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Metamorphism: the process that changes ugly ducklings into swans

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Metamorphism as the process that changes ugly ducklings into swans can be illustrated by comparing a Middle Lias mudstone sediment, which was fine-grained, with its metamorphosed equivalent, a schist containing garnets or beautiful minerals such as kyanite. Another example is the Carboniferous Limestone found around Bristol and South Wales which contains fossils and consists of clays and carbonates. When this is metamorphosed under the right conditions the end product contains garnets and wollastonite.

Metamorphism as a process of mineralogical and structural change in rocks which takes place in the solid state. This process occurs in response to controls, to physical and chemical changes, which are different from those in which the rocks formed. This can be illustrated with diagrams of a basin environment filling with sediments. The bottom of the basin is dropping as the sediments are deposited so that a thick series of sediments many kilometres deep forms. The sediments at the bottom are squeezed by the pressure of the sediments above. This lithostatic pressure increases with depth and would be about 2 kilobars at around 6 kilometres depth. Also the temperature increases with increased depth. This varies at different points on the Earth s surface, but this rate of change of temperature with depth, the geothermal gradient, is on average 20° or 30°C per kilometre, but can be as much at 500°C per kilometre. Sedimentary rocks are formed from sediments by diagenetic processes which are continuous over a range of temperatures. A boundary of 200°C is chosen for the diagenetic/metamorphic process boundary.

Different controls all have a part to play in determining the type of metamorphic rock formed. The list of important controls include: lithostatic pressure, directed stress, fluid pressure, the chemical activity, temperature, time, presence of water and the type of original rock and its constituents.

The principal agent of metamorphism is heat, but without water many reactions will not reach fruition, or indeed will not start at all. Water occurs in rocks in several different ways: as pore water and some rocks have porosity of up to 90 per cent, but with increased depth porosity decreases.

However, water is carried down to depth by adsorbed or interlayer water and most importantly by crystalline, bound or potential water which is water that is part of the structure of the minerals themselves. For instance, gibbsite contains around 30 per cent water. It has been calculated that there is as much water bound within rocks in the Earth's crust, not counting pore water, as in the oceans. The effect of water upon metamorphic processes can be illustrated by the example of a chemical reaction between magnesium oxide and silica which in the solid state at 750°C and with no water proceeds too slowly to be measured. However in the presence of water the reaction will proceed about 106 to 1010 faster. This would be the equivalent of the reaction proceeding in an hour instead of a million years!

Also water has a part to play when rocks melt. For solids to melt in dry conditions under high pressure the temperature needs to be high also. However, in the presence of water at the same pressure the same solids will melt at lower temperatures. For instance, for granite to begin to melt in dry conditions at atmospheric pressure it needs to be heated to 900°C. However in the presence of water and under 10 kilobar pressure granite will begin to melt at about 630°C.

The variety of metamorphic rocks produced by different sediments can be illustrated as follows. An almost pure sandstone containing only quartz composed of silica, bound by a siliceous cement will only change texturally during metamorphism but not mineralogically. Similarly for a limestone containing 99 per cent calcium carbonate no mineralogical change occurs in nature for although the reaction:

$$CaCO_3 \rightarrow CaO + CO_2$$

will proceed at 800°C and atmospheric pressure, to get this temperature in nature the pressure is high and the reaction will not proceed – thus most changes will be purely textural.

Thus a fine grained chalk will produce a fine grained marble in which the minerals may have a preferred orientation and traces of other elements will produce the distinctive marble colours (e.g.. manganese produces a pink colour).

Rocks from Norway that had started off as being similar to the Middle Lias mudstones were then considered. It was explained that the history of these rocks could be deduced as they started as mud sediments, after burial heating to about 200°C plus directed stress would have produced slates, further pressure and heat would have produced schists in which mineralogical changes would have taken place. After an initial 'seeding', mineral constituents tend to migrate and large minerals grow, such as chlorite and biotite mica. With further temperature increases garnets might form, growing over whatever was in the rock before – these are termed porphyroblasts (the equivalent of phenocrysts in igneous rocks).

Examination of metamorphic rocks from granite intrusion aureoles where there was lithostatic pressure and heat but no directed stress and the resulting hornfels has an almost homogeneous texture.

Many metamorphic rocks are formed at subduction zones where there is great stress. When rocks are squeezed near the surface of the crust they are brittle and break. However, at depth at fairly high temperatures they are ductile and flow. Minerals can show growth at different stages. garnets often show inclusions and from this it can be deduced that the garnets may have grown at an early stage and overgrown an earlier schistosity. Inclusions may be curved showing that the garnets grew under stress; other minerals may grow at a later stage and show a different orientation.

Some minerals, such as kyanite, andalusite and sillimanite, have the same chemical formulas. They are polymorphs, but the chemical constituents are arranged differently to produce the separate minerals. These polymorphs form under different conditions. At high temperatures sillimanite predominates, at high pressures kyanite predominates, but at low temperatures and low pressures andalusite predominates. Thus where these minerals are found much can be deduced about the conditions prevailing when they were formed.

Finally, rocks could be metamorphosed under extreme pressure only, which is dynamic metamorphism, and the resulting rocks show a granulate texture. Also, if temperatures are sufficiently high, above 650°C, in the presence of water, some melting may occur which, when followed by cooling, would give granitic patches within metamorphic rocks – these are migmatites.

In conclusion, it should be remembered that the whole process is cyclic in that sediments at the surface are buried and, under the right conditions, they are metamorphosed, but these rocks return to the surface again (otherwise we would not be able to collect and study them!) to be eroded to become sediments once more.

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