Mineral Associations

Classification of Mineral Associations

On the basis of the temperature and pressure of their formation, mineral associations, or parageneses, can be divided into three groups.

1. **Magmatic**
2. **Supergene**
3. **Diagenetic**
4. **Metamorphic**

Magmatic

Those associated with local centres of heat sufficient to melt part of the rocks.

Included here are the products of crystallization of melts, and of gases and solutions derived from them.

Supergene

Those produced at ordinary temperatures and pressures at, or near, the earth's surface, by processes of weathering or precipitation; and concentrations of minerals produced by the processes of transport and sedimentation.

Diagenetic

This associations develop as unconsolidated sediment is transformed into rock at shallow depths of burial.

Metamorphic

Those associated with the general rise of temperature and pressure with depth in the crust.

Like most classifications in natural history, these divisions are not hard and fast. There will be deposits that partake of the character of more than one group (e.g. contact metamorphic deposits formed close to magmatic rocks, which commonly contain material introduced from the magma).

Chemical analyses of rocks from the different environments, taken in conjunction with the amounts of these rocks, furnish estimates of the abundance of the elements in the crust.

These are summed up in Fig. 149. The most obvious point of the figure (bearing in mind that it is on a logarithmic scale) is the great relative abundance of the eight elements O, Na, Mg, Al, Si, K, Ca, and Fe. These are the major elements of the crust.

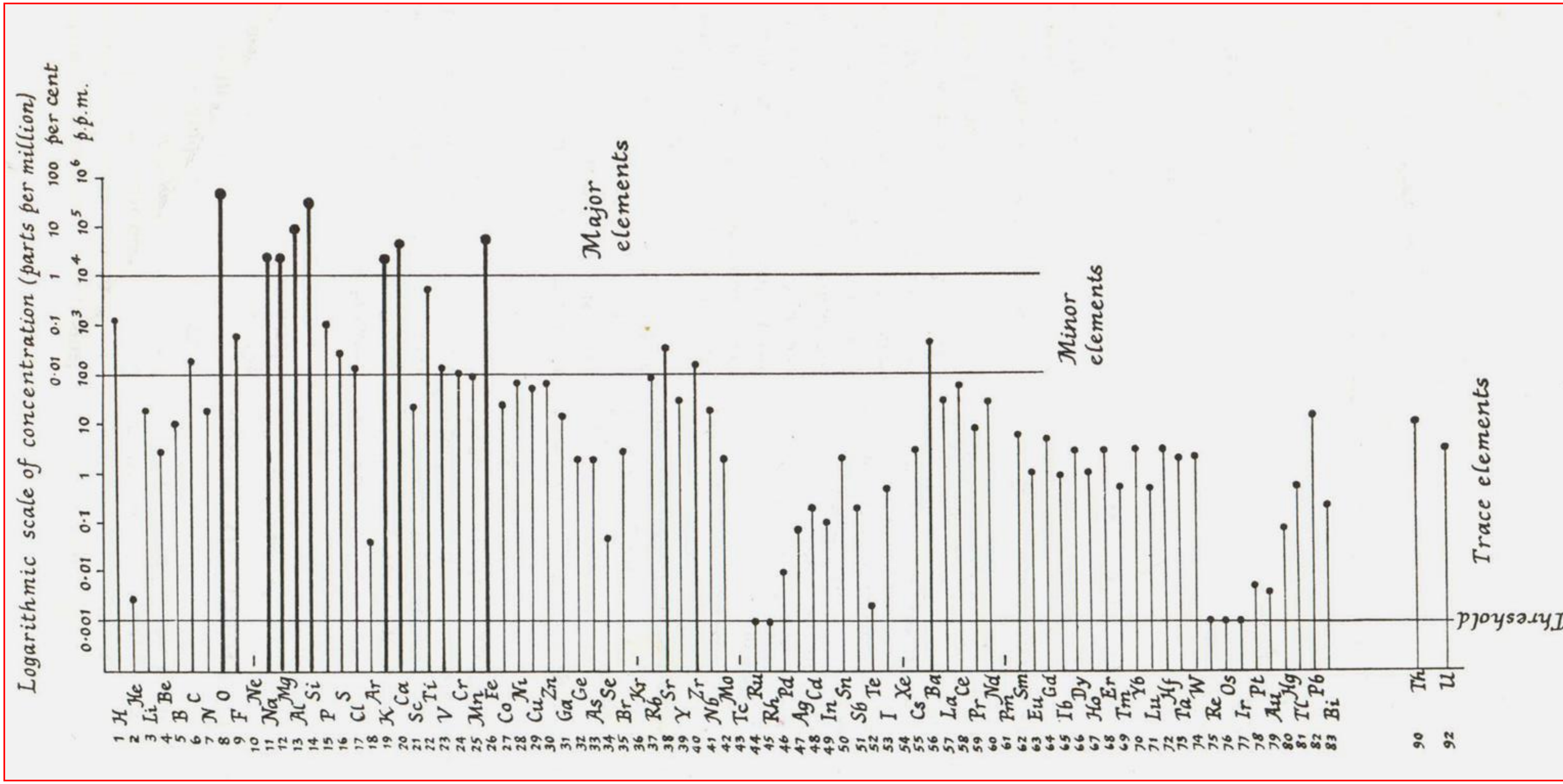

Fig. 149. The abundances of the elements.

The picture that emerges from the data on abundance is that of small amounts of many elements immersed in a vast abundance of a few.

The many that occur in small amounts may be subdivided into minor elements and trace elements, with the boundary between them at 0.01 per cent, as shown in Fig. 149.

The marked inequality in amounts of the elements leads to a second subdivision of minerals.

1. **Rock-forming minerals**
2. **Ore minerals**

1. Rock forming Minerals

Chiefly silicates, with a few oxides and carbonates, of the elements Al, Fe, Ca, Na, K and Mg. These build the common rocks of the crust. They may contain traces of other elements as substituting atoms in the lattice.

2. Ore minerals

All other minerals represent unusual concentrations of one of the minor or trace elements, and must form by special processes of concentration

Rock-forming minerals may themselves sometimes segregate to form ores (e.g. magnetite, apatite).

These two elements of classification,

- **(1) the physical environment and**
- **(2) the distinction between rock-forming minerals and ores,**

are combined in the following survey of mineral associations.

Magmatic Associations

The sequence of separation of minerals from a silicate melt is now well-established, and is summed up by N. L. Bowen's Reaction Series of igneous minerals shown in Fig. 150.

This series is one in which, as crystallization proceeds, SiO_2, Na_2O, K_2O and H_2O are concentrated in the residual liquid and enter into late-formed minerals. The degree of oxidation becomes greater as the sequence proceeds.

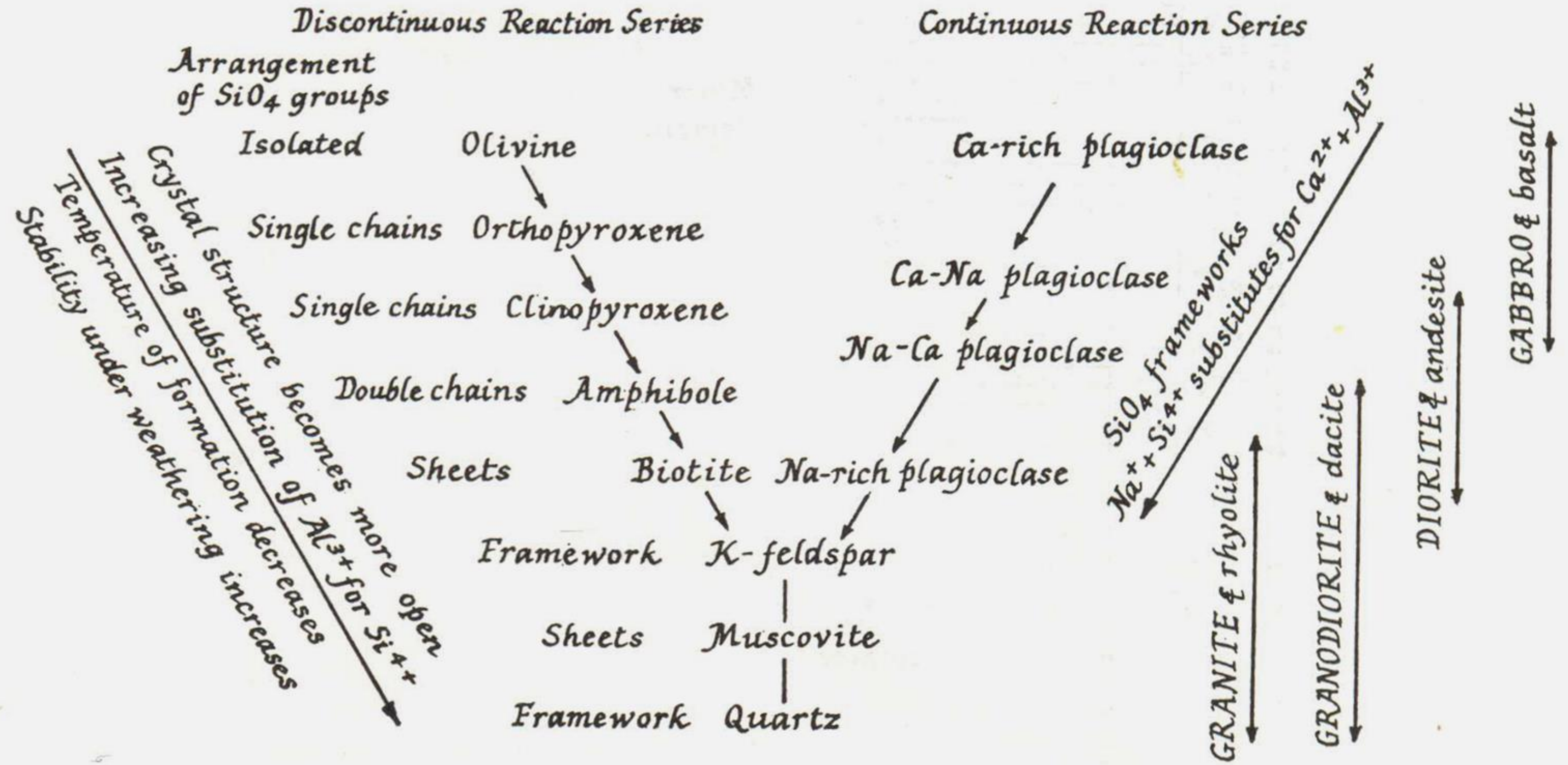

Fig. 150. Bowen's reaction series of the igneous rock-forming minerals.

Classification of Magmatic Rocks

Magmatic rocks are classified chemically on the basis of the ratio of Si02 to other oxides present, and this old-established classification links closely with the Reaction Series.

The groups ultrabasic, basic, intermediate and acid constitute a series with progressively increasing Si02 content* (Table 16).

A separate group, the alkaline rocks, are characterized by a high content of Na2Oand K2O relative to the other

Table 16. Classification of non-feldspathoidal magmatic rocks.

(Members of the main calc-alkali series heavily underlined
PLUTONIC rocks in capitals, Volcanic rocks in lower case)

Ratio of light to dark minerals	Group chemistry	Feldspar mainly alkali (K, Na)	Alkali feldspar ≃ plagioclase	Feldspar mainly plagioclase
Felsic—light minerals (quartz and feldspar) > 60% by volume	Acid	GRANITE Rhyolite	ADAMELLITE Rhyo-dacite	GRANODIORITE Dacite
	66% SiO_2			
Mesotype—light minerals < 60% > 30% by volume quartz < 10%, plagioclase has Ab/An > 50/50	Intermediate	SYENITE Trachyte	MONZONITE Trachyandesite	DIORITE Andesite
	52% SiO_2			
Mafic—rich in dark (ferromagnesian) minerals (> 60% by volume) plagioclase has Ab/An < 50/50	Basic	ALKALI GABBRO Alkali basalt	SYENO-GABBRO Trachybasalt	GABBRO Basalt (and dolerite)
	45% SiO_2			
Ultramafic—almost feldspar-free	Ultrabasic			DUNITE PERIDOTITE PYROXENITE

Magmatic rocks are also classified into two groups related to the depth of burial during crystallization.

1. **Plutonic, and**
2. **Volcanic**

Plutonic rocks are those crystallized at depth within the crust.

Deep burial retards heat loss and loss of volatile constituents, and leads to slow cooling, coarse grain-size (> 1 mm) of the minerals, and a relatively low temperature of final consolidation.

Some later-formed minerals retain H20 in their lattices and opportunity is given for post-consolidation changes, such as exsolution of crystals that were formed as homogeneous solid solutions and alteration to lower temperature assemblages of early-formed high-temperature phases.

Volcanic rocks have crystallized from magma poured out at the surface of the earth or introduced at shallow depth.

They have cooled relatively rapidly, the grain-size of their crystals is small (< 1 mm), some part of the melt may be chilled to a glass.

Volatiles are lost, and anhydrous minerals of high temperature of crystallization are prevalent.

Types of Magmatic Ore-deposits

The ore-deposits associated with magmatic rocks may occur either as segregations of the minerals separating from the silicate melt itself, or as minerals crystallized from the residual fluids after the main rock-forming minerals have precipitated.

The following succession of stages can be recognized.

i. **Magmatic Crystallization**
ii. **Pegmatitic Crystallization**
iii. **Hydrothermal Crystallization**

(i) magmatic—crystallizing earlier than, or at the same time as the principal rock-forming minerals;
(ii) pegmatitic—crystallizing from vapours or supercritical fluids during the later stages of crystallization of the rock-forming minerals;

(iii) hydrothermal—crystallizing from watery solutions remaining after the rock-forming minerals have crystallized.

The last group may be divided into:

1. **Hypothermal deposits (close to the magmatic source),**
2. **Mesothermal deposits, and**
3. **Epithermal deposits (distant from the magmatic source).**

These classes contain minerals of progressively lower temperature of crystallization.

The mineralogy of the principal magmatic rock groups and their associated ores is given in the following sections.

Ultrabasic rocks (table 18)

These are the rocks called dunite (essentially olivine only), peridotite (olivine + pyroxene) and pyroxenite. They are believed to be formed by accumulation of early-formed crystals from magma of basic composition.

Their bulk composition does not represent that of any liquid melt and they are plutonic rocks only, without volcanic representatives.

Table 18. The Ultrabasic group of rocks.

Rock types: dunite, peridotite, pyroxenite, kimberlite

Rock-forming minerals: olivine, hypersthene, augite, hornblende, phlogopite, subordinate bytownite or labradorite, chromite, magnetite (garnet, ilmenite in kimberlite)

Ore minerals:

Stage / Element	Magmatic	Hydrothermal
Cr	chromite	
Pt, Pd, Ir, Os	native Pt iridosmine sperrylite	
Ni	pyrrhotite, pentlandite (also in veins)	
C	diamond (in kimberlite)	
Mg		chrysotile-asbestos talc magnesite

Rock-forming minerals (Ultrabasic rocks)

Olivine, pyroxene and minor Ca-rich plagioclase feldspar are the essential minerals of ultrabasic rocks. Amphibole and biotite occur in some.

Chromite and other spinel minerals are accessories.

The olivine and pyroxene are commonly altered to serpentine, talc and carbonates.

Ore-Minerals

A number of ore minerals are entirely confined to ultrabasic rocks.

Segregations of chromite, often as layers, are found only in these rocks. Chrysotile asbestos is restricted to serpentinized ultrabasics in which it forms veins. Native platinum is only found in basic and ultrabasic rocks.

Nickel-bearing pyrrhotite and pentlandite occur in sulphide segregations from ultrabasic and basic plutonic rocks.

Talc, talc- magnesite and quartz-magnesite veins are found associated with some serpentinized peridotites.

Diamond, except when obtained from gravels, is exclusively associated with the special ultrabasic rock kimberlite.
The rock-forming minerals here are olivine (and serpentine), the mica phlogopite

Corundum is found associated with some peridotites. The associated rock-forming minerals are notable for being Al-poor, and some introduction of aluminium must be involved in these occurrences.

Magnetite segregations are found in this association also, but are not confined to it. In general, the elements concentrated in the mineral association of ultrabasic rocks are those that find ready acceptance into the lattices of high-temperature precipitates from silicate melts.

Basic Rocks (Table 19)

The plutonic representatives here are the gabbros; the volcanic rocks are the basalts and dolerites.

Rock-forming minerals

Pyroxene and Ca-rich plagioclase feldspar are the essential minerals. Olivine is often present. The accessory minerals are ilmenite, magnetite and apatite.

Table 19. The Basic group of rocks.

Rock types: gabbro, basalt

Rock-forming minerals: olivine, hypersthene, augite, labradorite, magnetite, ilmenite, apatite

Ore minerals:

Stage / Element	Magmatic	Hydrothermal
Ti	ilmenite	
Ti, Fe	titanomagnetite (concentrated as placers)	
Cu		native Cu (in amygdales)
Na, K, Ca		pumpellyite epidote calcite zeolites
Cl		scapolite

Ore Minerals

Ilmenite occurs as segregations from gabbroic magmas, with some associated magnetite.

Although magnetite and titanomagnetite occur in gabbros and basalts as widespread and conspicuous accessory minerals, these do not generally form concentrated deposits in the magmatic rock.

Weathering of the rocks and sorting by wave or river action may, however, concentrate them in placer deposits as in the black sand beaches of the world.

Calc-alkaline, Intermediate and Acid rocks

The petrographic classification of intermediate and acid rocks is shown in Table 16.

As far as the broader mineral associations are concerned, it is more appropriate to divide them into a series from diorite to granite (and andesite to rhyolite), heavily underlined in the Table; and a syenite-trachyte group which is associated with alkali syenites.

Table 16. Classification of non-feldspathoidal magmatic rocks.

(Members of the main calc-alkali series heavily underlined
PLUTONIC rocks in capitals, Volcanic rocks in lower case)

Ratio of light to dark minerals	Group chemistry	Feldspar mainly alkali (K, Na)	Alkali feldspar ≃ plagioclase	Feldspar mainly plagioclase
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	66% SiO_2			
Mesotype—light minerals < 60% > 30% by volume quartz < 10%, plagioclase has Ab/An > 50/50	Intermediate	SYENITE Trachyte	MONZONITE Trachyandesite	DIORITE Andesite
	52% SiO_2			
Mafic—rich in dark (ferromagnesian) minerals (> 60% by volume) plagioclase has Ab/An < 50/50	Basic	ALKALI GABBRO Alkali basalt	SYENO-GABBRO Trachybasalt	GABBRO Basalt (and dolerite)
	45% SiO_2			
Ultramafic—almost feldspar-free	Ultrabasic			DUNITE PERIDOTITE PYROXENITE

The diorite-granite series, called the calc-alkaline series, is characteristic of the belts of mountain folding around the earth.

Both the rocks and the ores associated with them are linked by continuous transitions and are dealt with together below.

The syenites and alkali-syenites form, on the whole, restricted centres in regions subject to block- faulting and rifting of the crust: they are brought together in a separate section.

Rock-forming Minerals

(Calc-alkaline, Intermediate and Acid rocks)

Amongst the iron- and magnesium-bearing (ferromagnesian) minerals, pyroxene, amphibole and biotite characterize this group. Pyroxene-granites are few, this mineral being mainly confined to the intermediate plutonic types (diorites).

It occurs more commonly in acid volcanics, however, because their rapid cooling freezes in high temperature minerals.

An iron-rich olivine occurs in some granites, but generally olivine is absent from the group.

Speaking broadly, pyroxene and hornblende are the dark minerals of diorites and andesites, while hornblende and biotite occur in granodiorites and dacites, granites and rhyolites.

The feldspar includes plagioclase ranging from andesine (with about 40 mol. per cent CaAl2Si208) in the diorites and andesites, to oligoclase and albite in the granites.

With increase in Si02 content, potash feldspar (orthoclase, microcline or sanidine) enters: it is found particularly in the granites and rhyolites.

The entry of quartz in amount greater than 10 per cent is taken as the dividing line between the intermediate and acid types.

Accessory minerals are apatite and magnetite, with zircon and sphene entering in granodiorites and granites.

Ore Minerals (Table 20)

(Calc-alkaline, Intermediate and Acid rocks)

A wide range of ores is found in this association. With the higher content of volatiles in intermediate and acid magmas, there is a change in the character of the associated mineral deposits.

They no longer consist of elements entering the lattices of high-temperature minerals, but include many that do not find a place in early precipitates, and hence concentrate in the residual fluids (gases, or liquids) of

Table 20. Classification of minerals according to temperature at time of deposition.

Falling temperature: increasing dilution →

Element	Pegmatites	Hypothermal	Mesothermal	Epithermal	Secondary
Li	lepidolite amblygonite spodumene petalite				
Be	beryl				
B	tourmaline axinite				
F	topaz apatite				
	fluorite				
R.E., Y, Th	monazite				
Nb, Ta	samarskite pyrochlore				
(P)	(monazite apatite amblygonite)				
Fe	magnetite				jarosite copiapite limonite
Sn	cassiterite				
Mo		molybdenite			
As		arsenopyrite		realgar orpiment	realgar orpiment
W		wolframite scheelite			tungstite
Bi		native bismuth bismuthinite		tetradymite	
Au		native gold (with glassy quartz)	native gold (with milky quartz)	Au selenides and tellurides native gold electrum (with chalcedony)	
Cu		chalcopyrite tetrahedrite bornite			native Cu cuprite chalcocite covellite bornite malachite azurite chrysocolla
Co, Ni		niccolite smaltite-chloanthite linnaeite			nickel and cobalt blooms
Zn			sphalerite		smithsonite hemimorphite willemite
Pb			galena (argentiferous)		cerussite anglesite linarite pyromorphite mimetite wulfenite crocoite
Ag			argentite	ruby silver hessite	native Ag cerargyrite stephanite
Sb				stibnite	cervantite senarmontite valentinite
Hg				cinnabar native Hg	
Gangue minerals	quartz changing from glassy through milky to chalcedonic and opaline				
	pyrite				
	microcline albite biotite muscovite	albite garnet pyroxene biotite muscovite magnetite ilmenite calcite	calcite dolomite ankerite barytes	calcite dolomite barytes adularia alunite sericite kaolin chlorite zeolites	

The chief residual fluid is H20, but others including F, CI and C02 are important, and they are collectively known as mineralizers. Borne by the mobile fluids, the elements that have not found a place in the high-temperature minerals precipitate as vein minerals in fissures traversing the magmatic rocks and radiating outwards from the magmatic centres into the surrounding country- rocks, which may be magmatic, metamorphic or sedimentary in origin.

The deposition of the transported elements as mineral compounds is greatly influenced by temperature, which falls as the solutions move upwards and outwards from the magmatic centre. The minerals with the lowest temperatures of crystallization (e.g. stibnite, cinnabar) may migrate very far.

Deposition is also influenced by the nature of the country-rocks. The fluids react with these in varying degree, to produce replacement deposits in the neighbourhood of the vein fissures.

In Table 20 the minerals listed as belonging to the pegmatitic stage, together with cassiterite, molybdenite, wolframite and scheelite, are particularly associated with granites.

The other minerals are found in association with both intermediate and acid rocks.

Supergene and Diagenetic Associations

Sedimentary rock forming minerals

The common sedimentary rocks, except conglomerates, can be represented as mixtures of three fractions, quartz sand, clay minerals and calcite (with dolomite).

(i) Quartz sand is a resistant product of breakdown by weathering of earlier rocks. Ultimately the quartz has its origin in igneous or metamorphic rocks or veins.

(ii) Clay minerals are formed by the breakdown of high-temperature silicates under weathering, and recombination of their constituents.

(iii) Calcite is precipitated from solution either as the hard parts of organisms or by rise of temperature and loss of C02 in shallow tropical waters.

Sandstone

These are composed of quartz, with variable amounts of clay and sometimes with a cement of calcite, or of silica as quartz, chalcedony or opal.

Other resistant minerals of the rocks weathered to yield the sediment constitute the heavy mineral suite of a sandstone and may include such minerals as zircon, rutile, tourmaline, garnet, ilmenite, staurolite and kyanite.

Pure windblown sandstone, or strongly leached quartz sandstone (ganister) below coal seams may provide a source of very pure silica for glass- making.

Shales

Shales consist of clay minerals, with varying amounts of quartz, carbonates and iron oxides. The crystallization of the clay minerals and iron oxides is often poor, there may be much colloidal matter, and it is necessary to use X-ray methods to obtain information about the minerals.

Unique amongst shales is the organic mud deposit forming the Kupferschiefer of Mansfield in Germany. The mineral association here includes bornite, chalcocite and rarely galena, sphalerite and tetrahedrite.

Limestone

Dominantly of calcite, these may contain dolomite formed by replacement of Ca by Mg from sea- water or circulating waters.

Flint and chert (impure forms of crypto-crystalline silica), pyrite and marcasite are concretionary minerals in limestones. Occasionally concentrations of celestine and strontianite occur. Magnesite may replace dolomitic limestones near igneous intrusions.

Because of their reactive nature, limestones assist the precipitation of minerals from vein- forming solutions, and veins often expand sideways and contain rich ore-deposits where they cut limestones.

Ironstone

Iron deposits of sedimentary origin are widespread in the geological succession. The characteristic parageneses are given below.

Bog iron ore

Limonite, siderite and minor vivianite of swamps and lakes in high latitudes, in Asia, Europe and North America.

Banded siliceous hematite-magnetite ores

These consist of interbanded fine-grained quartz or jasper and layers rich in hematite or magnetite. Siderite and greenalite are also important minerals.

The occurrences are found amongst the ancient rocks of the continental shields, and local concentrations of the original sedimentary iron ore have been produced by circulating waters and metamorphic processes.

Marine Evaporite Deposits

The evaporation of sea-water in basins partly cut off from the open sea has led in the past to the formation of salt deposits.

The common mineral associations in a typical evaporite succession are given below, with the lowest stratum at the bottom of the list and the latest at the top.

The short list is: sylvine, halite, anhydrite, dolomite.

Terrestrial Evaporites

In desert areas, where temporary lakes of enclosed basins dry out, or dissolved salts are brought to the surface by capillarity, deposits of halite, borax and gypsum may be formed.

They are deposited on the floors of playa lakes and as incrustations and cements in the soil or sand and gravel.
The soda nitre deposits of the Atacama Desert in Chile are unique.

Sedimentary Phosphate Deposits

Residual Deposits

The regolith, or crust of weathering, has its greatest importance in providing the mineral matter of soils. The principal soil minerals are:

(i) The resistates, **minerals resistant to chemical breakdown by weathering, of which quartz is by far the most important.**

(i) The layer silicates kaolinite,, illite, montmorillonite, chlorite and their relatives, which are grouped together as clay minerals. These do not all occur together: different environments of parent rock, drainage, aeration and acidity favour different members or assemblages.

(iii) The oxides of iron and aluminium, goethite, hematite, gibbsite and diaspore.

Where chemical weathering and leaching under tropical or warm-temperate conditions has proceeded very thoroughly, to great depth, deposits of bauxite or laterite may form.

These are respectively mixtures of aluminium and iron oxides and hydroxides.

Bauxite is the ore of aluminium and is composed of gibbsite, boehmite* or diaspore, or of mixtures of gibbsite and boehmite.

Laterite contains hematite and sometimes maghemite. It is widespread in tropical countries: it may sometimes furnish low-grade iron ore and is used for building purposes.

Transport of weathered material leads to the concentration of heavy resistate minerals in the gravels and sands of rivers and beaches, by the winnowing action of water-currents. The concentrations so formed are called placer deposits.

Minerals concentrated as placers include gold, platinum, diamond, cassiterite, rutile, monazite, zircon, ruby, sapphire, columbite-tantalite, ilmenite and magnetite.

Ancient gold-bearing conglomerates, including the famous Witwatersrand banket, are believed by some to be fossil placers.

Metamorphic Associations

Sedimentary assemblages of minerals undergo progressive reorganization and recrystallization from the time of their deposition onwards. The earlier stages of this process are grouped together as diagenesis and lithification, terms embracing the changes that transform unconsolidated sediment into sedimentary rock.

After lithification, the rocks may undergo further recrystallization with the production of new minerals.

When the outlines of original sedimentary grains are obliterated, and the texture or fabric of the rock is decisively altered, the changes may be said to have passed beyond the stage of diagenesis and to have entered that of metamorphism.

Though at times the boundary between these two processes may be vague, in practice sedimentary and metamorphic rocks are usually quite distinct.

Magmatic rocks may also undergo metamorphism, recognized by a change in fabric.

Since they are originally formed at high temperatures, and often at high pressures, their minerals are likely to be changed in the first instance to an assemblage stable at a lower temperature than that at which the original association crystallized.

Metamorphism may be of two kinds.

(1) Contact metamorphism (or thermal metamorphism) is due to local heating of the rock by the intrusion of magma nearby.

(2) Regional metamorphism extends over wider areas and is the result of deep burial with consequent rise of temperature and static pressure, usually with the help of the folding movements that accompany the formation of mountain ranges.

Contact Metamorphism

In contact metamorphism the purer sediments produce little variety of minerals.

Pure sandstones recrystallize to quartzites composed of quartz with perhaps a little biotite derived from any impurities. Pure limestones yield calcite marbles.

When a greater variety of elements is present in the rock a larger number of minerals can form. The resulting metamorphic rock is given the general name of hornfels.

Regional Metamorphism

Typical rock-forming minerals of regionally metamorphosed shales are:

chlorite, epidote, the micas biotite and muscovite, chloritoid, garnet, staurolite, kyanite and sillimanite.

These minerals enter successively into the constitution of the rocks as the temperature of metamorphism rises in roughly the order listed,

being accompanied by quartz and albite in the early stages, quartz and oligoclase in the middle stage, and quartz, plagioclase and orthoclase at the highest grades.

In regionally metamorphosed limestones zoisite, grossular, vesuvianite and diopside are common. Tremolite and forsterite appear in dolomitic limestones.

In calcareous shales epidote and green hornblende develop.

Amongst regionally metamorphosed basic igneous rocks, hornblende with plagioclase is a common association, often accompanied by garnet.

High temperatures and pressures of metamorphism of rocks of this composition produce hypersthene-augite-plagioclase-(orthoclase) granulites, in which quartz may appear if the original composition is more acid.

Skarns

These deposits characteristically occur at the contact of granites with limestones.

They contain a wide variety of minerals including often magnetite, garnet, diopside, enstatite, forsterite, small amounts of sulphides and various rarer minerals containing elements such as fluorine and boron derived from the granite.

Cassiterite and tourmaline are sometimes found in this association.

Thanks