1: Igneous rocks

Cambridge University Press
978-0-521-29184-2 - Petrology for Students
S. R. Nockolds, R. W. O'B. Knox and G. A. Chinner
Excerpt
More information

I

Igneous rocks and their textures

Igneous rocks are formed from relatively high-temperature melts or *magmas*, as such melts are usually termed. When a magma cools it solidifies to give a rock that may consist of an aggregate of minerals, or of minerals and glass or, more rarely, of glass alone. The mutual relationship of the mineral constituents, including glass when present, defines the *texture* of the rock. The nature of the texture developed depends mainly on the rate of cooling of the magma, its viscosity, and the molecular concentrations of its components.

Some insight into the way in which at least some textures of igneous rocks are produced is provided by experimental work on simple melts (1). As a melt of a given substance cools down from its melting point, the number of centres of crystallisation (*nuclei*) formed in unit volume in unit time (the *nucleus number*) gradually increases. This increase is slow at first and then, at a given degree of undercooling, reaches a maximum value, thereafter sinking almost to zero.

The *viscosity* of the melt at first increases slowly with increasing undercooling until a *critical temperature* is reached at which the rate of increase rises rapidly until, finally, a glass may be formed. The marked increase in viscosity occurs in many cases just at that temperature where the nucleus number reaches its maximum. But with some substances the tendency towards spontaneous crystallisation is greatest when the melt has become rigid while, with other substances, the nucleus number attains its maximum value well above the point at which the great increase in viscosity becomes evident. The *initial* viscosity depends to a large degree on the composition of the melt. Thus, the viscosity increases with increasing SiO_2 content, the increase being rapid when the latter exceeds some 60 per cent. A large content of Al_2O_3 causes an increase, but the presence of much FeO or MnO causes a marked decrease: the substitution of some of the CaO in basic slags by MgO also decreases the viscosity of the melt, and the same effect is observed when MgO is substituted for CaO in soda-silicate glasses.

The *rate of growth* of the crystals forming in the melt rises to a maximum for a given degree of undercooling, and then decreases gradually. The maximum of the growth rate lies at a temperature above that at which the marked increase in viscosity sets in and, usually, above that defining the maximum of the nucleus number.

The facts outlined above may be applied most directly to the textures of lavas and very shallow-seated intrusions. Here, the volatile constituents of the magma have been largely lost, giving rise to essentially dry melt conditions, and cooling is relatively rapid.

If the cooling is very rapid, the magma quickly reaches the point where the marked increase in viscosity occurs, preventing the formation of any crystals, and causing the whole to solidify as a glass. The resulting rock is said to be *holohyaline*. Siliceous magmas are particularly prone to solidify as glass, once they have lost their volatile constituents; basic magmas much less so, owing to their lower initial viscosity. More often than not, incipient crystallisation of the magma has taken place so that *crystallites* (which do not react to polarised light), in the form of tiny globules, rods or hair-like bodies, or the somewhat larger *microlites*, having prismatic, acicular or arborescent forms, are scattered through the glass.

A glass is metastable and always has a tendency to crystallise, or *devitrify*. As a result, few natural glasses are known from before the Carboniferous era. Nevertheless, their former presence may frequently be proved, even after complete devitrification, by the presence of characteristic curved cracks, known as *perlitic* cracks (fig. 4.1A).

Spherulitic and *felsitic* textures are produced with a rather less rapid rate of cooling than that which provides a glass. Experimental work indicates that *spherulitic crystallisation*, involving the formation of acicular crystals radially arranged in the form of a sphere (spherulites) (fig. 4.2), takes place at a fairly moderate degree of undercooling when the nucleus number is still low but the growth rate is rather large. It also requires a certain degree of viscosity in the melt and is thus quite commonly found in siliceous lavas and siliceous furnace slags but is much rarer and less well developed in basic lavas and basic furnace slags, and practically unknown in highly fluid melts, such as those of metals. The less well-developed texture of this kind found in basic lavas is the *variolitic* texture in which irregular branching fibres of the mineral concerned (commonly plagioclase feldspar) have a crudely spherical disposition. In ultramafic lavas a different quench texture, the *spinifex* texture, is due to the rapid crystallisation of bladed skeletal olivine crystals (see p. 152).

Felsitic texture (fig. 4.1B), comprising an almost cryptocrystalline, more or less equigranular, aggregate of minerals, is formed at a greater degree of undercooling where the nucleus number is approaching its maximum, the growth rate has been reduced considerably, and the viscosity of the melt is high. It is thus possible to find spherulites embedded in a felsitic or a glassy groundmass (2).

The felsitic texture is found in siliceous lavas but basic lavas, cooling at approximately the same rate, do not normally show it because of their lower viscosity and because one of the main minerals to crystallise out, plagioclase feldspar, has a very strong tendency to develop a lath-like habit. Instead, either the *intergranular* texture, in which wedge-shaped areas between the plagioclase laths are filled with granules of the other minerals, or the *intersertal* texture, in which the interstices between the minerals are filled with glass (fig. 12.1), is developed.

A texture somewhat resembling the last is found in some lavas of intermediate composition. This is the *hyalopilitic* texture, in which a felt of crystals is set in a residuum of glass (fig. 9.1B). Again, certain lavas are composed of little feldspar laths aligned parallel to the direction of flow of the magma, giving rise to the *trachytic* texture (fig. 6.1).

Many lavas, and many of the rocks found in shallow-seated intrusions, carry larger crystals (*phenocrysts*) embedded in their fine-grained or glassy groundmasses. This is the *porphyritic* texture (fig. 4.3). One way in which this may develop is when the magma starts to cool slowly at greater depths and is then extruded, or intruded at a higher level, where, owing to the more rapid cooling, the loss of volatiles, and consequent increased viscosity, the remainder solidifies as a fine-grained aggregate, or as a glass.

But in some instances it is clear that the phenocrysts commenced to grow after the emplacement of the magma. During the normal cooling of such a magma there is, however, an early period some time before the marked increase in viscosity occurs and during which the nucleus number is small, while the growth rate may be relatively large. Phenocrysts might well be expected to form under these conditions, providing the magma remained long enough within the appropriate temperature interval (3). Phenocrysts may be grouped or clustered together to form *glomeroporphyritic aggregates*. This is one aspect of the phenomenon of *synneusis*, the process of drifting together and mutual attachment of crystals suspended in a melt (4).

The textures considered so far have been produced under conditions more or less comparable with those of artificial melts, but in magmas that solidify at an appreciable depth below the surface, the crystallised product is coarser in grain. Another factor enters here, namely, the presence of volatile constituents. These will lower the general viscosity and, more especially, prevent the marked increase of viscosity in the later stages as the volatiles become concentrated in the residual liquid. This, while important, should not be overemphasised. The dominant factor is the slower rate of cooling (5).

If cooling is slow enough, the characteristic texture produced is the *subhedral-granular* (or *granitic*) texture (fig. 3.4A) in which some of the constituents are anhedral while others have a more or less subhedral outline. The *microgranitic* texture (fig. 4.4A) is developed with more rapid rates of cooling, and there are all transitions from this to granitic texture on the one hand, and from this to felsitic on the other (6).

In some basic igneous rocks whose plagioclase feldspar has started to crystallise out early and then been joined by pyroxene, a *subophitic* texture may take the place of the subhedral-granular. In this, wedge-shaped areas between the subhedral crystals of plagioclase are occupied by plates of pyroxene that may be in optical continuity over a considerable area (fig. 11.1).

If the nuclei of some particular constituent are widely separated in comparison with those of the other constituents then the *poikilitic* texture, in which relatively large plates of one constituent enclose grains of the others, may result. *Micropoikilitic* texture is the same on a finer scale.

These textures, listed above as being formed by the relatively slow cooling and crystallisation of a magma, have their analogues in igneous rocks formed in a different way. These are the accumulative rocks (or *cumulates*), in which the minerals have been aggregated to a large extent by gravitational processes or by deposition during convective circulation in the magma chamber. Such consist, in their pristine state, of solid crystals and a variable amount of interstitial liquid that eventually solidifies. In their final state the rocks may have a more or less granular texture (fig. 11.2B), a subhedral-granular texture, a poikilitic texture (fig. 13.2) or a subophitic texture, depending on the way in which the interstitial liquid crystallises (7).

An entirely different class of textures embraces those due to the simultaneous crystallisation of two or more constituents under appropriate conditions. The first of these is the *graphic* texture, in which apparently isolated rods and wedges of one mineral are embedded in the other, the whole bearing a resemblance to ancient cuneiform writing. *Micrographic*, or *granophyric*, texture is the same on a finer scale (fig. 4.4B). The minerals most commonly involved in this texture are quartz

Cambridge University Press
978-0-521-29184-2 - Petrology for Students
S. R. Nockolds, R. W. O'B. Knox and G. A. Chinner
Excerpt
More information

and feldspars with the latter forming the host. But it may sometimes occur with other minerals, e.g. titanaugite and nepheline, and may be found with magnetite and fayalite at the eutectic composition in magnetite–fayalite slags.

That a particular rate of cooling, degree of supercooling (8), or other condition is necessary for the formation of textures of this kind is well shown in the case of certain granite-aplites whose quartz and feldspars have crystallised out simultaneously. It is possible to find two such aplites, of virtually the same composition, one of which shows a micrographic intergrowth of quartz with potash feldspar and with plagioclase, while the other shows a microgranular aggregate of the same constituents.

Though at first sight an unlikely-looking texture, the *ophitic* texture is also due to the simultaneous crystallisation of its constituents (9). As far as rocks are concerned, it consists of a plexus of plagioclase laths partially and wholly enclosed in plates of pyroxene (fig. 12.2). The spacing of the nucleii of the constituents was unsuitable for the development of graphic intergrowth, and a more or less granular texture was inhibited by the wide spacing of the nucleii of one of the constituents. A similar texture is observed in magnetite–fayalite slags when the magnetite and fayalite are crystallising together under conditions that preclude the formation of a graphic texture.

References and notes

(1) Tamman, G., 1926. *The states of aggregation*. London: Constable, especially chapter IX. Eitel, W., 1954. *The physical chemistry of silicates*. University of Chicago Press, 569–84.
For an early application of the experimental work to the texture of igneous rocks see Vogt, J. H. L., 1931. The physical chemistry of the magmatic differentiation of igneous rocks, III second half. *Skrift. der Norsk Vidensk.-Akad. Oslo. I Mat.-Nat.-Kl.* 1930, no. **3**, 177–208.

(2) This applies to primary spherulitic and felsitic textures. Secondary spherulitic, particularly microspherulitic, and felsitic textures may be produced by the devitrification of glass (see pp. 39, 50), and by the secondary crystallisation of ash-flow tuffs (see p. 214).

(3) Hawkes, L., 1930. On rock glass, and the solid and liquid states. *Geol. Mag.* **67**, 23–4.

(4) Vance, J. A., 1969. On synneusis. *Contr. Miner. Petrol.* **24**, 7–29.

(5) As, in general, the temperature of the country rock increases with depth, a deep-level intrusion would be expected to have a coarser texture than one of the same size intruded at a higher level. This is usually the case, but when a magma solidifies in the lower parts of a volcanic conduit where the walls have been heated to a considerable degree by the continued passage of lava, coarse-grained rocks may result at very shallow depths. These are the *subvolcanic* rocks of Washington.

(6) It is believed that these textures may be produced also, in some cases, by unmixing and recrystallisation as, for instance, in some subsolvus granites (p. 19). See Tuttle, O. F. & Bowen, N. L., 1958. Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O. *Mem. geol. Soc. Am.* **74**, 137–42.

(7) See Wager, L. R., Brown, G. M. & Wadsworth, W. J., 1960. Types of igneous cumulates, *J. Petrology* **1**, 73–85. Good illustrations of textures found in cumulate igneous rocks can be seen in Jackson, E. D., 1961. Primary textures and mineral associations in the ultramafic zone of the Stillwater complex, Montana. *Prof. Pap. U.S. geol. Surv.* **358**, 106 pp.

(8) Dunham, A. C., 1965. The nature and origin of the groundmass textures in felsites and granophyres from Rhum, Inverness-shire. *Geol. Mag.* **102**, 8–22.

(9) Bowen, N. L., 1928. *The evolution of the igneous rocks.* Princeton University Press, 68–9.

Cambridge University Press
978-0-521-29184-2 - Petrology for Students
S. R. Nockolds, R. W. O'B. Knox and G. A. Chinner
Excerpt
More information

2

The classification of igneous rocks

The ideal classification of igneous rocks would be a *genetic* one, and tentative steps in this direction are now being made. The most important of these has been the recognition of igneous rock series whose members may range in composition from mafic (or ultramafic) to felsic but all of which have certain features in common. Such series can be grouped into three categories.

1. Tholeiitic igneous rock series are relatively rich in iron throughout and show a varying degree of absolute iron enrichment in the intermediate members. Typical tholeiitic rocks include tholeiitic basalts, tholeiitic andesites, ferrodacites, ferrorhyodacites and ferrorhyolites, many gabbros, some ultramafic rocks, ferrodiorites, ferrogranodiorites and ferrogranites.

2. Calc-alkali igneous rock series, relatively poor in iron throughout, show little or no absolute iron enrichment in the intermediate members and are generally richer in alumina than the rocks of tholeiitic series. Typical calc-alkali rocks include calc-alkali basalts, andesites, latite-andesites, dacites, rhyodacites and rhyolites, certain gabbros and ultramafic rocks, diorites, monzodiorites, tonalites, granodiorites and granites.

3. Alkali igneous rock series are very variable in character, some showing a rather feeble absolute enrichment in iron in intermediate members, others not, but all are characterised by a higher content of alkalies for a given silica percentage than tholeiitic or calc-alkali series. Typical alkali rocks include mildly alkaline types such as alkali basalts, hawaiites and mugearites, alkali gabbros, alkali monzodiorites and alkali monzonites; and more highly alkaline types such as basanites, essexites, teschenites and ultra-alkaline rocks. Felsic types include phonolites and nepheline syenites, peralkaline and alkali trachytes, peralkaline and alkali syenites, peralkaline and most alkali rhyolites, peralkaline and most alkali granites.

Cambridge University Press
978-0-521-29184-2 - Petrology for Students
S. R. Nockolds, R. W. O'B. Knox and G. A. Chinner
Excerpt
More information

Much work remains to be done, however, in sorting out the various rock series within each of these three main groups before a true genetic classification can be erected.

At present it is necessary to be content with a *convenient* classification which, as far as possible, brings out the relationship of similar, or closely allied, rocks. Many and varied are the attempts which have been made to this end, and some of the factors involved will now be reviewed briefly.

In the first place, it is possible to make a very broad subdivision of igneous rocks, based on their mode of occurrence, into extrusive (or *volcanic*), shallow-seated intrusive (or *hypabyssal*), and deep-seated intrusive (or *plutonic*). This was essentially the method adopted to define the three main groups in the classification of the great nineteenth-century German petrologist, H. Rosenbusch, and some classifications in use today adopt the same plan.

Difficulties arise, however, if these distinctions are rigidly applied. Thus the chilled margin of a deep-seated mass intruded into cold country rocks may have all the characters of a hypabyssal rock; and the chilled margin, or even the whole, of a hypabyssal rock occurring, for instance, as a thin dyke may have all the characters of a volcanic rock. If, therefore, mode of occurrence is rigidly enforced as the prime classificatory characteristic, identical rocks may have to be placed in different subdivisions. Moreover, the exact mode of occurrence of some particular specimen may not be known and its degree of crystallinity must then be relied upon to place it in its appropriate group.

As a consequence, these terms, as used nowadays, have come more and more to indicate degree of crystallinity rather than mode of occurrence. Igneous rocks are said to be coarse grained if the average grain size of their constituents is greater than 5mm; medium grained if the grain size lies between 5mm and 1mm; fine grained if the grain size is between 1mm and 0.05mm; and very fine grained if the grain size is less than 0.05mm. On this basis, 'plutonic' rocks are those of medium to coarse grain, 'hypabyssal' rocks are fine-grained, and 'volcanic' rocks are very fine grained to glassy.

Some petrologists do not attach much importance to this three-fold division and are content to divide igneous rocks into *phanerocrystalline*, in which the constituents can be detected by the eye, and *aphanitic* in which the constituents are no longer visible to the eye.

In the second place, the mineralogical composition of the igneous rock may be used and it is on this that most of the classifications in general use depend. The simpler classifications are qualitative in nature, the various rock groups being determined simply by the presence or absence