Chapter 3*

MINERALOGY AND PETROLOGY

3.1 MINERALS AND THEIR PROPERTIES

Rocks are composed of **minerals** which are natural inorganic substances with particular chemical compositions, or ranges of compositions, and regular atomic structures.

Mineralogy involves the study of these minerals. The average composition of rocks in the earth's crust is given in the Table 3.1.

Table 3.1 Average composition of crustal rocks

SiO_2	59.26 %	Na_2O	3.81 %
Al_2O_3	15.35 %	K_2O	3.12 %
Iron Oxides	6.88 %	H_2O	1.26 %
CaO	5.08%	Others	1.78 %
MgO	3.46 %	**Total**	**100.00 %**

Source: Blyth and de Freitas 1985

3.1.1 *Properties of Rocks*

From Table 3.1, it can be observed that silicon and oxygen are the most abundant elements. These combine to form silicates, the main rock-forming minerals. Some common silicates are: feldspar, quartz, mica, amphibole, and garnet. Also commonly found in minerals are oxides such as hematite and limonite. Common sulfide minerals include pyrite, chalcopyrite, and sphalerite.

Minerals are most commonly distinguished by physical properties such as crystal form, colour, streak, lustre, cleavage, fracture, hardness, specific gravity, tenacity, electrical properties, such as magnetism and conductivity, and special properties such as taste (rock salt) and feel (talc).

a. **Form** describes the shapes of groups of minerals and individual crystal shapes. Figures 3.1 and 3.2 show common mineral forms, and Figure 3.3 illustrates crystal forms.

b. **Colour** can be misleading, as many minerals assume different colours from the content of impurities. However, certain minerals are identified on the basis of their typical colours.

- Jasper - red
- Malachite - green
- Pyrite - bronze yellow

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* Figures and Tables without credit lines in this Chapter are compiled by the author(s).

c. **Streak** is the colour of a mineral's powder which is produced by rubbing on an unglazed porcelain tile or streak plate, or other rough surface. It is useful in distinguishing metallic minerals. This property is more diagnostic than colour in a mineral's identification.

Mineral	Colour	Streak
Haematite	Black	Cherry Red
Magnetite	Black	Greyish black

d. **Lustre** is a mineral's appearance under reflected light and can be described as metallic or non-metallic. The non-metallic minerals can be classified as vitreous or glassy, resinous or greasy, pearly, silky, dull, etc.

vitreous - quartz
pearly - biotite
silky - asbestos

e. **Cleavage** is the tendency of a mineral to part easily in directions parallel to crystal faces producing cleavage planes. It can be described as perfect, good, moderate, or poor, and often the number of cleavage directions is also given. For example, biotite mica has one perfect cleavage, whereas calcite has three perfect cleavages.

f. **Fracture** refers to the nature of the surface of a mineral in a direction other than that of cleavage in crystallised minerals and in any direction in massive minerals.

The terms **conchoidal, hackly, uneven**, and **even** describe the various types of fracture (Fig. 3.4).

Examples:

concoidal - quartz
even - chart
uneven - tourmaline

g. **Hardness** is the resistance offered by the mineral when it is scratched. It is measured on Moh's Scale which gives a relative scale of 10 minerals.

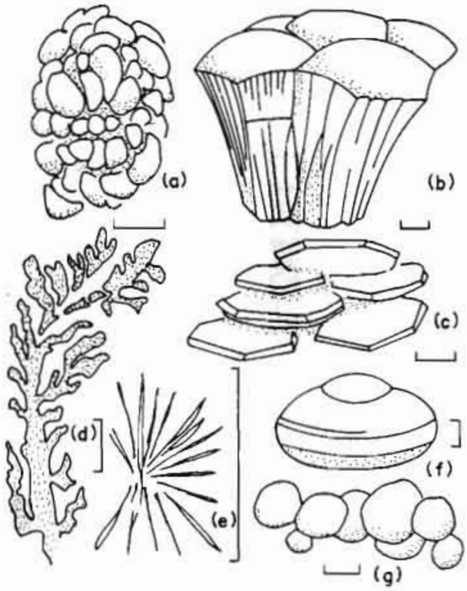
1.	Talc	6.	Orthoclase
2.	Gypsum	7.	Quartz
3.	Calcite	8.	Topaz
4.	Fluorite	9.	Corundum
5.	Apatite	10.	Diamond

The other tools, often used for testing hardness, are the finger nail (H=3), window glass (H=5), and a knife (H=6).

h. **Specific gravity** (Table 3.2) is the density of a mineral and expressed as:

$$SG = \frac{\text{weight in air}}{(\text{weight in air - weight in water})}$$

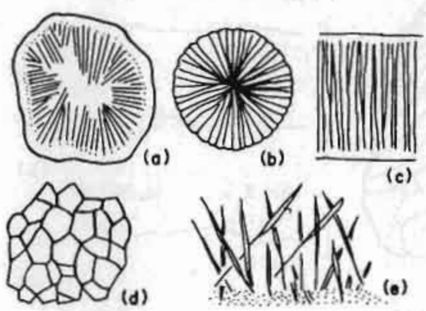
i. **Tenacity** denotes the response of a mineral to cutting by a knife. For example, **malleable** minerals are gold and copper, **brittle** minerals include quartz and feldspar, **sectile** minerals, such as copper, can be sliced with a knife, and **elastic** minerals, such as muscovite, spring back after bending.



Source: Blyth and de Freitas 1985

Fig. 3.1 Common shapes of mineral clusters

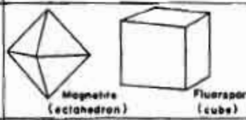
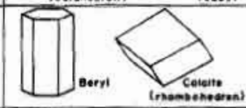
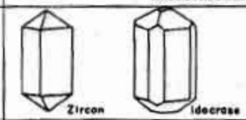
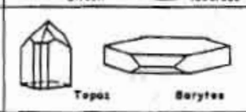
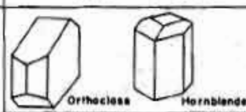
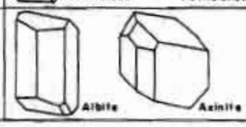
a. Botryoidal b. Reniform c. Tabular
d. Dendritic e. Acicular f. and g. Concretionary



Source: Blyth and de Freitas 1985

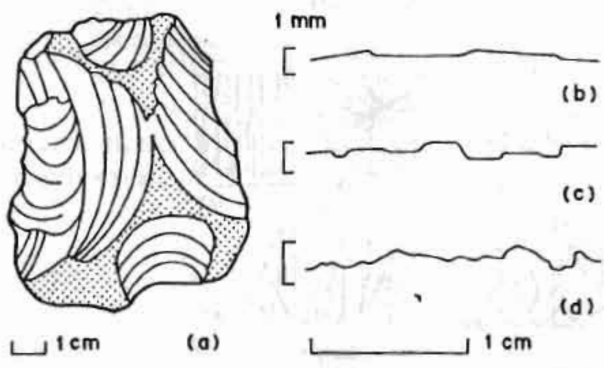
Fig. 3.2 Relationship between minerals in clusters

a. Drusy b. Radiating c. Fibrous
d. Granular e. Reticulated

Crystal system	Crystal form	
Cubic		Examples Garnet, leucite, fluorite, rocksalt, zinc-blende, pyrite
Hexagonal and trigonal		Beryl, nepheline, apatite tourmaline, calcite quartz
Tetragonal		Zircon, cassiterite (tin-stone), idocrase
Orthorhombic		Olivine, enstatite, topaz, barytes
Monoclinic		Orthoclase, feldspar, hornblende, augite, biotite, gypsum
Triclinic		Plagioclase feldspars, axinite

Source: Modified after Blyth and de Freitas 1985

Fig. 3.3 Common crystal forms and systems



Source: Blyth and de Freitas 1985

Fig. 3.4 Fracture of minerals

a. Conchoidal b. Even c. Uneven d. Hackly

Table 3.2 Specific gravity of common minerals

Feldspar	2.56 - 2.7
Caletite	2.7
Quartz	2.65
Dolomite	2.85
Chlorite	2.2 - 3.3
Muscovite	2.8 - 3.0
Hornblende	3.2
Tourmaline	3.0 - 3.2

Source: Anbalagan 1991

Table 3.3 Non-metallic Minerals

Mineral	Hardness	Lustre	Cleavage	Colour	Remarks
Talc $Mg_3Si_4Al(OH)_2$	1	Greasy	1 perfect	White, light green	Usually as alteration in mafic/ultramafic rocks. Often with serpentine, sometimes with magnesite.
Chlorite (Fe,Mg)5 $Si_3Al_2O_{10}(OH)_2$	2-2.5	Dull to resinous	1 perfect	Clear to white	In low to medium grade metamorphic and igneous rocks.
Muscovite K Al_2 $(AlSi_3)O_{10}(OH)_2$	2-2.5	Pearly	1 perfect	Clear to white	Occurs in granites and felsic rocks, gneisses, schists, and sedimentary rocks. Sericite is a fine-grained secondary alteration.
Biotite K $(Mg,Fe)_3$ (Si_3Al) $O_{10}(OH)_2$	2.5-3	Pearly to submetallic	1 perfect	Brown to black	In igneous rocks, gneisses and schists. Commonly alters to chlorite.
Plagioclase feldspar -Albite $(NaAlSi_3O_8)$ -Anorthite $(CaAl_2Si_2O_8)$	6-6.5	Vitreous	2 good at 90°, 1 poor	White, grey, blue, yellow	Twining striae common on cleavages. Often occurs with orthoclase. Common in igneous and some metamorphic and sedimentary rocks.
Dolomite $CaMg(CO_3)_2$	3.5	Pearly to vitreous	3 perfect	White to brown	Effervesces in warm HCl, or when powdered. Major constituent of dolostone deposits.

Mineral	Hardness	Lustre	Cleavage	Colour	Remarks
Garnet Group $X_3 Y_2 (SiO_4)_3$ where X = Ca, Mg, Fe^{+2}, Mn^{+3} and Y = Al, Fe^{+3}, Cr	6.5-7.5	Vitreous to resinous	Conchoidal fracture	Red, brown, yellow, green	Dodecahedron or trapezohedron form. Most of metamorphic origin, some of igneous origin. Also occurs in hydrothermal deposits such as skarns.
Quartz SiO_2	7	Vitreous none	Conchoidal	Colour-white, yellow, brown, grey	Hexagonal prismatic crystals. In granitic rocks as clear, glassy crystals. Also as phenocrysts and in veins and infillings. Abundant in gneisses, schists, and arenaceous sandstones.
Tourmaline Na $(Mg P_1 Fe)_3$ $Al_6 (BO_3)_3 (Si_6O_{18}$ $(OH_1F)_4$	7-7.5	Vitreous	Conchoidal fracture	Black (most common), blue, pink, yellow, multi-coloured	Hexagonal or trigonal crystals, sometimes radiating. In igneous and metamorphic rocks. Often in hydrothermal deposits.
Amphibole Group-Hornblende $(Ca\ Mg\ Na\ Al)_3$	5-6	Vitreous to resinous	2 perfect at 56° and 124°	Brown to greenish black	Usually as monoclinic bladed crystals. Common in igneous and metamorphic rocks. Alteration to chlorite.
Pyroxene Group-Monoclinic pyroxene e.g. Augite $(CaMgFeAl)_2 (SiAl)O_3$	5-6	Vitreous to resinous	2 good at 93° & 87°	Brown to greenish black	Usually as 8-sided prisms in mafic to ultramafic rocks.
Orthorhombic e.g. Hypersthene $(Mg\ Fe)SiO_3$ Enstatite $MgSiO_3$	5-6	Vitreous to resinous	2 good at 93° & 87°	Dark to green	8-sided prisms in mafic igneous and some ultramafic rocks.
Epidote Ca $(FeAl)_3$ $(SiO_4)_3 (OH)_2$	6-7	Vitreous	2 moderate	Pistachio green	Monoclinic crystals, generally in radial clusters. Alteration product of anorthitic plagioclase, pyroxenes or hornblendes. Also a metamorphic mineral, in igneous veins, and as volcanic rock vesicles.
Orthoclase feldspar $KAlSi_3O_8$	6-6.5	Vitreous	2 good at 90° 1 poor	White, pink, grey, blue, brown	Perthitic intergrowth common. In granites, gneisses, and sandstones. Often as porphyroblasts in gneissic rocks. Alters to kaolinite and sericite.

Source: Dhital 1991

Table 3.4 Metallic Minerals

Mineral	Hardness	Streak	Colour	S.G.	Lustre	Comments
Graphite (C)	1	Black	Black	2.2	Metallic	Layered mineral. Marks paper, slippery feel. In veins, metamorphic rocks.
Copper (Cu)	2.5	Copper-red	Copper-red	8.9	Metallic	Malleable. Native copper is rare.
Gold (Au)	2.5	Yellow	Yellow	19.3	Metallic	Malleable. Usually as fine disseminations with sulfides such as pyrite and in quartz veins.
Galena (PbS)	2.5	Lead-grey	Lead-grey	7.4 - 5.1	Metallic	Dense feel. Perfect cubic cleavage. Infillings and fractures, skarn replacements.
Bornite (Cu_5FeS_4)	3	Greyish black	Bronze-brown, Irrid-escent peacock tarnish	4.9-5.1	Metallic	Common with other copper minerals in hydrothermal deposits & veins.
Malachite $Cu_2 (OH)_2 Co_3$	3.5	Dull to silky	-		Green	Copper ore produced by weathering of copper minerals. Appears as staining. Botryoidal form common.
Sphalerite (ZnS)	3.5-4	Brown-yellow	Yellow, brown, red, black	4	Resinous	In sedimentary and hydrothermal replacement deposits.
Chalcopyrite ($CuFeS_2$)	3.5-4	Green-ish black	Brass yellow	4.2	Metallic	Main source of Cu in varied environments. Usually with pyrite and other Cu minerals in veins. Also in metamorphic rocks.
Limonite Fe_2O_3 $(3H_2O)$	5	Yellow brown	Yellow to brown	3.8	Earthy	Along fractures, weathered surfaces as weathering deposits.
Hematite (Fe_2O_3)	5 - 6	Red	Cherry red	5.3	Metallic	Common source of iron ore. Also in igneous rocks, metamorphic rocks, in hydrothermal deposits.
Magnetite (Fe_3 O_4)	5.5-6.5	Black	Black	5.2	Metallic	Strongly magnetic. Igneous and clastic sedimentary rocks. Also in metamorphic and hydrothermal deposits.
Pyrite (FeS_2)	6.5	Black	Brass - yellow	4.9 - 5.2	Metallic	Similar to gold. Disseminated crystals common in veins, quartzites, igneous and metamorphic rocks. The most widespread sulfide.

Source: Dhital 1991

3.2 PETROLOGY

Petrology studies the origin, distribution, and composition as well as alterations of rocks occurring in the earth's crust. Rock is an aggregate of minerals, and there are three main categories of it according to origin. They are igneous, metamorphic, and sedimentary rocks. Texture is an important property in identifying the types of rock. Texture is defined as the relationship among the mineral grains of which the rock is constituted. The texture includes size, shape, and arrangement of constituent particles. Table 3.5 provides a general classification of rocks.

Table 3.5 General classification of rcks

Rocks

Igneous	Metamorphic	Sedimentary
Plutonic	Thermal	Clastic
Hypabyssal	Dynamothermal	Chemical
Volcanic		Organic

Source: Anbalagan 1991

3.2.1 *Igneous Rocks*

Igneous rocks are the product of solidification of lava or magma on or below the earth's surface.

Plutonic rocks have cooled deeper below the earth's surface and are also known as **intrusive** rocks. **Volcanic**, **effusive**, or **extrusive** rocks are formed due to ejection of magma through volcanic pipes and vents and cool on the earth's surface. They can be classified as **flows** or **pyroclastics** depending upon their mode of extrusion. While extremely rare in Nepal, these rocks are common in North Western India, in the Deccan traps, in South-central Tibet, and Northern Burma, to mention a few places.

a. *Intrusive (or plutonic) Rocks*

These rocks are formed by cooling of magma at greater depth beneath the earth's surface. They differ in texture from other rocks because of their cooling history. Depending on their size they are classified as major or minor intrusions.

i. <u>Major intrusions</u>

These are classified as **batholiths** (Fig. 3.5) and **stocks** in decreasing order of size. It is generally accepted that major intrusions are the result of forceful injection, that is, they physically push aside the surrounding rocks. Evidence in the form of **xenoliths**, which are remains of the country rock present within the intrusions, supports this theory. However, in some areas, intrusions grade gradually into country rocks, with no apparent break. This kind of evidence supports the theory of partial melting of country rocks and solid state diffusion known as **granitisation** (i.e., becoming granite).

ii. Minor intrusions

Leading from major intrusions are often fingers of magma, forming dykes, veins, sills, laccoliths, and lopoliths.

Dykes (Fig. 3.5) are tabular bodies which cross-cut country rock. They vary in width from several cm to about 5m and may be continuous over several kilometres. **Dyke swarms** are groups of dykes arrayed either in a parallel or radiating manner.

Sills are approximately parallel to the layers of rocks they intrude and are usually fed by vertical and sub-vertical dykes (Fig. 3.5).

b. *Hypabyssal Rocks*

The rocks that are formed by solidification of magma at shallow depth are called hypabyssal rocks. They are characterised by the inequigranular size of minerals ranging from coarse to fine. This type of texture is called 'porphyry'. These rocks generally occur as minor intrusions.

c. *Volcanic Rocks*

The rocks that crystallise on or very near the surface are known as volcanic rocks. They are formed as a result of the eruption of lava along conduits leading from the earth's surface down to a magma chamber. Usually, a crater is formed on eruption (Fig. 3.5). The type of volcanic eruption, violent or quiet, depends upon the viscosity, chemical composition, and gas content of the magma. Normally, mafic magmas, such as basalts, which have low silica contents, extrude quietly as lava flows. Highly siliceous rocks are generally viscous and commonly contain high amounts of gases. These erupt violently to form glowing avalanches of debris and lava called *nuées ardentes*. **Pyroclastic** rocks are formed as a result of violent eruptions. The plateau basalts of the Deccan Plateau in India are examples of quiet eruptions, while Krakatoa in Java, in 1883, erupted so forcefully that dust from the eruption circled the earth's upper atmosphere for a year after the explosion. Hot springs are often, though not always, associated with the warning phases of a volcanic area.

i. Engineering considerations

Because of the complex processes involved, volcanic rocks can produce very complicated associations. Periods of volcanism are interrupted by quiescence, during which different rocks are formed. Volcanic episodes may also produce different rocks depending upon the magma's chemical and fluid composition, both of which are highly variable.

The inter-trappean beds, which include the sediments deposited between successive volcanic activities, have different engineering properties compared to the rocks above and below. When major structures such as dams are planned on these rocks, the non-homogeneity of the foundation condition causing differential settlements may be studied in detail.

Pyroclastic rocks (breccia and tuff) are generally quite porous, but rhyolitic lavas are not. Thus, weathering zones may be hidden by strong basaltic lavas and large variations in thickness are to be expected.

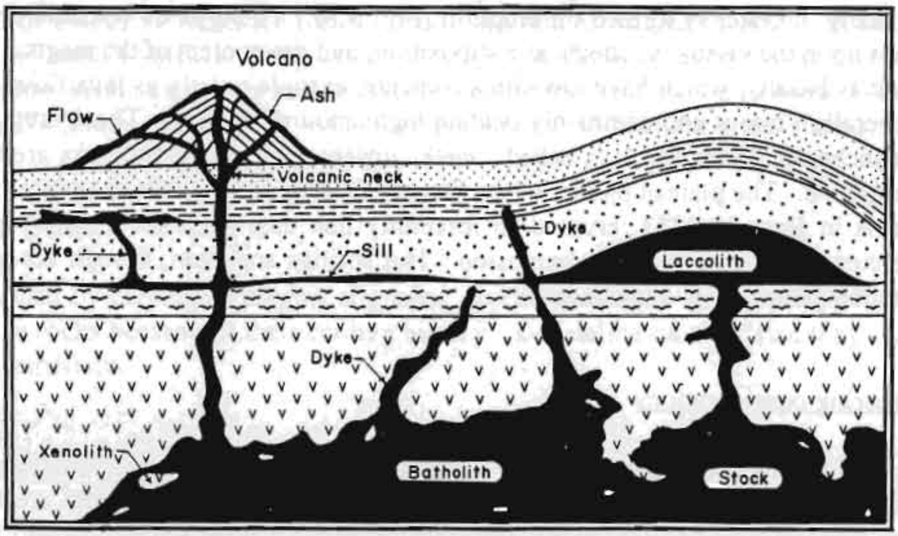
These considerations highlight the importance of detailed mapping and careful interpretation in volcanic terrain. Proper selection of representative samples for laboratory and field tests are required due to the possible variability of these rocks. Cross sections are essential in the case of detailed studies.

d. *Classification*

Igneous rocks are classified by their texture and mineral composition. Table 3.6 shows the common textures of igneous rocks and Table 3.7 provides a detailed classification of igneous rocks.

The texture of an igneous rock depends upon its mode of emplacement. Thus, a volcanic rock, which cools quickly on the earth's surface, is finer grained than a plutonic rock which solidifies over long periods in the earth's crust.

The texture and composition of an igneous rock has great bearing on its engineering characteristics. A highly vesicular basalt, with many holes, called **vesicles**, is highly porous and weak and weathers readily to clay. On the other hand, a dense, quartz-rich rhyolite flow is harder than any granite and is highly resistant to weathering. It is thus imperative that an engineer recognizes the different rock types and is able to classify their texture. As many descriptive terms as possible should be used in describing a rock's physical characteristics.



Source: Skinner and Porter 1987

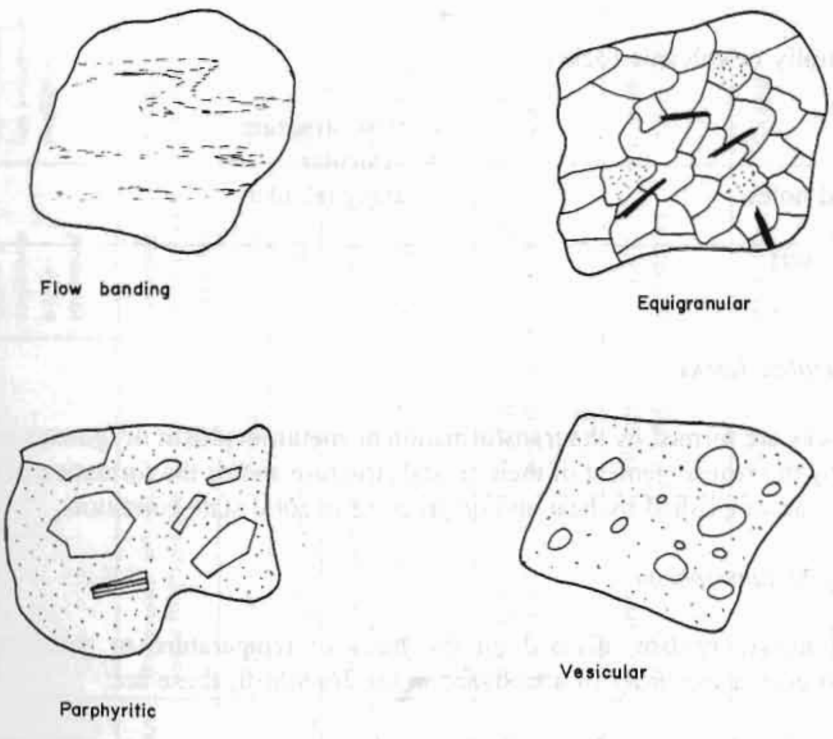
Fig. 3.5 Block diagrams illustrating a pluton, dykes, and sills

The common textures seen under a microscope are shown in Fig. 3.6. The mineral composition of a rock is dependent upon its chemistry. Broadly, igneous rocks are classified as felsic (or acidic) and mafic (or basic) depending upon their silica (SiO_2), alkali (Na_2O, K_2O, and CaO) and ferromagnesian content. Felsic rocks are lighter in colour than mafic ones. Ultramafic rocks are very dark coloured.

e. *Engineering Considerations*

The mineral composition of igneous rocks affects their weathering and other properties. Pyroxenes and amphiboles, both high-temperature minerals, are unstable on the earth's surface and decompose readily to chlorite and other clays. These minerals are common in veins and dykes, basalt tuffs and flows, and mafic plutonic rocks such as gabbro. The engineer should be alerted to these rocks as potentially unstable units and use discretion in construction, excavation, and blasting.

On the other hand, granites are generally quite strong, although their feldspars can weather to clays under tropical and sub-tropical conditions. The interrelationship between igneous rocks and their country rocks should also be observed. Horizontal sills may have a destabilizing effect on a hillslope by allowing ground water to accumulate above it, giving rise to perched water tables. Interlayered, impervious igneous sills and sedimentary rocks have also been blamed for piping failures due to the preferential movement of water above the sills.



Source: Blyth and de Freitas 1985

Fig. 3.6 Common igneous rock textures described in Table 3.6.

Table 3.6 Commonly used terms for describing igneous rock texture

1. *Crystal size*			
Intrusive rocks	> 2 mm	= coarse-grained	Phaneritic
	0.06 - 2 mm	= medium-grained	(crystals visible)
	< 0.06 mm	= fine-grained	
Volcanic rocks	< 0.06 mm	= aphanitic	(crystals not visible)
Crystals not present		= glassy	
2. *Crystal Shape*			
Well-defined		= euhedral	
Ill-defined		= anhedral	
3. *Relative crystal size*			
Same size		= equigranular	
Some larger than others		= inequigranular	
Large crystals set among small crystals		= porphyritic	
4. *Others* (generally in volcanic rocks)			
Banding		= flow structure	
With holes		= vesicular	
With in-filled holes		= amygdaloidal	

Source: Dhital 1991

3.2.2 *Metamorphic Rocks*

Metamorphic rocks are formed by the transformation or **metamorphism** of igneous or sedimentary rocks into new rocks by the rearrangement of their crystal structure and/or the formation of new minerals. This transformation is accomplished by heat and/or pressure in solid state condition.

a. *Types of Metamorphism*

Three types of metamorphism, divided on the basis of temperature or pressure controls, can be distinguished. In decreasing order of abundance in the *Himalaya*, these are:

i. regional metamorphism, divided on the basis of temperature and pressure has affected a large area due to confinement of overlying rocks, shearing stresses due to plate movements, and large igneous intrusions;

Table 3.7 Classification of Igneous Rocks

TEXTURE		MINERAL COMPOSITION							
	Dark Minerals	Subordinate (biotite and/or amphibole, less commonly pyroxene)		Abundant (biotite and/or amphibole and/or pyroxene)	Dominant (pyroxene and/or olivine less commonly amphibole	Predominant (olivine and/or pyroxene; less commonly amphibole)			
	Feldspars	Predominant orthoclass, minor Na Plagioclase		Dominant (mostly Na-Ca plagioclase)	Abundant (Ca-plagioclase)	Little or no feldspar			
	Quartz	With quartz	No quartz	No quartz	No quartz	No quartz			
	Fragmental	TUFF (lithified ash)		VOLCANIC	BRECCIA	UNCOMMON	Lava flows Volcanic explosion (pyroclastic)	Extrusive	Volcanic
	Glassy	OBSIDIAN (dark glass)		PUMICE					
	Aphanitic (< 0.06 mm) (micro crystalline)	RHYOLITE TRACHYTE FELSITE		ANDESITE	BASALT				
	Porphyritic (Phenocrysts in aphanitic groundmass)	RHYOLITE PORPHYRY	TRACHYTE PORPHYRY	ANDESITE PORPHYRY	BASALT PORPHYRY		Small or tabular shallow bodies and lava flows		Hypabyssal
	Porphyritic (Phenocrysts in pheneritic groundmass)	GRANITE PORPHYRY	SYENITE PORPHYRY	DIORITE PORPHYRY	GABBRO PORPHYRY				
	Pheneritic (coarsely crystalline) (> 2 mm)	GRANITE	SYENITE	DIORITE	GABBRO	PERIDOTITE PYROXENITE HORNBLENDITE	Medium to large, deep-seated masses	Intrusive	Plutonic
		Light Coloured	Intermediate		Dark Coloured				
		Acidic			Basic	Ultrabasic			

Source: Anbalagan 1991

ii. dynamic or cataclastic metamorphism, where pressure (in the form of stress) is the dominant control, in fault and shear zones, and

iii. contact or thermal metamorphism, where heat is the most important control, as in contact aureoles around igneous bodies.

Each of the above metamorphic types has distinct textural and mineralogical features which affect its physical properties.

i. Regional Metamorphism

As the name suggests, this process acts over large areas, typically hundreds to thousands of square kilometres, and develops due to the heat and stresses arising from burial, shearing, and igneous intrusions.

With increasing depth, pressure and temperature increase. As rocks are subjected to ever-increasing pressure and temperature regimes, they undergo facies changes (Fig. 3.7). Each **facies** is distinguished by sets of index minerals and particular textural types. The first occurrence of any one of these minerals marks the beginning of a particular facies.

For instance, during the metamorphism of a shale, the following rocks and corresponding facies are observed:

Rock name	shale	slate	phyllite	gneiss	migmatite
Metamorphic facies	unmeta-morphosed	zeolite	green-schist	amphi-bolite	partial melt

As metamorphism increases the **texture** of a rock changes. At very low metamorphic grades, shale will preserve its bedding and other sedimentary textures. As pressure increases, it is transformed into slate which possesses both bedding and cleavage (Fig 3.8). In some places, slaty cleavage may be parallel to bedding but, in others, it may be perpendicular to it (Fig 3.8).

With increasing metamorphism, a highly foliated, shiny rock named **phyllite** results. Micas such as chlorite and muscovite begin to grow along foliation planes perpendicular to the principal stress. This rock cleaves easily along its foliation planes and, together with quartzite, causes mass movements. **Schists** are crystalline, foliated rocks whose minerals can be distinguished in hand specimens (Fig 3.9). They are composed of micas, quartz, and hornblende, depending upon the original rock. Generally, metamorphosed clay-rich sedimentary rocks are rich in micas. Likewise quartzites are rich in quartz and meta-volcanics are rich in chlorite and hornblende. **Gneisses** (Fig 3.10) are coarse-grained, crystalline rocks with thick, sometimes indistinct, bands of quartz, feldspar, and mafic minerals. Breakages along foliation are sometimes accompanied by breakages across it.

In the *Himalaya*, augen (eye-shaped) gneisses are common (Fig 3.10), in which the foliation wraps around elongated feldspar and quartz-feldspar masses. These rocks may behave unexpectedly during loading because of their heterogeneous nature. On further application of heat and pressure, partial melting occurs and a rock called **migmatite** forms. Migmatite is a mixed rock of plutonic and gneissic components and has the properties of both.

ii. Cataclastic Metamorphism

During movement along faults, the mechanical breaking and shearing of rock occurs, resulting in fine-grained rocks known as **mylonite**. With further shearing, partial fusion occurs giving rise to **cataclasite**. These rocks contain large amounts of hydrous minerals, such as mica and amphibole, because of the abundance of hydrothermal solutions found along fault zones. **Mylonite zones** occupy large areas and are common along the Main Central Thrust and Main Boundary Thrust, as well as other thrusts. In Southern Tibet, they are also present in the Indus-Tsangpo Suture Zone.

iii. Contact Metamorphism

Contact metamorphism is produced by the intrusion of hot igneous bodies into country rocks. Here the increased temperature is the dominant agent producing changes and the degree of crystallization bears a simple relation to it. Hornfels and allied rocks are formed in the contact aureoles bordering the bodies of plutonic rocks (Fig. 3.11). Hornfels are hard and granular rocks with no preferred orientation of minerals.

b. *Classification*

Metamorphic rocks are classified by their texture and structure, crystal size, and mineral composition. Most metamorphic rocks have pronounced preferred orientations in which the foliations are very well developed. Some rocks, however, such as quartzites and marbles, which contain a low amount of clay minerals, have little or no foliation.

i. Texture and Structure

Foliation describes the lining up of platy minerals and/or surfaces due to differential stress regimes.

Lineation describes a series of aligned minerals or traces of foliation on a rock surface.

Porphyroblasts are coarser grained minerals within a finer grained matrix. When sheared, these give rise to **augens** (Fig. 3.10).

Crystal size - Contact metamorphic rocks are very fine grained to microscopic.
Cataclastic rocks are also very fine grained.

Regionally metamorphosed rocks range in grain size from microscopic to very coarse grained depending on metamorphic grade.

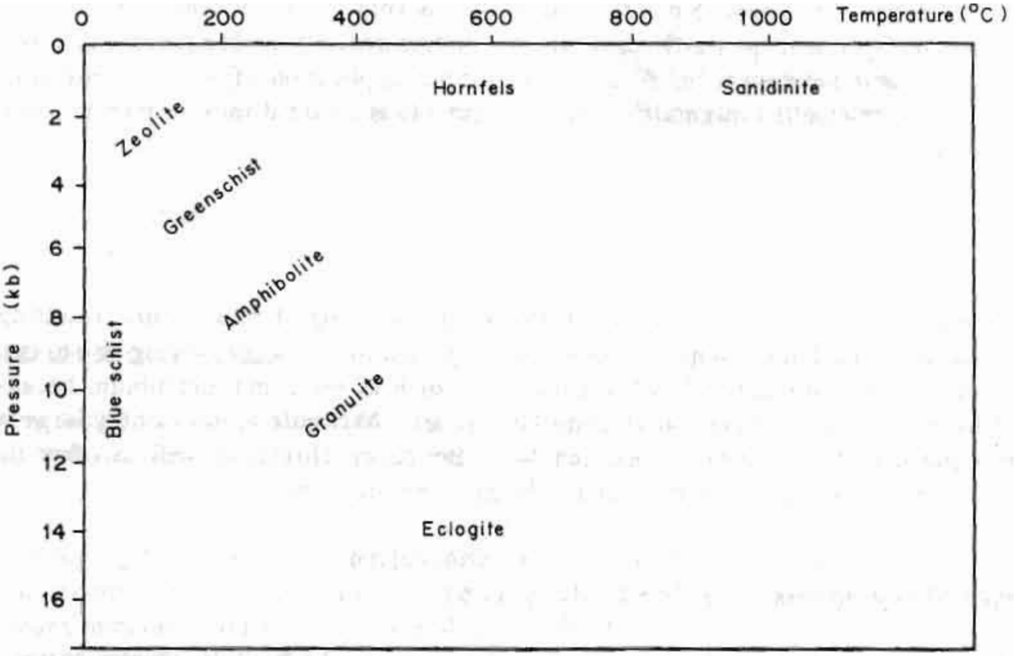


Fig. 3.7 Metamorphic facies according to pressure temperature regimes

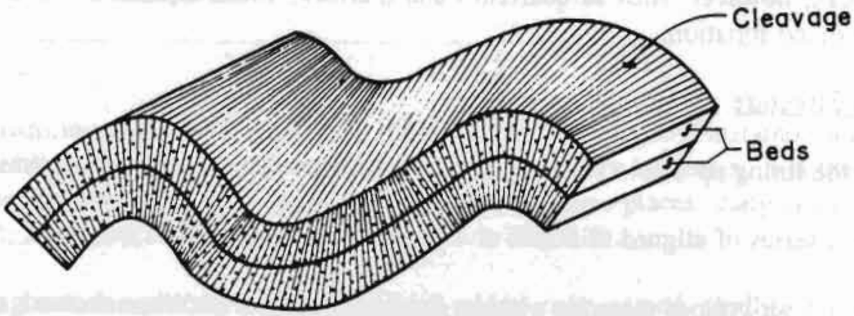


Fig. 3.8 Slaty cleavage and bedding

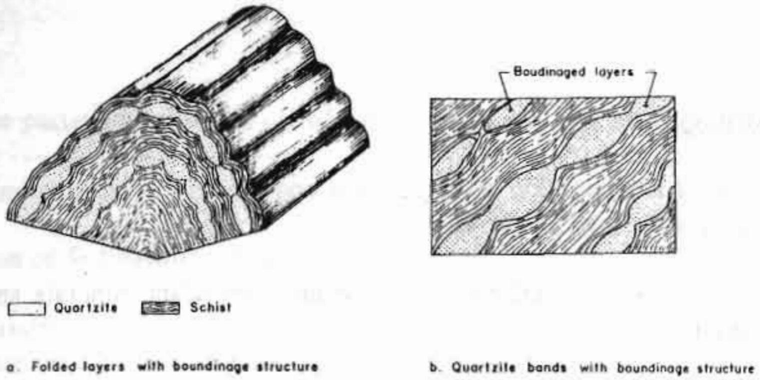


Fig. 3.9 Boudinage structure in gneiss with schistose layers

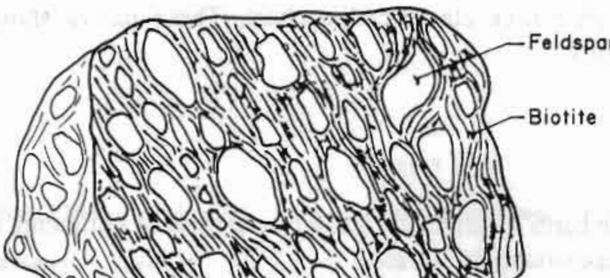


Fig. 3.10 Augen gneiss with 'stretched' porphyroblasts

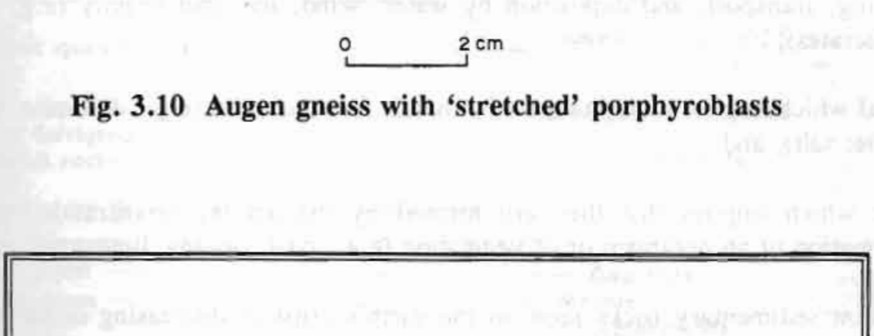


Fig. 3.11 Contact aureoles around igneous intrusion

ii. Mineral Composition

The mineral composition of metamorphic rocks depends upon their original composition, metamorphic grade, and presence of hydrothermal solutions.

Generally, a metamorphic rock is named by listing the most abundant minerals and rock name, e.g., quartz-biotite-garnet schist.

iii. Rock Name

Figure 3.12 gives a metamorphic rock classification chart. These names should be preceded by the predominant minerals and texture.

3.2.3 *Sedimentary Rocks*

These are formed at or near the earth's surface by the accumulation of sediments in a basin of deposition. According to their mode of deposition, they are:

- **detrital** or **clastic** which means the particles are derived from pre-existing rocks by mechanical weathering, transport, and deposition by water, wind, ice, and gravity (e.g. sandstones and conglomerates);
- **chemical** which implies precipitation of minerals from solution (e.g., dolomite, various types of limestone, salt), and
- **organic** which implies that they are formed by the action, fossilization, preservation, or transformation of an organism or of vegetation (e.g., coal, organic limestone, and oil shale).

The most common sedimentary rocks seen on the earth's crust in decreasing order are **shale** (4%), **sandstone** (0.75 %), and **limestone** (0.25%).

a. *Formation of Sedimentary Rocks*

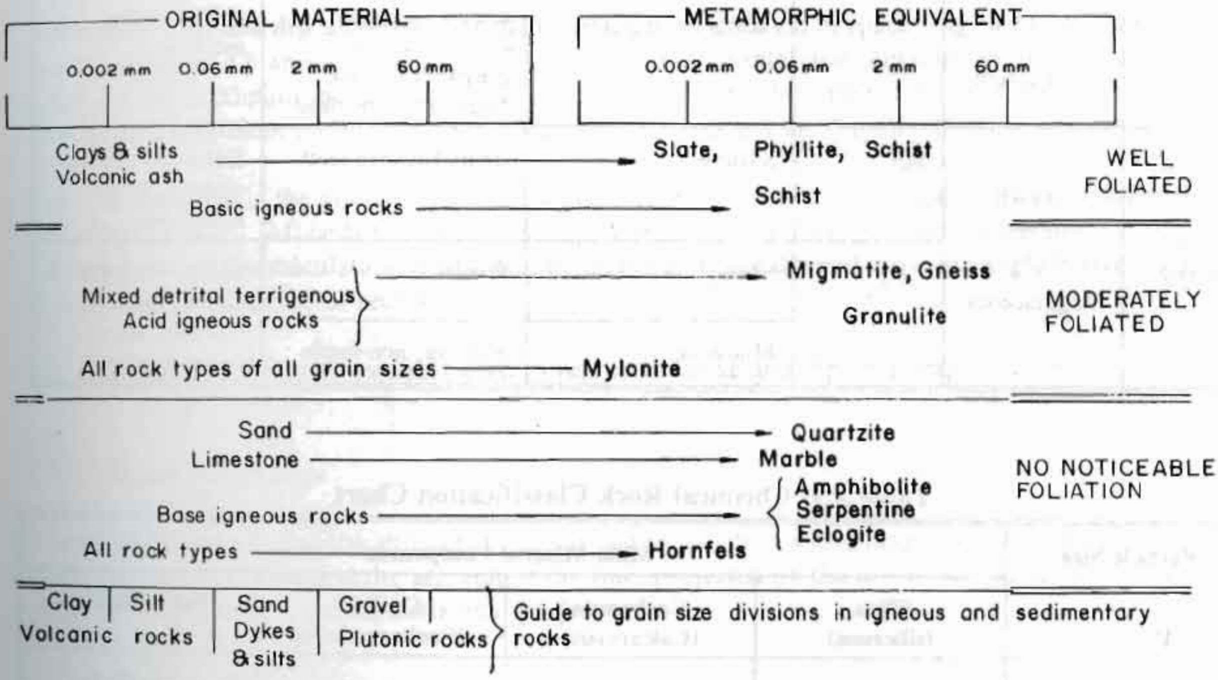
An understanding of the formation processes of sedimentary rocks is essential for predicting their behaviour during construction. Three important processes occur and they are:

1. **deposition** - accumulation of sediments,
2. **compaction** - decrease in volume by weight of overlying sediments (muds are more affected than sands and gravels, as they contain more pore water which is extruded during compaction), and
3. **cementation** - subsequent cementation of particles due to precipitation of minerals (cement) by percolating waters.

The change of loose particles to rock is called **lithification**. It is a chemical process that reduces the original porosity.

b. *Classification of Sedimentary Rocks*

In Table 3.8, the classification of detrital sediments is based on the grain size of the particles. Chemical sedimentary rocks are classified differently, the size limits not being the standards (Table 3.9).



Source: Blyth and de Freitas 1985

Fig. 3.12 Metamorphic rock classification chart

Table 3.8 Detrital sedimentary rock classification chart

Particle size (mm)	Unconsolidated Sediment		Sedimentary rock name	Field identification	Environment of deposition
		Boulder			
200	Rudaceous	Cobble	Conglomerate	Rounded fragments in fine-grained matrix; indicates long transport	Glacial moraine, storm beaches, landslide colluvium
60		Gravel	Breccia	Angular fragments in fine-grained matrix; indicates short transport	River bottoms and banks, deltas, glacial streams
60	Arenaceous	Sand	Sandstone (arkose, greywacke, arenite)	Predominent minerals arkose - feldspar arenite - quartz greywacke - rock fragments with fines	Beaches, river banks, deserts, deltas, glacial moraine
0.06		Silt	Silstone	Gritty between teeth	Estuaries, glacial outwash plains, mudflows
0.002	Argillaceous	Clay	Shale	Fissile	Glacial outwash plaints, till, sea-bottoms, lakes, and mudflows
			Mudstone	Massive, non-fissile	

Table 3.9 Chemical Rock Classification Chart

Particle Size	Main Mineral Component			
	Silica (siliceous)	Carbonate (Calcareous)	Carbon (Carbonaceous)	Salts (Saline)
Megacrystalline > 2 mm		Limestone, Dolomite		Evaporites (after diagenesis)
Mesocrystalline 0.6 - 2 mm			Peat, Coal	Evaporites - rock salt, gypsum, anhydrite
Microcrystalline < 0.06 mm	Flint, chert, jasper, radiolarite, diatomite			