

METAMORPHIC ROCKS

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Contents

1. Introduction: What are Metamorphic Rocks?
 2. Controls on Metamorphism
 - 2.1. Heat
 - 2.2 Pressure
 - 2.3 Fluids
 - 2.4 Time
 - 2.5 Rock Composition
 3. Metamorphic Reactions
 4. Metamorphic Textures
 5. Classification of Metamorphic Rocks
 - 5.1 Classification of Foliated Rocks
 - 5.2 Classification of Nonfoliated Rocks
 6. Types of Metamorphism
 7. Metamorphic Zones and Facies
 8. Metamorphism and the Rock Cycle
 9. Metamorphism and Plate Tectonics
- Glossary
Bibliography
Biographical Sketches

Summary

Metamorphic rocks form below the Earth's surface primarily as a result of pressure, heat and circulating fluids, which cause changes in the mineral composition and texture of the parent rocks. Metamorphic processes contrast with sedimentary processes, which take place at the Earth's surface, and with igneous processes because metamorphic changes occur while the rock remains a solid.

Temperatures in the crust and upper mantle typically increase with depth. The rate of increase in a given region is known as the geothermal gradient and varies depending on the tectonic environment. In stable continental regions, temperature increases by about

20° to 25°C per km. The geothermal gradient is much lower near subduction zones and significantly higher near magmatic arcs. Heat, pressure and fluids are the agents of metamorphism. In order for a rock undergoing metamorphism to reach a new state of equilibrium, sufficient time is needed for the reactions that produce stable minerals to take place. As the rate of reaction increases exponentially with temperature, reactions tend to go to completion in the lower crust, but are sluggish in the upper crust.

Confining pressure is a pressure that acts on the rock equally in all directions and results in a change in volume, but not shape and, therefore, produces rocks that lack mineral alignment (nonfoliated). Directed pressure occurs when the push in one direction is stronger than another and leads to a change in shape and the formation of a foliation, produced by the alignment and segregation of minerals. Fluids facilitate metamorphism by transporting energy and ions to the site of mineral reactions. The chemistry of the parent rock also has a profound influence on the metamorphic minerals formed. Metamorphic rocks are subdivided into foliated and nonfoliated varieties and are respectively classified according to grain size and composition. With increasing grain size, foliated metamorphic rocks are termed slate, phyllite, schist and gneiss. Under extreme metamorphic conditions, in which partial melting occurs, the mix of melt and solid residue is called a migmatite. Nonfoliated metamorphic rocks are characterized by textures of interlocking crystals. Metamorphic transformations can be written as balanced chemical reactions. Increasing temperature favours the mineral assemblage that occupies the greater volume. Increasing pressure, on the other hand, generally favours the stability of denser minerals. In reactions involving fluids, increasing temperature favours the side of the reaction that contains fluid.

Regional metamorphism takes place over wide areas, is usually associated with mountain building and, therefore, typically produces foliated rocks. Contact metamorphism occurs when a rock is heated by an adjacent igneous body and produces nonfoliated rocks, such as hornfels. Dynamic metamorphism occurs adjacent to fault zones and involves crushing or smearing of rocks. Impact metamorphism is the result of meteorite impacts and produces high pressure minerals, such as stishovite. Hydrothermal metamorphism is produced by the circulation of hot fluids. Differences in mineralogy between metamorphic rocks of similar composition reflect variations in the grade of metamorphism. Some mineral assemblages are very common, implying that they formed within a range of pressure and temperature conditions characteristic of the crust. Metamorphism of various rocks under similar conditions of pressure and temperature produces what is known as a metamorphic facies.

Uplift and erosion of mountain belts eventually exhumes deeper crustal levels so that metamorphic rocks are exposed at the Earth's surface. Metamorphic rocks tend to preserve their highest temperature assemblage because reaction rates are highest at elevated temperatures. The rate of uplift is also usually too rapid for the mineral assemblage to adjust, and the rock will have lost fluid so that "retrograde" reactions are inhibited. Variations in the amount of uplift result in the reaction surfaces intersecting the Earth's surface, allowing isograds to be mapped. Metamorphism due to subduction or collision produces two types of metamorphic belts, known as paired metamorphic belts. The descent of cold oceanic lithosphere cools the adjacent rocks, resulting in a low geothermal gradient (about 5°C per km) and high pressure-low temperature metamorphism producing minerals that are typical of either the blueschist or eclogite

facies. Above the subduction zone, the ascent of fluids and magma warms the crust, producing minerals typical of high temperature-low pressure metamorphism. Collisional settings typically involve the thrusting of one plate on top of another, producing crustal thickening. The effects of thrusting are essentially instantaneous and result in dramatic increases in pressure in the lower plate. As silicate rocks are poor conductors of heat, increases in temperature lag behind pressure increases. However, when the temperatures eventually increase, the crust may undergo partial melting and form migmatites.

1. Introduction: What are Metamorphic Rocks?

Metamorphic rocks, one of three basic rock categories, are formed by the recrystallization of older (pre-existing) rocks due to changes in temperature, pressure and/or fluid conditions at depths below the Earth's surface. This action results in changes in mineral composition and texture while the rock remains in a solid state (meaning the rock does not melt). Metamorphic rocks can be derived from igneous, sedimentary, or even from other metamorphic rocks. The origin of metamorphic rocks, therefore, contrasts with the origin of igneous rocks, which derive from the cooling of molten rock, and sedimentary rocks, which are the products of surface processes. The study of metamorphic rocks enables us to learn about the processes and conditions that exist at various levels within the Earth's crust.

Metamorphism is defined as the mineralogical, textural, chemical, and structural adjustments of rocks to new conditions and/or environments that have been imposed at depth in the Earth's crust. The new environment differs from the original conditions under which the rocks formed. Metamorphism (from the Greek words meaning "to change form") is recrystallization in the solid state in order to restore/achieve equilibrium with the new environment. It is essentially an isochemical process (no new elements or chemical compounds are introduced or removed), with the exception of volatiles (water-rich fluids), which may be added or expelled.

When crustal rocks are buried, they become subjected to increasing temperatures and pressures with depth, and interact with hot fluids present in the crust. The original minerals of the parent rock may become unstable and react to produce minerals that are stable under these new conditions. If the physical conditions cause the rock to change in volume, or the minerals to alter their shape, then the rocks may also alter their texture.

Should significant chemical changes occur during recrystallization, the process is termed metasomatism. Metasomatism is a replacement process by which a new mineral (or minerals) of partly or wholly different chemical composition may grow in the body of an old mineral aggregate. It involves the removal of old material and the addition of new material (by a loss and gain of ions and atoms). Metasomatism accompanies the formation of many ore deposits.

As metamorphic processes have operated throughout Earth's history, they have affected most crustal rocks. However, since these processes typically take place at depth, they are generally hidden from direct observation. They become exposed at the surface by the uplift and erosion of overlying rocks, which typically occur in the later stages of mountain building. Metamorphism can occur anywhere from the base of the crust to

within a few kilometers of the Earth's surface. As many mineral assemblages have only a limited stability range, their identification indicates the pressure and temperature of metamorphism, whereas the textures provide important clues about the nature of stresses that occur at various levels in the crust. (For related kinds of rocks see *Volcanic and Magmatic Rocks* and *Sedimentary Rocks*).

2. Controls on Metamorphism

The agents of metamorphism include heat, pressure, and chemically active fluids, which typically act in combination. Although it is often difficult to distinguish the effects of individual agents in a metamorphic rock, the contribution of each agent may vary from one setting to another. These agents take the rock from an unstable state towards a state of equilibrium. However, minerals respond to these changing conditions very slowly. For equilibrium to be achieved, sufficient time is required for the mineralogical reactions and textural adjustments to proceed to completion. In addition, the minerals formed in a given metamorphic rock depend on the chemical composition of the parent rock, or protolith. The chemistry of the parent rock provides the basic ingredients for the changes that take place. As in preparing a meal, the end product is pre-determined by the starting ingredients.

2.1. Heat

Heat is probably the most important factor contributing to metamorphism. It provides the energy to power chemical reactions that form new minerals. Heat is a measure of the total kinetic energy of all the molecules in a substance, whereas temperature is the average kinetic energy of those molecules. As the temperature rises in a given mineral, the vibrations of its ions become more violent/rapid and collisions with neighboring ions may occur. To accommodate the increase in temperature, the mineral expands, so that the average distance between neighboring ions increases. As a result, the chemical bonds that hold the mineral together become strained. Continued heat input may eventually cause the bonds to break, allowing new minerals to form while old ones are destroyed. The new minerals, which are stable at higher temperatures, have more open (less tightly packed) crystal structures and a lower specific gravity.

Heat also plays an important role in accelerating the rate of the metamorphic/chemical reactions that produce new minerals. The rates of reaction rise exponentially with temperature and, therefore, mineral reactions and growth take place more rapidly at deeper crustal levels where temperatures are high. As a consequence, in most environments, the grain size of a metamorphic rock tends to increase with depth in the crust. Heat also mobilizes water and gases in the rock. These fluids facilitate element exchange within the rock mass and accelerate the reaction rates. In addition, heat modifies the mechanical properties of the rocks and enables them to be plastically deformed.

Temperatures within the Earth's hard outer shell, or lithosphere, typically increase with depth. The rate of temperature increase associated with increasing depth is known as the geothermal gradient (Figure 1). Depending on the tectonic environment, the geothermal gradient varies from about 10°C to 30°C per km (see *Internal Forces*).

In general, metamorphism occurs at temperatures high enough to change the parent rock, but not so high that it melts. The range of temperatures of metamorphism varies from about 200°C to 1200°C depending on the pressure, amount of fluids, and rock composition. In tectonically stable continental interiors, a temperature of 200°C generally corresponds to a depth of about 10 km. In tectonically active regions, this temperature may be achieved at a shallower depth, especially if the rocks were close to hot magmatic intrusions.

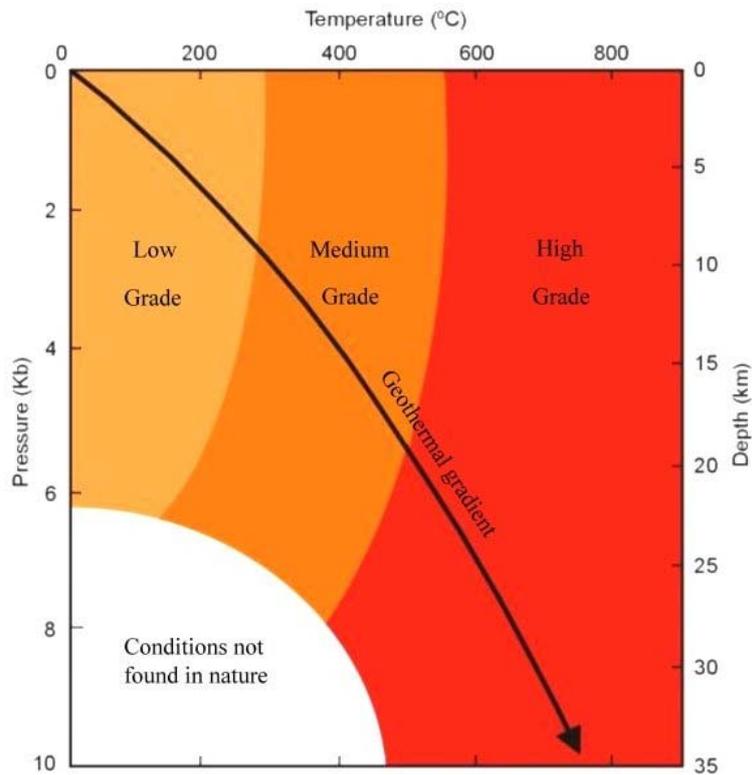


Figure 1. Metamorphic grade increases with depth because temperature and pressure rise with depth. The curve shows the path of increasing temperature and pressure with depth (geothermal gradient) in a normal area of the continental crust.

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Biographical Sketches

Jaroslav Dostal received his initial education in geology at Charles University in Prague, Czechoslovakia. He was a lecturer at that university before emigrating to Canada where he received his doctoral degree from McMaster University in Hamilton, Ontario, in 1974. After a year of postdoctoral studies at Dalhousie University, Halifax, Nova Scotia, he was hired by Saint Mary's University in Halifax where he is now a professor of geology. Dr. Dostal has also worked as a researcher at the Universite de Montpellier, and the Universite d'Aix-Marseille, France, and the Universita di Modena, Italy. He has authored or co-authored over 150 papers in academic journals as well as more than 200 conference abstracts and other publications.

Brendan Murphy is an Irish citizen who completed high school and his B.Sc. degree in Ireland, before emigrating to Canada in 1975. He acquired an M.Sc. from Acadia University in Wolfville, Nova Scotia, in 1977 and a doctorate degree from McGill University (Montreal, Quebec) in 1982. In 1982, he joined St. Francis Xavier University, where he is now a professor of geology. He has published over 100 scientific articles in academic journals, book chapters, monographs, or geological field guidebooks, and has authored or co-authored more than 120 conference abstracts.

Damian Nance is a citizen of both the United Kingdom and the United States. He received his education in geology in England with a B.Sc degree from the University of Leicester in 1972 and a doctoral degree from Cambridge University before emigrating to Canada in 1976 to teach at St. Francis Xavier University in Nova Scotia. In 1980, he joined Ohio University where he is now a professor of geology. He has published over 150 scientific articles in academic journals, books and government documents, and has authored or co-authored more than 180 conference abstracts.