UNIVERSITY OF ZAMBIA

SCHOOL OF MINES

DEPARTMENT OF GEOLOGY

GG 4070

IGNEOUS PETROLOGY

LECTURE NOTES

THE EVOLUTION OF MAGMA

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THE EVOLUTION OF MAGMAS

Compulsory Reading: Ehlers and Blatt (1982), Chapters 3 (pp. 84-99) and 5.
Additional Reading: best (1982), Chapter 9.

The origin of magma is, of course, not known from direct observations, so our understanding of the chemistry and physics of magmas is based on observations of volcanic products and synthetic magmas made in the laboratory. Another source of information are the studies carried out on the geophysical properties of the earth, such as density, seismic properties and on the regional structures of the earth's crust. Over the past decades we have obtained significant knowledge about the circumstances under which magma may be generated and about the mechanisms by which it is emplaced in the earth's crust.

Magma source region is the term used for the place within the earth's interior where a magma starts its evolution, the place where for some reason a volume of solid rock starts to melt. (As will be explained below) it is **partial melting** that usually takes place, which means that a (variable) amount of liquid is separated from a solid residue. The melt formed at the source region is called **primary magma** or **parent magma**.

As we have seen in the geological phase diagrams of Chapter 3 each mineral in a rock has its own melting point; therefore, when a rock is heated certain minerals will melt first, followed by others in a definite sequence. As a result ***partial*** melting of a rock may produce magma quite different in composition from the original rock. (Complete melting, of course, would produce a magma with identical composition).

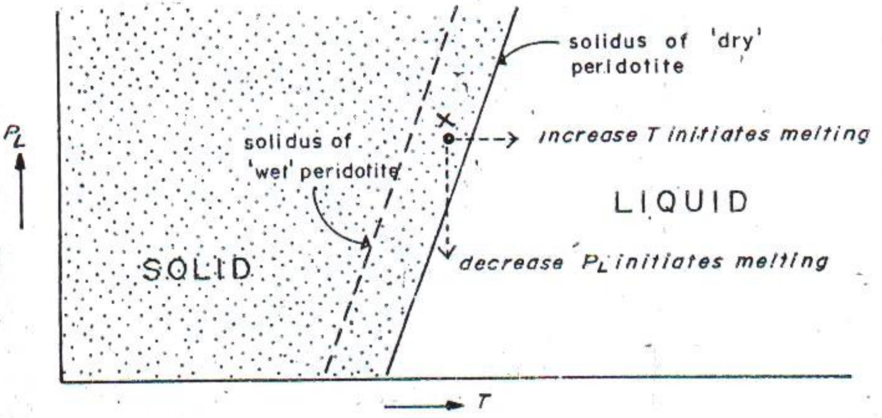


Figure 5-1 A schematic P-T diagram showing the melting curves of peridotite: solid line for "dry" systems, broken line for peridotites containing a few percent H_2O. It is clear that "dry" rock X will melt by an increase in T or a decrease in P. An influx of water would shift the melting curve from solid line to broken line causing X to melt.

FIGURE 5-1

The **mechanisms of melting** are as follows (see (Figure 5-1):

(i) An increase in temperature, which may have various reasons (transport of rocks into hotter zones, heat produced by radioactive decay, and so on);

(ii) A decrease of lithostatic pressure, due to tectonic reasons mainly; and

(iii) A change in composition, notably an addition of fluids: for example by addition of H_2O the melting points of the rock-forming minerals are lowered.

5.1 The Evolution of Basaltic Magmas

The basalts of the earth are so abundant, and their chemical and mineralogical compositions so uniform, that they are often interpreted as having crystallized from primary magmas, that were generated by a relatively simple, reproducible process within the upper mantle. As the upper mantle consists of peridotite (usually called pyrolite after the synthetic version of mantle peridotite), it means that partial melting of ***ultra*** –basic rocks must account for the production of large volumes of basic (basaltic) magma. This can be best illustrated with the aid of the ternary system Diopside-Forsterite-Anorthite, a simplified version of which is given in Figure 5-2.

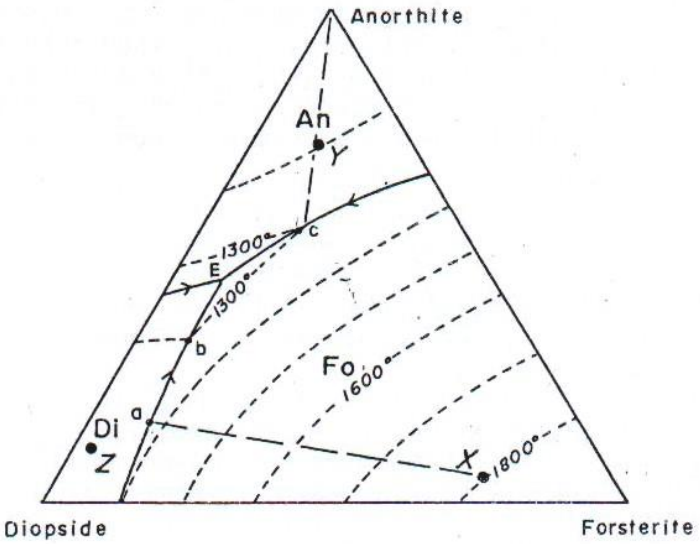


Figure 5-2 Simplified phase diagram of the system Diopside-Forsterite-Anorthite (at 1 atm) showing the melting path of a peridotite of composition X. The shaded area represents the compositional range of natural basalts.

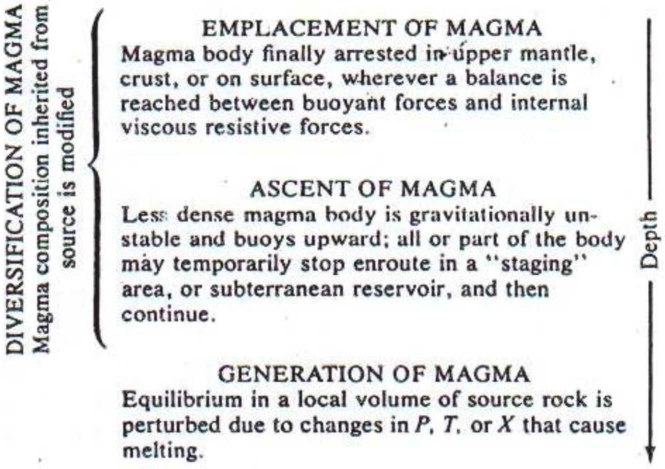
FIGURE 5-2

Let us consider equilibrium melting of rock Y. The first crystals to melt will be anorthite, diopside and forsterite in eutectic proportions, at the ternary eutectic temperature of 1270°C. Soon anorthite will be eliminated and the composition of the liquid will change from E towards a while diopside and forsterite melt simultaneously. In the meantime the temperature increases to 1350°C. With a further temperature increase forsterite will continue to melt until all crystals have been eliminated and a melt of composition X is produced, at 1800°C.

Partial melting of the same rock Y can produce liquids of various compositions, depending on the amount of melt that is formed, which is related to the temperature reached and the mechanism by which the melt is separated from the solid rock. For example, if rock Y is subjected to temperatures up to melt can concentrate and separate themselves from the parent rock a primary magma of composition *b* has been generated. When the partial melt is separated from the rock at a lower temperature the resultant magma would have a composition closer to point E.

Rock Y, which is rich in anorthite, would also start melting at 1270°C, i.e. it can produce an identical melt E of eutectic composition. Further heating would move the melt composition towards *c*, and so on. (The shaded area in Figure 5-2 represents the field of natural basalt compositions). It can be concluded that basaltic magma can originate from ***any*** rock (X,Y<Z etcetera) in the system Fo-Di-An, provided that melting is not complete.

Segregation of partial melts (collection of small volumes of melt into a larger volume), their **separation** from the peridotite residue and their **ascent**, due to lower density of the melt, are the initial stages in the evolution of basaltic magmas. From these initial stages up to the final stage of crystallization somewhere in the crust or at the earth's surface the magmas undergo a series of changes leading to their **diversification** or **differentiation**. This is schematically summarized in Figure 5-3.



EMPLACEMENT OF MAGMA
Magma body finally arrested in upper mantle, crust, or on surface, wherever a balance is reached between buoyant forces and internal viscous resistive forces.

ASCENT OF MAGMA
Less dense magma body is gravitationally unstable and buoys upward; all or part of the body may temporarily stop enroute in a "staging" area, or subterranean reservoir, and then continue.

GENERATION OF MAGMA
Equilibrium in a local volume of source rock is perturbed due to changes in *P*, *T*, or *X* that cause melting.

Figure 5-3 Schematic summary of magma generation and diversification (from Best, 1982).

FIGURE 5-3

5.2 Magmatic Differentiation

Magmas evolve from the parent magma by **differentiation** or **diversification processes** that are both internal and external, in the sense that the system is open to exchange of matter with its surroundings. The diversification processes account for the wide variety of chemically different igneous rocks that can be produced from a single homogeneous parent magma.

External processes are:

Hybridization, mixing of two (or more) magmas of different composition. This occurs best at depth before extensive crystallization of either melt has taken place.

Assimilation, contamination of the magma because of interchange of matter across its contact with the country rock. Apart from a chemical interchange, the development of a thermal gradient is also important.

Internal processes are:

Liquid immiscibility, certain types of high temperature silicate melts split into two immiscible portions (*cf.* the system $MgO-SiO_2$, section 3.3.4).

+Volatile transfer. Some magma bodies contain bubbles of gas floating on top of the magma body. They consist chiefly of H_2O and CO_2 but may contain small amounts of K, Na and other chemical constituents. Thus the top of the magma body would be enriched in K and Na relative to lower parts.

BY FAR THE MOST IMPORTANT DIFFERENTIATION PROCESS IS:

Fractional crystallization. This internal process involves the separation of crystals from the liquid during the crystallization of the magma. The mechanisms of this crystal-liquid separation are:

- ***crystal settling*** or ***gravitational crystallization,*** a very important process Especially in intrusive bodies of basaltic magma. Crystals of olivine and pyroxene may sink to the bottom of the magma chamber where they accumulate on the floor of the body, because their densities are greater than the density of the melt in which they are suspended. The crystal-rich base of the body assumes a peridotitic composition. The upper portion of the magma chamber will be depleted in olivine and pyroxene and therefore greatly depleted in MgO, because both olivine and orthopyroxene are rich in this oxide, and possibly in CaO, which is contained in clinopyroxene. As we have seen before, in section 3.3.4, the effects of removal of forsterite from a crystallizing melt in the system

$MgO-SiO_2$ can bring about a major change in the chemical and mineralogical compostion of the final rock.

- ***flowage differentiation***, common in veins and dykes when (a crystal –laden) Magma moves upward; the cooler portion of the magma near the walls will move slower than the magma in the centre of the vein; the faster-moving central portion will carry most crystals, and therefore will have a different composition from the magma near the walls.

- ***filter pressing***, when crystals are squeezed from the magma due to tectonic processes.

The most important concept of magma evolution is that an initial primary magma, the parent magma, is acted upon by secondary diversification processes that produce less primitive, more evolved magmas. The associated igneous rocks of various compositions that we often find in the field are related to each other by these processes. A schematic overview of possible diversification processes that may act on already variable magmas ascending from source regions is given in Figure 5-4.

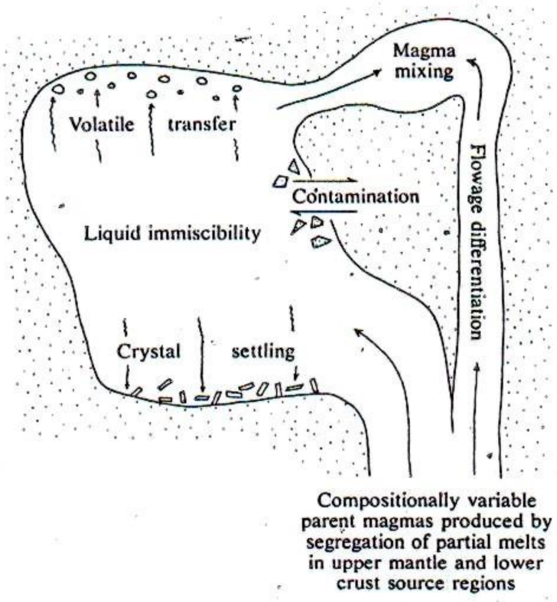


Figure 5-4 Possible processes of magmatic diversification that may act on ascending parent magma (from Best,1982).

FIGURE 5-4

5.3 Bowen’s Reaction Series

Laboratory experiments with silicate melts and observations of textures in igneous rocks have led to the formulation of an ideal sequence in which crystals crystallize, called **Bowen’s reaction series**. Originally Bowen (1928) felt, that all magma types evolved from one single type of basaltic parent magma, and he used his reaction series as an illustration of the mechanisms of differentiation. Nowadays we know that all igneous rocks are not derived from a basaltic melt, but Bowen's reaction series is still used to explain the wide variety of igneous rocks that may originate from one magma.

Bowen's reaction series consists of two branches (see Figure 5-5). The plagioclases on the right side form a **continuous reaction series**, as plagioclases grade into each other by solid solution. During crystallization the crystals react continuously with the melt changing their composition toward the albite endmember (Na substitutes for Ca). The left branch comprises the ferro-magnesium minerals which form a **discontinuous reaction series** giving rise to the kind of reaction rims illustrated in Figure 3-11. The type of reactions involved are related to incongruency (peritectic reactions, e.g. olivine reacts to orthopyroxene) and to hydration (e.g. pyroxenes react with H_2O to amphibole). Notice that the minerals at the upper portion of the series are characteristic of basalts, and crystallize at high temperatures. Minerals are characteristic of basalts, and crystallize at high temperatures. The minerals characteristic of granite, at the bottom of the diagram, crystallize at the lowest temperatures.

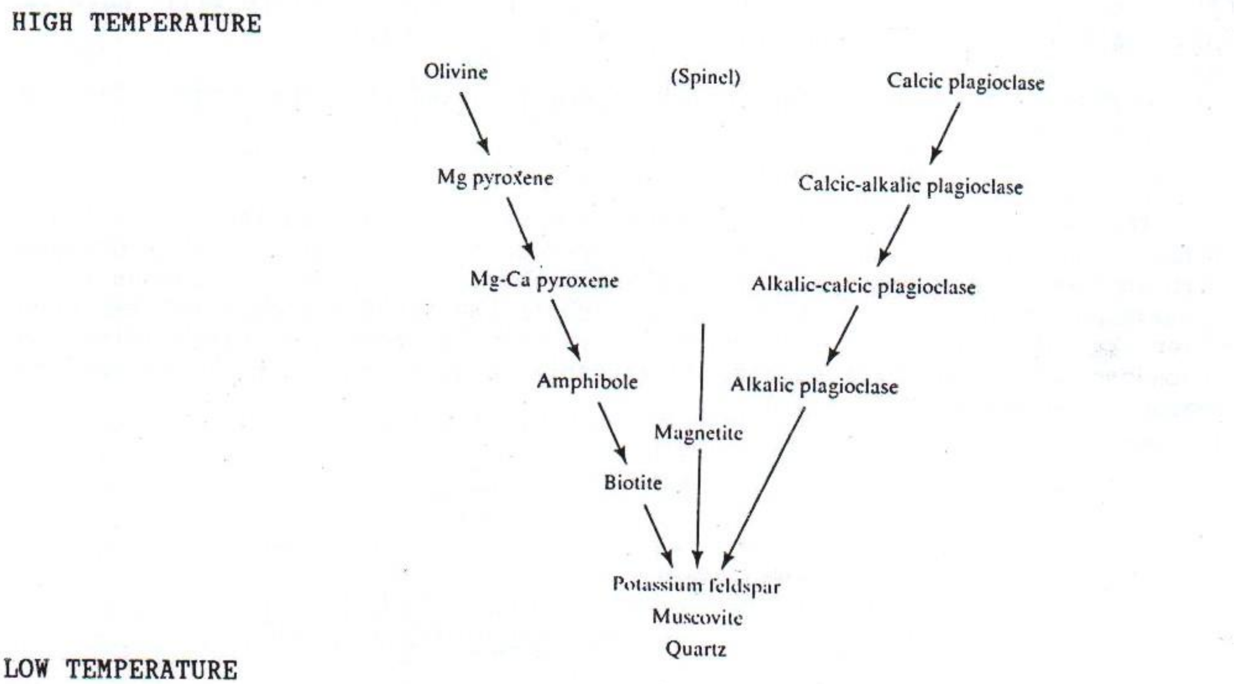


Figure 5-5 Bowen's reaction series. The minerals on the left side are related by a series of discontinuous reactions, those on the right side form a continuous reaction series as they are related by solid solution (from Ehlers and Blatt,1982).

FIGURE 5-5

Let us consider a basaltic magma, which should yield (with *equilibrium crystallization*) a rock consisting of pyroxene and plagioclase of calcic composition. Cooling of the magma results in the initial crystallization of Ca-rich plagioclase, olivine, and perhaps a mineral of the spinel group. Under equilibrium conditions the calcic plagioclase should react with the melt and become more sodic; in addition, at a certain temperature olivine should react with the melt to produce an orthopyroxene (enstatite or hypersthenes). Olivine may be eliminated, while the rest melt precipitates more pyroxene (at this stage the clinopyroxene augite might join in) and more sodic plagioclase. The end product would be a basalt or a gabbro. The shortage of silica and water in the original melt would not permit the formation of minerals lower in the series, such as hornblende or biotite.

Fractional crystallization depends on non reaction or incomplete reaction of the magma with its crystalline products. Non reaction of the silica-poor minerals (olivine, orthopyroxene) permits the remaining melt to become more silica-rich. Crystallization and non reaction of Ca-rich plagioclase results in a relative increase in Na content in the melt. In fact, any element that is not present in the crystallizing phases, is relatively enriched in the remaining portion of the magma. Thus, due to fractional crystallization the melt becomes progressively enriched in "acid components" (SiO_2, Na_2O, K_2O, H_2O *and often* FeO) and depleted in "basic components" (MgO *and* CaO). This can lead to sufficient enrichment of alkalies and silica for the final liquids to crystallize alkali feldspar and quartz, thereby forming granitic rock.

Bowen originally thought to have found an explanation for the origin of all granitic rocks: by fractionation of a basaltic melt. But the amounts of granitic and basaltic rocks exposed on the earth's surface are about equal. If all granites were produced by Bowen's reaction series, there would have to be at least ten times as much basaltic magma as granitic magma; moreover, you would expect that granitic rocks would always be associated with large amounts of basic rocks, which is not the case. Clearly, a different mechanism of origin exists for ***most*** granites.

5.4 The Origin of Granites

Granites and associated rocks such as granodiotite, tonalite form the largest group of intrusive igneous rocks, comprising over 90% of the total. This contrasts sharply with extrusive rocks where basalt is the most common rock type. Part of the reason for this contrast lies in the difference in composition between the granitic and basaltic magma's (see section 5.4), but the answer also lies in the difference in mode of origin of the respective magmas.

It is possible for small quantities of granitic rock to be formed by differentiation of primary basic magma, (as has been discussed above). However, most granites must have originated by another mechanism. A clue to their origin is provided when the distribution of granites is studied. We find that the vast majority are associated with the continental crust, usually within former orogenic belts. The chemical composition of the lower continental crust closely approximates to that of granite, and the orogenic areas are regions where temperatures and pressures are high. Theoretically, therefore, granites could have been formed by the melting of the lower continental crust (but is this possible in practice?).

Anhydrous (dry) granite begins to melt at about 950 to 1000°C at the pressures encountered in the crust (see Figure 5-6 A). As the geothermal gradient[1], (at the time of orogenic activity), could have been as high as 30°C/km, the temperatures required to produce melting are found at a depth of less than 35 km, which is well within the continental crust in orogenic areas. Hydrous (wet) granitic melt can be produced at even shallower levels in the crust as the temperature required is only about 650°C (see Figure 5-6 B), which is reached at a depth of 20-25 km. Therefore, it is perfectly possible for granites to be produced by the heating up and eventual (partial) melting of continental crust. The term used for partial melting of crustal rocks is **anatexis**, and it is a process discussed both in igneous petrology and in metamorphic petrology, because anatexis can be seen as the ultimate stage of metamorphism in orogenic areas.

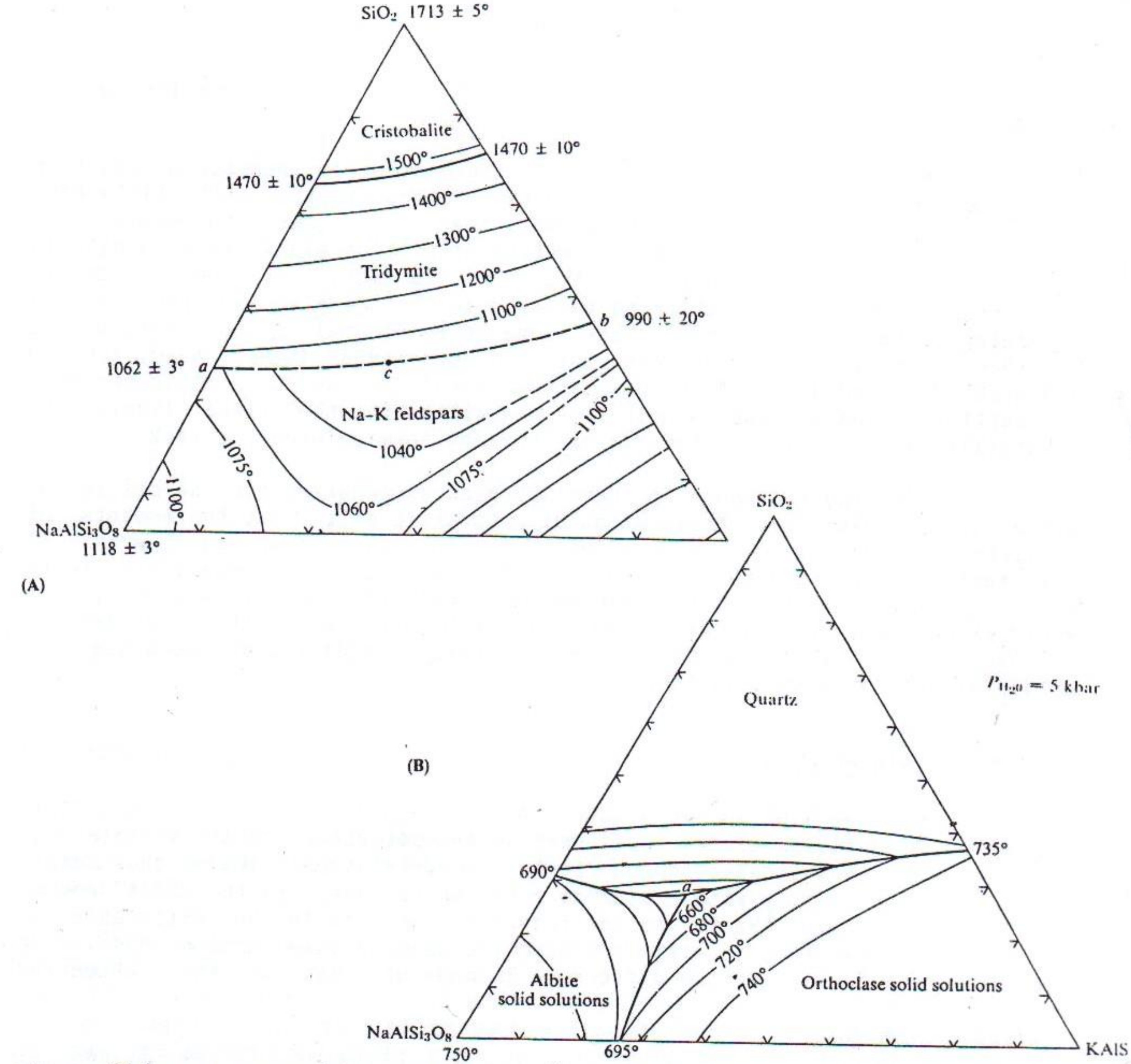


Figure 5-6 The simplified granite system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O (the leucite field has been eliminated for simplification) A. The anhydrous sytem. A single boundary curve ab exists with a thermal minimum at c of appr.950° C. B. The system at $P_{H_2O}=5$ kb has two alkali feldspar primary fields and a ternary eutectic point at **a** with a temperature of appr.650° C (from Ehlers and Blatt,1982).

FIGURES 5-6

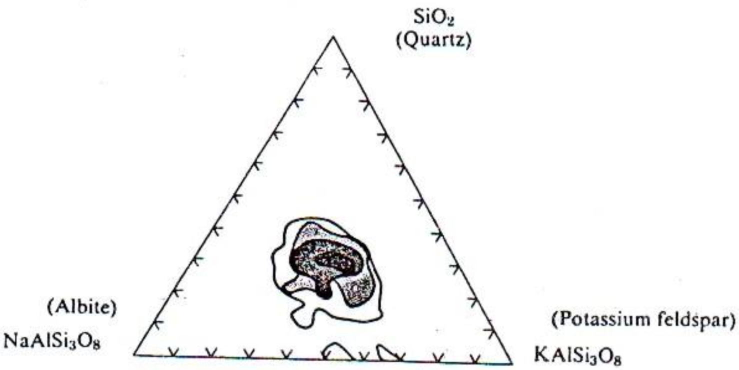


Figure 5-7 The composition of 1190 natural granites plotted on the Albite-Orthoclase-Silica ternary diagram (from Ehlers and Blatt, 1982).

FIGURES 5-7

On the basis of field occurrence a distinction has been made between two types of granites:

(i) ***Anatectic granites associated with migmatites***

It is very common to find granites in orogenic belts in close association with high grade metamorphic rocks and migmatites. A **migmatite**, literally mixed rock, consists partly of metamorphic residue, partly of granite (once forming a partial melt, now solidified again). Migmatites are considered as the link between high grade metamorphism and magmatism (the formation of granitic magma). (The granitic bodies in such areas, often of batholitic dimensions, bear the characteristics of Buddington's catazone (see Figure 5-8, compare Figure 1-9). The granites are clearly formed ***in situ***, i.e. they have not moved from their place of origin. They serve as proof that the bulk of the granitic intrusive rocks originate by anatexis in the lower crust.

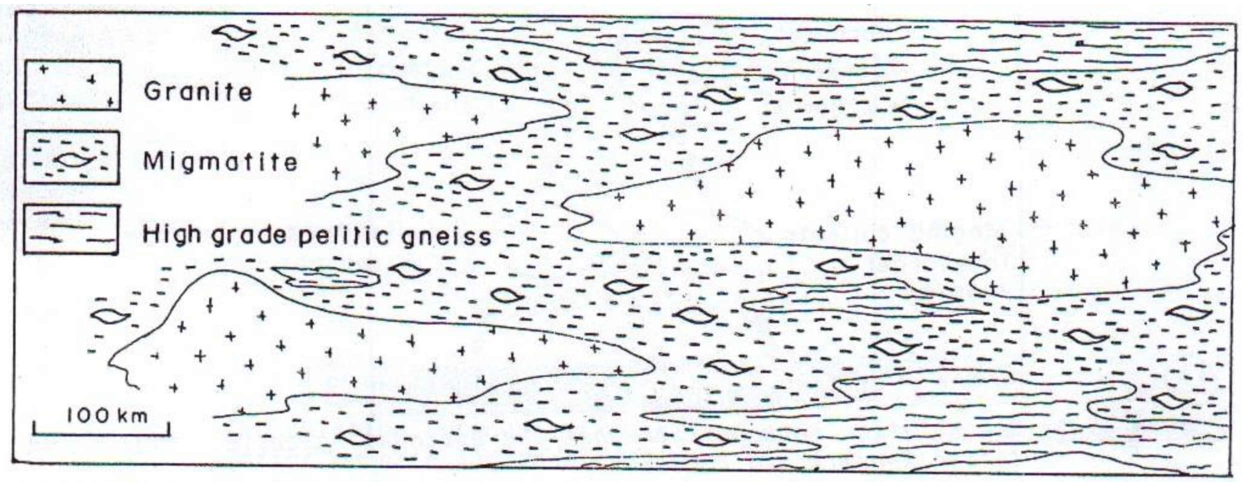


Figure 5-8 Diagrammatic map of anatectic granites associated with migmatites.

Figure 5-8

(ii) ***Magmatic granites***

Epizonal or mesozonal granites typically show the characteristics of magmatic intrusion: (1) sharp and discordant contracts, (2) contact aureoles (3) chilled borders, and so on (see Chapter 1). In general, they tend to be smaller, more homogeneous bodies than the granites that have been generated in situ and that are associated with processes of migmatization. The contact relations with the country rock make it clear that the intrusions originated from a hot, mobile magma that was emplaced in the higher levels of the earth's crust.

The relation between the two types of granites is shown in Figure 5-9. In the deeper levels of the crust granitic melts are formed by anatexis of crustal material. The melt may then consolidate in situ, (at the site of its formation). Sometimes, however, the granitic melt becomes mobile and, because it has a relatively low density compared to the rocks around it, it will then move upwards to intrude into the higher levels of the crust, where it will crystallize to form a magmatic granite, or it may extrude and form an acid volcano.

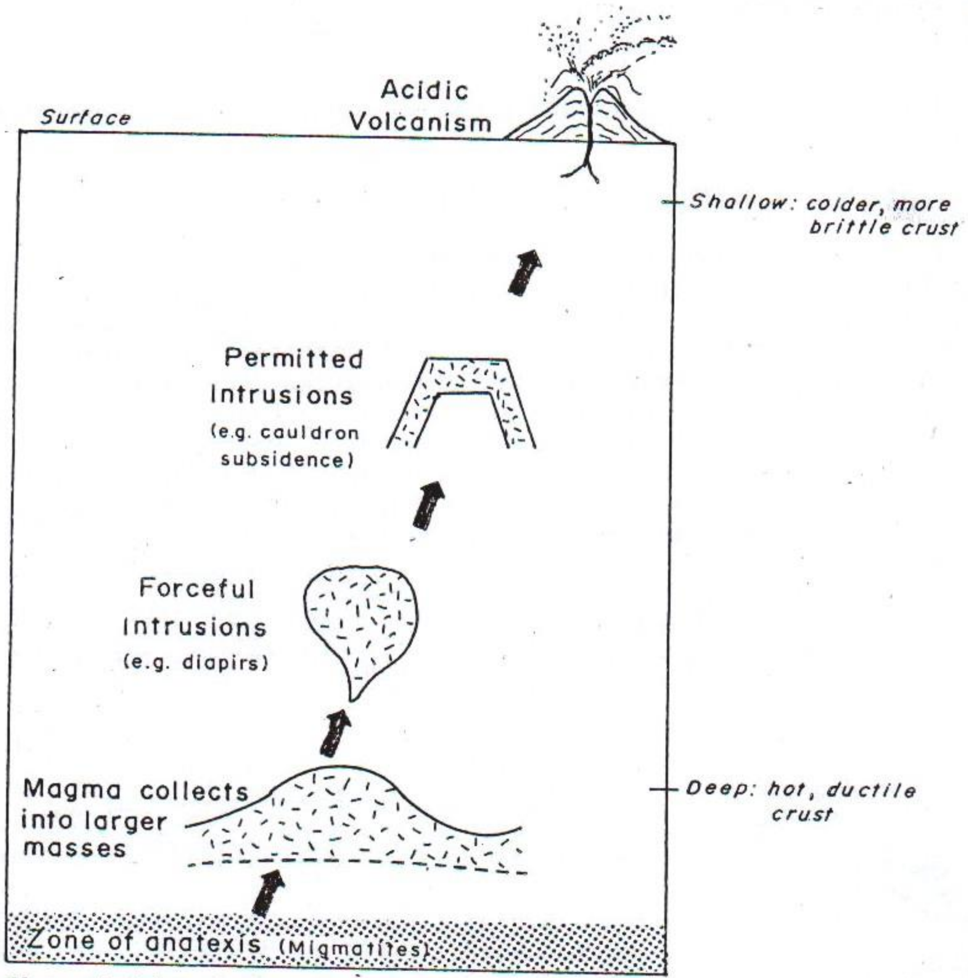


Figure 5-9 The relation between catazonal and epizonal granite intrusions. (after Kennett and Ross,1983)

FIGURE 5-9

The ascent of magmatic granites must involve a mechanism by which the existing country rocks are displaced: the space occupied by the granite body was formerly occupied by the country rocks. The mechanisms of emplacement of a magma body fall into two broad groups known as **forceful** and **permitted intrusions**. Forceful intrusions make room for themselves by shouldering aside the country rocks. The density of the hot magma tends to be less than the density of the surrounding rocks and so this magma can flow slowly upwards pushing the existing rocks out of the way. This may simply result in the formation of a granite **dome** around which the country rocks are bent but further upward motion of the magma will rupture the country rocks and form a **diaper** (see Figure 5-9). Other types of forceful intrusions (already discussed in Chapter 1) are dykes (the magma occupying space between parallel faults, laccoliths and lopoliths. Lopoliths, however, are mainly associated with basic magmas.

Many examples of permitted intrusions of granitic magma are known: the process of **cauldron subsidence** is the main mechanism of permitted intrusion, a process which is called **magmatic stoping** when it occurs on a smaller scale. Repeated cauldron sinking leads to the formation of a **ring complexes**. (This has already been discussed and illustrated in Chapter 1 (Figure 1-5)).

Accepting anatexis of crustal rocks as the main process in the generation of granitic magma, there are still two questions which have to be solved:

(i) If most granites can be referred back to crustal melting, how can it be explained that granites show little variation in composition, although the crustal rocks from which they are derived are very variable?

(ii) Why do granitic magmas mainly form ***intrusive*** rocks, whereas basic magmas prefer to extrude onto the surface of the earth as basalts?

Let us start with the first question. Mineral analyses of 1190 granitic rocks were plotted and contoured on the simplified diagram of the granite system Ab-Or-Q (see Figure 5-7), (and it appeared that the compositions cluster around the thermal minimum of the hydrous system (*cf.* Figure 5-6 B). It is concluded that granites have compositions close to that of the ternary eutectic point of the granite system. Thus, they are ***either*** highly differentiated (fractionated) melts in the granite system, ***or*** partial melts that were separated from the solid rock shortly after eutectic melting. The second possibility, of course, is valid in the case of anatexis. A rock which consists of a mixture of Ab, Or and Q will, when it starts to melt, *always* initially produce a melt of eutectic composition. If the temperatures in the lower crust are not raised significantly above that of the thermal minimum in the system Ab-Or-Q it explains why the melts formed have similar chemical compositions, regardless the composition of the rocks from which they are derived.

The second question will be answered in the following section, as it concerns the difference in H_2O content between acid and basic magmas.

5.5 Effects of Pressure on the Melting and Crystallization of Magma

As a result of burial, rocks are subjected to pressure, called **confining pressure** or **lithostatic pressure** or **load pressure** or **burial pressure**, which is dependent upon the overlying mass of materials. The lithostatic pressure P_L increases with depth at a rate of approximately 250-300 bar/km. It has been confirmed experimentally that an increase in lithostatic pressure causes an increase of the melting temperatures of anhydrous $\left(H_2O\ free\right)$ minerals. A simple example is shown in Figure 5-10, which is a schematic sketch of the binary system albite-silica subjected to high and low lithostatic pressure. Note the shift of the position of the eutectic point to the left when the lithostatic pressure is raised.

Within a rock liquid may be present. The pressure of the fluid is called P_{fluid} and it is independent of P_{load}. Magmas may contain volatile components which are usually able to mix into ***one*** vapour phase. The P_{fluid} of a magma can be regarded as the sum of all b partial pressures: $P_{fluid} = P_{H_2O} + P_{CO_2} + P_{O_2}$ and