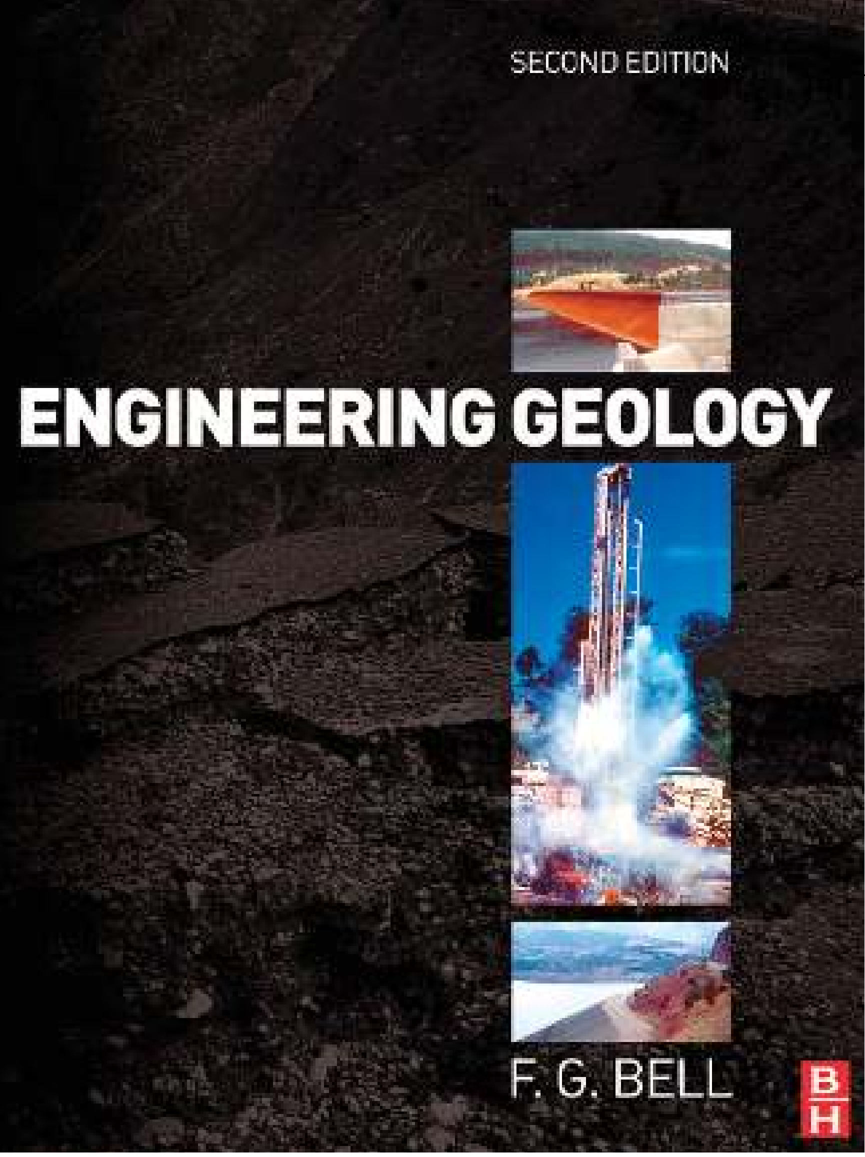
SECOND EDITION
ENGINEERING GEOLOGY
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Engineering Geology

Second Edition

F. G. Bell

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Preface

As noted in the Preface to the first edition, engineering geology can be defined as the application of Geology to engineering practice. In other words, it is concerned with those geological factors that influence the location, design, construction and maintenance of engineering works. Accordingly, it draws on a number of geological disciplines such as geomorphology, structural geology, sedimentology, petrology and stratigraphy. In addition, engineering geology involves hydrogeology and some understanding of rock and soil mechanics.

Similar to the first edition, this edition too is written for undergraduate and post-graduate students of engineering geology. It is hoped that this will also be of value to those involved in the profession, especially at the earlier stages of their careers. However, it is aimed at not just engineering geologists but also at those in civil and mining engineering, water engineering, quarrying and, to a lesser extent, architecture, planning, surveying and building. In other words, those who deal with the ground should know something about it.

No single textbook can cover all the needs of the variety of readers who may use it. Therefore, a list of books is suggested for further reading, and references are provided for those who want to pursue some aspect of the subject matter to greater depth. However, some background knowledge also is assumed. Obviously, students of geology will have done much more reading on geology than the basic geological material covered in this book. They presumably will have done or will do some reading on soil mechanics and rock mechanics. On the other hand, those with an engineering background will have read some soil and rock mechanics, but need some basic geology, hopefully, this book will meet their needs. Moreover, any book will reflect the background of its author and his or her view of the subject. However, this author has attempted to give a balanced overview of the subject.

The text has been revised and extended to take account of some subjects that were not dealt with in the first edition. Also, some of the chapters have been rearranged. Hopefully, this should have improved the text.

The author gratefully acknowledges all those who have given permission to publish material from other sources. Individual acknowledgements are given throughout the text.

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Rock Types and Stratigraphy

According to their origin, rocks are divided into three groups, namely, the igneous, metamorphic and sedimentary rocks.

Igneous Rocks

Igneous rocks are formed when hot molten rock material called magma solidifies. Magmas are developed when melting occurs either within or beneath the Earth's crust, that is, in the upper mantle. They comprise hot solutions of several liquid phases, the most conspicuous of which is a complex silicate phase. Thus, igneous rocks are composed principally of silicate minerals. Furthermore, of the silicate minerals, six families – the olivines [$(Mg,Fe)_2SiO_4$], the pyroxenes [e.g. augite, $(Ca, Mg, Fe, Al)_2(Al,Si)_2O_6$], the amphiboles [e.g. hornblende, $(Ca,Na,Mg,Fe,Al)_{7-8}(Al,Si)_8O_{22}(OH)_2$], the micas [e.g. muscovite, $KAl_2(AlSi_2)_{10}(O,F)_2$; and biotite, $K(Mg,Fe)_2(AlSi_3)O_{10}(OH,F)_2$], the feldspars (e.g. orthoclase, $KAlSi_3O_8$; albite, $NaAlSi_3O_8$; and anorthite, $CaAl_2Si_2O_8$) and the silica minerals (e.g. quartz, SiO_2) – are quantitatively by far the most important constituents. Figure 1.1 shows the approximate distribution of these minerals in the commonest igneous rocks.

Igneous rocks may be divided into intrusive and extrusive types, according to their mode of occurrence. In the former type, the magma crystallizes within the Earth's crust, whereas in the latter, it solidifies at the surface, having erupted as lavas and/or pyroclasts from a volcano. The intrusions have been exposed at the surface by erosion. They have been further subdivided on the basis of their size, that is, into major (plutonic) and minor (hypabyssal) categories.

Igneous Intrusions

The form that intrusions adopt may be influenced by the structure of the host or country rocks. This applies particularly to minor intrusions.

Dykes are discordant igneous intrusions, that is, they traverse their host rocks at an angle and are steeply dipping (Fig. 1.2). As a consequence, their surface outcrop is little affected by topography and, in fact, they tend to strike a straight course. Dykes range in width up to

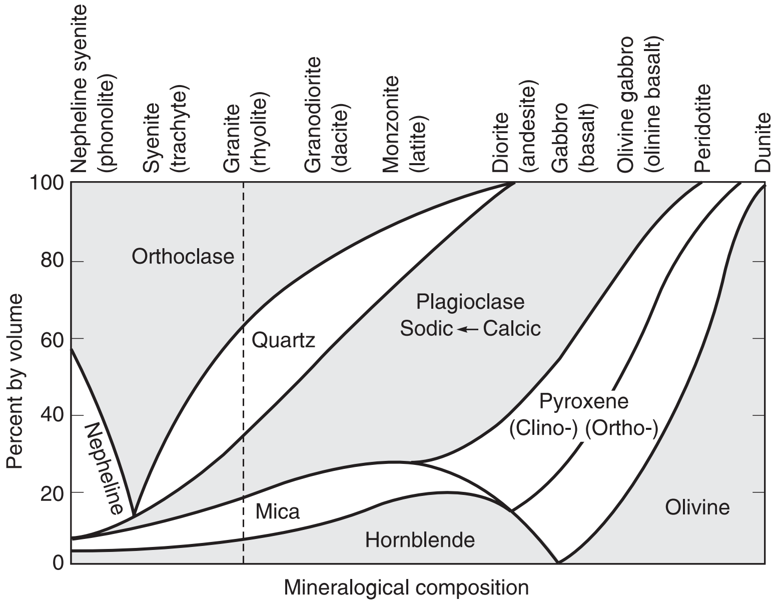

Figure 1.1

Approximate mineral compositions of the more common types of igneous rocks, e.g. granite approximately 40% orthoclase, 33% quartz, 13% plagioclase, 9% mica and 5% hornblende (plutonic types without brackets, volcanic equivalents in brackets).

Figure 1.2

Dyke on the south side of the Isle of Skye, Scotland.

several tens of metres but their average width is on the order of a few metres. The length of their surface outcrop also varies; for example, the Cleveland Dyke in the north of England can be traced over some 200 km. Dykelets may extend from and run parallel to large dykes, and irregular offshoots may branch away from large dykes. Dykes do not usually have an upward termination, although they may have acted as feeders for lava flows and sills. They often occur along faults, which provide a natural path of escape for the injected magma. Most dykes are of basaltic composition. However, dykes may be multiple or composite. Multiple dykes are formed by two or more injections of the same material that occur at different times. A composite dyke involves two or more injections of magma of different composition.

Sills, like dykes, are parallel-sided igneous intrusions that can occur over relatively extensive areas. Their thickness, however, can vary. Unlike dykes, they are injected in an approximately horizontal direction, although their attitude may be subsequently altered by folding. When sills form in a series of sedimentary rocks, the magma is injected along bedding planes (Fig. 1.3). Nevertheless, an individual sill may transgress upwards from one horizon to another. Because sills are intruded along bedding planes, they are said to be concordant, and their outcrop is similar to that of the host rocks. Sills may be fed from dykes, and small dykes

Figure 1.3

The Whin Sill, Northumberland, England.

may arise from sills. Most sills are composed of basic igneous material. Sills may also be multiple or composite in character.

The major intrusions include batholiths, stocks and bosses. Batholiths are very large in size and are generally of granitic or granodioritic composition. Indeed, many batholiths have an immense surface exposure. For instance, the Coast Range batholith of Alaska and British Columbia can be traced over 1000 km in length and over approximately 130 to 190 km in width. Batholiths are associated with orogenic regions. They often appear to have no visible base, and their contacts are well-defined and dip steeply outwards. Bosses are distinguished from stocks in that they have a more or less circular outcrop. Both their surface exposures are of limited size, frequently less than 100 km^2. They may represent upward extensions from deep-seated batholiths.

Certain structures are associated with granite massifs, tending to be best developed at the margins. For example, particles of elongate habit may be aligned with their long axes parallel to each other. Most joints and minor faults in batholiths possess a relationship with the shape of the intrusion. Fractures are developed in the solidified margins of a plutonic mass and may have been filled with material from the interior when it was still liquid. Cross joints or Q joints tend to radiate from the centre of the massif. They are crossed approximately at right angles by steeply dipping joints termed longitudinal or S joints. Pegmatites or aplites (see the following text) may be injected along both types of joints mentioned. Diagonal joints are orientated at 45° to Q and S joints. Flat-lying joints may be developed during or after formation of the batholith and they may be distinguished as primary and secondary, respectively. Normal faults and thrusts occur in the marginal zones of large intrusions and the adjacent country rocks.

Volcanic Activity and Extrusive Rocks

Volcanic zones are associated with the boundaries of the crustal plates (Fig. 1.4). Plates can be largely continental, oceanic, or both. Oceanic crust is composed of basaltic material, whereas continental crust varies from granitic in the upper part to basaltic in the lower. At destructive plate margins, oceanic plates are overridden by continental plates. The descent of the oceanic plate, together with any associated sediments, into zones of higher temperature leads to melting and the formation of magmas. Such magmas vary in composition, but some, such as andesitic or rhyolitic magma, may be richer in silica, which means that they are more viscous and, therefore, do not liberate gas so easily. The latter type of magmas are often responsible for violent eruptions. In contrast, at constructive plate margins, where plates are diverging, the associated volcanic activity is a consequence of magma formation in the lower crust or upper mantle. The magma is of basaltic composition, which is less

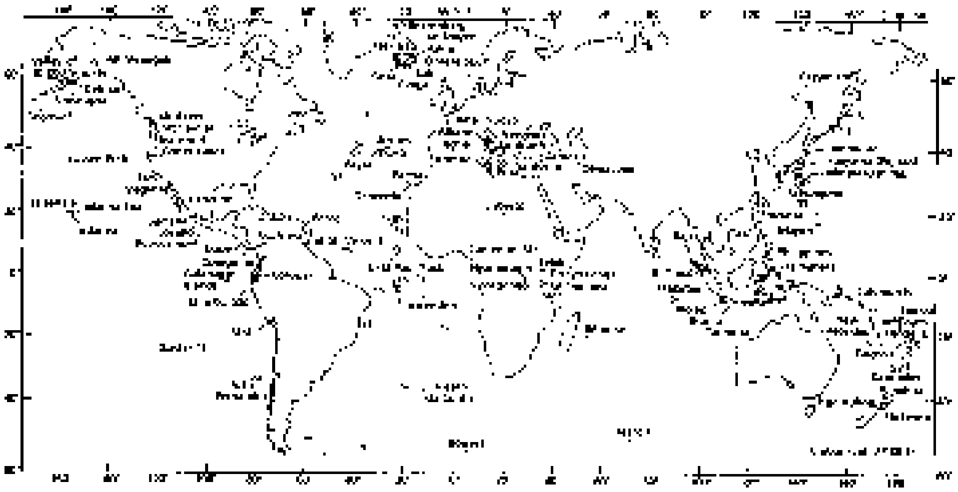

Figure 1.4

Distribution of the active volcanoes in the world. S, submarine eruptions.

viscous than andesitic or rhyolitic magma. Hence, there is relatively little explosive activity and the associated lava flows are more mobile. However, certain volcanoes, for example, those of the Hawaiian Islands, are located in the centres of plates. Obviously, these volcanoes are unrelated to plate boundaries. They owe their origins to hot spots in the Earth’s crust located above rising mantle plumes. Most volcanic material is of basaltic composition.

Volcanic activity is a surface manifestation of a disordered state within the Earth’s interior that has led to the melting of material and the consequent formation of magma. This magma travels to the surface, where it is extravasated either from a fissure or a central vent. In some cases, instead of flowing from the volcano as lava, the magma is exploded into the air by the rapid escape of the gases from within it. The fragments produced by explosive activity are known collectively as pyroclasts.

Eruptions from volcanoes are spasmodic rather than continuous. Between eruptions, activity may still be witnessed in the form of steam and vapours issuing from small vents named fumaroles or solfataras. But, in some volcanoes, even this form of surface manifestation ceases, and such a dormant state may continue for centuries. To all intents and purposes, these volcanoes appear extinct. In old age, the activity of a volcano becomes limited to emissions of gases from fumaroles and hot water from geysers and hot springs.

Steam may account for over 90% of the gases emitted during a volcanic eruption. Other gases present include carbon dioxide, carbon monoxide, sulphur dioxide, sulphur trioxide, hydrogen sulphide, hydrogen chloride and hydrogen fluoride. Small quantities of methane, ammonia, nitrogen, hydrogen thiocyanate, carbonyl sulphide, silicon tetrafluoride, ferric chloride, aluminium chloride, ammonium chloride and argon have also been noted in volcanic gases. It has often been found that hydrogen chloride is, next to steam, the major gas produced during an eruption but that the sulphurous gases take over this role in the later stages.

At high pressures, gas is held in solution, but as the pressure falls, gas is released by the magma. The rate at which it escapes determines the explosivity of the eruption. An explosive eruption occurs when, because of its high viscosity (to a large extent, the viscosity is governed by the silica content), the magma cannot readily allow the escape of gas until the pressure that it is under is lowered sufficiently to allow this to occur. This occurs at or near the surface. The degree of explosivity is only secondarily related to the amount of gas the magma holds. On the other hand, volatiles escape quietly from very fluid magmas.

Pyroclasts may consist of fragments of lava that were exploded on eruption, of fragments of pre-existing solidified lava or pyroclasts, or of fragments of country rock that, in both latter instances, have been blown from the neck of a volcano.

The size of pyroclasts varies enormously. It is dependent on the viscosity of the magma, the violence of the explosive activity, the amount of gas coming out of solution during the flight of the pyroclast, and the height to which it is thrown. The largest blocks thrown into the air may weigh over 100 tonnes, whereas the smallest consist of very fine ash that may take years to fall back to the Earth’s surface. The largest pyroclasts are referred to as volcanic bombs. These consist of clots of lava or of fragments of wall rock.

The term lapilli is applied to pyroclastic material that has a diameter varying from approximately 10 to 50 mm (Fig. 1.5). Cinder or scoria is irregular-shaped material of lapilli size. It usually is glassy and fairly to highly vesicular.

The finest pyroclastic material is called ash. Much more ash is produced on eruption of acidic than basic magmas. Acidic igneous rocks contain over 65% silica, whereas basic igneous rocks contain between 45 and 55%. Those rocks that have a silica content between acid and basic are referred to as intermediate, and those with less than 45% silica are termed ultrabasic. As mentioned, the reason for the difference in explosivity is because acidic material is more viscous than basic or basaltic lava.

Beds of ash commonly show lateral variation as well as vertical. In other words, with increasing distance from the parent vent, the ash becomes finer and, in the second case, because the heavier material falls first, ashes frequently exhibit graded bedding, with coarser material occurring at the base of a bed, and becoming finer towards the top. Reverse grading may

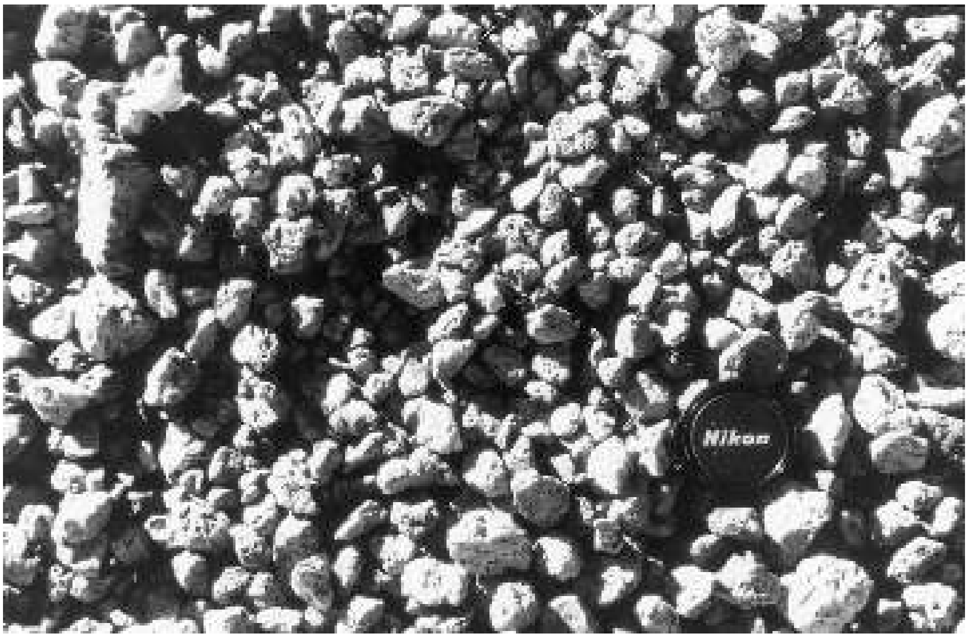

Figure 1.5

Lapilli near Crater Lake caldera, Oregon.

occur as a consequence of an increase in the violence of eruption or changes in wind velocity. The spatial distribution of ash is influenced by wind direction, and deposits on the leeward side of a volcano may be much more extensive than on the windward. Indeed, they may be virtually absent from the latter side.

After pyroclastic material has fallen back to the ground surface, it eventually becomes indurated. It then is described as tuff. According to the material of which tuff is composed, distinction can be drawn between ash tuff, pumiceous tuff and tuff breccia. Tuffs are usually well bedded, and the deposits of individual eruptions may be separated by thin bands of fossil soil or old erosion surfaces. Pyroclast deposits that accumulate beneath the sea are often mixed with a varying amount of sediment and are referred to as tuffites. Rocks that consist of fragments of volcanic ejectamenta set in a fine-grained groundmass are referred to as agglomerate or volcanic breccia, depending on whether the fragments are rounded or angular, respectively.

When clouds or showers of intensely heated, incandescent lava spray fall to the ground, they weld together to become welded tuff. In other cases, because the particles become intimately fused with each other, they attain a largely pseudo-viscous state, especially in the deeper

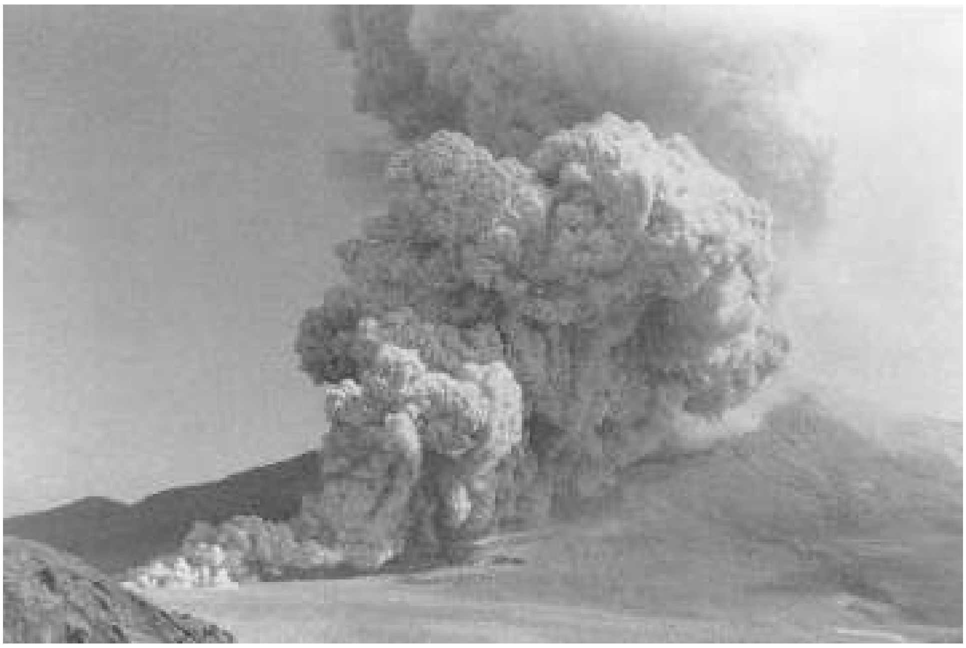

Figure 1.6

Nuee ardente erupting from Mt. St. Helens in May 1980, Washington State.

parts of the deposit. The term ignimbrite is used to describe these rocks. If ignimbrites are deposited on a steep slope, they begin to flow, and they resemble lava flows. Ignimbrites are associated with nuées ardentes (Fig. 1.6).

Lavas are emitted from volcanoes at temperatures only slightly above their freezing points. During the course of their flow, the temperature falls until solidification takes place somewhere between 600 and 900°C, depending on their chemical composition and gas content. Basic lavas solidify at higher temperatures than do acidic ones.

Generally, flow within a lava stream is laminar. The rate of flow of lava is determined by the gradient of the slope down which it moves and by its viscosity that, in turn, is governed by its composition, temperature and volatile content. Because of their lower viscosity, basic lavas flow much faster and further than do acid lavas. Indeed, the former type has been known to travel at speeds of up to 80 km h^{-1}.

The upper surface of a recently solidified lava flow develops a hummocky, ropy (termed pahoehoe); rough, fragmental, clinkery, spiny (termed aa); or blocky structure (Fig. 1.7a and b). The pahoehoe is the most fundamental type, however, some way downslope from the vent,

Figure 1.7

(a) Ropy or pahoehoe lava, Craters of the Moon, Idaho.

it may give way to aa or block lava. In other cases, aa or block lava, may be traceable into the vent. The surface of lava solidifies before the main body of the flow beneath. Pipes, vesicle trains or spiracles may be developed in the lava, depending on the amount of gas given off, the resistance offered by the lava and the speed at which it flows. Pipes are tubes that project upwards from the base and are usually several centimetres in length and a centimetre or less in diameter. Vesicles are small spherical openings formed by gas. Vesicle trains form when gas action has not been strong enough to produce pipes. Spiracles are openings formed by explosive disruption of the still-fluid lava by gas generated beneath it. Large flows are fed by a complex of streams beneath the surface crust so that when the supply of lava is exhausted, the stream of liquid may drain away leaving a tunnel behind.

Thin lava flows are broken by joints that may run either at right angles or parallel to the direction of flow. Joints do occur with other orientations but are much less common. Those joints that are normal to the lava surface usually display a polygonal arrangement, but only rarely do they give rise to columnar jointing. These joints develop as the lava cools. First, primary joints form, from which secondary joints arise, and so it continues.

Figure 1.7, cont'd

(b) Clinkery or aa lava, Craters of the Moon, Idaho.

Typical columnar jointing is developed in thick flows of basalt (Fig. 1.8). The columns in columnar jointing are interrupted by cross joints that may be either flat or saucer-shaped. The latter may be convex up or down. These are not to be confused with platy joints that are developed in lavas as they become more viscous on cooling, so that slight shearing occurs along flow planes.

Texture of Igneous Rocks

The degree of crystallinity is one of the most important items of texture. An igneous rock may be composed of an aggregate of crystals, of natural glass, or of crystals and glass in varying proportions. This depends on the rate of cooling and composition of the magma on the one hand and the environment under which the rock developed on the other. If a rock is completely composed of crystalline mineral material, it is described as holocrystalline. Most rocks are holocrystalline. Conversely, rocks that consist entirely of glassy material are referred to as holohyaline. The terms hypo-, hemi- or merocrystalline are given to rocks that are made up of intermediate proportions of crystalline and glassy materials.

Figure 1.8

Columnar jointing in basalt, Giant's Causeway, Northern Ireland.

When referring to the size of individual crystals, they are described as cryptocrystalline if they can just be seen under the highest resolution of the microscope or as microcrystalline if they can be seen at a lower magnification. These two types, together with glassy rocks, are collectively described as aphanitic, which means that the individual minerals cannot be distinguished with the naked eye. When the minerals of which a rock is composed are mega- or macroscopic, that is, they can be recognized with the unaided eye, it is described as phanerocrystalline. Three grades of megascopic texture are usually distinguished, namely, fine-grained, medium-grained and coarse-grained, the limits being under 1-mm diameter, between 1- and 5-mm diameter, and over 5-mm diameter, respectively.

A granular texture is one in which there is no glassy material and the individual crystals have a grain-like appearance. If the minerals are of approximately the same size, the texture is described as equigranular, whereas if this is not the case, it is referred to as inequigranular. Equigranular textures are more typically found in plutonic igneous rocks. Many volcanic rocks and rocks that occur in dykes and sills, in particular, display inequigranular textures, the most important type being the porphyritic texture. In this texture, large crystals or phenocrysts are set in a fine-grained groundmass. A porphyritic texture may be distinguished as macro- or micro-porphyritic, according to whether or not it may be observed with the unaided eye, respectively.

The most important rock-forming minerals are often referred to as felsic and mafic, depending on whether they are light or dark coloured, respectively. Felsic minerals include quartz, muscovite, feldspars and feldspathoids, whereas olivines, pyroxenes, amphiboles and biotite are mafic minerals. The colour index of a rock is an expression of the percentage of mafic minerals that it contains. Four categories have been distinguished:

(1) leucocratic rocks, which contain less than 30% dark minerals
(2) mesocratic rocks, which contain between 30 and 60% dark minerals
(3) melanocratic rocks, which contain between 60 and 90% dark minerals and
(4) hypermelanic rocks, which contain over 90% dark minerals

Usually, acidic rocks are leucocratic, whereas basic and ultrabasic rocks are melanocratic and hypermelanic, respectively.

Igneous Rock Types

Granites and granodiorites are the commonest rocks of the plutonic association. They are characterized by a coarse-grained, holocrystalline, granular texture. Although the term granite lacks precision, normal granite has been defined as a rock in which quartz forms more than 5% and less than 50% of the quarfeloids (quartz, feldspar, feldspathoid content), potash feldspar constitutes 50 to 95% of the total feldspar content, the plagioclase is sodi-calcic, and the mafites form more than 5% and less than 50% of the total constituents (Fig. 1.1).

In granodiorite, the plagioclase is oligoclase or andesine and is at least double the amount of potash feldspar present, the latter forming 8 to 20% of the rock. The plagioclases are nearly always euhedral (minerals completely bounded by crystal faces), as may be biotite and hornblende. These minerals are set in a quartz–potash feldspar matrix.

The term pegmatite refers to coarse or very-coarse-grained rocks that are formed during the last stages of crystallization from a magma. Pegmatitic facies, although commonly associated with granitic rocks, are found in association with all types of plutonic rocks. Pegmatites occur as dykes, sills, veins, lenses or irregular pockets in the host rocks, with which they rarely have sharp contacts (Fig. 1.9).

Aplites occur as veins, usually several tens of millimetres thick, in granites, although like pegmatites they are found in association with other plutonic rocks. They possess a fine-grained, equigranular texture. There is no important chemical difference between aplite and pegmatite, and it is assumed that they both have crystallized from residual magmatic solutions.

Figure 1.9

Pegmatite vein cutting through Shap Granite, Cumbria, England.

Rhyolites are acidic extrusive rocks that are commonly associated with andesites. They are generally regarded as representing the volcanic equivalent of granite. They are usually leucocratic and sometimes exhibit flow banding. Rhyolites may be holocrystalline, but very often they contain an appreciable amount of glass. They are frequently porphyritic, the phenocrysts varying in size and abundance. The phenocrysts occur in a glassy, cryptocrystalline or microcrystalline groundmass. Vesicles are usually found in these rocks.

Acidic rocks occurring in dykes or sills are often porphyritic, quartz porphyry being the commonest example. Quartz porphyry is similar in composition to rhyolite.

Syenites are plutonic rocks that have a granular texture and consist of potash feldspar, a subordinate amount of sodic plagioclase and some mafic minerals, usually biotite or hornblende.