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"Let knowledge grow from more to more
and thus be human life enriched."

Metamorphic Rocks

Metamorphic rocks are rocks that have recrystallized as a result of changes in the physical environment. Such changes may occur by reactions involving only the solid state (*i.e.*, the mineral grains) or, more commonly, by reaction in a fluid medium, which makes up a very small percentage of the volume of the rock at any given instant. Commonly, the fluid medium is an aqueous film present in rock pores and on the boundaries between mineral grains. In a sense, metamorphic rocks are the most common rock types of the solid Earth, primarily because the Earth is a dynamic system whose temperatures and pressures tend to fluctuate in space and time. Because the pressure–temperature (*P–T*) conditions to which rocks of all igneous and sedimentary types may be subjected are almost infinite, the variety of metamorphic rock types is very large indeed.

Mineral response to metamorphism

A very simple mineralogical system and its response to changing pressure and temperature provide a good illustration of what occurs in metamorphism. An uncomplicated sediment at the Earth's surface, a mixture of the clay mineral kaolinite [$Al_4Si_4O_{10}$ $(OH)_8$] and the mineral quartz (SiO_2), provides a good example. Most sediments have small crystals or grain sizes but great porosity and permeability, and the pores are filled with water. As time passes, more sediments are piled on top of the surface layer, and it becomes slowly buried. Accordingly, the pressure to which it is subjected increases because of the load on top, or overburden. For rocks with a density of two to three grams per cubic centimetre, the pressure will increase by 200 to 300 bars (one bar equals atmospheric pressure at an altitude of about 100 metres [300 feet] above sea level) for each kilometre of overburden. At the same time, the temperature will increase because of radioactive heating within the sediment and heat flow from deeper levels within the Earth. On the average, the temperature increases by about 30° C for each kilometre (87° F per mile) of burial.

In the first stages of incremental burial and heating, few chemical reactions will occur in the sediment layer, but the porosity decreases, and the low-density pore water is squeezed out. This process will be virtually complete by the time the layer is buried by five kilometres of overburden. There will be some increase in the size of crystals; small crystals with a large surface area are more soluble and less stable than large crystals, and throughout metamorphic processes there is always a tendency for crystals to grow in size with time, particularly if temperature is rising, because it increases the speed of reaction.

Eventually, when the rock is buried to a depth at which temperatures of about 300° C (600° F) obtain, a chemical reaction sets in, and the kaolinite and quartz are transformed to pyrophyllite and water:

kaolinite + quartz → pyrophyllite + water

$$Al_4Si_4O_{10}(OH)_8 + 4SiO_2 \rightarrow 2Al_2Si_4O_{10}(OH)_2 + 2H_2O.$$

The exact temperature at which this occurs depends on the fluid pressure in the system, but in general the fluid and rock-load pressures tend to be rather similar during such reactions. The water virtually fights its way out by lifting the rocks. Thus, the first chemical reaction is a dehydration reaction leading to the formation of a new hydrate. The water released is itself a solvent for silicates and promotes the crystallization of the product phases.

A second dehydration reaction

If heating and burial are continued, another dehydration reaction sets in at about 400° C, in which the pyrophyllite is transformed to andalusite and quartz and water:

pyrophyllite → andalusite + quartz + water

$$Al_2Si_4O_{10}(OH)_2 \rightarrow Al_2SiO_5 + 3SiO_2 + H_2O.$$

After the water has escaped, the rock becomes virtually anhydrous, containing only traces of fluid in minute and small inclusions in the product crystals. Both of these dehydration reactions tend to be fast, because water, a good silicate solvent, is present.

Although the mineral andalusite is indicated as the first product of dehydration of pyrophyllite, there are three minerals with the chemical composition Al_2SiO_5. Each has unique crystal structures, and each is stable under definite *P–T* conditions (Figure 1). Such differing forms with identical composition are called polymorphs. If pyrophyllite is dehydrated under high-pressure conditions, the polymorph of Al_2SiO_5 formed would be the mineral kyanite (the most dense polymorph). On the other hand, if the original temperature gradient persists, then at a depth of burial corresponding to about 700° C (1,300° F) the polymorphic transformation from andalusite to sillimanite will occur:

andalusite → sillimanite

$$Al_2SiO_5 \rightarrow Al_2SiO_5$$

Sillimanite is more stable than andalusite at high temperatures, but, unless a small amount of water is present in the rock, this reaction may not go to completion even in geological time. If sillimanite does form, however, then the temperature range within the Earth's crust will preserve the sillimanite–quartz assemblage unchanged.

If the forces leading to burial and sinking are reversed when the base of the sedimentary column has reached the sillimanite stage, then the thick column may be pushed up into a mountain range, permitting its observation. The reactions that proceeded during burial tend not to be reversed: with the water of the original sediments gone, the hydrates cannot reform, and chemical reaction rates are always faster in response to rising than to lowering temperatures. The re-exposed column would reveal the metamorphic history of the pile of sediments.

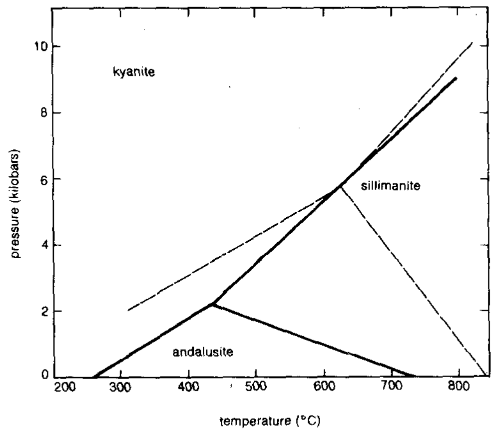

Figure 1: Pressure–temperature regions where the three polymorphic modifications of Al_2SiO_5 are stable. The dashed and solid lines are boundaries provided by different laboratories (see text).

The types of reaction cited here are typical of all metamorphic changes. Gases are lost (hydrates lose water, carbonates lose carbon dioxide), and mineralogical phases undergo polymorphic or other structural changes; low-volume, dense mineral species are formed by high pressures, and less dense phases are favoured by high temperatures. Considering the immense chemical and mineralogical complexity of the Earth's crust, it is clear that the number of possible reactions is vast. In any given complex column of crustal materials some chemical reaction is likely for almost any incremental change in pressure and temperature. This is a fact of immense importance in unravelling the history and mechanics of the Earth, for such changes constitute a vital record and are perhaps the primary reason for the study of metamorphic rocks.

Observations show that pressure is only rarely hydrostatic (equal in all directions) at any point within the Earth's crust. In real cases, consequently, stresses operate that may lead to flow or fracture of materials. Such occurrences produce certain characteristic fabrics or structures in metamorphic rocks that may be observed at the level of the orientation of small crystals in a rock or as a pattern of folds in a mountain range. One of the principal characteristics of most metamorphic rocks is that the arrangement of crystals is not isotropic, or random, but that there is a strong preferred orientation related to the direction of stress components of pressure.

Economic aspects of metamorphic rocks

Many metamorphic reactions result in the gain or loss of water and other volatile compounds, such as the gaseous forms of hydrogen sulfide, carbon dioxide, and hydrochloric acid. At moderate temperatures and pressures, a good solvent for silicates is water; for carbonates, carbon dioxide in water; and for sulfides and elements such as gold, sodium chloride in water. Because large quantities of fluids may take part (perhaps 5 percent by weight of the rocks) in metamorphism, these fluids may transport economically important quantities of other minerals, which either may form deposits in veins or be disseminated in more permeable rocks. Various types of veins often have a very simple mineralogy and are characteristic of metamorphic rocks.

A large number of ore deposits are formed in metamorphic rocks. Practically all gold concentration occurs during metamorphism, even though sedimentary processes may lead to reworking and further concentration. Most important among the many other elements characteristically associated with metamorphic processes are copper, tungsten, zinc, lead, and mercury.

Other metamorphic rocks have useful application as building materials, often because of their peculiar grain sizes and fabrics. Thus, slates characterized by their ability to split or show slaty cleavage have applications wherever erosion- and corrosion-resistant thin materials are wanted. The uses of marble are associated with the increased grain size resulting from the metamorphism of limestones. Serpentines find application because of their beauty when polished; they form during metamorphism by the hydration of certain classes of basic igneous rocks (peridotites and dunites). At times, nickel deposits form during this process. Some metamorphic minerals are of value because of their physical properties or purity. Thus, garnet is often used in abrasives and kyanite as a source of pure aluminum silicate in certain refractory materials.

This article includes treatment of the formation of metamorphic rocks, their physical and chemical characteristics, and their occurrence and distribution as metamorphic facies—*i.e.*, rocks that are associated with a particular set of formative conditions that has given rise to distinctive mineral assemblages or other rock characteristics. For further information on the properties of rocks and minerals and the processes of metamorphism, see MINERALS; SILICATE MINERALS; ROCKS, PHYSICAL PROPERTIES OF; ROCK METAMORPHISM, PRINCIPLES OF; and GEOCHEMICAL EQUILIBRIA AT HIGH TEMPERATURES AND PRESSURES. See also IGNEOUS ROCKS and SEDIMENTARY ROCKS for an overview of rock types that become subject to metamorphism; and ROCK DEFORMATION; MOUNTAIN-BUILDING PROCESSES; and ORE DEPOSITS for coverage of topics intimately related to metamorphic processes.

FORMATION AND CLASSIFICATION OF METAMORPHIC ROCKS

Thermal gradients and pressures

The common metamorphic rocks observed on the Earth's surface, in mountain ranges and areas of deep erosion, are formed from materials within the crust. The average thickness of the crust is around 30 kilometres (20 miles) under the continents and six to eight kilometres (four to five miles) under the oceans. These thicknesses correspond to load pressures on the order of ten kilobars and two to three kilobars, respectively (one kilobar is very nearly 1,000 atmospheres pressure). Occasionally, crustal thickness may approach 60 kilometres (40 miles), and, hence, pressures may approach 20 kilobars. From place to place on the Earth's surface, thermal gradients are quite variable. The average figure quoted is about 30° C per kilometre of depth, but in some regions the thermal gradient is much less (about 10° C per kilometre), and in some active hydrothermal regions it may exceed 100° C per kilometre (300° F per mile) (see EARTH, HEAT FLOW IN). If the temperature at any point in the crust becomes very high, melting will commence, and metamorphic processes will give way to igneous processes. Thus, the melting temperatures of common rocks (800° C [1,500° F] for granites; 1,200° C [2,200° F] for basalts) represent the upper limits of metamorphic temperatures, and in a general way the limits of formation of common metamorphic rocks can be considered to be 100°–1,200° C (200°–2,200° F) and 1–20,000 bars.

Because most of the Earth's mantle (the region beneath the crust) is solid, metamorphic processes may also occur there. Mantle rocks are seldom observed at the surface, because they are too dense to rise, but occasionally a glimpse is presented by their inclusions in solid volcanic materials and in rapid gaseous volcanic extrusions. Such rocks may represent samples from a depth of a few hundred kilometres, where pressures of about 100 kilobars may be operative. The class of rocks known as kimberlites, which contains diamond, the high-pressure form of carbon, is an example. Experiments at high pressure have shown that few of the common minerals that occur at the surface will survive at depth within the mantle without changing to new high-density phases in which atoms are packed more closely together. Thus, the common form of SiO_2, quartz, with a density of 2.65 transforms to a new phase, stishovite, with a density of 4.29. Such changes are of critical significance in the geophysical interpretation of the Earth's interior.

The Earth's oldest rocks

Geologists believe the Earth is about 4,600,000,000 years old. This is also the age of meteoric materials and probably the age of the Moon. The oldest rocks on Earth are found on the continents; ages of about 3,500,000,000 years from Africa and the Soviet Union have been substantiated. These ages were obtained from analyses of igneous rocks, but the rocks themselves intrude metamorphosed sedimentary rocks. The oldest rocks found on earth at this time are metamorphic rocks from Greenland with an age of 3,800,000,000 years. It may be argued, therefore, that the oldest rocks on Earth are metamorphic and that metamorphic processes of the same type as those existing today have been operating since the earliest times, when the Earth was cool enough to allow fragments of the crust to survive. Thus, metamorphic processes affect almost all rocks except those that are being formed at the surface today.

Because metamorphism represents a response to changing physical conditions, those regions of the Earth's surface where dynamic processes are most active will also be regions where metamorphic processes are most intense and easily observed. The vast region of the Pacific margin, for example, with its seismic and volcanic activity, is also a region in which materials are being buried and metamorphosed intensely. In fact, the margins of continents and regions of mountain building are also regions where metamorphic processes proceed with intensity. But in quiet places, where sediments may accumulate at slow rates, less spectacular changes occur; these record changing conditions of pressures and temperatures that act upon each mineral grain. Metamorphic rocks are therefore distributed throughout the geologic column.

Types of metamorphism. It is convenient to distinguish several general types of metamorphism in order to simplify the description of the various metamorphic phenomena. Recognized here are contact, regional, hydrothermal, dynamic, and retrograde metamorphism, each of which will be described in turn.

Contact metamorphism. Whenever the crust is invaded at any level by silicate melts (magmas, from which igneous rocks crystallize within the Earth), they perturb the normal thermal regime and cause a heat increase in the vicinity. If a mass of basaltic liquid coming from the upper mantle is trapped in the crust and crystallizes there, it will heat up the surroundings; and the amount of heating and its duration will be a direct function of the mass of igneous material and its shape. Contact-metamorphic phenomena thus occur in the vicinity of hot igneous materials and at any depth. Under such circumstances pressure and temperature are not simply correlated. Thermal gradients are often very steep unless the igneous mass is very large. Contact aureoles—the surrounding zones of rock that become altered or metamorphosed—vary in thickness from inches (around tabular bodies such as dikes and thin sills) to several kilometres (around large granitic intrusions).

Contact-aureole thickness

If small fragments of rock are totally enclosed in a magma, they may be heated to the temperature of the magma itself. Their metamorphism represents an upper limit to temperature and is sometimes called pyro-metamorphism.

Regional metamorphism. The general term applied to large-scale metamorphism that affects either sedimentary or igneous rocks that are subject to burial is regional metamorphism. Normally there is a simple relationship between depth of burial, pressure, and temperature. Metamorphic rocks are developed on the scale of a mountain range, but among systems (*e.g.*, the Alps or the Urals) the pattern of thermal gradients may differ. Stress is normally operative, and the rocks produced by regional metamorphism have a well-developed fabric.

When low pressures are associated with regional metamorphism, the term burial metamorphism is applied. It occurs on a large scale, and the general distinguishing feature is the presence of a rather low-temperature mineral assemblage and often a lack of any pronounced mineral fabric.

Hydrothermal metamorphism. Changes that occur in rocks near the surface, where there is intense activity of hot water, are categorized as hydrothermal metamorphism. Such areas include Yellowstone National Park, United States; Wairakei, New Zealand; and the Salton Sea, California. It is now generally recognized that the circulating groundwaters that often become heated by proximity to igneous materials produce the metamorphism. Migration of chemical elements, vein formation, and other kinds of mineral concentration may be extreme on account of the large volumes of water circulated.

Dynamic metamorphism. When directed pressure or stress is the dominant agent of metamorphism, it is termed dynamic; other terms are dislocation, kinematic, and mechanical metamorphism. Mineralogical changes occurring on a fault plane provide an obvious example. In some such cases, the action may simply be a grinding up of existing grains or realignment of minerals that have non-equidimensional crystals. If the action is intense, friction may even lead to melting.

The general irreversibility of metamorphic reactions

Retrograde metamorphism. Two reasons explain why metamorphic reactions that occur in response to rising pressure and temperature are not reversed when the rocks ultimately are returned to the Earth's surface, when pressures and temperatures are lower. First, if prograde (initial) reactions involve loss of volatile constituents such as water and carbon dioxide, then, unless these can be supplied again during unloading (erosional stripping away of the overlying rocks), the changes cannot be reversed. This is the most general case. Second, reaction rates generally increase with temperature; thus, prograde reactions are faster than retrograde reactions. Nevertheless, there are few metamorphic rocks that do not show at least some traces of retrograde processes, and these traces may record details of the unloading history.

Metamorphic grade refers to the pressure–temperature relations that are associated with particular metamorphic minerals or mineral assemblages. High-grade metamorphism involves minerals produced under high temperatures and pressures; low-grade metamorphism, the reverse. When rocks are subjected to more than one metamorphic event, the first event may be of a higher or lower grade than subsequent events. If the first metamorphic event affected a given rock at a higher grade than conditions of a later event, the rock may be quite unresponsive chemically, even though new deformation structures may appear. But, if the later metamorphic phase carries the rock into higher grades, the first event may be obliterated, totally or partly. Careful studies of rock textures may reveal the primary metamorphism. Rocks that are products of dry metamorphism, such as eclogites and granulites, are highly susceptible to later events. Low-grade facies such as glaucophane–lawsonite schists are also likely to be altered by later, higher grade changes.

Types of metamorphic rocks. Because of the diverse chemistry, mineralogy, and primary origin of metamorphic rocks and because of the diverse fabrics or textures that may develop depending on the stresses that may operate during their formation, there is no simple, universally used classification of these rocks. In addition, different countries may have their own special terms. In general, any classification of metamorphic rocks tends to stress either their fabric, mineralogy, or primary origin. Some of the most common metamorphic rock types will be described here. Rocks in which metamorphic minerals are easily seen by eye or hand lens and in which the mineral grains have a highly orientated fabric are called schists (Figure 2). Grains of acicular (needlelike) or platy minerals (amphiboles and micas) tend to lie with their long directions parallel or their planar directions parallel. Often the rocks show a pronounced mineralogical layering; quartz layers a few millimetres or centimetres in thickness may lie between mica layers, for example. Other words often qualify schist: greenschist is a schist rich in the green mineral chlorite; blueschist is rich in the blue amphibole, glaucophane; mica-schist is rich in mica; and a graphite-schist is rich in graphite. Schists that are rich in the amphibole hornblende and are often derived by metamorphism of common igneous rocks of the basalt–gabbro type are called amphibolites.

Rock types according to structures and fabrics

A very fine grained metamorphic rock (usually developed from clay-rich sediments) exhibiting perfect planar layering and perfection of splitting into layers (slaty cleavage) is slate. Such rocks are normally rich in micas

By courtesy of W.S. Fyfe

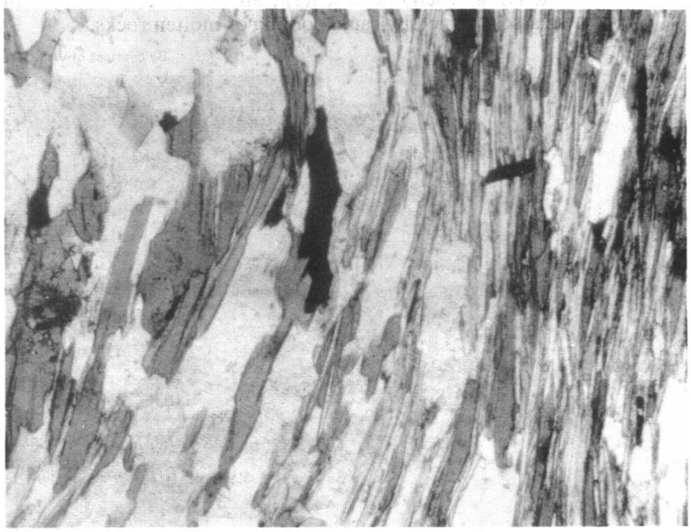

Figure 2: Photomicrograph of a staurolite–biotite schist from Scotland showing strong orientation of biotite crystals (dark) in a matrix of quartz and feldspars (magnification 50 X).

and chlorites. As the intensity of metamorphism increases, a few large crystals may grow (porphyroblasts); such slates are sometimes termed spotted slates. As metamorphism proceeds, the average crystal size increases, and mineral segregation develops; the rock then may be termed a phyllite (Figure 3).

By courtesy of W.S. Fyfe

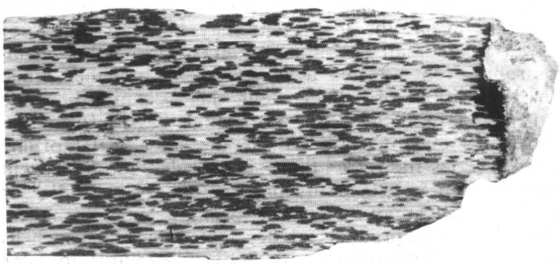

Figure 3: Cross-sectional view of a spotted phyllite from Cornwall, showing the intense stretching of spots (chlorite) in the quartz-rich (white) matrix.

A gneiss is produced by intense metamorphism, at high temperature and pressure. The grain size is coarser than that in schists, and layering is often well developed; mineral orientation is less perfect than in schists, however. Very common granitic gneisses (Figure 4) of Precambrian (more than 570,000,000 years in age) areas have been derived from metamorphism of granitic igneous rocks.

Hornfelses, formed by contact metamorphism, often show little sign of the action of directed pressure. They are fine-grained rocks in which crystals show little orientation. Granulites are products of ultrametamorphism (perhaps often the residue from partial fusion and melting). They tend to be coarse-grained and lack minerals such as amphiboles and micas capable of exhibiting strong orientation. Often they may resemble igneous rocks in appearance.

Rocks derived from the metamorphism of carbonate sediments containing calcite or dolomite are marbles (*q.v.*). The main result of metamorphism is an increase in grain size. Because of the rather equidimensional habit of calcite and dolomite crystals, they rarely appear schistose unless they contain other minerals such as mica.

Mylonites and cataclasites are rocks in which the texture is the result of mechanical shattering of grains. Often they show only slight if any development of new minerals. They form on fault planes or in zones of intense shearing. If the crustal rocks have an appropriate composition, phyllonites may develop where new mica crystals grow parallel to the shearing direction. If shearing is extreme, melting may occur, locally producing a pseudotachylite. Tachylite is a term applied to certain types of glasses formed by rapid cooling of molten rocks.

By courtesy of W.S. Fyfe

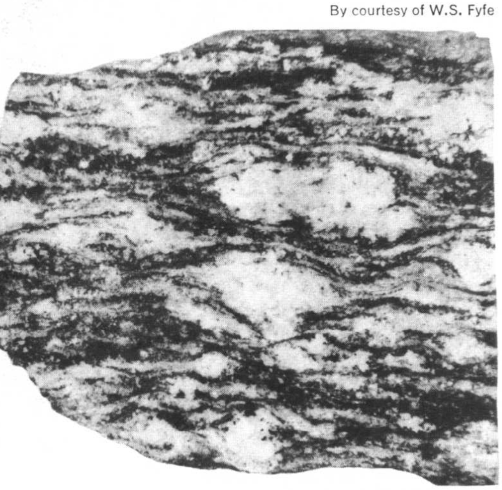

Figure 4: Typical granitic gneiss from Africa with large crystals of feldspar and a matrix containing dark biotite flowing around them.

Rock types according to chemistry and primary origins

Most of the above terms indicate structural or fabric classification of metamorphic rocks. Sometimes terms are used to indicate chemical features. Several types of schists, for example, include the following: pelitic schists contain much Al_2O_3 and often are derivatives of clay-rich sediments; quartzofeldspathic schists are high in SiO_2 and feldspars and often are derivatives of sandstones or quartz-rich igneous rocks; calcareous schists have a high content of lime (CaO) and often are derivatives of impure limestones, dolomites, or calcareous muds; and basic schists contain the elements of basic igneous rocks, namely, calcium, magnesium, and iron.

In addition to the fabric and chemical features of rocks, the primary origin of the material that has been metamorphosed serves as the basis of such names as metagraywacke, the metamorphic product of the voluminous sediment type called graywacke (a sandstone with muddy matrix and profuse rock fragments); meta-basalt, which is derived from basalt; and meta-sediment, a general term stressing the sedimentary origin of the metamorphic rocks.

PHYSICAL AND CHEMICAL CHARACTERISTICS

Metamorphic minerals. It is clear that many more metamorphic minerals than igneous or sedimentary minerals might be expected to exist, simply because the conditions of formation of metamorphic minerals cover a much wider range of temperatures and pressures than those of igneous or sedimentary environments. The most common characteristic minerals of metamorphic rocks are listed in the accompanying Table. Generally, if such minerals are found well developed in a rock, then the rock will be metamorphic. Under some conditions, however, a sediment may contain such mineralogical debris, as from metamorphic rocks that are being weathered and eroded. In such a case, fabric and microscopic study may be needed to identify the rock as metamorphic. To stress changes that occur in response to increasing temperature and pressure, the common metamorphic minerals are listed in that order—*e.g.*, quartz is associated with the lowest temperatures and pressures. Minerals marked with an asterisk may have a wide range of stability; quartz, for example, may be stable in sediments, igneous melts, or almost any type of metamorphic rock. Phases marked with a dagger (†) are minerals of a composition for which more than one form (polymorph) may be found. In some cases a single mineral may be characteristic of a metamorphic facies, but more commonly an assemblage is needed to indicate conditions of metamorphism.

Metamorphic minerals display the complete range of silicate structural types from low-density, open-type structures (*e.g.*, zeolites) to high-density phases, such as garnets and jadeite. Changes in the atomic structural arrangement reflect the geothermal regime quite clearly.

Relation of metamorphic and original rock composition

Rock composition. Common metamorphic rock types have essentially the same chemical composition as what must be their equally common igneous or sedimentary precursors. Common greenschists have essentially the same compositions as basalts; marbles are like limestones; slates are similar to mudstones or shales; and many gneisses are like granodiorites. In general, then, the chemical composition of a metamorphic rock will closely reflect the primary nature of the material that has been metamorphosed. If there are significant differences in composition between a parent material and the metamorphic equivalent, such differences tend to affect only the most mobile (soluble) or volatile elements; water and carbon dioxide contents change significantly, for example. An impure limestone in the system $CaCO_3$–SiO_2 (calcium carbonate–silica) may end up in the system CaO–SiO_2 (calcium oxide–silica). An extreme example is provided by buried salt deposits. In their primary state the chemistry of evaporites (*q.v.*) commonly falls in the system $CaCO_3$–NaCl–$CaSO_4$–H_2O (calcium carbonate–sodium chloride–calcium sulfate–water). They are not represented in the more advanced stages of metamorphism except perhaps by rocks in the system $CaCO_3$–$CaSO_4$ (calcium carbonate–calcium sulfate). Often the greatest part of the rock has been dissolved by metamor-

Common Minerals of Metamorphic Rocks

mineral	composition
Quartz*†	SiO_2
Kaolinite	$Al_4Si_4O_{10}(OH)_8$
Montmorillonite	$(\frac{1}{2}Ca, Na)_{0.7}(Al, Mg, Fe)_4[(Si, Al)_8O_{20}](OH)_4 \cdot nH_2O$
Albite*	$NaAlSi_3O_8$
Calcite*†	$CaCO_3$
Dolomite*	$CaMg(CO_3)_2$
Analcite	$NaAlSi_2O_6 \cdot H_2O$
Laumontite*	$CaAl_2Si_4O_{12} \cdot 4H_2O$
Adularia†	$KAlSi_3O_8$
Chlorite*	$(Mg, Al, Fe)_{12}[(Si, Al)_8O_{20}](OH)_{16}$
Prehnite	$Ca_2Al(AlSi_3O_{10})(OH)_2$
Pumpellyite	$Ca_4(Mg, Fe^2)(Al, Fe^3)_5O(OH)_3(Si_2O_7)_2(SiO_4)_2 \cdot 2H_2O$
Stilpnomelane	$(K, Na, Ca)_{0-1.4}(Fe^3, Fe^2, Mg, Al, Mn)_{5.9-8.2}(Si_8O_{20})(OH)_4(O, OH, H_2O)_{3.6-8.5}$
Epidote*	$Ca_2Fe^3Al_2O(OH)(Si_2O_7)(SiO_4)$
Muscovite*	$KAl_2(AlSi_3O_{10})(OH)_2$
Magnetite*	Fe_3O_4
Hematite*	Fe_2O_3
Pyrite	FeS_2
Glaucophane	$Na_2Mg_3Al_2(Si_8O_{22})(OH, F)_2$
Jadeite	$NaAlSi_2O_6$
Omphacite	a complex solid solution mainly of $NaAlSi_2O_6 - CaMgSi_2O_6 - NaFeSi_2O_6$
Lawsonite	$CaAl_2(Si_2O_7)(OH)_2 \cdot H_2O$
Aragonite†	$CaCO_3$
Magnesite	$MgCO_3$
Tremolite	$Ca_2Mg_5(Si_8O_{22})(OH)_2$
Actinolite	$Ca_2(Mg, Fe)_5(Si_8O_{22})(OH)_2$
Talc	$Mg_3(Si_4O_{10})(OH)_2$
Serpentine†	$Mg_3(Si_2O_5)(OH)_4$
Hornblende*	$(Na, K)_{0-1}Ca_2(Mg, Fe^2, Fe^3, Al)_5(Si_{6-7}Al_{2-7}O_{22})(OH, F)_2$
Plagioclase*	$(NaAlSi_3O_8, CaAl_2Si_2O_8)$
Kyanite†	Al_2SiO_5
Sillimanite†	Al_2SiO_5
Andalusite†	Al_2SiO_5
Microcline†	$KAlSi_3O_8$
Garnet*	a complex solid solution of
	pyrope $Mg_3Al_2Si_3O_{12}$
	almandine $Fe^2{}_3Al_2Si_3O_{12}$
	spessartite $Mn_3Al_2Si_3O_{12}$
	grossularite $Ca_3Al_2Si_3O_{12}$
	andradite $Ca_3Fe^3{}_2Si_3O_{12}$
Staurolite	$(Fe^2, Mg)_2(Al, Fe^3)_9O_6(SiO_4)_4(O, OH)_2$
Chloritoid	$(Fe^2, Mg, Mn)_2(Al, Fe^3)Al_3O_2(SiO_4)_2(OH)_4$
Anthophyllite	$Mg_7Si_8O_{22}(OH)_2$
Orthoclase†	$KAlSi_3O_8$
Anorthite	$CaAl_2Si_2O_8$
Diopside	$CaMgSi_2O_6$
Phlogopite*	$KMg_3(AlSi_3O_{10})(OH)_2$
Scapolite	$(Na, Ca, K)_4[Al_3(Al, Si)_3Si_6O_{24}](Cl, SO_4, CO_3OH)$
Biotite*	$K_2(Mg, Fe^2)_{6-4}(Fe^3, Al, Ti)_{0-2}(Si_{6-5}Al_{2-3}O_{20})(OH, F)_4$
Cordierite	$Al_3(Mg, Fe^2)_2(Si_5AlO_{18})$
Wollastonite	$CaSiO_3$
Forsterite	Mg_2SiO_4
Hypersthene	$(Mg, Fe)SiO_3$
Enstatite	$MgSiO_3$
Tridymite†	SiO_2
Corundum	Al_2O_3
Periclase	MgO
Mullite	$3\,Al_2O_3 \cdot 2\,SiO_2$
Sanidine†	$KAlSi_3O_8$
Larnite	Ca_2SiO_4

*Indicates wide range of stability. †Indicates more than one form (polymorph) exists.

phic fluids, which have carried it to the surface. These fluids, rich in halides, or salts, may play a key role in the transport of ore minerals.

Metamorphic rocks only rarely exhibit a chemical composition that is characteristically "metamorphic." This statement is equivalent to saying that diffusion of materials in metamorphism is a slow process, and various chemical units do not mix on any large scale. But occasionally, particularly during contact metamorphism, diffusion may occur across a boundary of chemical dissimilarity leading to rocks of unique composition. If a granite is emplaced into a limestone, the contact region may be flooded with silica and other components leading to the formation of a metasomatic rock. Often such contacts are chemically zoned. A simple example is provided by the metamorphism of magnesium-rich igneous rocks in contact with quartz-rich sediments. A zonation of the type serpentine–talc–quartz may be found such as:

$$Mg_6(Si_4O_{10})\,(OH)_8/Mg_3\,(Si_4O_{10})\,(OH)_2/SiO_2.$$

In this case the talc zone has grown by silica diffusion into the more silica-poor environment of the serpentine. Economic deposits are not uncommon in such situations; *e.g.*, the formation of the $CaWO_4$ (calcium tungstate) scheelite when tungstate in the form of WO_3 moves from a granite into a limestone contact. The reaction can be expressed as:

$$\underset{\text{calcite}}{CaCO_3} + WO_3\ \text{(solution)} \rightarrow \underset{\text{scheelite}}{CaWO_4} + CO_2\ \text{(gas)}.$$

Metamorphic facies. Metamorphic petrologists working on contact metamorphism early in the 20th century introduced the idea of metamorphic facies to correlate metamorphic events. The concept was first defined in 1914 by a Finn, Pentti Eelis Eskola, as any rock of a metamorphic formation that has attained chemical equilibrium through metamorphism at constant temperature and pressure conditions, with its mineral composition controlled only by the chemical composition. In current usage, a metamorphic facies (Figure 5) is a set of metamorphic mineral assemblages, repeatedly associated in space and time, such that there is a constant and therefore predictable relation between mineral composition and chemical composition.

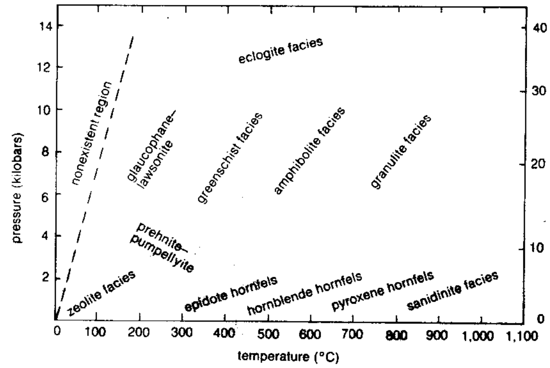

Figure 5: Approximate pressure–temperature regions of the major metamorphic facies (see text).

The facies concept is basically observational. In a layered sequence of sediments, for example, if each layer exhibits a different chemical composition, then it is reasonable to suppose that the different minerals within any single layer represent a response to similar conditions. In other words, the rocks belong to the same facies. In another region, in which the composition is equivalent to that in only one of the sediment layers in the first sequence, the facies concept permits correlation with the more complex assemblages. A facies is defined by a set of rock types, but the naming of facies tends to follow some single common type. The greenschist facies is named after schists formed from basaltic compositions; other facies, such as the zeolite facies, are named after some characteristic mineral type in the rock; still others are named after a textural feature. The definitions of facies suggest that during most metamorphic processes there is a close approach to some equilibrium state, and experimental studies of metamorphic processes substantiate this deduction.

Grades, zones, and facies series

The intensity of metamorphism is called metamorphic grade. A line on a map where the grade of metamorphism is similar would be called an isograd. During regional mapping of metamorphic rocks it is common to record where a particular mineral appears in progressive metamorphism. If the mineral was biotite or garnet in rocks of the greenschist facies, this would be recorded as the biotite or garnet zone. Zones of development of various minerals in contact metamorphism are often mapped and indicate the type of thermal gradient around an igneous intrusion.

If the thermal gradient is very low (high pressure at low temperature), transitions will occur from zeolite facies to glaucophane-schist facies with increasing burial. If the gradient is moderate, the transitions involve zeolite facies that lead to greenschist facies that lead to amphibolite facies that lead to facies of still higher grades. The concept of facies series arises from the attempt to describe and emphasize such major geothermal trends, which have great significance in the major features of Earth dynamics. Thus, the zeolite–glaucophane-schist trend is found only when the rate of downbuckling of the crust is very fast. This type of motion occurs on continental margins and is associated with continental drift.

Textures and fabrics. The study of the fabric of metamorphic rocks has become a highly specialized subject. Modern work has been based on the classic investigation in 1930 of Bruno Sander of Innsbruck, Austria. The study of fabric or structure may reveal the nature and direction of forces acting during dynamic processes within the Earth. If hydrostatic forces prevailed, there would be no reason for the crystals in a rock to show pronounced preferred orientation of their axes, but such preferred orientation of crystals and mineral grains is perhaps the most striking difference between a metamorphic rock and other rock types.

The most obvious features of a metamorphic rock are certain planar features that are often termed s-surfaces. The simplest planar features may be primary bedding (akin to the layering in sedimentary rocks). As the rock crystallizes or recrystallizes under directed pressure, new crystals may grow in some preferred direction, sometimes subparallel to the primary bedding but often at new angles defining new planar structures. At the same time, folding of layers may occur, leading to folds on scales with amplitude of kilometres or millimetres. Fabric symmetry may be represented by nature of deformed fossils, pebbles in a conglomerate, or any objects with a known shape prior to deformation (Figure 6).

By courtesy of J. Ramsay, Imperial College, London

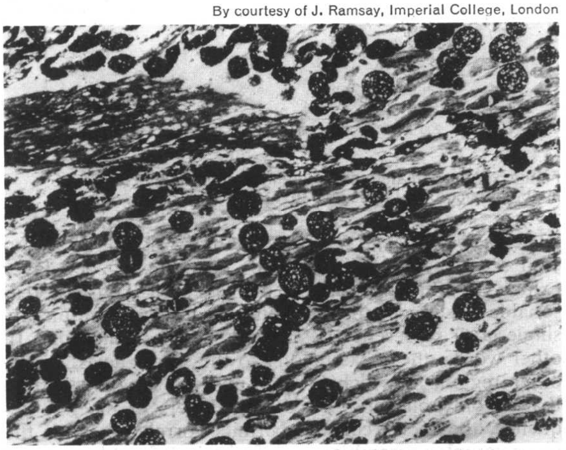

Figure 6: A deformed dolomite–calcite marble from Sardinia containing spherical fossil objects (oolites) about three millimetres in size. Oolites made of dolomite (black circles) are not deformed. Oolites made of calcite (gray), a weaker solid, are smeared out in S forms.

A few terms that commonly are used to describe several types of preferred orientation in metamorphic rocks include foliation, a general term describing any type of s-surface, bedding, or crystal orientation; slaty cleavage, a planar structure leading to facile cleavage that is normally caused by the preferred orientation of mica crystals; schistosity, a term used to describe repetitive and pronounced foliation of the type that is present in schists; and lineation, which is any linear structure, such as the axis of the fold, grooves on a fault plane, or the direction of stretching of pebbles.

Crystalloblastic fabric and laminations

The various mineral phases of a metamorphic rock have different physical properties and symmetries. When a rock is subjected to recrystallization in a stress field, different substances will behave differently according to such physical properties and symmetries. Some crystals always tend to grow in better formed crystals than others; rates of nucleation may differ, and this can lead to different patterns of growth of crystals—there may be a few large crystals or a mass of small crystals. Minerals can be arranged in order of their tendency to form crystals showing planar surfaces, namely, magnetite, garnet, epidote, mica, calcite, quartz, and feldspar. Crystals that tend to form large single crystals (*e.g.*, garnet) are termed porphyroblasts. Porphyroblastic crystals and their contained inclusions often record details of the mechanism of deformation and flow. A spectacular example is provided by the so-called snowball garnets, which have spiral trails of inclusions that indicate rotation during growth (Figure 7).

By courtesy of J. Ramsay, Imperial College, London

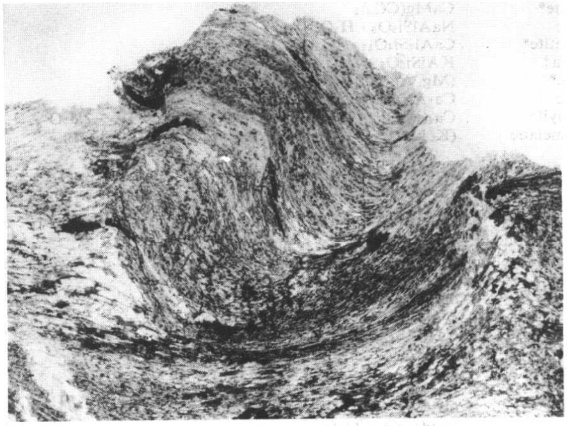

Figure 7: A large garnet crystal (enlarged; one centimetre) growing in a quartz–mica matrix. The garnet contains trails of inclusions and has rotated during growth in the flowing rock medium.

There is a distinct tendency for many types of metamorphic rocks to become laminated, and the separate laminae may have distinct chemical compositions. A rather homogeneous sediment may become inhomogeneous on a scale of millimetres or centimetres. When graywackes are metamorphosed within the greenschist facies, for example, laminae rich in quartz and feldspar alternate with others rich in epidote, chlorite, and muscovite. The precise causes of this process are not well-known, but it must result from a combination of extensive deformation accompanied by recrystallization. In a sense, it is a type of flow unmixing. It is often important to recognize that this structure need have no relation to original bedding in the unmetamorphosed sediments.

ROCKS OF THE PRINCIPAL FACIES

Facies associated with contact metamorphism. Possibly the simplest of all types of metamorphic processes to envisage are those in which hot silicate liquids are intruded into rocks at rather shallow depths. The hot liquids heat up the originally cool rocks, and the extent of the aureole that is formed depends on the size of the intruding igneous body and its temperature. The contact metamorphic rocks of the aureole zone often lack any obvious schistosity or foliation. The facies associated with contact metamorphism include the sanidinite, pyroxenite–hornfels, hornblende–hornfels, and albite–epidote–hornfels facies.

Sanidinite facies. Rocks of the sanidinite facies are represented by small fragments of aureole materials that have often been totally immersed in silicate liquids or by the aureole rocks surrounding volcanic pipes. Very high temperatures are attained, often at very low pressures. The dominant feature of the mineralogy of this facies is an almost complete lack of minerals containing water or carbon dioxide. Many of the minerals show similarity to those of igneous rocks themselves. If the duration of heating is short, adjustment to the imposed temperature is often imperfect.

Typical pelitic rocks

Pelitic rocks (high in Al_2O_3) contain minerals such as mullite, sillimanite, sanidine, cordierite, spinel, hypersthene, anorthite, tridymite, and even glass. One of the classic localities of such rocks is the island of Mull, off the west coast of Scotland, but in most regions of volcanism such rocks can be found.

Calcareous rocks (originally impure limestones or dolomites) tend to lose almost all their carbon dixoide, but pure calcite may survive. Typical metamorphic minerals are: quartz, wollastonite, anorthite, diopside, periclase, and in some places (the classic is Scawt Hill in Northern Ireland) an array of complex calcium silicates such as spurrite, larnite, rankinite, melilite, merwinite, and monticellite. These minerals result from the addition of varying amounts of silica to impure mixtures of calcite and dolomite. In a general way the minerals of this facies are reminiscent of those of industrial slags.

Pyroxene–hornfels facies. Rocks of the pyroxene-hornfels facies are characteristically formed near larger granitic or gabbroic bodies at depths of a few kilometres or at pressures of a few hundred bars. The mineral assemblages are again largely anhydrous, but, unlike the sanidinite facies, the minerals reflect distinctly lower temperatures. One of the classic descriptions of such rocks is from the Oslo district of Norway.

In pelitic rocks, minerals such as quartz, orthoclase, andalusite, sillimanite, cordierite, hypersthene, and plagioclase occur. Sometimes the hydrate biotite is developed. In calcareous rocks the minerals found include plagioclase, diopside, grossularite, vesuvianite (a hydrate), wollastonite, and sometimes the more complex calcium silicates monticellite, melilite, spurrite, tilleyite, and clinohumite.

Hornblende–hornfels facies. A generally deeper level of contact metamorphism where pressures of a few kilobars may be active is represented by the hornblende–hornfels facies. Hydrated phases become stable, and the transition to regional metamorphism becomes apparent. Because of the generally greater depth, this type of aureole is often superposed on a more normal metamorphism, and the rocks may appear schistose and show the development of new thermally generated minerals on a pre-existing assemblage. This type of metamorphism develops the classic "spotted" texture in which new porphyroblasts grow in slates and phyllites of a previous episode of metamorphism. Typically, these rocks are developed near most of the world's large granite batholiths, where these have moved to higher levels in the Earth's crust.

Typical minerals of pelitic assemblages include quartz, muscovite, biotite, andalusite, sillimanite, cordierite, plagioclase, microcline, and staurolite. Calcareous assemblages include calcite, quartz, diopside, grossularite, plagioclase, wollastonite, brucite, talc, forsterite, tremolite, and clinozoisite. Basaltic compositions include plagioclase, hornblende, diopside, quartz, biotite, and almandine garnet.

Formation of spectacular skarns

When rather pure limestone and dolomite come into direct contact with granitic rocks, elements such as silicon, iron, magnesium, and aluminum diffuse into the limestone, forming spectacular rocks termed skarns. These rocks often consist of large garnet crystals (grossularite) with green diopside and vesuvianite or epidote.

Albite–epidote–hornfels facies. Rocks of the albite–epidote–hornfels facies are characteristically found as the outer zones of contact aureoles where the thermal episode fades out and the rocks pass into their regional grade of metamorphism. The mineral assemblages are quite similar to those found in regional greenschist-facies metamorphism, except for the presence of low-pressure phases such as andalusite. Characteristic minerals include quartz, muscovite, biotite, chlorite, andalusite, actinolite, calcite, dolomite, albite, and epidote.

Conditions of formation of the contact facies. The mineralogical reactions included in the rocks described above are varied, and laboratory studies have provided a rather exact picture of the conditions of formation of these facies. It should be stressed that all correspond to conditions of pressure and temperature such that a thermal accident or abnormal thermal gradient is necessary to produce the observed mineral phases. This accident is the rise of silicate melt from depth.

Facies associated with regional metamorphism. Regional metamorphism is associated with the major events of Earth dynamics, and the vast majority of metamorphic rocks are so produced. They are the rocks involved in the cyclic processes of erosion, sedimentation, burial, metamorphism, and mountain building, events that are all related to major convective processes in the Earth's mantle. Two particular trends of facies can be noted: a cold trend, in which the geothermal gradient is low (about 10°–15° C per kilometre [30°–45° F per mile]), leading from zeolite facies to glaucophane schist facies; and the more general trend for normal gradients (20°–30° C per kilometre [57°–87° F per mile]), from zeolite facies to greenschist facies to amphibolite facies to a zone of crustal fusion. In almost all such crustal events at different times and places, however, there is uniqueness as well as conformity to a general pattern. Metamorphic events in the European Alps, the Urals, and the Himalayas all show specific differences: to unravel such differences and their significance is a great task of metamorphic petrology.

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 facies of burial metamorphism

The zeolite facies was first described from southern New Zealand, but similar rocks have now been described from the rocks of many younger mountain regions of the 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 (600° 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 laumonite and the feldspar albite dominate the mineral assemblage. In New Zealand these are developed in a rock column that is about 15 kilometres (nine 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 the Celebes. The facies is transitional, bridging the path to the glaucophane–lawsonite 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 glaucophane–lawsonite 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. Again, the facies has been most described from younger mountain ranges of the Pacific margin.

Glaucophane–lawsonite schist facies. Rocks of the glaucophane–lawsonite schist facies are known to 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 glaucophane schists are to be 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 known examples of glaucophane schists predating the Paleozoic Era (570,000,000 to 225,000,000 years ago). Because of the common presence of the blue amphibole glaucophane (this facies is also sometimes termed the blueschist facies) 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. Lawsonite, aragonite, and jadeite are found in no other metamorphic facies. In general, the facies is characterized by many high-density minerals reflecting a high pressure of formation.

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 (Figure 8). 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 the Earth's oldest rocks (about 3,000,000,000 years old) of the continental-shield areas are in this facies, classic examples of which are in the Appalachians, Scottish Highlands, New Zealand, the European Alps, Japan, and Norway.

By courtesy of W.S. Fyfe

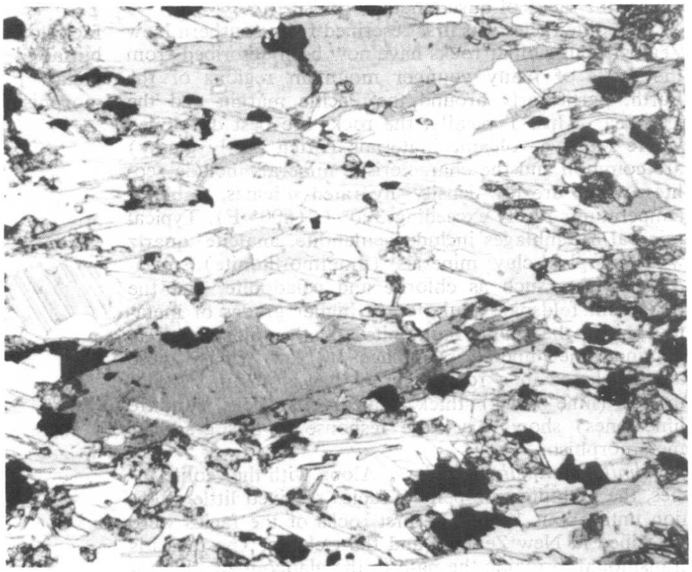

Figure 8: A typical greenschist from Scotland; the gray minerals are biotite and chlorite showing strong preferred orientation. The black crystals are magnetite, and the white areas are albite–quartz. Epidote and calcite are also present (magnification 50 X).

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 spessartite, stilpnomelane, kyanite, rutile, sphene, 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 liberating carbon dioxide. The typical minerals of this facies have low water contents as compared to the zeolite facies minerals.

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 Scottish Highlands, New Hampshire, Vermont, Switzerland, and the Himalayas.

Hornblende, the most common amphibole

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

Conditions of formation of the regional metamorphic facies. Most workers on the metamorphic facies of regional metamorphism considered above agree that progressive metamorphic reactions occur in a regime in which fluid pressure is about the same as the lithostatic (rock) pressure. Furthermore, because water is the common fluid phase and will be diluted by CO_2 (carbon dioxide) only in exceptional circumstances, the fluid pressure will approximately equal the pressure of water. Current thought on the regions of formation of metamorphic facies is shown in Figure 5, where the coordinates are the pressure of water and temperature. No matter how imperfect these estimates are in absolute terms, there is little doubt about their relative significance: they emphasize the uniqueness of metamorphic events.

The eclogite and granulite facies. The fact that the eclogite and granulite facies have no hydrated phases has led to considerable debate as to the place of such rocks among other metamorphic facies. They could represent dry equivalents of other metamorphic rocks, or their conditions of formation may be unique. Experimental studies have shown the extreme thermal stability of hornblende in rocks of basaltic composition. If a crustal rock contains this mineral, then at moderate pressures its dehydration reactions may lead to partial melting of the crust and the onset of igneous phenomena.

Eclogite facies. Eclogite facies are recognized only in rocks whose composition is near that of basalt. Two minerals dominate the mineralogy—omphacite pyroxene and garnet. 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, the hydrate zoisite, and hornblende may be present. The rocks are of high density and frequently show little or no schistosity.

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, and the European Alps could also come from the mantle by tectonic processes (crustal movements). Some eclogites are known to have been produced within the crust from former surface materials (*e.g.*, basalt lava flows). It also is known that eclogites form over a wide range of temperatures, perhaps from 400° to 1,000° C (750° to 1,800° F). These conditions overlap greenschist, amphibolite, and granulite facies temperatures.

Upper mantle as source of eclogite

Experimental studies have demonstrated that eclogites can be stable (except under certain upper-mantle conditions) only if water pressure is much lower than load pressure. The facies represents dry, high-pressure metamorphism of basaltic materials. The exact mechanism by which these metamorphic reactions take place is still a matter of considerable argument.

Granulite facies. The granulite facies is an anhydrous facies that develops gradationally from amphibolites but without any suggestion of a desiccated environment. Granulite-facies rocks are often found best developed in ancient Precambrian-shield areas of the continents. No large-scale development of such rocks has been observed in post-Cambrian metamorphism.

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, kyanite, sillimanite, and hypersthene. 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 Madras, India), essentially a hypersthene granite, is normally included in this facies.

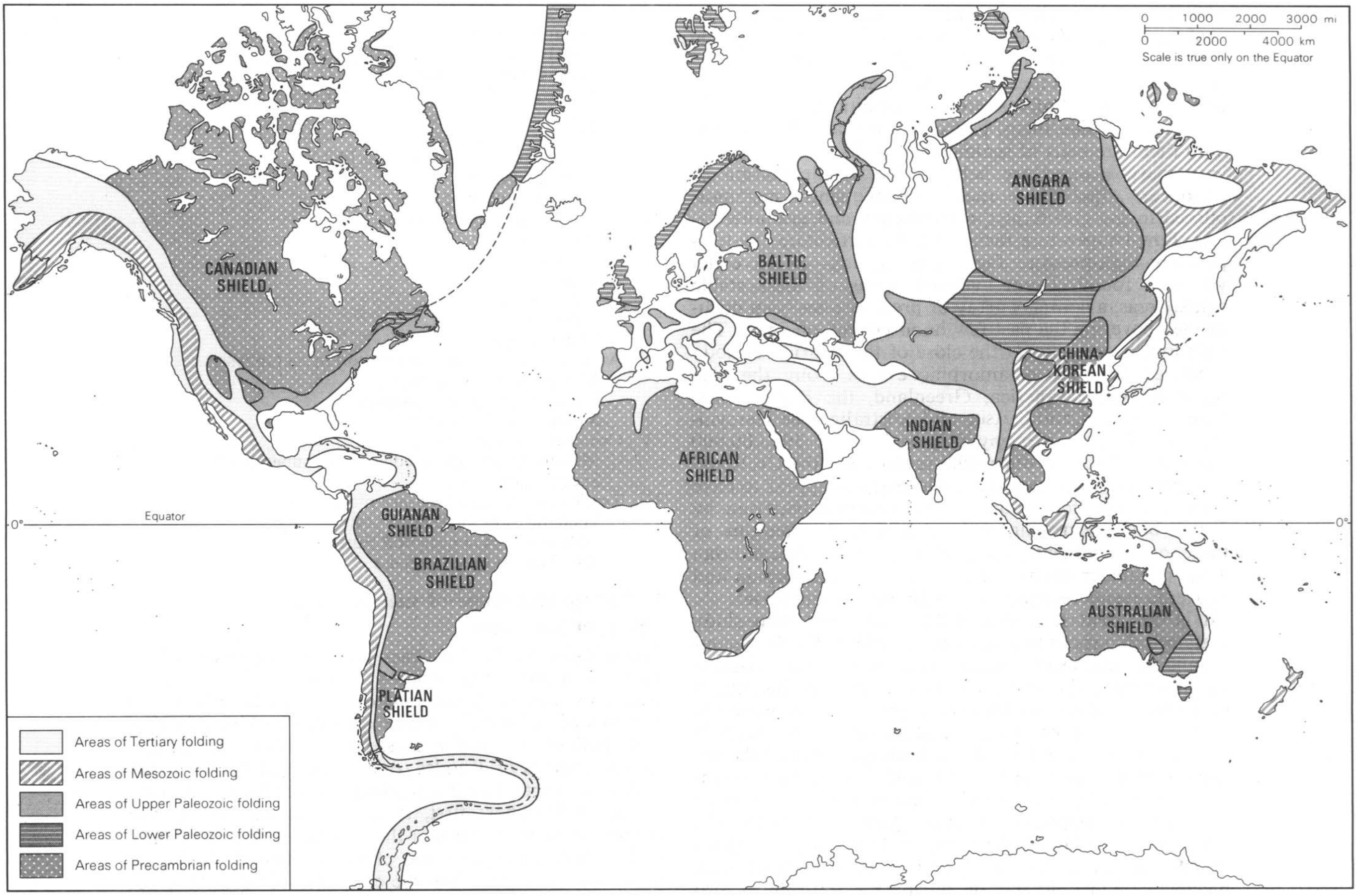

Figure 9: Tectonic units of the continents: shields and orogenic (fold) belts.
From J. Umbgrove, *The Pulse of the Earth*

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

$$\text{biotite} + \text{other minerals} \rightarrow \text{melt} + \text{residue}$$
$$\text{hornblende} + \text{other minerals} \rightarrow \text{melt} + \text{residue.}$$

The probable process of granulite formation

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 systems of their own composition. The residue in the above equations is a granulite-facies metamorphic rock containing phases such as pyroxene and sillimanite or kyanite. Thus it is probable but certainly not universally proved that most granulites are formed only in the presence of a silicate liquid. This liquid may, of course, move to higher crustal levels. As with eclogites, this facies represents metamorphism in which the partial pressure of water is lower than total pressure. Granulites may be very common rocks in the base of the crust. The lowering of pressure is caused by solution and dilution of water in a silicate melt. Rocks whose appearance suggests that they were once a mixture of liquid and solid parts are often called migmatites.

DISTRIBUTION OF METAMORPHIC ROCKS

A high-grade metamorphic rock is one that formed at a depth of tens of kilometres and subsequently returned to the surface. Hence, metamorphic regions are also regions of former or recent intense orogeny (mountain building). More stable regions of the Earth's crust tend to be covered with sediments, and only deep drilling will reveal the metamorphic rocks below.

The Earth's crust is made up of two basic units, the continents and ocean basins. Exploration of ocean floors has revealed that old, thick sedimentary piles are missing. Doubtless this is related to the processes of continental drift or sea-floor spreading (*qq.v.*); sediments are continuously swept up by continental motion and are added to the continents or returned to the upper mantle. Nearly all studies of metamorphic rocks have concentrated on the continents for this reason.

There are few large areas of the Earth's crust that are not affected by some type of igneous event from time to time. Although the intensity of volcanism may be focussed in certain geographic regions (*e.g.*, the Pacific margin), volcanism appears to be a rather random phenomenon, at times even occurring in the stable shield areas of the continents. In this sense, contact-metamorphic events may be found almost everywhere at almost any time on Earth. But these metamorphic events are of trivial volumetric significance compared to those of regional or burial metamorphism.

Belts of mountain building and shield areas

During the past 500,000,000 years or so of Earth history, major tectonic, seismic, igneous, and metamorphic events have been concentrated on continental margins (Figure 9). This has been a period of depression and uplift of the Earth's crust associated with the formation of the present continental distribution. The processes are still going on at dramatic rates in ocean trench environments. These modern regions of activity form immense linear belts. One such belt runs virtually around the entire Pacific margin and another through the Mediterranean and southern Asia to fuse with the circum-Pacific belt. It is in these belts that the spectacular development of zeolite facies, prehnite–pumpellyite facies, glaucophane-schist facies, and, occasionally, eclogite facies, as well as the more universal facies of regional metamorphism, have occurred. The granulite facies is almost missing.

The central and often dominant feature of most continents is their vast Precambrian-shield area; examples include the Canadian Shield, Brazilian Shield, African

Shield, and Australian Shield. In these rocks, dating reveals ages of 1,000,000,000 to 3,500,000,000 years, and they have been little affected by tectonic events postdating the Cambrian. But these shield areas are themselves complex. They consist of vast areas of granitic or granodioritic gneisses. Inside them, between them, and overlapping onto them are belts of sedimentary rocks quite like those in modern sedimentary belts of the Pacific margin or European Alps. These rocks are frequently metamorphosed in the greenschist, amphibolite, and granulite facies. Low-temperature facies and, in particular, low-temperature–high-pressure facies are missing—or have not yet been found. From marginal areas of these stable shield areas, a complex array of processes has been documented covering the past few hundred million years. The Caledonian orogeny (at the close of the Silurian Period) produced tectonic–metamorphic events along the east coast of North America, Greenland, the British Isles, Fennoscandia, Central Asia, and Australia. The Hercynian, or Variscan, orogeny followed about 300,000,000 years ago, affecting subparallel regions and the Urals and European Alps. In fact, the shield margins appear to have been subjected to a more or less constant battering by forces both destroying and rebuilding the margins of these protocontinents. As geologists study Precambrian areas in greater detail, the number of metamorphic and orogenic events recognized on a global scale increases.

It is the great task and problem of those who study metamorphic rocks to deduce the record of Earth dynamics and thermal history from metamorphic rocks. Among the questions to be answered are (1) whether the pattern of facies development through time—*e.g.*, the granulite facies in the Archean to glaucophane–lawsonite facies in the Tertiary—is a reflection of a cooling Earth and the decline of radioactivity in the crust and (2) whether the increase in size of global tectonic–metamorphic belts through time reflects changes in convective patterns in the mantle.

As understanding of the pressure–temperature regimes of metamorphism increases, and as knowledge of rock mechanics and fluid motion during metamorphism also increases through field and laboratory studies, it may become possible to understand the details of the motion of the chemical elements during such processes and hence much of the subject of economic geology or the search for man's essential raw materials.

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Metaphysics

Metaphysics is the philosophical study whose object is to determine the real nature of things—to determine the meaning, structure, and principles of whatever is insofar as it is. Although this study is popularly conceived as referring to anything excessively subtle and highly theoretical, and although it has been subjected to many criticisms, it is presented by metaphysicians as the most fundamental and most comprehensive of inquiries, inasmuch as it is concerned with reality as a whole.

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I. Nature and scope of metaphysics

ORIGIN OF THE TERM

Etymologically, the term metaphysics is quite unenlightening. It means "what comes after physics"; it was the phrase used by early students of Aristotle to refer to the contents of Aristotle's treatise on what he himself called "first philosophy," and was used as the title of this treatise by Andronicus of Rhodes, one of the first of Aristotle's editors. Aristotle had distinguished two tasks for the theoretical philosopher: first, to investigate the nature and properties of what exists in the natural or sensible world, and second, to explore the characteristics of "Being as such" and to inquire into the character of "the substance that is free from movement," or the most real of all things, the intelligible reality on which everything in the world of nature was thought to be causally dependent. The first constituted "second philosophy" and was carried out primarily in the Aristotelian treatise now known as the *Physica;* the second, which Aristotle had also referred to as "theology" (because God was the unmoved mover in his system), is roughly the subject matter of his *Metaphysica.* Modern readers of Aristotle are inclined to take both the *Physica* and the *Metaphysica* as philosophical treatises; the distinction their titles suggest, between an empirical and a conceptual inquiry, has little real foundation. Aristotle was not indifferent to factual material either in natural or in metaphysical philosophy, but equally he was not concerned in either case to frame theories for empirical testing. It seems clear, nevertheless, that if the two works had to be distinguished, the *Physica* would have to be described as the more empirical, just because it deals with things that are objects of the senses, what Aristotle himself called "sensible substance"; the subject matter of the *Metaphysica,* "that which is eternal, free of movement, and separately existent," is on any account more remote. It is also evident that the connection marked in the original titles is a genuine one: the inquiries about nature carried out in the *Physica* lead on naturally to the more fundamental inquiries about Being as such that are taken up in the *Metaphysica* and indeed go along with the latter to make up a single philosophical discipline.

The background to Aristotle's divisions is to be found in the thought of Plato, with whom Aristotle had many disagreements but whose basic ideas provided a framework within which much of his own thinking was conducted. Plato, following the early Greek philosopher Parmenides, who is known as the father of metaphysics, had sought to distinguish opinion or belief from knowledge and to assign distinct objects to each. Opinion, for Plato, was a form of apprehension that was shifting and unclear, similar to seeing things in a dream or only through their shadows; its objects were correspondingly unstable. Knowledge, by contrast, was wholly lucid; it carried its own guarantee against error, and the objects with which it was concerned were eternally what they were, and so were exempt from change and the deceptive power to appear to be what they were not. Plato called the objects of opinion phenomena or appearances; he referred to the objects of knowledge as noumena (objects of the intelligence) or quite simply as realities. Much of the burden of his philosophical message was to call men's attentions to these contrasts and to impress them with the necessity to turn away from concern with mere phenomena to the investigation of true reality. The education of the Platonic philosopher consisted precisely in effecting this transition: he was taught to recognize the contradictions involved in immediate appearances and to fix his gaze on the true realities that lay behind them, the realities that Plato himself called Forms or Ideas. Philosophy for Plato was thus a call to recognize the existence and overwhelming importance of a set of higher realities that ordinary men—even those, like the Sophists of the time, who professed to be enlightened—entirely ignored. That there were such realities, or at least that there was a serious case for thinking that there were, was a fundamental tenet in the discipline that later became known as metaphysics. Conversely, much of the subsequent controversy about the very possibility of metaphysics has turned on the acceptability of this tenet and on whether, if it is rejected, some alternative foundation can be discovered on which the metaphysician can take his stand.

Appearances and realities for Plato

CHARACTERIZATIONS OF METAPHYSICS

Before considering any such question, however, it is necessary to examine, without particular historical references, some ways in which actual metaphysicians have attempted to characterize their enterprise, noticing in each case the problems they have in drawing a clear line between their aims and those of the practitioners of the exact and empirical sciences. Four views will be briefly considered; they present metaphysics as: (1) an inquiry into what exists, or what really exists; (2) the science of reality, as opposed to appearance; (3) the study of the world as a whole; (4) a theory of first principles. Reflection on what is said under the different heads will quickly establish that they are not sharply separate from one another, and, indeed, individual metaphysical writers sometimes invoke more than one of these phrases when asked to say what metaphysics is—as, for example, the British Idealist F.H. Bradley does in the opening pages of his work *Appearance and Reality* (1893).

An inquiry into what exists. A common set of claims on behalf of metaphysics is that it is an inquiry into what exists; its business is to subject common opinion on this matter to critical scrutiny and in so doing to determine what is truly real.

Unreliability of common opinion

It can be asserted with some confidence that common opinion is certainly an unreliable guide about what exists, if indeed it can be induced to pronounce on this matter at all. Are dream objects real, in the way in which palpable realities such as chairs and trees are? Are numbers real, or should they be described as no more than abstractions? Is the height of a man a reality in the same sense in which he is a reality, or is it just an aspect of something more concrete, a mere quality that has derivative rather than substantial being and could not exist except as attributed to something else? It is easy enough to confuse the common man with questions like these and to show that any answers he gives to them tend to be ill thought out. It is equally difficult, however, for the metaphysician to come up with more satisfactory answers of his own. Many metaphysicians have relied, in this connection, on the internally related notions of substance, quality, and relation; they have argued that only what is substantial truly exists, although every substance has qualities and stands in relation to other substances. Thus, this tree is tall and deciduous and is precisely 50 yards north of that fence. Difficulties begin, however, as soon as examples like these are taken seriously. Assume for the moment that an individual tree—what might be called a concrete existent—qualifies for the title of substance; it is just the sort of thing that has qualities and stands in relations. Unless there were substances in this sense, no qualities could be real: the tallness of the tree would not exist unless the tree existed. The question can now be raised what the tree would be if it were deprived of all its qualities and stood in no relations. The notion of a substance in this type of metaphysics is that of a thing that exists by itself, apart from any attributes it may happen to possess; the difficulty with this notion is to know how to apply it. Any concrete thing one picks on to exemplify the notion of substance turns out in practice to answer a certain description; this means in effect that it cannot be spoken of apart from its attributes. It thus emerges that substances are no more primary beings than are qualities and relations; without the former one could not have the latter, but equally without the latter one could not have the former.

There are other difficulties about substance that cannot be explored now—*e.g.*, whether a fence is a substance or simply wood and metal shaped in a certain way. Enough has already been said, however, to indicate the problems involved in defining the tasks of metaphysics along these lines. Nevertheless, there is an alternative way of understanding the notion of substance: not as that which is the ultimate subject of predicates but as what persists through change. The question "What is ultimately real?" is, thus, a question about the ultimate stuff of which the universe is made up. Although this second conception of substance is both clearer and more readily applicable than its predecessor, the difficulty about it from the metaphysician's point of view is that it sets him in direct rivalry with the scientist. When the early Greek philosopher Thales inquired as to what is ultimately real and came up with the surprising news that all is water, he might be taken as advancing a scientific rather than a philosophical hypothesis. Although it is true that later writers, such as Gottfried Wilhelm Leibniz, a German Rationalist philosopher and mathematician, were fully aware of the force of scientific claims in this area and nevertheless rejected them as metaphysically unacceptable, the fact remains that the nonphilosopher finds it difficult to understand the basis on which a Leibniz rests his case. When Leibniz said that it is monads (*i.e.*, elementary, unextended, indivisible, spiritual substances that enter into composites) that are the true atoms of nature and not, for example, material particles, the objection can be raised as to what right he has to advance this opinion. Has he done any scientific work to justify him in setting scientific results aside with such confidence? And if he has not, why should he be taken seriously at all?

The ultimate stuff of the universe

The science of ultimate reality. To answer these questions, another description of metaphysics has been proposed: that it is the science that seeks to define what is ultimately real, as opposed to what is merely apparent.

The contrast between appearance and reality, however, is by no means peculiar to metaphysics. In everyday life, people distinguish between the real size of the sun and its apparent size, or again between the real colour of an object (when seen in standard conditions) and its apparent colour (nonstandard conditions). A cloud appears to consist of some white, fleecy substance, although in reality it is a concentration of drops of water. In general, men are often (though not invariably) inclined to allow that the scientist knows the real constitution of things as opposed to the surface aspects with which ordinary men are familiar. It will not suffice, therefore, to define metaphysics as knowledge of reality as opposed to appearance; scientists, too, claim to know reality as opposed to appearance, and there is a general tendency to concede their claim. It seems that there are at least three components in the metaphysical conception of reality. One characteristic, which has already been illustrated in Plato, is that reality is genuine as opposed to deceptive. The ultimate realities that the metaphysician seeks to know are precisely things as they are—simple and not variegated, exempt from change, and therefore stable objects of knowledge. Plato's own assumption of this position perhaps reflects certain confusions about the knowability of things that

Components in the metaphysical conception of reality change; one should not, however, on that ground exclude this aspect of the concept from metaphysical thought in general. Ultimate reality, whatever else it is, is genuine as opposed to sham. Second, it is original in contrast to derivative, self-dependent rather than dependent on the existence of something else. When Aristotle sought to inquire into the most real of all things, or when medieval philosophers attempted to establish the characteristics of what they called the *ens realissimum* ("the most real being"), or the original and perfect being, they were looking for something that, in contrast to the everyday things of this world, was truly self-contained and could accordingly be looked upon as self-caused. Likewise, the 17th-century Rationalists defined substance as that which can be explained through itself alone. Writers like René Descartes and Benedict de Spinoza were convinced that it was the task of the metaphysician to seek for and characterize substance understood in this sense; the more mundane substances with which physical scientists were concerned were, in their opinion, only marginally relevant in this inquiry. Third, and perhaps most important, reality for the metaphysician is intelligible as opposed to opaque. Appearances are not only deceptive and derivative, they also make no sense when taken at their own level. To arrive at what is ultimately real is to produce an account of the facts that does them full justice. The assumption is, of course, that one cannot explain things satisfactorily if he remains within the world of common sense, or even if he advances from that world to embrace the concepts of science. One or the other of these levels of explanation may suffice to produce a sort of local sense that is enough for practical purposes or that forms an adequate basis on which to make predictions. Practical reliability of this kind, however, is very different from theoretical satisfaction; the task of the metaphysician is to challenge all assumptions and finally arrive at an account of the nature of things that is fully coherent and fully thought out.

The task of the metaphysician

It should be obvious that, to establish his right to pronounce on what is ultimately real in the sense analyzed, the metaphysican has a tremendous amount to do. He must begin by giving colour to his claim that everyday ways of thinking will not suffice for a full and coherent description of what falls within experience, thus arguing that appearances are unreal—although not therefore nonexistent—because they are unstable and unintelligible. This involves a challenge to the final acceptability of such well-worn ideas as time and space, thing and attribute, change and process—a challenge that metaphysicians have not hesitated to make, even though it has been treated with skepticism both by ordinary men and by some of their fellow philosophers (*e.g.*, G.E. Moore, a 20th-century British thinker who has greatly influenced modern Analytic philosophy). Second, granted that there are contradictions or incoherencies in the thought of common sense, the metaphysician must go on to maintain that they cannot be resolved by deserting common sense for science. He will not deny that the concepts of science are in many respects different from those of everyday thought; to take one aspect only, they are altogether more precise and sharply defined. They permit the scientist to introduce into his descriptions a theoretical content that is lacking at the everyday level, and in so doing to unify and render intelligible aspects of the world that seem opaque when considered singly. The metaphysician will argue, however, that this desirable result is purchased at a certain price: by ignoring certain appearances altogether. The scientist, in this way of thinking, does not so much offer a truer description of the phenomena of which ordinary thought could make no sense; he merely gives a connected description of a selected set of phenomena. The world of the scientist, restricted as it is to what can be dealt with in quantitative terms, is a poor thing in comparison with the rich if untidy world of everyday life. Alternatively, the metaphysician must try to show that scientific concepts are like the concepts of common sense in being ultimately incoherent. The premises or presuppositions that the scientist accepts contain unclarities that cannot be resolved, although they are not so serious as to prevent his achieving results that are practically dependable. Many ingenious arguments on these lines have been produced by philosophers, by no means all of whom could be said to be incapable of a true understanding of the theories they were criticizing. (Leibniz, for example, was a physicist of distinction as well as a mathematician of genius; G.W.F. Hegel, a 19th-century German Idealist, had an unusual knowledge of contemporary scientific work; and Alfred North Whitehead, a pioneer of 20th-century metaphysics in the Anglo-Saxon world, was a professor of applied mathematics, and his system developed from physics and contained a wealth of biological ideas.) The fact remains, nevertheless, that few if any practicing scientists have been seriously troubled by such arguments.

Even if the metaphysician were thus able to make good the negative side of his case, he would still face the formidable difficulty of establishing that there is something answering to his conception of what is ultimately real and of identifying it. The notion of an original being, totally self-contained and totally self-intelligible, may not itself be coherent, as the 18th-century British philosopher David Hume and others have argued; alternatively, there may be special difficulties in saying to what it applies. The fact that different metaphysicians have had widely different accounts of what is ultimately real is certainly suspicious. Some have wanted to say that there is a plurality of ultimately real things, others that there is only one; some have argued that what is truly real must be utterly transcendent of the things of this world and occupy a supersensible realm accessible only to the pure intellect, while others have thought of ultimate reality as immanent in experience (the Hegelian Absolute, for example, is not a special sort of existent, but the world as a whole understood in a certain way). That metaphysical inquiry should issue in definitive doctrine, as so many of those who engaged in it said that it would, is in these circumstances altogether too much to hope for.

The science of the world as a whole. Another way in which metaphysicians have sought to define their discipline is by saying that it has to do with the world as a whole.

The implications of this phrase are not immediately obvious. Clearly, a contrast is intended in the first place with the various departmental sciences, each of which selects a portion or aspect of reality for study and confines itself to that. No geologist or mathematician would claim that his study is absolutely comprehensive; each would concede that there are many aspects of the world that he leaves out, even though he covers everything that is relevant to his special point of view. By contrast, it might be supposed that the metaphysician is merely to coordinate the results of the special sciences. There is clearly a need for the coordination of scientific results in recent conditions in which scientific research has become increasingly specialized and departmentalized; individual scientific workers need to be made aware of what is going on in other fields, sometimes because these fields impinge on their own, sometimes because results obtained there have wider implications of which they need to take account. One can scarcely see metaphysicians, however, or indeed philosophers generally, performing this function of intellectual contact man in a satisfactory fashion. It might then be supposed that their concern with the world as a whole is to be interpreted as a summing up and synthesizing of the results of the particular sciences. Plato spoke of the philosopher as taking a "synoptic" view, and there is often talk about the need to see things in the round and avoid the narrowness of the average specialist, who, it is said, knows more and more about less and less. If, however, it is a question of looking at scientific results from a wider point of view and so of producing what might be called a scientific picture of the world, the person best qualified for the job is not any philosopher but rather a scientist of large mind and wide interests. Metaphysics cannot be satisfactorily understood as an account of the world as a whole if that description suggests that the metaphysician is a sort of superscientist, unlimited in his curiosity and gifted with a capacity for putting together other people's findings with a skill and imagination that none of them individually commands. Only a scientist could hope to become such a superscientist.

Metaphysics as an account of the world

More hope for the metaphysician can be found, perhaps, along the following lines. People want to know not only what the scientist makes of the world but also what significance to assign to his account. People experience the world at different levels and in different capacities: they are not only investigators but also agents; they have a moral and a legal, an aesthetic and a religious life on top of their scientific life. Man is a many-sided being; he needs to understand the universe in the light of his different activities and experiences. There are philosophers who appear to find no mystery here; they argue that there can be no question of the possibility of, say, a moral or a religious vision of the world that rivals the scientific vision. In this view, morals and religion are matters of practice, not of theory; they do not rival science, but only complement it. This neutralist attitude, however, finds little general favour; for most thinking people there is a question of choosing whether to go all the way with science, at the cost of abandoning religion and even morals, or to stick to a religious or moral world outlook even if it means treating scientific claims with some reserve. The practice of the moral life is often believed to proceed on assumptions that can hardly be accepted if science is taken to have the last word about what is true. Accordingly, it becomes necessary to produce some rational assessment of the truth claims of the different forms of experience, to try to think out a scheme in which justice is done to them all. Many familiar systems of metaphysics profess to do just that; among others there are Materialism, which favours the claims of science, Idealism, which sees deeper truth in religion and the moral life, and the peculiar dualism of the 18th-century German philosopher Immanuel Kant, which holds that science gives the truth about phenomena, while reserving a noumenal, or supersensible, sphere for moral agency.

This conception of metaphysics as offering an account of the world or, as is more often said, of experience as a whole accords more obviously with the practice of those who see ultimate reality as immanent, or inherent in what is immediately known, than of those who take it to be transcendent, or beyond the limits of ordinary experience. It is possible, in fact, to subscribe to the legitimacy of metaphysics as so understood without postulating the existence of any special entities known only to the metaphysician—a claim that plain men have often taken to connect metaphysics with the occult. This is not to say, of course, that metaphysical problems admit of easy solutions when understood along these lines. There is a variety of widely different ways of taking the world as a whole: each depends on which aspect or aspects of experience the individual metaphysician finds especially significant; each claims to be comprehensive and to confute the claims of its rivals, yet none has succeeded in establishing itself as the obviously correct account. Even systems that are widely condemned as impossible, such as Materialism, turn out in practice to command constantly renewed support, as new discoveries in the sciences suggest new ways of dealing with old difficulties. A cynic might take such facts as meaning that people subscribe to theories of this sort more as a matter of emotional than of rational conviction; metaphysics, as Bradley remarked with surprising frankness, consists in the finding of bad reasons for what one believes upon instinct.

The science of first principles. Another phrase used by Bradley in his preliminary discussion of metaphysics is "the study of first principles," or ultimate, irrefutable truths.

First principles as basic truths

Metaphysics could be said to provide a theory of first principles if it furnished men with a set of concepts in the light of which they could arrive at the connected account of experience as a whole just spoken of, and the two descriptions of the subject would thus be two sides of a single coin. The idea that metaphysics has to do with first principles, however, has wider implications.

The term first principles is a translation of the Greek word *archai*. An *archē* is something from which an argument proceeds—either a primary premise or an ultimate presupposition. Plato, in a famous passage in *The Republic*, contrasted two different attitudes to *archai:* that of the mathematician, who lays down or hypothesizes certain things as being true and then proceeds to deduce their consequences without examining them further; and that of the dialectician, who proceeds backward, not forward, from his primary premises and seeks to ground them in an *archē* that is not hypothesized at all. Unfortunately, no concrete details exist of the way in which Plato himself thought this program could be carried out; he spoke of it only in the most general terms. Nevertheless, the suggestion that metaphysics is superior to any other intellectual discipline in having a fully critical attitude toward its first principles is one that continues to be made, and it needs some examination.

As regards mathematics, for example, it might be said that mathematicians could be uncritical about the first principles of their science in the following ways: (1) They might take as self-evidently true or universally applicable some axiom or primary premise that turned out later not to possess this property. (2) They might assume among their first principles certain propositions about existence—to the effect that only certain kinds of things could be proper objects of mathematical inquiry (rational as opposed to irrational numbers, for example)—and time might show that the assumption was inappropriate. The remedy for both sorts of error, however, is to be found within mathematics itself; the development of the discipline has consisted precisely in eliminating mistakes of this kind. It is not clear even that the discovery and removal of antinomies in the foundations of mathematics is work for the metaphysician, although philosophically minded persons like Gottlob Frege, a German mathematician and logician, and Bertrand Russell, perhaps the best known English philosopher of the 20th century, have been much concerned with them. The situation is not fundamentally different when the empirical sciences are considered. Admittedly, the exponents of these sciences give more hostages to fortune insofar as they have to assume from the first the general correctness of the results of other disciplines; there can be no question of their checking on these for themselves. Mathematicians, too, assume the validity of common argument forms without making any serious attempt to validate them, and there is nothing seriously wrong with their doing so. If confidence in bad logic has sometimes been responsible for holding up mathematical advance, bolder mathematicians have always known in practice that the right thing to do is let the argument take them where it will on strictly mathematical lines, leaving it to logicians to recognize the fact and adjust their theory at leisure.

Metaphysicians as self-critical

It thus seems that the assertion that a special science like mathematics is uncritical about its *archai* is false; there is a sense in which mathematicians are constantly strengthening their basic premises. As regards the corresponding claim about metaphysics, it has at one time or another been widely believed (1) that it is the business of metaphysics to justify the ultimate assumptions of the sciences, and (2) that in metaphysics alone there are no unjustified assumptions. Concerning (1), the question that needs to be asked is how the justification is supposed to take place. It has been argued that the metaphysician might, on one interpretation of his function, be said to offer some defense of science generally by placing it in relation to other forms of experience. To do this, however, is not to justify any particular scientific assumptions. In point of fact, particular scientific assumptions get their justification, if anywhere, when a move is made from a narrower to a more comprehensive science; what is assumed in, for example, geology may be proved in physics. But this, of course, has nothing to do with metaphysics. The difficulty with (2) is that of knowing how any intellectual activity, however carefully conducted, could be free of basic assumptions. Some metaphysicians (such as Bradley and his Scottish predecessor J.F. Ferrier) have claimed that there is a difference between their discipline and others insofar as metaphysical propositions alone are self-reinstating. For example, the Cartesian proposition *Cogito,* *ergo sum* ("I think, therefore I am") is self-reinstating: deny that you think, and in so doing you think; deny that you exist, and the very fact gives proof of your existence. Even if it could be made out that propositions of this kind are peculiar to metaphysics, however, it would not follow that everything in metaphysics has this character. The truth is, rather, that no paradox is involved in denying most fundamental metaphysical claims, such as the assertion of the Materialist that there is nothing that cannot be satisfactorily explained in material terms, or the corresponding principle of Aristotle that there is nothing that does not serve some purpose.

The view that metaphysics, or indeed philosophy generally, is uniquely self-critical is among the myths of modern thought. Philosophers rely on the results of other disciplines just as other people do; they do not pause to demonstrate the legitimacy of the principles of simple arithmetic before entering on calculations in the course of their work, nor do they refrain from employing the *reductio ad absurdum* type of refutation (*i.e.*, showing an absurdity to which a proposition leads when carried to its logical conclusion) until they have assured themselves that this is a valid way of confuting an opponent. Even in their own field they tend, like painters, to work within traditions set by great masters rather than to think everything out from scratch for themselves. That philosophy in practice is not the fully self-critical activity its exponents claim it to be is shown nowhere more clearly than in the reception that philosophers give to theories that are unfashionable; they more often subject them to conventional abuse than to patient critical examination. Nevertheless, it is from the conviction that philosophy, and especially metaphysical philosophy, operates without unjustified assumptions that current claims about the superiority of this branch of thinking derive their force. This conviction connects with the views already mentioned, that metaphysics is the science of first principles, and that the principles in question are ineluctable, in the sense that they are involved in their own denial.

METAPHYSICS AND OTHER BRANCHES OF PHILOSOPHY

The view of metaphysics as the queen of the sciences

It may be useful at this point to consider the question of the relations of metaphysics to other parts of philosophy. A strong tradition, derided by Kant, asserted that metaphysics was the queen of the sciences, including the philosophical sciences. The idea presumably was that those who worked within fields such as logic and ethics, as well as physicists and biologists, proceeded on assumptions that in the last resort had to be approved or corrected by the metaphysician. Logic could be conceived as a special study complete in itself only if the logician were allowed to postulate a correspondence between the neat and tidy world of propositions, which was the immediate object of his study, and the world existing in fact; metaphysics might and sometimes did challenge the propriety of this postulate. Similarly, ethics, like law, could get nowhere without the assumption that the individual agent is a self-contained unit answerable in general terms for what he does; metaphysics had the duty of subjecting this assumption to critical examination. As a result of such claims it was widely believed that any results obtained by logicians or ethicists must at best be treated as provisional; followers of Hegel, who advanced these claims with passionate conviction, were inclined in consequence to regard logic and ethics alike as minor branches of philosophy. It has been a feature of 20th-century philosophical thought, especially in Britain and the United States, to dispute these Hegelian contentions and argue for the autonomy of ethics and logic; that is, for their independence of metaphysics. Thus, formal logicians of the school of Frege and Russell were apt to claim that the principles of logic applied unequivocally to all thinking whatsoever; there could be no question of their having to await confirmation, still less correction, from the metaphysician. If metaphysical arguments suggested that fundamental laws of logic such as the principle of noncontradiction—that a statement and its contradictory cannot both be true—might not be in order, the only conclusion to draw was that such arguments must be confused: without observation of the laws of logic there could be no coherent thinking of any sort.

Similarly, G.E. Moore, in a celebrated section of his *Principia Ethica* (1903), tried to show that statements like "This is good" are *sui generis* and cannot be reduced to statements of either natural or metaphysical fact; the Idealist belief that ethics ultimately depends on metaphysics rested on a delusion. Moore perhaps failed to see the force of the Idealist challenge to the individualist assumptions on which much ethical thinking proceeds, and he did not note that, in one respect at least, ethical results can be dependent on those of metaphysics: if metaphysics shows that the world is other than it is initially taken to be, conclusions about what to do must be altered accordingly. Again, the reaction among logicians to Hegelian attempts to merge logic into metaphysics certainly went too far. There is a genuine philosophical problem about the relation between the world of logic and the world of fact, and it cannot be solved by simply repeating that logic is an autonomous discipline whose principles deserve respect in themselves. None of this, however, shows that metaphysics is the fundamental philosophical discipline, the branch of philosophy that has the last word about what goes on in all other parts of the subject.

METAPHYSICS AND ANALYSIS

Modern British and American philosophers commonly describe themselves as engaged in philosophical analysis, as opposed to metaphysics. The interests of a metaphysician, according to this view, are predominantly speculative; he wants to reveal hitherto unknown facts about the world and on that basis to construct a theory about the world as a whole. In so doing he is necessarily engaged in activities that rival those of the scientist, with the important difference that scientific theories can be brought to the test of experience, whereas metaphysical theories cannot. Eschewing this conception of philosophy as impossible, the critic of metaphysics believes that philosophy should confine itself to the analysis of concepts, which is a strictly second-order activity independent of science and which need involve no metaphysical commitment.

Analysis in philosophy

The notion of analysis in philosophy is far from clear. Analysis on any account is meant to result in clarification, but it is not evident how this result is to be achieved. For some, analysis involves the substitution for the concept under examination of some other concept that is recognizably like it (as Gilbert Ryle, an English Analyst, elucidated the concept of mind by replacing it with the notion of "a person behaving"); for others, analysis involves the substitution of synonym for synonym. If the latter understanding of analysis is required, as in Moore's classic example of the analysis of brother as male sibling, not much enlightenment is likely to ensue. If, however, the philosopher is permitted to engage in what is sometimes pejoratively described as "reductive analysis," he will produce interest at the cost of reintroducing speculation. Ryle's *Concept of Mind* (1949) is a challenging book just because it advances a thesis of real metaphysical importance—that one can say everything one needs to say about minds without postulating mental substance.

A further aspect of the situation that deserves mention is this. If it is the case, as is often claimed, that analysis can be practiced properly only when the analyst has no metaphysical presuppositions, by what means does he select concepts for analysis? Would it not be appropriate for him, in these circumstances, to take any concept of reasonable generality as a suitable subject on which to practice his art? It turns out, in fact, however, that the range of concepts commonly recognized as philosophical is more limited than that, and that those concepts to which Analytic philosophers give their attention are chosen because of their wider philosophical bearings. Thus, recent philosophers have paid particular attention to the concept of knowledge not just because it is a notion whose analysis has long proved difficult but also because on one account at least it involves an immediately experienced mental act—something that many Analysts would like to proscribe as mythical. Similarly, the celebrated analysis of the idea of causality put forward by David Hume was