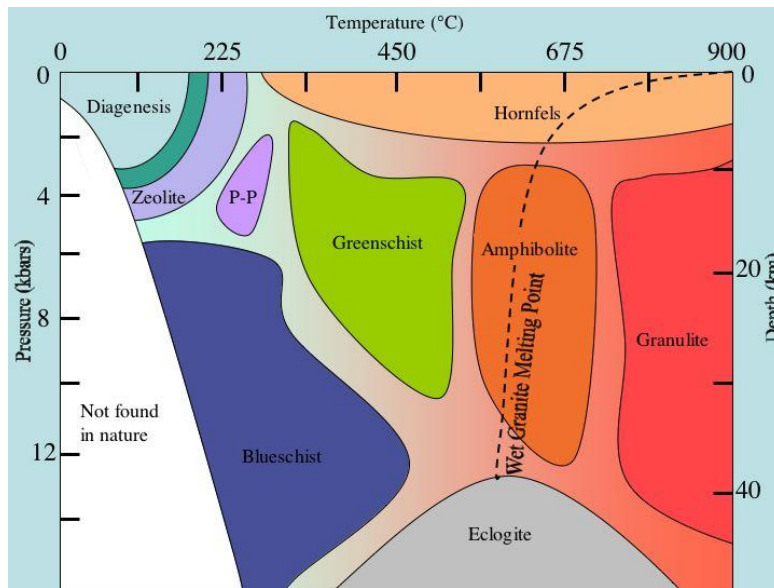


Metamorphic Facies Series



Zeolite facies

In the zeolite facies, sediments and volcanic debris show the first major response to burial. Reactions are often not complete, and typical metamorphic fabrics may be poorly developed or not developed at all. This is the facies of burial metamorphism.

The zeolite facies was first described from southern New Zealand, but similar rocks have now been described from many younger mountain regions of Earth, particularly around the Pacific margin and the European Alps. Typically, the rocks are best developed where reactive volcanic materials (often partly glassy) are common and the characteristic minerals include zeolites, which are low-density hydrated silicates, stable at temperatures rarely exceeding 300 °C (572 °F). Typical mineral assemblages include heulandite, analcite, quartz with complex clay minerals (montmorillonite), micaceous phases such as chlorite and celadonite, and the potassium feldspar adularia. At higher grades of metamorphism, the zeolite laumontite and the feldspar albite dominate the mineral assemblage. In New Zealand these are developed in a rock column that is about 15 km (9.3 miles) thick. Calcareous rocks (impure limestones) show very little response to this grade of metamorphism.

Prehnite-pumpellyite facies

Along with the zeolite facies, the prehnite-pumpellyite facies received little attention until about 1950. The first rocks of the facies were described in New Zealand and Celebes. The facies is transitional, bridging the path to the blueschist facies or the greenschist facies. It is particularly well developed in graywacke-type sediments. The two minerals prehnite and pumpellyite replace the zeolite minerals of the zeolite facies and are themselves replaced by epidote minerals in the greenschist facies and by lawsonite and pyroxenes in the blueschist facies. Typical minerals in this facies are quartz, albite, prehnite, pumpellyite, chlorite, stilpnomelane, muscovite, and actinolite. Almost all the minerals are hydrated, and, except for chlorite, they bear little resemblance to the minerals of sediments. This facies has been most described from younger mountain ranges of the

Pacific margin.

Blueschist facies

Rocks of the blueschist facies represent deep metamorphism under conditions of a low thermal gradient. The characteristic locale for this type of metamorphism appears to be along a continental margin being underthrust by an oceanic plate. Regions in which blueschists are found are also regions of great seismic and volcanic activity, such as the Pacific margin. The best described examples of this class of metamorphism come from California, Japan, New Caledonia, Celebes, the Alps, and the Mediterranean region. At present there are no confirmed examples of glaucophane schists predating the Paleozoic Era. Because of the presence of the blue amphibole glaucophane and minerals such as garnet and jadeite, these schists are among the most attractive of metamorphic rocks.

Characteristic minerals of the facies include quartz, glaucophane, lawsonite, jadeite, omphacite, garnet, albite, chlorite, muscovite, paragonite, epidote, and kyanite. In calcareous rocks, calcite may be replaced by the high-pressure polymorph aragonite. In general, the facies is characterized by many high-density minerals reflecting a high pressure of formation.

Eclogite facies

The eclogite facies was initially recognized in rocks only of basaltic composition, which are transformed at the pressure-temperature conditions of the eclogite facies into spectacular red and green rocks composed of the anhydrous mineral assemblage garnet plus omphacite. The garnet is rich in the high-pressure species pyrope, and the omphacite is rich in the high-pressure pyroxene jadeite. Small amounts of minerals such as kyanite, zoisite, and hornblende may be present. The rocks are of high density and frequently show little or no schistosity. It is now known that protoliths other than basalt also can be metamorphosed to pressures and temperatures characteristic of the eclogite facies, and a wide variety of mineral assemblages can be stable at these conditions, including several hydrous mineral phases. Minerals that have been observed in metapelites include magnesium-rich chloritoid and staurolite, kyanite, garnet, phengite (a muscovite mica with high magnesium and silicon and low aluminum content), chlorite, and talc. Experimental work shows that pelitic rocks composed primarily of talc and kyanite, which are referred to as whiteschists, can be stable from pressures of approximately 6 kilobars (about 5,900 standard atmospheres) up to greater than 30 kilobars (about 29,600 standard atmospheres). Minerals observed in eclogite-facies calcareous rocks include magnesite, dolomite, zoisite or epidote, and omphacite.

Because of the high density and composition, it was proposed long ago that part of the upper mantle might be made of eclogite. Such a view is supported by eclogitic intrusions in volcanic rocks and by eclogitic inclusions in diamond-bearing kimberlite, which must come from the upper mantle. Some workers also think that eclogites found in metamorphic terrains in Norway, California, U.S., and the European Alps could also come from the mantle by tectonic processes (see tectonic landform).

Early experimental work on eclogites of basaltic bulk composition suggested that eclogites could generally be stable only if water pressure was much lower than the lithostatic pressure (the stress

exerted on a body of rock by surrounding rock), and the facies was thus thought to represent dry high-pressure metamorphism of basaltic protoliths. Subsequent work on the more diverse protolith compositions revealed, however, that a wide range of water pressures is possible in the eclogite facies and that fluid compositions in equilibrium with the eclogite minerals also probably vary greatly. Indeed, fluid inclusions (tiny bubbles of fluid trapped within mineral grains) in eclogite samples provide evidence of fluids containing nitrogen, salts, and carbon dioxide in addition to water. Eclogite metamorphism is therefore not confined to dry environments but results instead from metamorphism of a variety of rock types at pressures above about 10 kilobars, corresponding to burial to approximately 35 km (21.7 miles), and at temperatures ranging from about 400 to 1,000 °C (752 to 1,832 °F). The temperatures of the eclogite facies overlap those of the greenschist, amphibolite, and granulite facies, but the higher pressures result in distinctly different mineral assemblages characterized by high-density mineral phases.

Greenschist facies

The greenschist facies was once considered the first major facies of metamorphism proper. The name comes from the abundance of the green mineral chlorite in such rocks. Because chlorite and muscovite are ubiquitous and because both exhibit a platy crystal habit, these rocks normally show a highly developed foliation and often exhibit strong metamorphic differentiation. They have been described from practically every metamorphic terrain on Earth, from earliest Precambrian to the young mountain regions. In fact, many of Earth's oldest rocks (about 3 billion to 4.28 billion years old) of the continental shield areas are in this facies, classic examples of which are in the Appalachians, the Highlands of Scotland, New Zealand, the European Alps, Japan, and Norway.

The dominant minerals of greenschists formed from silicate-rich sediments include quartz, albite, muscovite, chlorite, epidote, calcite, actinolite, magnetite, biotite, and paragonite. Minerals less common include the manganese-rich garnet spessartine, stilpnomelane, kyanite, rutile, sphene (titanite), pyrophyllite, and chloritoid. Calcareous rocks are dominated by calcite, dolomite, and quartz; the major carbonate minerals are thermally stable. It is only when large quantities of water flush away carbon dioxide or keep its partial pressure low that carbonate-silicate reactions take place and liberate carbon dioxide. The typical minerals of this facies have lower water contents than the zeolite facies minerals do.

Amphibolite facies

The amphibolite facies is the common high-grade facies of regional metamorphism, and, like the greenschist facies, such rocks are present in all ages from all over the world. Their characteristic feature is the development of the most common amphibole, hornblende, in the presence of a plagioclase feldspar and garnet. The rocks are normally highly foliated or schistose. Many zones or isograds subdividing the facies have been recognized, and classic studies have been made in the Highlands of Scotland, New Hampshire and Vermont in the United States, Switzerland, and the Himalayas.

Characteristic minerals derived from pelitic rocks are quartz, muscovite, biotite, garnet, plagioclase, kyanite, sillimanite, staurolite, and orthoclase. Minerals derived from basaltic rocks include hornblende, plagioclase, garnet, epidote, and biotite. Those derived from calcareous rocks are

calcite, diopside, grossular (garnet), zoisite, actinolite (hornblende), scapolite, and phlogopite. Minerals from magnesium-rich ultramafic rocks are chlorite, anthophyllite, and talc. In most common types, water is present in minerals only of the mica and amphibole families, and, with their water contents of only about 1 to 3 percent, dehydration is nearing its metamorphic climax.

Granulite facies

In rocks of basaltic composition, the granulite facies is an anhydrous facies that results from progressive dehydration of amphibolites at high temperature. Rocks of other bulk compositions may retain some hydrous minerals, such as biotite and hornblende, but it is likely that water pressure is lower than lithostatic pressure during most granulite facies metamorphism. Evidence for relatively low water pressures comes from fluid inclusion data indicating carbon dioxide-rich fluid compositions and from preservation of some bulk compositions that should have undergone nearly total melting at granulite temperatures if water pressure had been equal to lithostatic pressure.

Rocks of this facies frequently have a granular texture quite similar to plutonic igneous rocks. Schistosity is only weakly developed. Typical minerals of the facies are quartz, alkali feldspar, garnet, plagioclase, cordierite, sillimanite, and orthopyroxene. In calcareous members, dolomite, calcite, diopside, and forsterite occur; and it is in this facies that minerals of the scapolite family are best developed. Small amounts of hornblende are often present. A rare mineral occurring in this facies is sapphirine. The rock type charnockite (from Tamil Nadu, India), essentially a orthopyroxene granite, is normally included in this facies.

It appears from experimental studies that during ultrametamorphism, when melting starts, the basic reactions which take place are of the type

biotite + other minerals → melt + residue

hornblende + other minerals → melt + residue.

The first melts to form are partly wet granitic or granodioritic melts, and phases such as biotite and hornblende break down by producing a partly wet melt from the least refractory phases in the rocks. They would persist to much higher temperatures in other systems of their own composition. The residue in the above equations is a granulite-facies metamorphic rock containing phases such as pyroxene and sillimanite. Thus it is probable, but certainly not universally accepted, that many granulites are formed only in the presence of a silicate liquid. This liquid may, of course, move to higher crustal levels.

Large areas of granulite facies rocks are confined almost entirely to Precambrian areas of the continents (those areas that were formed more than 541 million years ago), with well-developed areas exposed in Canada, India, Africa, Antarctica, Greenland, and the Adirondack Mountains of New York in the northeastern United States. Smaller areas of granulite facies rocks occur in younger mountain belts, with Paleozoic examples in New England (U.S.) and Brittany and Paleogene and Neogene examples (those formed between about 66 million and 2.6 million years ago) in British

Columbia (Canada) and Timor. The apparent decrease in the volume of granulite facies rocks with decreasing age of metamorphism has led some geologists to postulate, as mentioned above, that plate-tectonic processes might have changed significantly with time—specifically that steady-state continental geotherms were hotter in Precambrian time than at the present time. Some work on pressure-temperature-time paths in granulites also suggests that Precambrian granulites were metamorphosed along distinctly different paths than younger granulites, lending credence to models invoking changes in tectonic processes. An alternative hypothesis is that large volumes of granulites have been formed throughout Earth history but that they have not yet been exposed by erosion. Pressures calculated from fragments of granulite-facies metamorphic rocks carried to the surface in young volcanic eruptions suggest that the fragments were derived from the lower crust. It is likely that the lower crust is currently composed largely of granulite-facies rocks that may be exposed by future episodes of mountain building, but it is also possible that these granulites will prove to be different from their Precambrian counterparts. In order to resolve some of the controversies surrounding the origin and composition of granulites, it is necessary that considerable studies of these rocks be conducted in the future.