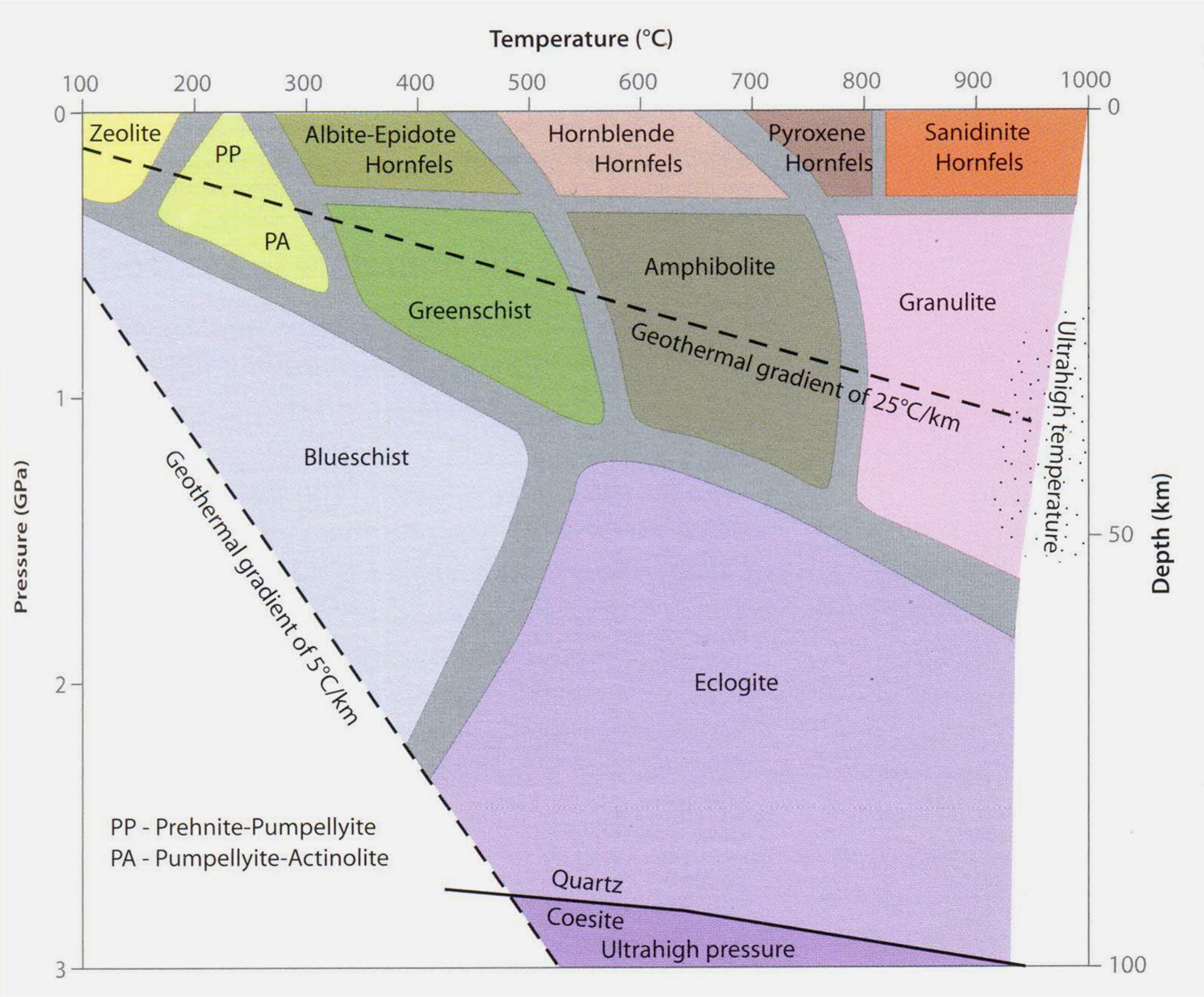
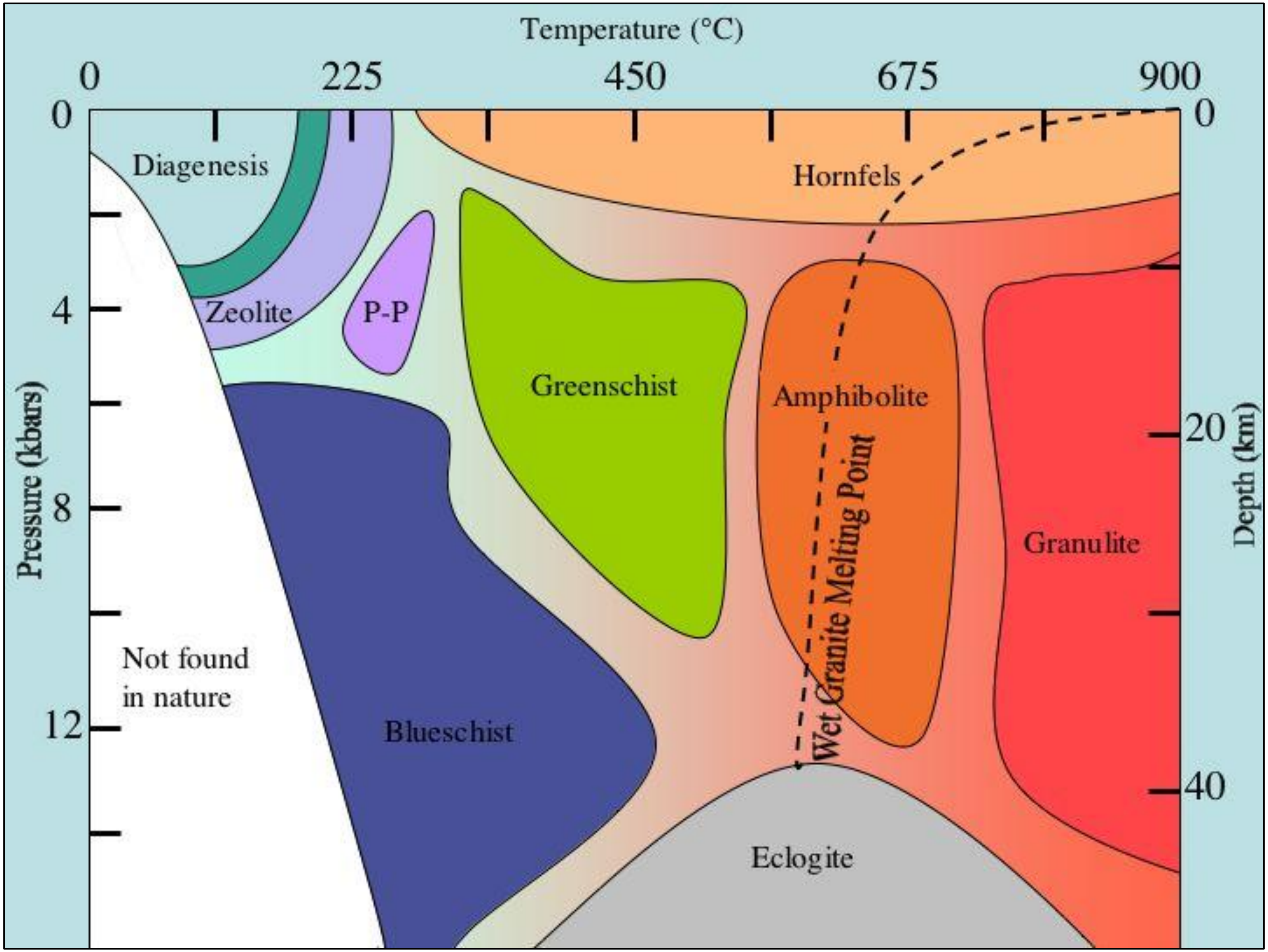


Fig. 14.4: Approximate pressure and temperature ranges of metamorphic facies when the activity of watrer is 1 (modified from Philpotts and Ague, 2009)



Types of metamorphic facies

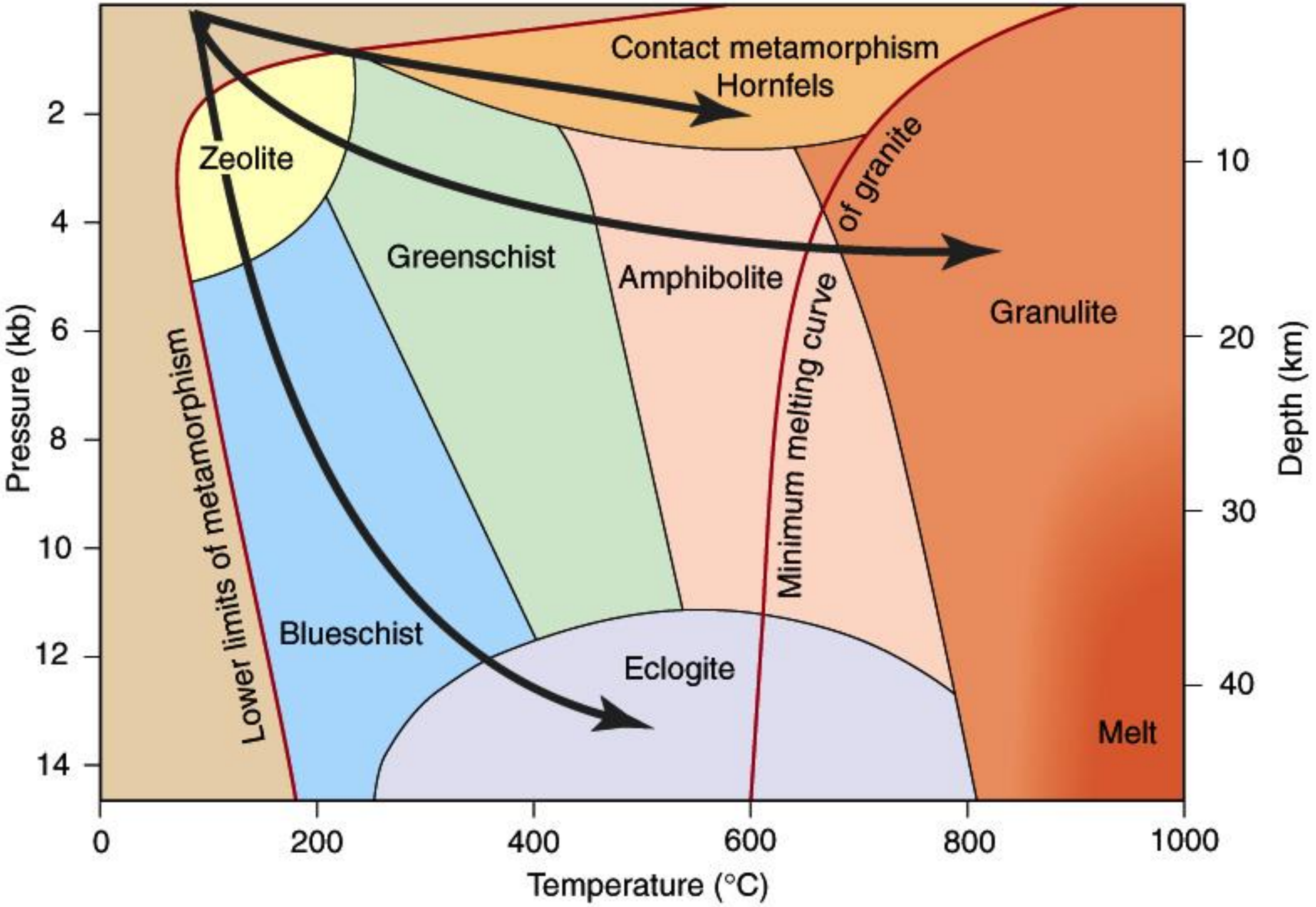
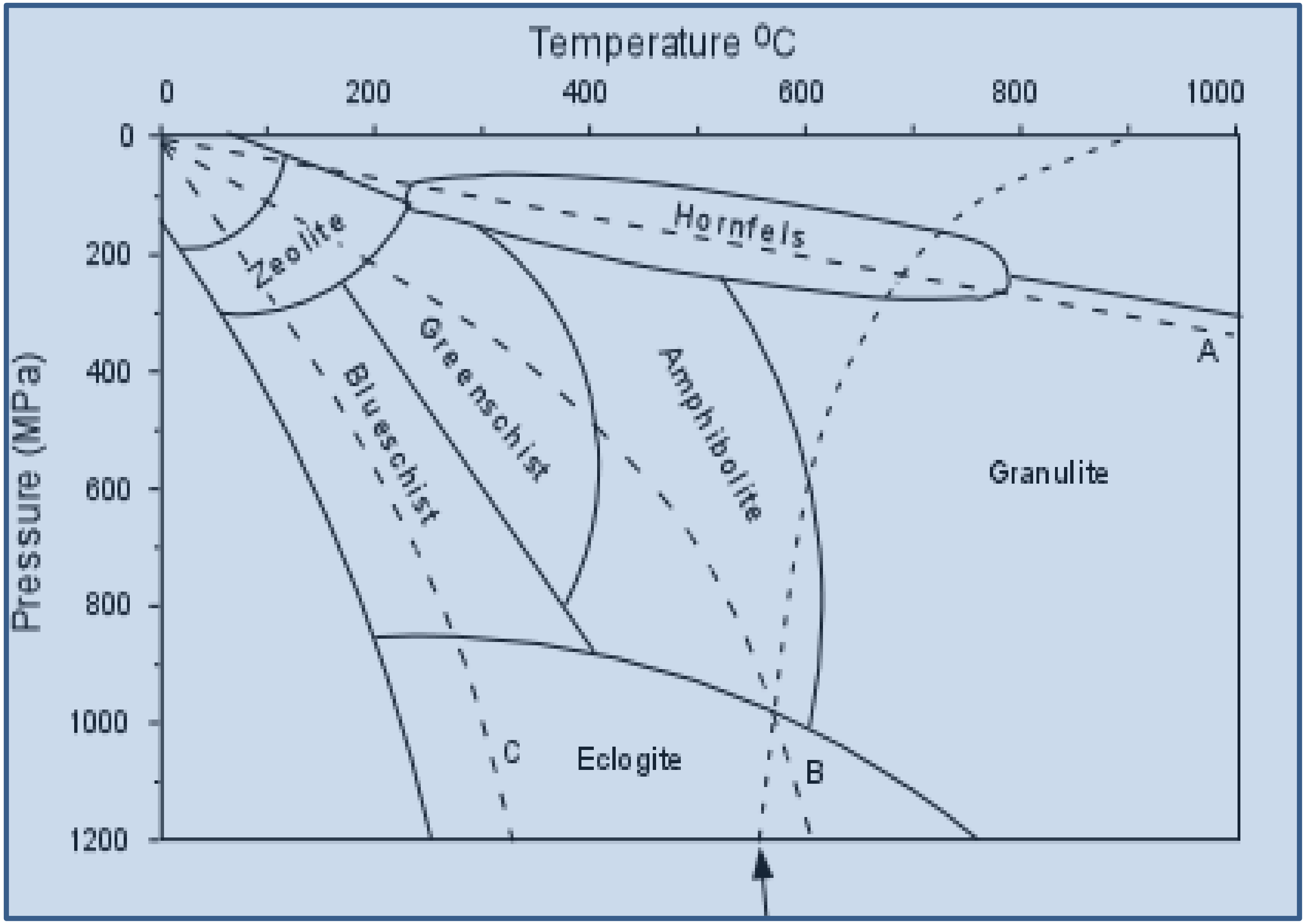


Fig. 6.15: Metamorphic facies are defined by a set of minerals stable at a certain temperature and pressure (depth) and independent of rock composition. The arrows show three possible paths of metamorphism. If temperature increased moderately with pressure, the sequence of facies would be zeolite, greenschist, amphibolite, and granulite (the middle rows). If the increase in temperature with depth was slight, changes in metamorphic facies would follow the path indicated by the lower arrow, with the formation of blueschist and then eclogite. Contact metamorphism is limited to zones of low pressure around shallow igneous intrusions (upper arrow).

Metamorphic facies



Wet Partial Melting of Granite

A= High Geothermal Gradient (contact metamorphism), Low P, High T

B = Normal Geothermal Gradient (regional metamorphism), High P, High T

C = Low Geothermal Gradient (subduction), High P, Low T

The boundaries between facies are broad zones because of the complex nature of the reactions separating them and the fact that many of the minerals belong to solid solution series.

In addition, because most prograde metamorphic rocks release water, the activity of water (relative humidity; see Sec. 8.4.2) plays an important role in determining the conditions under which the reactions occur.

In Figure 14.4, the activity of water is taken to be 1; that is, the minerals coexist with a pure water fluid.

If the activity were less than 1, the boundaries would occur at lower temperatures.

The names of the facies are based on the typical hand specimen appearance of metamorphosed basalt in each of these facies.

Thus, a metabasalt at low grade would contain abundant chlorite and so is called a green- schist,

whereas at higher grade it would contain abundant amphibole and is called an amphibolite, and

at the highest grade it would contain granular pyroxene and plagioclase and is called a granulite.

Eskola recognized that the changes in temperature and pressure associated with progressive metamorphism led to three common sequences of metamorphic facies or metamorphic facies series.

(1) A low-pressure,
(2) high-temperature series, including the albite-epidote hornfels, the hornblende hornfels, the pyroxene hornfels, and the
(3) sanidinite hornfels facies (Fig. 14.4), is typically associated with contact metamorphic aureoles but is also found in regional metamorphic terranes.

A common metamorphic facies series found in many regionally metamorphosed orogenic belts includes the:

1. **zeolite,**
2. **greenschist,**
3. **amphibolite, and**
4. **granulite facies.**

Metamorphic facies and their mineral assemblages

1. Zeolite facies
2. Prehnite-pumpellyite-facies
3. Greenschist facies
4. Amphibolite-facies
5. Granulite facies
6. Blueschist facies
7. Eclogite facies
8. Albite-epidote-hornfels facies
9. Hornblende-hornfels facies
10. Pyroxene-hornfels facies
11. Sanidinite facies

This series shows a progressive increase toward both *high temperature and pressure,* with both rising approximately along a geothermal gradient of ~25°C/ km (Fig. 14.4).

A third series, marked by *high pressures at low temperatures* includes the prehnite-pumpellyite, blueschist, and eclogite facies.

Although these are the most common series, intermediate series also occur.

Recently, *ultrahigh-pressure* (UHP) metamorphic rocks have been found in subduction zones in which the high-pressure polymorph coesite is the stable form of silica rather than the low-pressure polymorph quartz (Sec. 7.7).

These rocks form at pressures of ~3 GPa, which correspond to depths of-100 km.

Some UHP rocks have even been found to contain diamonds, which indicates depths of 200 km.

How rocks from such great depth return to the surface remains a puzzle and is the subject of current research.

In addition, *ultrahigh-temperature* (UHT) rocks have been found that equilibrated near 1000°C.

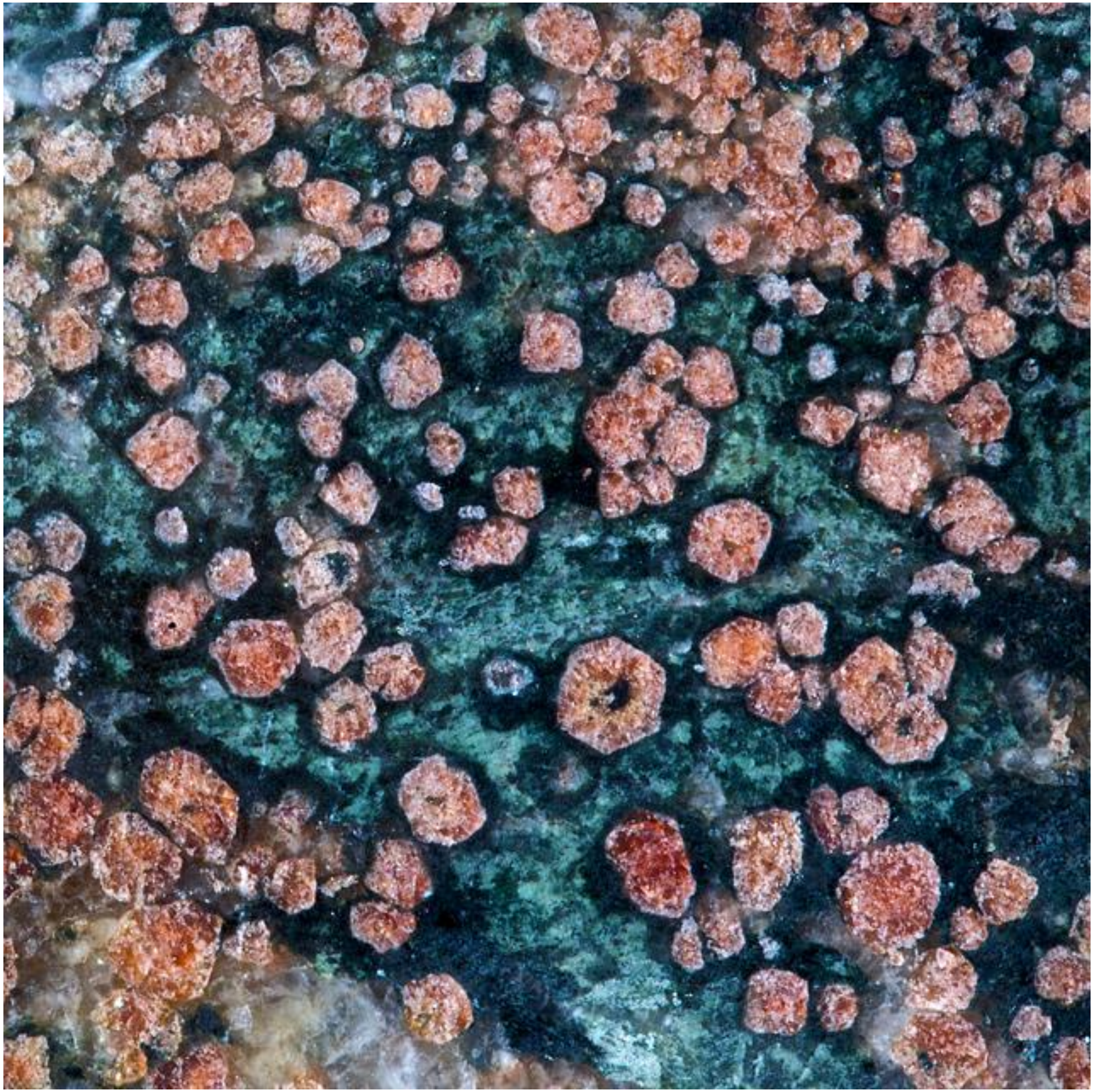
These temperatures are attained in rocks that lack a low-melting fraction or have had all of a low-melting fraction removed at an earlier stage of metamorphism.

The large latent heat of fusion of rocks normally puts a cap on metamorphic temperatures.

Assigning a rock to a particular metamorphic facies requires careful study of the mineral assemblage, usually through the use of thin sections.

Some of the most common minerals found in the different metamorphic facies are given in Table 14.1.

These may help us determine an approximate metamorphic grade, but it is important to emphasize that assignation to a metamorphic facies is dependent on an entire mineral assemblage and not the presence of a single mineral.



Eclogite from the Mariánské Lázně Complex in the west Czech Republic. Keele collection. Check out those gorgeous pink garnets!
Photo courtesy of Ian Stimpson.

A Scottish eclogite from the Lewisian inlier, Glen Beag, Glenelg.Keele collection. Photo courtesy of Ian Stimpson.

Thank you

Metamorphic Facies

(Tarbuck and Lutgens

A metamorphic facies is a set of metamorphic Mineral assemblages that were formed under similar pressures and temperatures.

The assemblage is typical of what is formed in conditions corresponding to an area on the two dimensional graph of temperature vs. pressure (See diagram at right).

Rocks which contain certain minerals can therefore be linked to certain tectonic settings, times and places in the geological history of the area.

The boundaries between facies (and corresponding areas on the temperature v. pressure graph) are wide because they are gradational and approximate.

The area on the graph corresponding to rock formation at the lowest values of temperature and pressure is the range of formation of sedimentary rocks, as opposed to metamorphic rocks, in a process called diagenesis.

The name facies was first used for specific sedimentary environments in sedimentary rocks by Swiss geologist Amanz Gressly in 1838.

Analogous with these sedimentary facies a number of metamorphic facies were proposed in 1920 by Finish petrologist Pentti Eskola.

Eskola's classification was refined by New-Zealand geologist Francis John Turner throughout his career.

A classic work of Turner's was the book he published in 1948 titled Mineralogical and Structural Evolution of Metamorphic Rocks.

Turner continued to work in the field, refining the metamorphic facies classifications through the end of his career in the early 1970s.

The different metamorphic facies are defined by the mineralogical composition of a rock.

When the temperature or pressure in a rock body change, the rock can cross into a different facies and some minerals become stable while others become unstable or metastable.

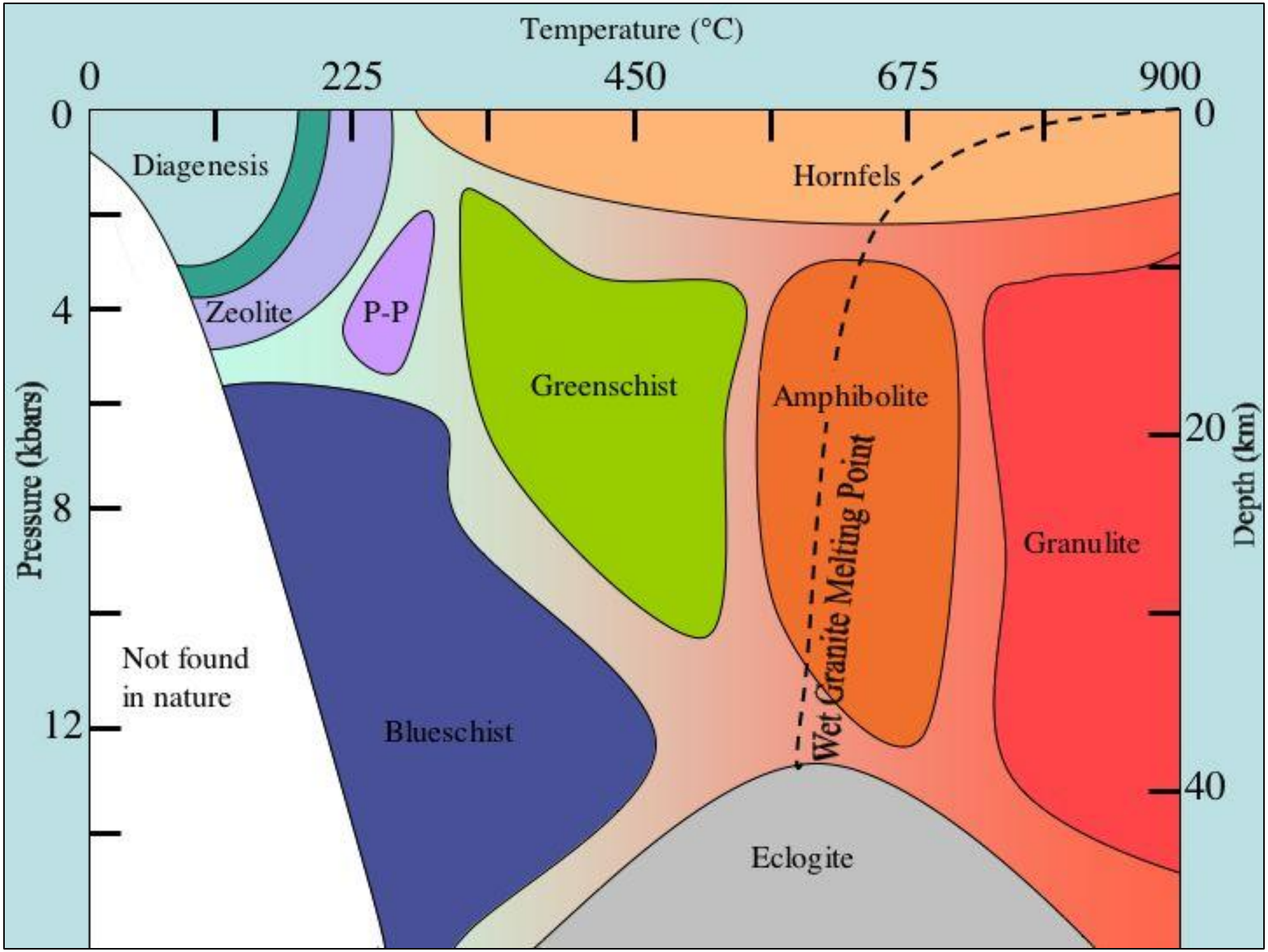
The minerals in a metamorphic rock and their age relations can be studied by optical microscopy or Scanning Electron Microscropy of thin sections of the rock.

Apart from the metamorphic facies of a rock, a whole terrane can be described by the abbreviations LT, MT, HT, LP, MP, HP (from low, medium or high; pressure or temperature).

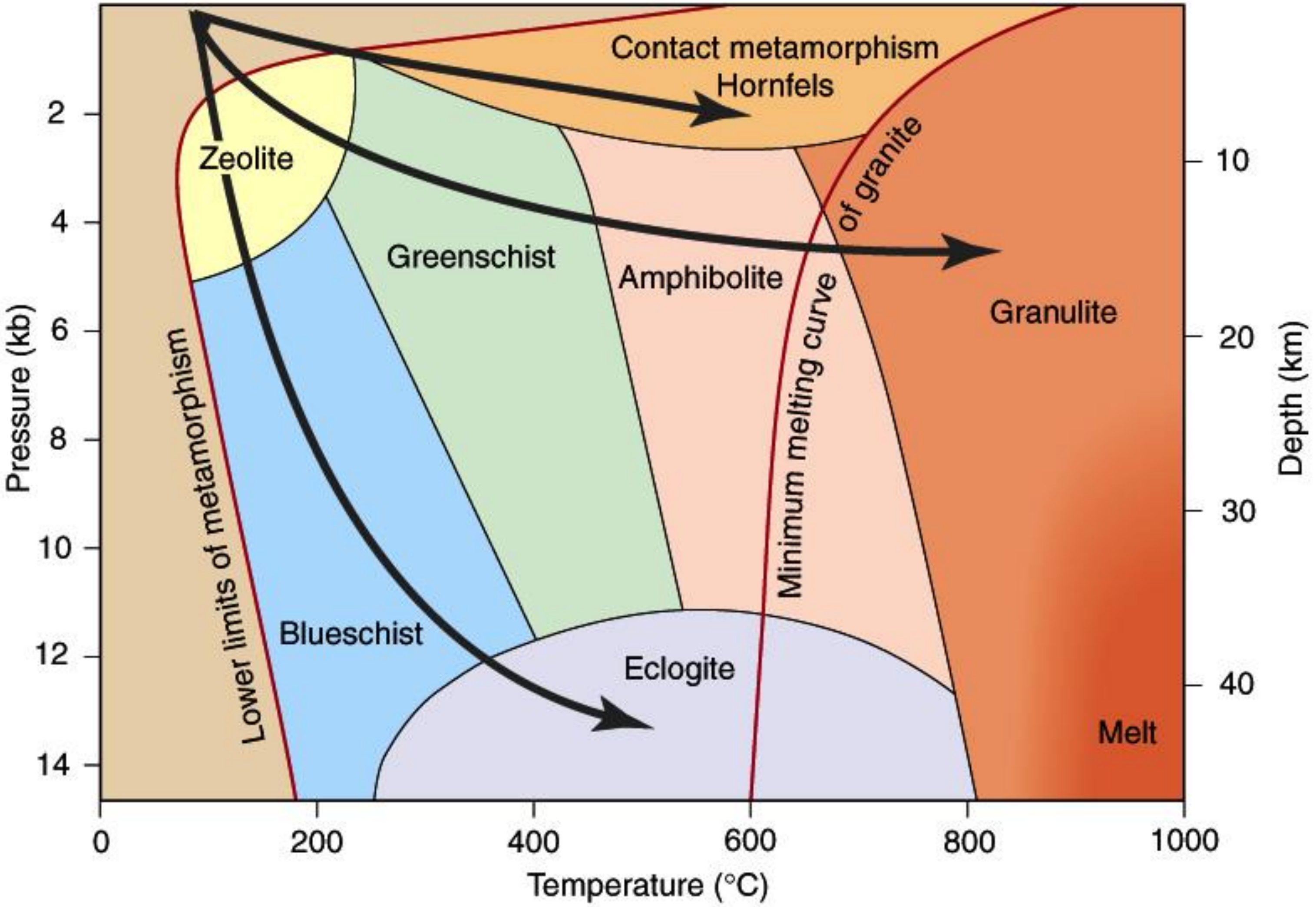
Since the 1980s the term UHP (ultra high pressure) is used for rocks that saw extreme pressures.

Which minerals grow in a rock is also dependent of the original composition of the protolith (the original rock before metamorphosis). Carbonate rocks have a different composition from say a basalt lava, the minerals that can grow in them are different too.

Therefore, a metapsammite and a meta pelite will have different mineralogical compositions even though they were in the same metamorphic facies.



Types of metamorphic facies



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Every metamorphic facies has some index minerals by which it can be recognized.

That does not mean these minerals will necessarily be visible with the naked eye, or even exist in the rock; when the rock did not have the right chemical composition they will not grow.

Very typical index minerals are the polymorphs of aluminosilicate (Al2SiO5, all are neosilicates).

Andalusite is stable at low pressure, kyanite is stable at high pressure but relatively low temperature and sillimantie is stable at high temperature.

End