Zeitschrift: Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie

Band: 68 (1988)

Heft: 1

Artikel: The zonation of granitic plutons : the "failed ring-dyke" hypothesis

Autor: Ayrton, Stephen

DOI: https://doi.org/10.5169/seals-52046

SCHWEIZ. MINERAL. PETROGR. MITT. 68, 1-19, 1988

The zonation of granitic plutons: the "failed ring-dyke" hypothesis

by *Stephen Ayrton*

Abstract

A mechanism leading to the zonation of granitic batholiths is proposed. Fundamentally, it is based on the common occurrence of mafic enclaves near the margins of plutons, on the realization that these enclaves were in a magmatic condition at time of incorporation, and on the observation that they very often play an essential role in the formation of schlieren. The latter represent the shearing through convection of these blobs of mafic magma within the rising and evolving pluton, which leads to progressive dispersal of the mafic material inwards until a threshold in temperature and viscosity is reached. This type of zonation, which does not exclude others, nor the simultaneous combination of several mechanisms of differentiation, would therefore be due to the mixing of two contrasted magmas, the mafic one, in the case of normal zonation, being injected marginally to form a failed ring-dyke. The two liquids may be derived from distinct sources, with far-reaching consequences.

Résumé

Un mécanisme aboutissant à la zonation de batholites granitiques est l'objet d'une hypothèse fondée sur la présence fréquente d'enclaves basiques près de la bordure des plutons, sur la réalisation que ces enclaves étaient largement liquides lors de leur incorporation dans le système granitique, et sur l'observation qu'elles sont essentielles, bien souvent, à la formation de schlieren. Ceux-ci représentent le cisaillement, par le flux convectif, de ces gouttes de magma basique au sein du pluton qui monte et évolue, ce qui entraîne une dispersion progressive du matériel basique vers l'intérieur jusqu'à ce que le système atteigne un seuil de température et de viscosité. Ce type de zonation, qui n'exclut pas d'autres, ni la combinaison simultanée de plusieurs mécanismes de différentiation, serait donc dû à un mélange de deux magmas contrastés, le magma basique, dans le cas d'une zonation normale, étant injectée en bordure pour former un dyke annulaire avorté. Les deux liquides dérivent souvent de sources distinctes, ce qui peut avoir des conséquences notables, en particulier d'ordre isotopique.

Keywords: granitoids, zoned batholiths, enclaves, schlieren, magma mixing, hybrids, convection, ring-dykes.

Introduction

Many granitic plutons are mineralogically and chemically zoned. In the general case, referred to as "normal zonation", a mafic outer zone of diorite or tonalite surrounds a central core of granite or granodiorite. The composition may change gradationally, or in steps, with sharp contacts separating intrusions emplaced at intervals, but it is of considerable importance that even where different members of a pluton were emplaced at different times, there is generally a compositional zonation.

Reverse patterns and more complicated situations involving normal and reverse relationships, a common occurrence, have also been documented. FRIDRICH and MAHOOD (1984), in their analysis of reverse zoning in the resurgent

Institut de Minéralogie de l'Université, UNIL - BFSH2, CH-1015 Lausanne.

intrusions of the Grizzly Peak cauldron (Colorado), list a number of other examples. Instances of recurrent zonation have been described by DEBON (1980), in his study of the genesis of three concentrically-zoned granitoid plutons in the Pyrenees, the Cauterets-Panticosa intrusions. To some extent, the points made in this paper may also apply to them, but normal zonation is the main concern.

Not only do many plutons show a more mafic rim, but they may also be partially or completely enclosed in a gabbroic ring-dyke, and it will be argued here that a relationship between these two features is plausible. It will also be argued that the mafic rocks, which may occur outside the limits of the pluton—as for instance the appinites of Ardara (Donegal)—represent a fundamental component of the igneous complex (although they may not be genetically related to the granitic members) and not fragments of country rock, as they often have been taken to be. A survey of the literature indicates that numerous intermediate situations exist between the classic ring-dyke (as for instance in the British Tertiary, to which we will refer further on), scattered masses of mafic rock along the margins of the pluton (good examples being the Ardara pluton, the Adamello batholith, the Tichka massif of Morocco, the Captains Bay pluton in the Aleutian Islands, amongst many others), and gradational zonation.

Of paramount importance is the presence, virtually ubiquitous, of mafic enclaves at or near the border of normally zoned plutons. It is now well established that, in most cases, these enclaves represent blobs of dispersed mafic magma which coexisted for a time with a liquid of granitic composition, with modifications of composition due to mechanical and chemical mixing. They are therefore not restites in the most common case, nor are they xenoliths, i.e. fragments of solid country rock incorporated into the magma. Neither are they fragments of mafic cumulates, as witnessed by their (igneous) textures. The main arguments for this conclusion are repeated here.

These enclaves are deformed into ellipsoids, which sheds light on some aspects of the formation and evolution of the diapir, whose growth was compared by H. CLOOS (1925) to that of a balloon in the process of inflation. Such a model does not, however, take into account the inevitable effects of convection, which must occur in most rising plutons. It will be suggested here that a certain type of banding, and especially the production of schlieren from the mafic enclaves, are the consequences of convective mixing.

Normally zoned plutons

The mineralogical variation in normally zoned plutons is clearly expressed by an increase, towards the walls, in mafic minerals, in the hornblende/biotite ratio, in An% of plagioclase, and in the plagioclase/K-feldspar ratio. TURNER and VERHOOGEN (1960) refer to the basification of granite in marginal zones, "strewn with hornblende- or biotite-rich xenoliths of modified country rock...." (comagmatic enclaves, in our opinion), and state, further on: "Thick zones of granodiorite developed along the margins of otherwise granitic bodies have very generally been interpreted as contaminated rocks formed by just such a process." This situation has been described and illustrated in the Sierra Nevada batholith, for instance (BATEMAN et al., 1963; BATEMAN and NOKLEBERG, 1978; BATEMAN and CHAPPELL, 1979; SWANSON, 1986). DREWES et al. (1961) have made the same assumption for the mafic border zones of the Shaler and Captains Bay plutons in the Aleutian islands (but see PERFIT et al., 1980). A number of observations in BATEMAN et al. (1963) are relevant to the present discussion: "Progressive decrease in the abundance of mafic inclusions away from the margins of many intrusives" (p. D18), grading of hornblende gabbro into granodiorite, the production of hybrid rocks "in part the products of contamination of the granitic rocks with more or less assimilated mafic material, and in part the products of addition of quartz and feldspar to mafic rocks" (p. D23). The conclusions (p. D18) that "generally there is some evidence of compositional zoning in intrusives in which mafic inclusions become less abundant away from the margins", that "it may be significant that mafic inclusions are present in the hornblende-bearing rocks and absent in the hornblende-free rocks", and that (p. D27) "in a general way the number and average size of mafic inclusions in the Sierran granitic rock vary with the mafic mineral content, and especially with the hornblende content, of the enclosing rock", may have very wide application, as this correlative relationship is common elsewhere.

It is not our intention to review the zoned plutons described in the literature. We will refer mainly to two well-known massifs for the purpose of demonstration: the Ardara pluton (see Fig. 3), about 500 Ma old, and the Ploumanac'h complex in Brittany, dated at 290 ma, both being late- to post-tectonic with respect to the Caledonian and Hercynian orogenies.

A number of hypotheses have been put forward to explain a zoned composition in a pluton. The effect of assimilation of foreign rock has long been considered to be an important agent in marginal modifications of composition. Such an hypothesis rests on the recognition of true xenoliths, a term which is often, demonstrably, a misnomer. Assimilation of fluids must also be considered, as isotopic evidence clearly indicates the percolation of crustal fluids within magmatic systems. This underscores the convective movements that must have affected the magmatic body. A P_{H_2O} gradient would have some influence on the path of crystallisation.

In addition, various types of metasomatic/metamorphic reactions have been invoked in this situation, due to chemical gradients between the acid component and rock of contrasted composition, with the formation of dark margins (see BISHOP, 1963). Much has been said on desilication, granitisation, basic fronts and basic behinds, in general referring to enigmatic reactions between a solid and a liquid (+ vapour). The activity of a gaseous phase has frequently been considered, as for instance by REYNOLDS (1954), in her fluidisation model, and by TUTTLE and BOWEN (1958) who suggested that selective solution of feldspar and quartz from the contact rock by a hydrous vapour might produce "the basic zones commonly formed at granite contacts". WINDLEY (1965) has proposed that the rapid release of gas from the magma might enhance the formation of a chilled margin. Chilling, however, is only of very local importance.

Grain dispersive pressure, a process of mechanical differentiation due to flow (KOMAR, 1976), may deplete the margins of an igneous body in early phenocrysts ("Bagnold zones"), but this does not seem capable of producing zoned compositions in bodies larger than 100 m across (BARRIÈRE, 1976). However, this mechanism may be of local importance within a pluton if flow is concentrated within restricted domains.

Filter-press differentiation may also operate in these circumstances. As a pluton expands, and as pressure is exerted against the walls by the influx of late pulses of magma in the core, residual liquid should be separated from early crystals. A cogenetic relationship between early solids and late liquids necessarily follows.

Preferential accretion of crystals nucleating in the magma to the walls of the magma chamber (see BATEMAN and CHAPPELL, 1979) is receiving considerable attention at present, especially in connection with convective fractionation and boundary-layer flow (SPARKS et al., 1984). This is indeed more plausible than classic crystal fractionation with gravitational settling of solids, the extent of which has recently been questioned, even in instances of vertical zonation (MCBIRNEY and NOYES, 1979).

Another mechanism appears increasingly to be of importance in a crystallising pluton, i.e. double diffusive fractional crystallisation. The complex interrelationship between thermal and chemical diffusion, coupled with convection, may be largely responsible for differentiation in magma chambers. The contribution of the Soret effect to natural phenomena is at present being strongly debated. The magnitude of the mechanism remains to be precisely determined. HILDRETH (1981) suggests it may be a function of the geometry of the chamber and that convection should greatly accelerate diffusion. It is possible that the more mafic nature of the margins of some granites is due to the Soret effect. In contrast, VISONA (1986) has advocated such a process, in combination with filter-pressing and grain dispersive pressure, for the acid border of the Bressanone granodiorite (Northern Italy). The trend towards higher contents of SiO_2 and alkalis in the margins is attributed to the transformation, through flow, of mechanical energy into heat.

Yet another mechanism, "solidification contraction" (PETERSEN, 1987), seems capable of producing large compositional effects in crystallising magmas. However, this should lead to the accumulation of solute-rich liquids along the walls of a chamber, with the production of a marginal, reverse compositional zonation.

There is clearly no shortage of hypotheses to explain zonations in plutons, but all those briefly mentioned here resort to interaction between one liquid and foreign solids, or to mechanisms within a closed system involving one liquid (excluding, in the present discussion, influx of H_2O-rich fluids from the country rocks). They ignore the fact that where the mafic enclaves exist, two magmas may have coexisted and, to some extent, mixed. Whether the two magmas were derived from the same source, or from two distinct sources, is not that important here. Both situations probably exist, the second having our biased preference from an assessment of available geological, petrographic, mineralogical, geochemical and crystallographic evidence.

This is not to say that the above-mentioned mechanisms do not occur. They may very well be the main or a contributing factor in certain occurrences of compositional zonation and probably operate simultaneously in many plutons (the granophyres in the Skaergaard complex owe their formation to at least three separate mechanisms: fractional crystallisation, partial fusion and immiscibility of liquids). The crux of the matter, however, lies in the presence and abundance of mafic enclaves near the margins of most granitoids (see Figs. 3, 5 and 7).

Mafic enclaves (see Fig. 1)

It is now well established that many mafic enclaves were in a magmatic state when incorporated into the crystallising granitic liquid. These are the microgranular, generally dioritic enclaves with which parts of most granitoids, especially belonging to the calc-alkaline suite, are studded. A number of observations are critical in this respect (see VERNON, 1984, for a summary):

- The textures are clearly igneous. They are typical of microdiorites, or basaltic andesites, sometimes lamprophyric. Laths of plagioclase occasionally exhibit an ophitic tendency.
- The shapes (and sizes) of the enclaves, the geometry of their contact against the granitoid, are suggestive of the juxtaposition of two liquids (containing a variable amount of crystals). These enclaves rarely have angular forms, typical of true xenoliths.
- The most important feature in this respect is the presence, within the enclave, of crystals clearly out of equilibrium with the latter, and in all probability xenocrysts. These include quartz ocelli, i.e. single crystals of quartz often rimmed by ferromagnesian minerals (pyroxene, amphibole, biotite), identical in shape and size to the quartz grains in the granite, the probable source. Some micas also appear to be derived from the surrounding granite. The best evidence here is arguably the presence within the enclaves of K-feldspars which are again identical in shape, size and composition to those of the granite, with the important difference that they generally have angular forms in the granite, and rounded ones in the enclave. In this situation, they may also be rimmed by plagioclase. Rapakivi textures are common in this context (STEWART, 1956, on granites in Maine, states that rapakivi ovoids are absent from the country rock, but "stages of reaction leading to their development" are preserved in xenoliths—see TURNER and VERHOOGEN, 1960, p. 363). All this underscores a mixing process, a bilateral mechanical exchange between enclave and granite, which we take to be proof of the (partially) liquid state of the enclave at time of incorporation. Chemical mixing also occurs, the extent of which is in the process of being assessed. A purely metasomatic mechanism seems incapable of explaining these features.
- There is a close relationship between these enclaves and synplutonic dykes. Indeed, in a number of occurrences, it has been demonstrated that they are identical in texture and composition, which is of great weight in considerations on the probable link between enclaves, lamprophyres, hornblende gabbros at many contacts of granitic plutons, and the classic appinites best described in Scotland, Ireland and the Channel Islands (but which certainly occur in many other places). The enclaves are clearly not restites, nor xenoliths (which was the assumption made by BATEMAN et al., 1963, p. D18—but see REID et al., 1983—for the mafic inclusions in the Sierra Nevada batholith). Neither are they fragments of cumulates. The term "amphibolite", commonly encountered in the literature in connection with them may be misleading. On closer microscopic inspection, many "amphibolitic xenoliths" may turn out to be microdiorites.

Schlieren (see Fig. 2)

Schlieren are layers of lenses a few centimetres in width and some centimetres or metres

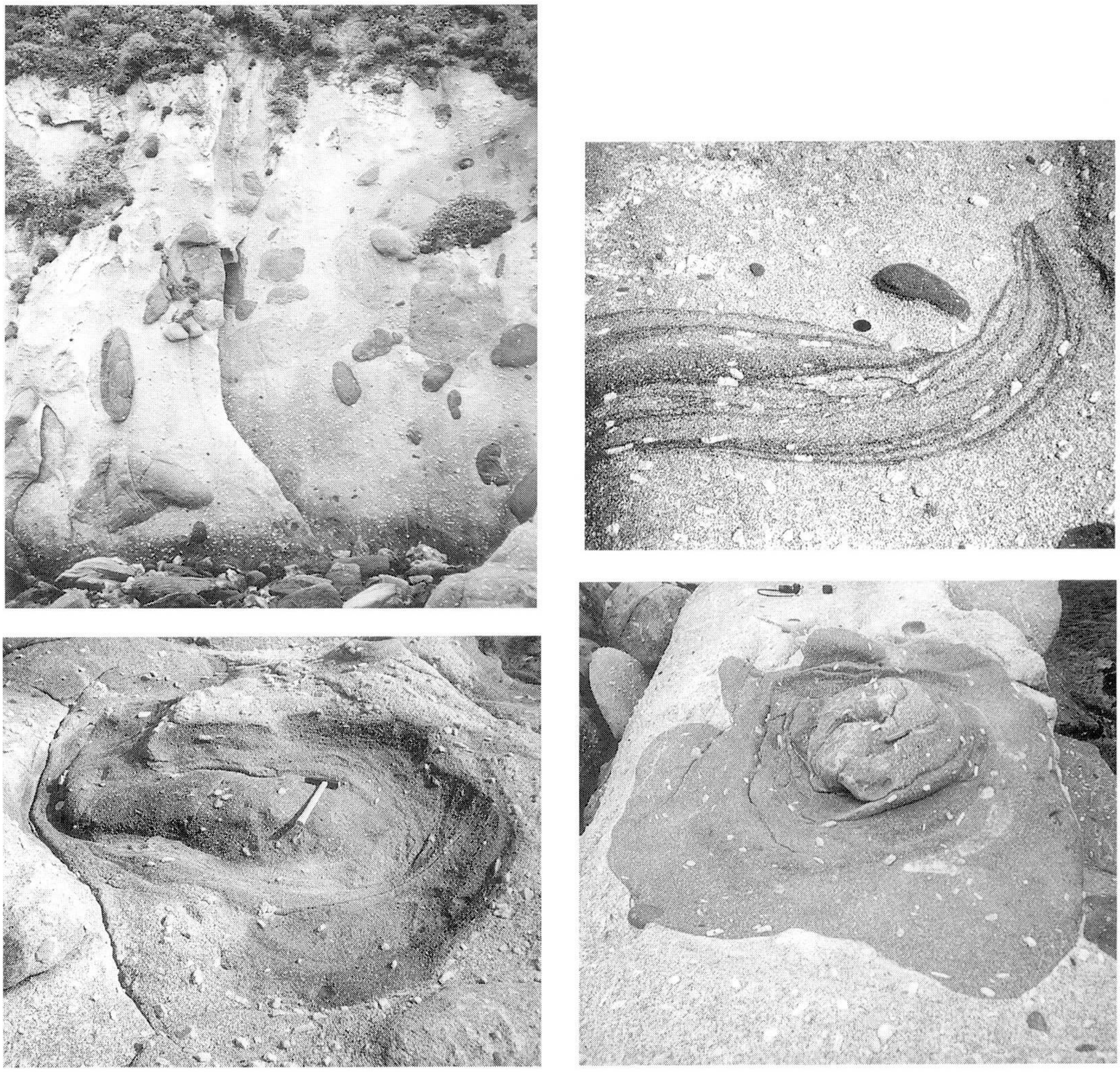


Fig. 1 The Elba granodiorite:
The northern rim of the Elba granodiorite, the youngest calc-alkaline intrusion in Western Europe (6–7 Ma), provides beautiful examples of mafic enclaves with all the usual features of mixing with the host granitoid. The enclaves are clustered along the margin of the pluton, which suggests that they represent a "failed ring-dyke". The most mafic compositions are identical to that of synplutonic dykes whose geometry indicates that the basic liquids were injected into a viscous or plastic crystal mush. The enclaves, therefore, also represent liquids.
Of particular interest is the observation that the enclaves exhibit banding parallel to their contact, even where the geometry of the contact is highly irregular, and that megacrysts of K-feldspar, identical to those of the surrounding granodiorite and certainly derived from the latter, are statistically aligned in the banded structure. This is considered to be a) evidence for mechanical mixing between enclave and granodiorite, b)evidence that shearing, due to laminar boundary flow, occurs between enclave and granodiorite. This represents, indeed, what we take to be operative on a much grander scale.
The enclaves have an irregular outline, attributed to the juxtaposition of crystallizing liquids with different viscosities. Some are cigar- or spindle-shaped. Flattening is, in this occurrence, uncommon.
a) Mafic enclaves along the northern margin of the pluton. Note the variety of shapes and shades of colour.
b) Schlieren with feldspar megacrysts aligned in the layering, and a microdioritic enclave.
c) and d) Mafic enclaves with internal layering which controls the statistical orientation of K-feldspar megacrysts derived from the host granodiorite.

long, which are concentrations of the minerals, mainly the ferromagnesian species, of a plutonic body. They grade into the surrounding rock, and may show internal grading, mainly of a compositional type. They may be single or repeated to form a banded structure.

It is likely that schlieren have several possible origins, but in a vast majority of occurrences, they are intimately related to mafic enclaves. A study of the well developed schlieren in the Ploumanac'h massif clearly shows that they are *always* associated with microgranular dioritic enclaves, and appear to be derived from them. Field observations strongly suggest that they represent drawn-out mafic enclaves; in other words, this type of schlieren forms through disruption of the latter, when these were still at least partially magmatic. The ferromagnesian fraction of the enclave is, in our opinion, smeared out along certain planar surfaces within the granitic mush, with which it is mixed. This may explain why, systematically, the grain size of the dark minerals of the schlieren are of the same size as the biotites and amphiboles normally found within the granite, and much larger than counterparts within the enclave (see PITCHER and BERGER, 1972, Fig. 5-14, p. 118).

Schlieren exhibit a wide variety of forms and attitudes, but they are in general steeply inclined. At Ploumanac'h, their dip is almost always subvertical, excepting where they form folds or more irregular, complex shapes, and this pattern emerges from most descriptions of plutons (see BALK, 1937). Such steep attitudes preclude an origin related to gravitational segregation.

The most plausible mechanism for the formation of schlieren is therefore strong laminar or viscous flow, resulting in the production of an igneous layering or foliation. Quotes from PITCHER and BERGER (1972) are of relevance here. On p. 117: "The number... of schlieren is directly proportional to the color index of the host, greatly increasing where swarms of xenoliths occur, and the deduction is obvious." On p. 174: "That imbibition actually occurs in this way is shown by the disintegration of xenoliths to form schlieren bands, rich in aggregates of hornblende and biotite..." The same authors conclude (p. 254–255) that the appinitic inclusions and host granite had same ductilities, which is more understandable if both were liquid at the same time. The folds that commonly affect the schlieren must be due to further or later deformation. They are indeed related to a schistosity and mineral lineation which represent a later stage in the evolution of the pluton. We shall return to this point further on.

The complex forms, including common, curved splays as if swept with a broom, may be due to more irregular, turbulent flow. These are well illustrated in BARRIÈRE (1977).

On a grand scale, schlieren arches or domes give a good insight into the overall geometry of a pluton, the classic example being the Riesengebirge granite made famous by CLOOS' elegant analysis (CLOOS, 1925). The Mt Blanc granite also appears to be a schlieren dome (VON RAUMER, 1967). Care must be taken, however, to distinguish between the original attitude of the schlieren and modifications thereof occurring in the late stages of the evolution of the pluton. BALK (1937) clearly distinguishes different structures in the Sierra Nevada batholith. Schlieren and a linear structure may intersect each other, the latter extending farther into the interior of the massif than do the schlieren.

The distribution of the schlieren is of paramount interest. Again, Ploumanac'h is an excellent example. There, very evidently, the schlieren are concentrated within a zone a few hundred metres wide, at some 500 to 1500 m from the edge of the massif. This zone also contains numerous enclaves, mafic dykes, and passes near to a large mass of gabbro (at Ste. Anne). A marginal position of the schlieren is a common feature.

A picture thus emerges of a zone, near to the margins of a pluton, in which mafic enclaves are drawn out into schlieren by viscous flow, to produce an igneous banding. In this situation, it is not uncommon for the enclaves to be spindle-shaped (see BALK on the Lausitz granite, or on the Boulder and Sierra Nevada batholiths; spindle-shaped enclaves can be seen in the marginal zone of the Elba granite), which indicates constrictional deformation, most probably due to laminar boundary flow. This is in contrast with the common "pancakes" reported in many plutons, but which represent a later stage in the development of the intrusion.

Structures

The basis for the analysis of the internal geometry of a pluton is of course found in the

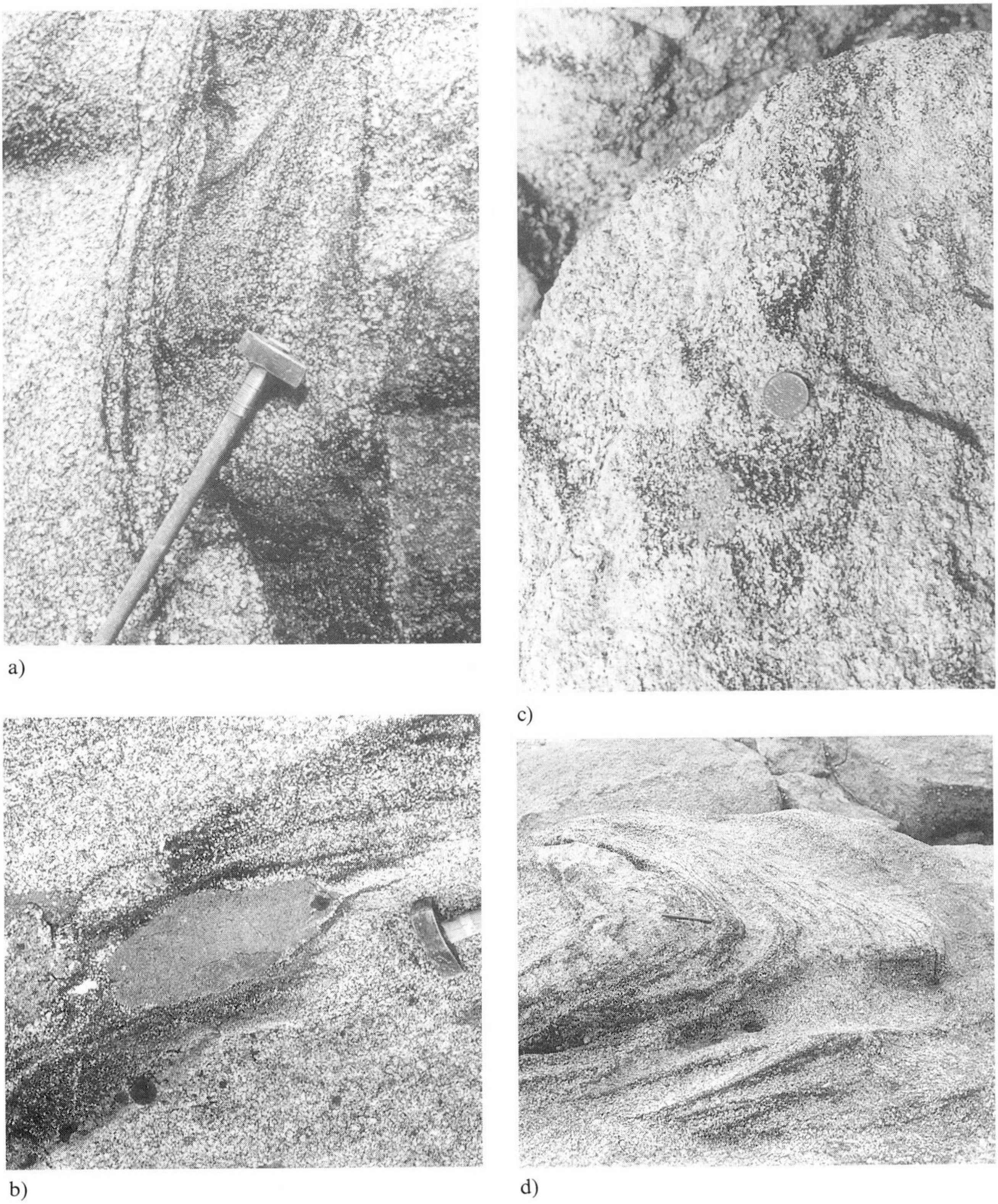


Fig. 2 Sheared enclaves, schlieren structures and folded schlieren:

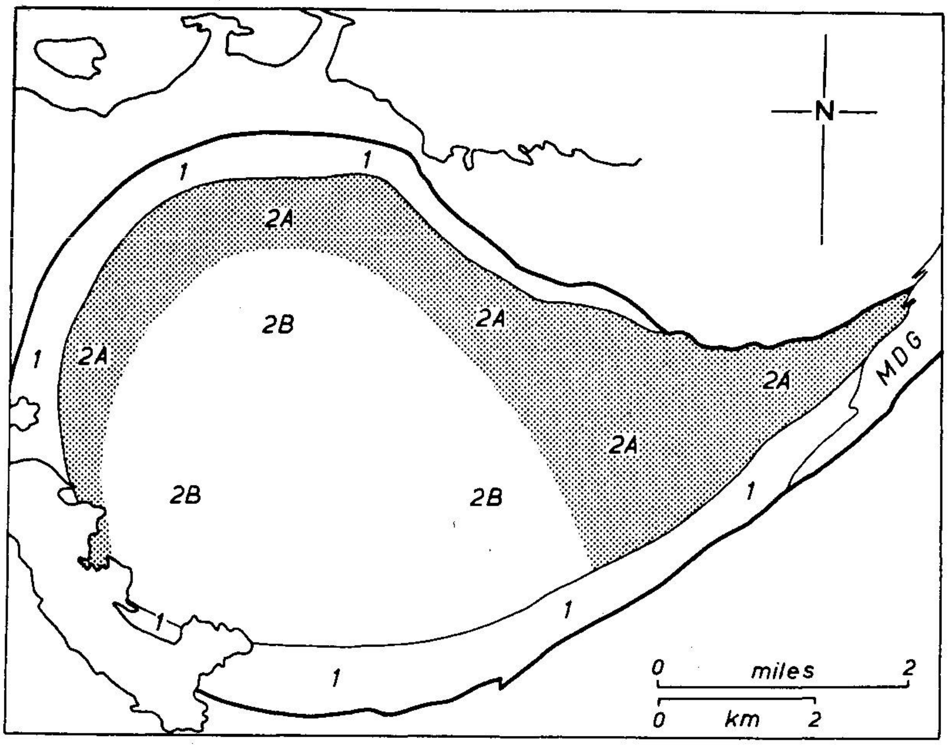
a) Shearing of a mafic enclave to produce a schlieren structure and igneous layering or banding. Ploumanac'h, Brittany. Courtesy of F. Bussy, University of Lausanne.

b) Id. Corsica. Courtesy of F. Bussy, University of Lausanne.

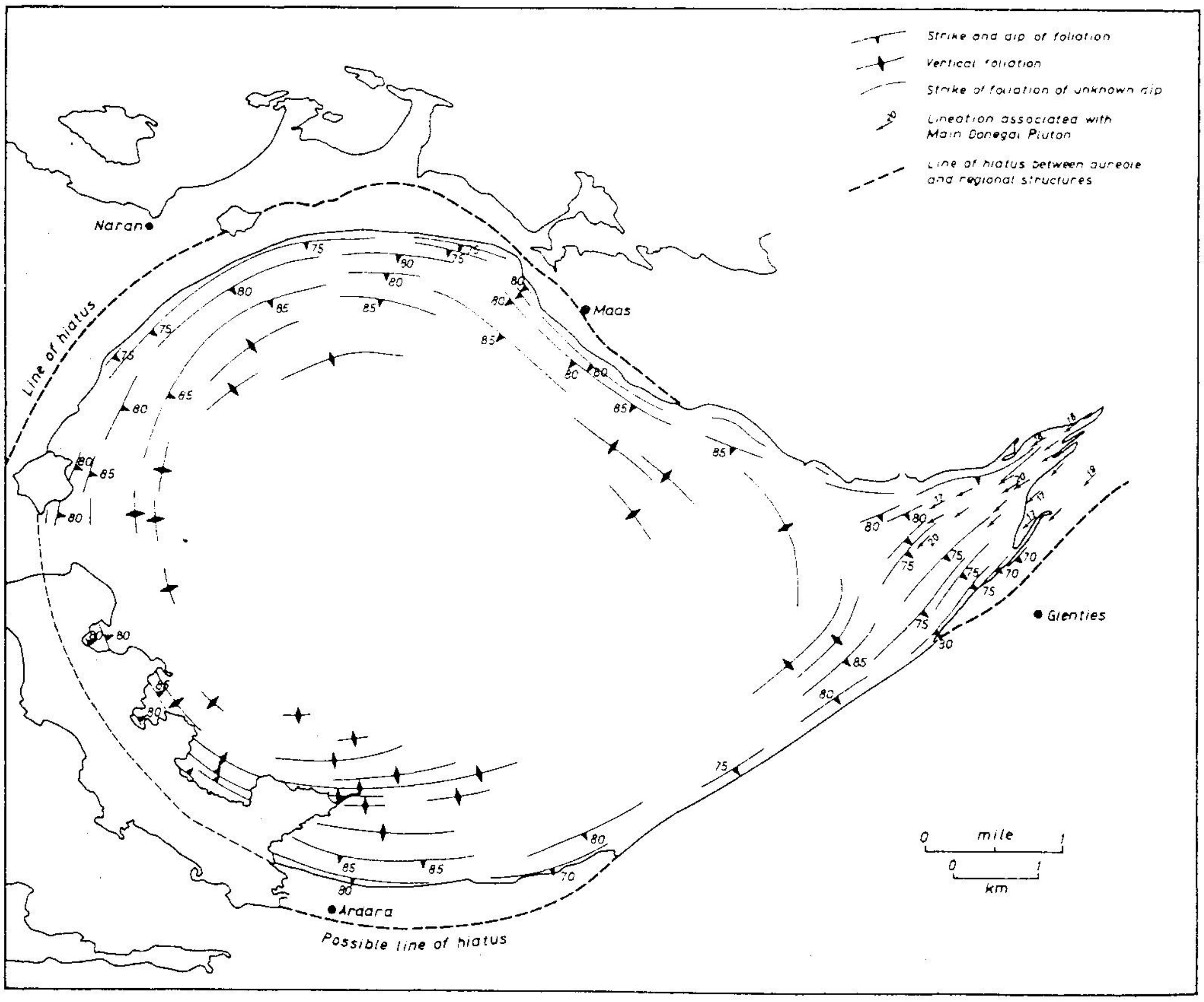
c) Folding of schlieren into generally tight folds with sub-vertical axial surfaces. Locally, isoclinal folds may be refolded. Ploumanac'h, Brittany.

d) Id.

3a)


N
1
2A
2B
MDG
0 miles 2
0 km 2

3b)


Strike and dip of foliation
Vertical foliation
Strike of foliation of unknown dip
Lineation associated with Main Donegal Pluton
Line of hiatus between aureole and regional structures
Naran
Maas
Glenties
Ardara
Line of hiatus
Possible line of hiatus
0 mile 1
0 km 1

3c)

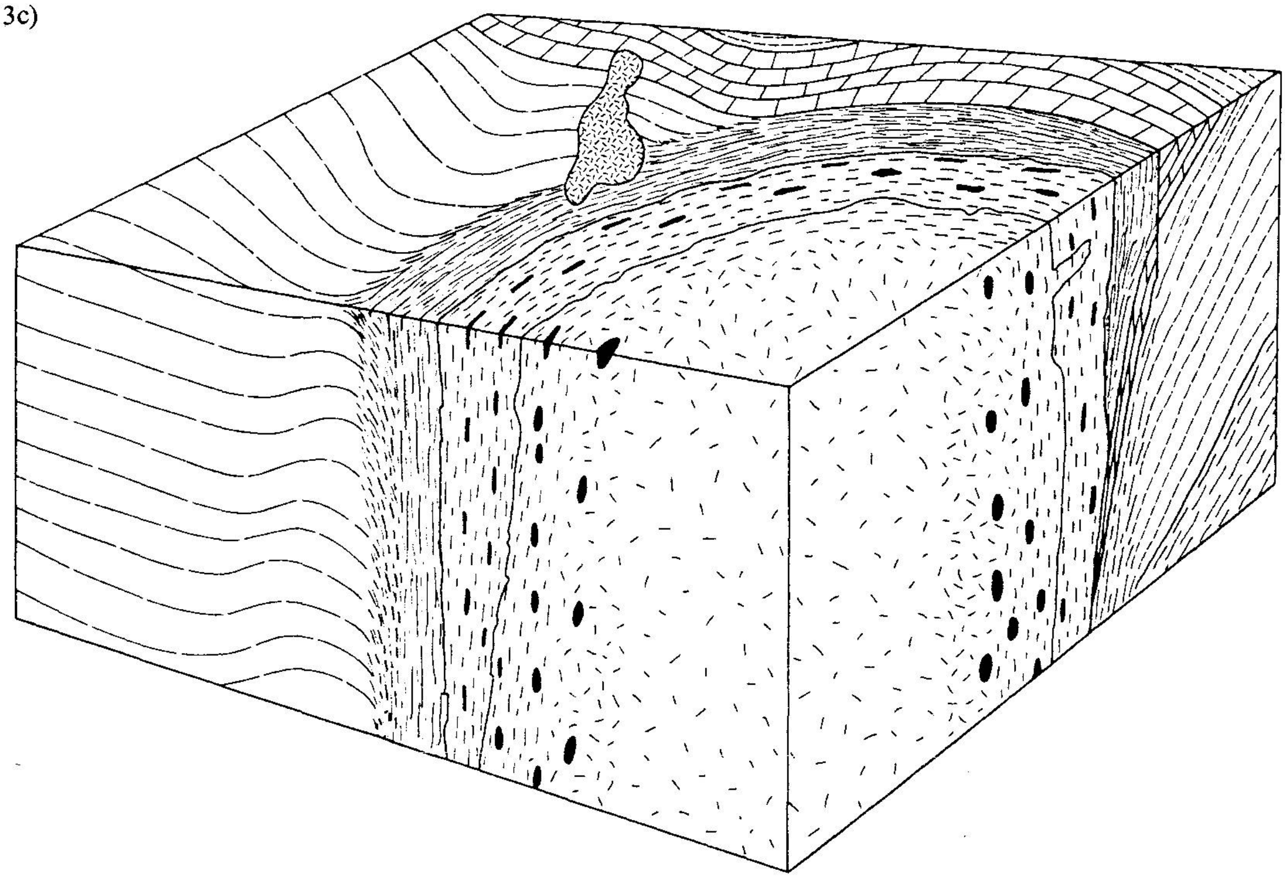


Fig. 3 The Ardara Pluton:

a) The components of the Ardara Pluton. 1) Outer Component, the quartz monzodiorite. 2) Central Component: (A) quartz monzodiorite or tonalite with many appinitic xenoliths; (B) granodiorite.

b) Structural map of the Ardara Pluton. Modified from AKAAD (1956).

c) Generalized block-diagram of the northwestern part of the Ardara Pluton showing progressive deformation in the carapace and the peculiarly restricted deformation on the envelope. Diagram shows schematically the progressive flattening of the basic patches and the strengthening of the alignment of the minerals within the pluton.

classic works of CLOOS (1925), BALK (1937), BERGER and PITCHER (1970), PITCHER and BERGER (1972). This also bears on mechanics of emplacement.

The main structures with which we are concerned here are:

- a *compositional banding*
- a *schistosity* defined by the preferred orientation of platy minerals
- *folds* defined by schlieren and / or by compositional banding
- a *mineral lineation*.

All four structures are strongly developed near the margins and in the most mafic lithologies (in the case of normal zonation), the central core being virtually structureless and massive.

The two planar structures, although often sub-parallel, are clearly distinct and may intersect. This is the case in the Chindamora batholith (Zimbabwe), where a compositional layering is best developed near the contact between the central adamellites and the external tonalites. The structure parallels the walls of the intrusion and is attributed to viscous flow mechanisms (RAMSAY, 1985).

Similar considerations are to be found in BALK (1937), who emphasizes that schlieren and the compositional banding generally have steep attitudes and are elements not to be confused with a younger planar structure (which we here consider to be a schistosity) and with "flow lines" (which we call here a "mineral lineation"). BALK also points to a very general feature, namely that early, more mafic members of a magmatic suite are more foliated than late, more felsic ones. Considering foliation in the Ardara pluton, PITCHER and BERGER)1972, p. 175) state: "There is, of course, the possibility that this structure is a composite one and that an early "flow foliation" was followed, especially in the margins of the pluton, by a deformative, "secondary foliation". Concerning the regular-banding of the Main Donegal Pluton, they refer (on p. 251) to "the possibility that the bands represent planes of shear generated during the actual emplacement of the pluton...", and acknowledge the difficulties in establishing the precise nature of the different structures (p. 255).

Schistosity

The other main planar structure is determined essentially by the preferred orientation of micas (and to some extent, of amphiboles) and megacrysts of K-feldspar. It is therefore appropriate to call it a "schistosity", as does RAMSAY (1985), who notes that the schistosity in the Chindamora batholith can be seen to cross-cut the banding. The two types of planar structure, he concludes, are independent of each other. The schistosity is most intense in the more mafic outer tonalite and granodiorite, and dies out inwards. The strike of the schistosity is generally sub-parallel to the contacts of the pluton, which means that it is often sub-parallel to the igneous banding as well, which may be the source of some confusion. The dip is steep, with local variations. The schistosity can be clearly matched in attitude and intensity with the deformation of the enclaves ("xenoliths"), from which strain ellipsoids of an almost perfect unaxial oblate ("pancake") type have been derived. The schistosity appears therefore to be consistent with a flattening type of deformation that is related by RAMSAY to a "balloon inflation" model of pluton growth and emplacement (see Figs. 3 and 7).

A classic example of the same features is to be found in the Ardara pluton (AKAAD, 1956; HOLDER, 1979; PITCHER and BERGER, 1972). A concentric schistosity within the intrusion is parallel to the cleavage in the country rocks. It is most intense in the outer tonalite and dies out towards the central granodiorite. Mafic enclaves, common in the outer quartz monzodiorite or tonalite, and identical to the components of the appinitic amphibolite complexes (which, in two cases, actually form the wall rock – see PITCHER and BERGER, 1972, p. 173), are progressively more deformed outwards towards the margins of the pluton, the finite strain being of pure flattening type. The central granodiorite is virtually devoid of schistosity (see Fig. 3). The fact that this structure crosses compositional variations and even the main contact indicates that it is indeed of a tectonic nature, and it is again attributed by HOLDER (1979) and by PITCHER and BERGER (1972) to inflation of the diapir. Textures which accompany the structure are of cataclastic or crystalloblastic type, suggesting that consolidation of the outer parts of the pluton was far advanced when the flattening occurred.

BALK (1937) makes similar comments, noting that a gneissic structure exists in the marginal zones of many batholiths (Idaho, Sierra Nevada, etc.) and also in ring-dykes of the Scottish Tertiary province. He also draws a clear distinction between the tectonic structures and the earlier igneous banding, and indeed, dykes can commonly be seen to cross-cut the banding and to be affected by the schistosity-forming event.

Another important point is the fact that this schistosity is the axial surface of the common folds which deform the schlieren or igneous banding. This is extremely well displayed at Ploumanac'h (and in BARRIÈRE, 1977), where tight, often steeply plunging similar folds (decimetric to metric), or more open shapes, exhibit this relationship virtually without exception. The structure is often marked by the parallel disposition of K-feldspar megacrysts. A similar situation in the Main Donegal Pluton is illustrated in PITCHER and BERGER (1972, p. 227).

There is also some indication of progressive deformation in the geometry of the folds. Axes are often steep which we take to be due to their rotation, through strong deformation, towards the X axis of the finite strain ellipsoid, a direction materialized in the field by the mineral lineation. Locally, isoclinal folds may themselves be folded, but this should not necessarily be attributed to discrete phases of deformation.

BARRIÈRE (1977) has also observed and analysed different planar structures at Ploumanac'h, a younger one being demonstrably a schistosity with flattening strains evidenced by the shapes of the enclaves. This structure is well developed in the outer zones of the annular complex. There are some indications of shearing associated with the earlier compositional structure.

At this stage, it is important to note that we are dealing with two types of planar structure which may owe their existence to very different mechanisms. The second one, the schistosity, may well express the inflation of a pluton in its final stages of emplacement. The first, the igneous banding, must be due to another mechanism. This is not to say that there might not be a continuum between the two, or even a superposition. Transitions between igneous and crystalloblastic textures have been observed in a number of granitoids (and this is the source of some confusion, and probably a factor in overemphasis on metasomatism in some interpretations). A study of the deformation of quartz in a granite by PHILLIPS (1965) illustrates the "change from plastic deformation without distortion of the crystal structure, through a phase of distortion and recrystallization of the parent crystal structure, to the final development of brittle fractures with some recrystallization but no reorientation of the crystal structure." Anorthosites exhibit similar features, showing that they too continue to ascend as the system crosses the solidus (DUCHESNE and MAQUIL, 1981).

It is also of relevance that constrictional strains have been observed in enclaves near the margins of plutons, for instance in the Main Donegal Pluton (see PITCHER and BERGER, 1972, p. 234), or near the border of the Elba granodiorite. BALK (1937) mentions spindle-shaped enclaves in the Lausitz granite, in the Boulder and Sierra Nevada batholiths, at Ascutney Mountain (Vermont) and the White Mountains (New Hampshire), etc. (see also MARRE, 1982). An earlier constrictional type of deformation may explain some of the variations that have been observed in the geometry of the deformed enclaves. Alternatively, as will be argued further on, the enclaves with purely flattening characteristics may represent a late marginal pulse of basic magma injection. ANDRÉ (1983) has proposed a model for the deformation of enclaves within a monzodiorite of the Massif des Ballons (Vosges), in which early rotational deformation due to a mechanism of simple shear is followed by intense flattening.

A word of caution concerns the physical state of enclave and host material at time of deformation. RAMSAY (1985) has argued that the containing liquid must transgress the threshold of plasticity before a xenolith may be deformed, and this is certainly valid. In the case of mafic enclaves, however, which were themselves blobs of crystallising magma within the developing pluton, this is no longer a necessary condition. Some of the deformation may have occurred during the purely igneous stage, and indeed, the textures of many enclaves show no sign of cataclastic or crystalloblastic phenomena. On the contrary, petrofabric analysis of mafic enclaves has shown that, in certain occurrences, they have flowed with and under the same conditions as the host granitic liquid (see MARRE, 1973, 1982). As is so often required, the study of the geometry of the enclaves must therefore be closely integrated with that of their textures.

Mineral lineation

Here, too, a distinction must be made between early igneous alignments, and late structural developments.

A first type of preferred mineral orientation is related to the formation of schlieren and to viscous flow. Micas and K-feldspar megacrysts lie on or in the schlieren and parallel to it.

The second mineral lineation is associated with the schistosity, in which it lies. It is generally steep and it can sometimes be shown to be parallel to the X direction of the strain ellipsoid (RAMSAY, 1985; BARRIÈRE, 1977). KING (1966) established the existence in some granites in Ireland of a steep magnetic linear fabric, whose intensity correlates well with that of the schistosity. Note that the author recognizes an early fabric due to fluid flow and a later one due to plastic deformation

That this second lineation is independent, as is the schistosity, of the compositional banding is shown by the observation that it may crosscut the latter (see PITCHER and BERGER, 1972, for references). BALK (1937), on the Sierra Nevada batholith, mentions that schlieren vary in strike and dip, whereas the linear parallelism of hornblende and biotite remains constant. He also refers to CLOOS (1925), who observed in a number of places at Strehlen

(Germany), an angle between schlieren surfaces and mineral lineation. This tectonic lineation is often the last structure to survive inwards into the massive, homogeneous core of a zoned pluton.

Convection (see Figs. 5, 6 and 7)

Convection in natural magmas has long been seriously considered, especially since the publication of the classic work by WAGER and DEER (1939) on the Skaergaard complex, and, since then, the problem has been tackled from various angles, including experimental modelling (for instance by NICKEL et al, 1967), or on a theoretical place (SHAW, 1965, 1974; BARTLETT, 1969, amongst others).

The conditions in which convection must occur are well known, and are expressed by the Rayleigh number:

$$Ra = \frac{g \alpha \Delta T L^3}{\gamma k}$$

in which L is usually the vertical dimension of the body, Δ T, the difference in temperature between the top and the bottom of the body, γ, kinematic viscosity, α, the coefficient of thermal expansion due to change of temperature, k, thermal diffusivity, and g, the acceleration of gravity (MCBIRNEY, 1984). Convection is inevitable if $Ra \approx 1700$ (BARTLETT, 1969), and the limit is no doubt easily attained in many plutons, even of moderate dimensions. The initiation of convection may be more sluggish if the melt with suspended crystals ceases to behave like a Newtonian fluid (WICKHAM, 1987), but the threshold will be rapidly exceeded if more energy, in the form of heat, is supplied to the system, which will happen if, as argued here, basic magma is injected into it.

The manner in which convection operates is no doubt complex. Of special importance is a zone near the margins of the pluton, in which three types of boundary layers will form, the narrowest being a compositional boundary layer, a wider boundary layer corresponding to a thermal gradient, and the widest being the momentum boundary layer (see MCBIRNEY, 1984, p. 63–67). It is evident that viscous flow will be mainly contained within this zone, and it follows that as crystallization proceeds inwards from the walls (and roof), a convection cell will move inwards towards the core of the pluton until the temperature has decreased, and viscosity increased, to a degree where convection is no longer possible (Fig. 7). This may be an alternative way of explaining the generally structureless core of many normally zoned plutons, rather than attributing its lack of structure to late intrusion (the two propositions are not, however, mutually exclusive).

A number of convective regimes are possible, and this may, to some degree, explain differences between normal, reverse and complex zonation in plutons. Examples of different types of magmatic convection are portrayed in MCBIRNEY (1984, p. 66). This author concludes that "An individual intrusion may pass through a number of these convective regimes during the course of cooling and solidification, and...each may have a different effect on the way an intrusion crystallizes and differentiates".

It appears that viscous flow will reach high rates in a boundary layer near the margin of the body, the velocity decreasing towards the core and outer contact (SHAW, 1974; see also BEST, 1982, p. 251 and 325, WILLIAMS and MCBIRNEY, 1979, p. 27, and MCBIRNEY and NOYES, 1979). Referring to Ploumanac'h, this may explain why schlieren are systematically concentrated into a zone a few hundred metres wide and at about 1000 metres from the contact with the wall rocks (Figs. 5, 6 and 7). It is also of considerable interest to note, with BARTLETT (1969), that in certain systems, convection may reach such intensities that complete redistribution of the crystal population ensues (see WICKHAM, 1987, p. 289). This underscores the potential inherent in convection for thorough mixing and the production of homogeneous compositions from two distinct starting materials.

Laminar boundary layer convection is, to conclude, a powerful mechanism which must occur in most plutons, and which must leave its mark on the structure and compositional pattern of an intrusion. It is a reasonable assumption that convection is responsible for the drawing-out of mafic enclaves into subvertical schlieren, leading to a form of igneous banding. This implies a redistribution and a dispersal of mafic material, often preferentially injected near the margins of a growing pluton[1].

[1] It is obvious that the enclaves one sees cannot be those that have been dispersed, which underscores the likelihood that basic magma is injected into the system over a long time span.

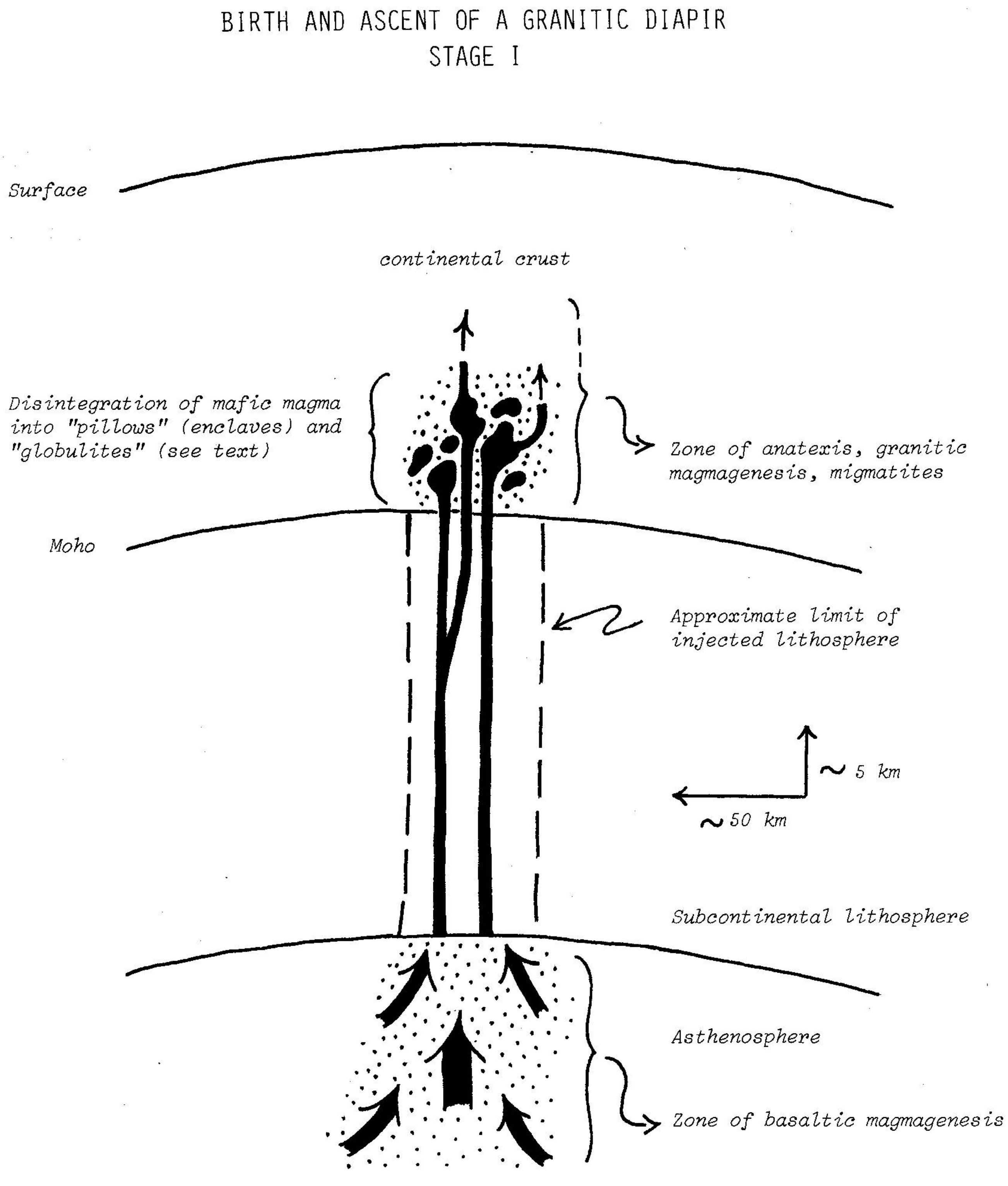


Fig. 4 Birth and ascent of a granitic diapir. Stage I:
The fundamental process portrayed here is a) the fusion of subcontinental mantle to produce basaltic magmas, b) the ponding of these magmas at the base of the crust, or their rise to higher levels, with attendant anatexis (lasting at least as long as basalt is injected into the crust, c) injection of basic magma into acid liquids to form "pillows" (enclaves)—see BLAKE et al. (1965); injection of basic magma into rock near the melting point will produce "globuliths" (see BERTHELSEN, 1970) in migmatites (synkinematic, but with coeval superposition of tectonic and flow structures), d) the possible ascent of the acid component to form a pluton, into which, if it is not detached from its root-zone, basaltic magma may again be injected.

This is consistent with the features of normal zonation, as banding weakens towards the core, with a concomitant decrease in the colour index. Mixing between the acid core and the mafic margins ceases where convection finally stops.

Ring-dykes

As it appears from a number of descriptions, there is often a tendency for the mafic (basic) liquids, now fossilized in the form of enclaves, to be injected near or at the margins of plutons, and sometimes even outside the limits of the intrusion. This suggests that there might be a correlative relationship between the situation of the enclaves and classic ring-dykes. In both cases, basic magma would be preferentially injected at or near the main discontinuity, i.e. the more or less cylindrical or conical fracture which marks the contact between pluton and wall rock.

A survey of the Central Complexes of the British Tertiary province (see EMELEUS, 1982) suggests that there are indeed many points common to zoned plutons with enclaves and such high level intrusions. It is noteworthy that basic magmas are available throughout the history of all the centres, and this is true of a vast number of granitic batholiths (synplutonic mafic dykes and late lamprophyres afford evidence in this respect). In both cases, the magmatism is essentially bimodal, with the mafic magmas playing the major role in the evolution of the Central Complexes. Of particular interest is the fact that a number of ring-dykes are composite, with clear signs of magma mixing. At Mull, certain ring-dykes show variation from gabbro at low levels to felsites and granophyres further up, with indications of hybridisation (the Glen More and Loch Bà ring-intrusions, for instance). The early ring-dykes of Ardnamurchan show similar features. Hybridisation is common in the Central Complexes, with the Marscoite suite on Skye as a good example of a hybrid ring-dyke. There are also a number of instances of mafic pillows in acid rock (Glen Dubh on Arran; the Mullach Sgar complex on St. Kilda, amongst others). Clearly, basic magma intruded the margins of these complexes at different times, and mixed to a variable degree with the acid melts.

It is pausible that a spectrum of situations exists between that in which a gabbroic ring-dyke is well individualized, with sharp contacts against the central, acid pluton, and a normally zoned pluton with a transition from a mafic outer zone with enclaves to a central, acid core lacking enclaves, and structureless. A particular occurrence will depend on a number of factors, such as:

1) the level of the Earth's crust at which intrusion and mixing have occurred, and the level of erosion / observation (the Ardara pluton is a deep-seated equivalent of a complex like Arran or Slieve Gullion): the local geothermal gradient;

2) the compositions and temperatures of the magmas involved;

3) the time gap between emplacement of the core and that of the ring-dyke (in the simplest case); the succession of events (most plutons in the British Tertiary are the result of a long, complex history).

A gradational series is thus to be expected, which is precisely what ROOBOL (1971) has proposed for acid-basic associations in the British Tertiary and Iceland.

The "Failed Ring-Dyke Hypothesis"
(see Figs. 4, 5, 6, 7)

We come now to the formulation of this concept which should emerge from the preceding considerations.

Convective mixing may be an important mechanism operating in and influencing the evolution of an igneous body. The basic magmas, responsible in many cases for melting of the crust, the formation of acid liquids, and the initiation of granitic diapirs, may continue to rise with the latter. It is plausible that, in general, they will be preferentially injected along or near to the major structural discontinuity of the system, i.e. the contact with the wall-rock, to form swarms of mafic enclaves, or discrete ring-dykes. Should this occur early enough, at a time when the pluton is still rising and growing, mixing will result through the action of laminar boundary flow, possibly the main expression of convection within the magma chamber. As the system cools, the convection cells should move inwards, continuing to dis-

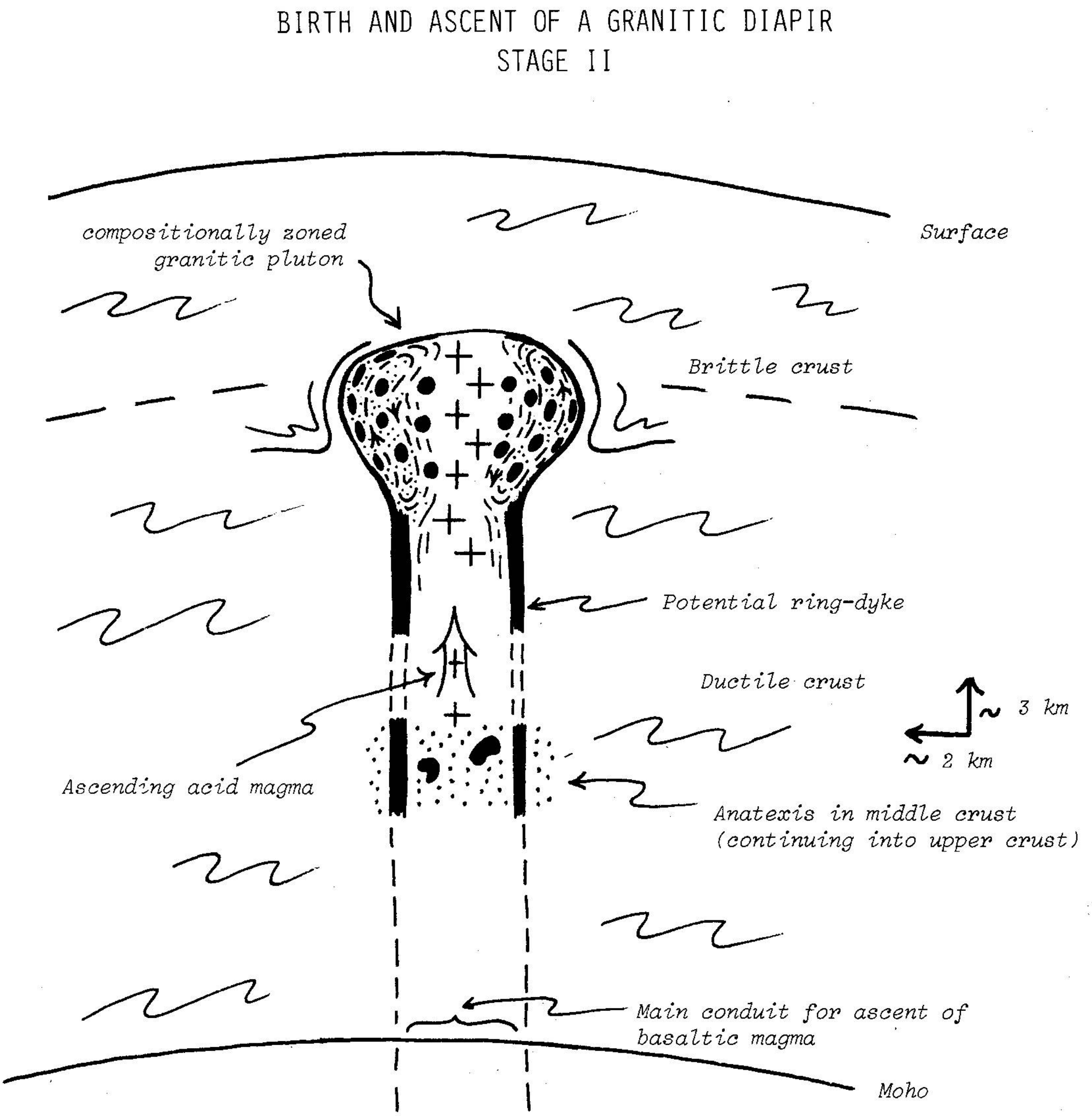


Fig. 5 Birth and ascent of a granitic diapir. Stage II:
The ascending diapir of acid liquid (+ crystals) begins to expand as its rise becomes increasingly difficult due, mainly, to variation in the nature of the upper crust. It is still connected to the root-zone and to the conduit into which basaltic liquids continue to be injected. This counterbalances to some degree the effect of cooling/increasing viscosity and drag through variation in properties of crust. It also maintains a sufficient density contrast, and contributes to the volumetric expansion of the diapir. The basaltic magmas will in general follow the external fracture (normal zonation), but may ascend in the central part of a diapir (reverse zonation). Convection must be initiated leading to disruption of basaltic magmas to form blobs (enclaves), which will be deformed by shear (laminar flow) into schlieren; this will impart a local foliation to the rock. Further disruption will disperse the mafic component within the volume affected by convective mixing, and will homogenize the mixture to the point where the composition will grade progressively from the outer (if normally zoned) gabbro/diorite to the inner granitoid.
Note that the enclaves vary from oblate ellipsoids near the margins to spherical shapes inwards (where still recognizable). The geometry of the convection cell is highly speculative and simplified. It is just one possibility amongst many.

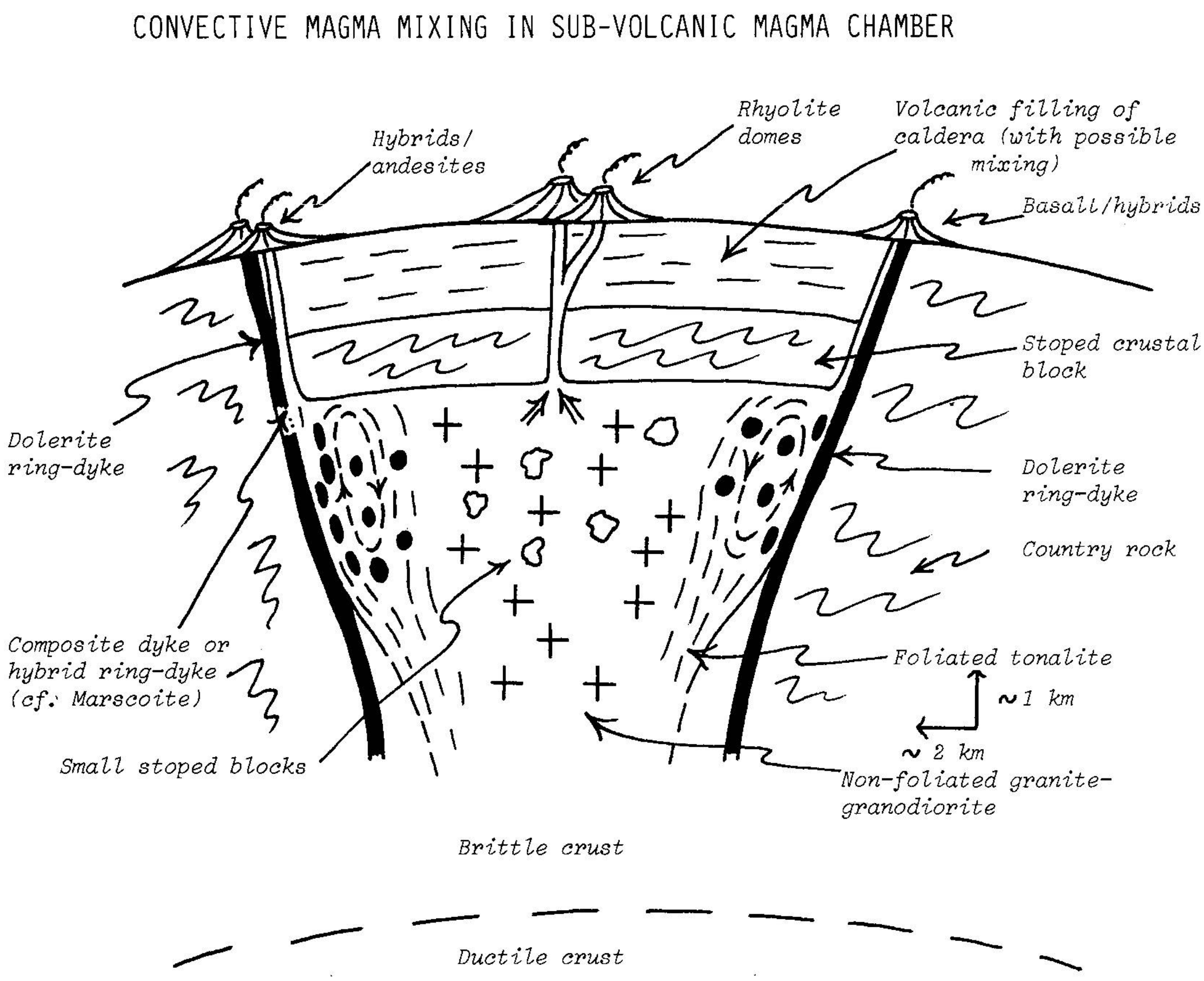


Fig. 6 Convective magma mixing in a sub-volcanic magma chamber:
Here, the pluton has reached a high level of the crust and is connected to the surface, with ensuing volcanic activity. Cauldron subsidence has allowed the final upward surge of the system, which continues to be connected at depth with basic feeder-dykes. Convective mixing continues to operate, which may 1) pursue the distribution of the mafic component within the magma chamber, 2) produce a homogeneous, hybrid liquid eventually injected as a ring-dyke (cf. the Marscoite Suite on Skye), or even erupted.
Mixing may continue to occur at very high levels (cf. the Gardiner River volcanics–WILCOX, 1944).
Composite dykes may form in this situation. Sharp contacts between acid and basic components may be due to difficulty of mixing, either because the duration of contact between liquids was limited, or because the necessary space was lacking, preventing convective mixing, or because of a time lag between the injections of the two components.
This is a "simple" model. Natural occurrences will of course be more complicated, and a great number of variations no doubt exist, for example in the geometry of convection, the loci and timing of injection of basaltic liquids into the magma chamber, etc.

perse[1] mafic material in ever-decreasing proportion until conditions of temperature and therefore viscosity impede the pursuance of convection. This stage is followed (the two regimes may be even partly superposed) by the inflationary stage of the diapir, which ends the history of emplacement, and which is responsible for the flattening strains recorded in the enclaves, with concomitant schistosity and mineral lineation.

[1] In passing, it should be noted that such dispersal of basic material, most probably drived from the mantle, must have profound consequences on the Sr87 / Sr86 ratio in zoned granitoids.

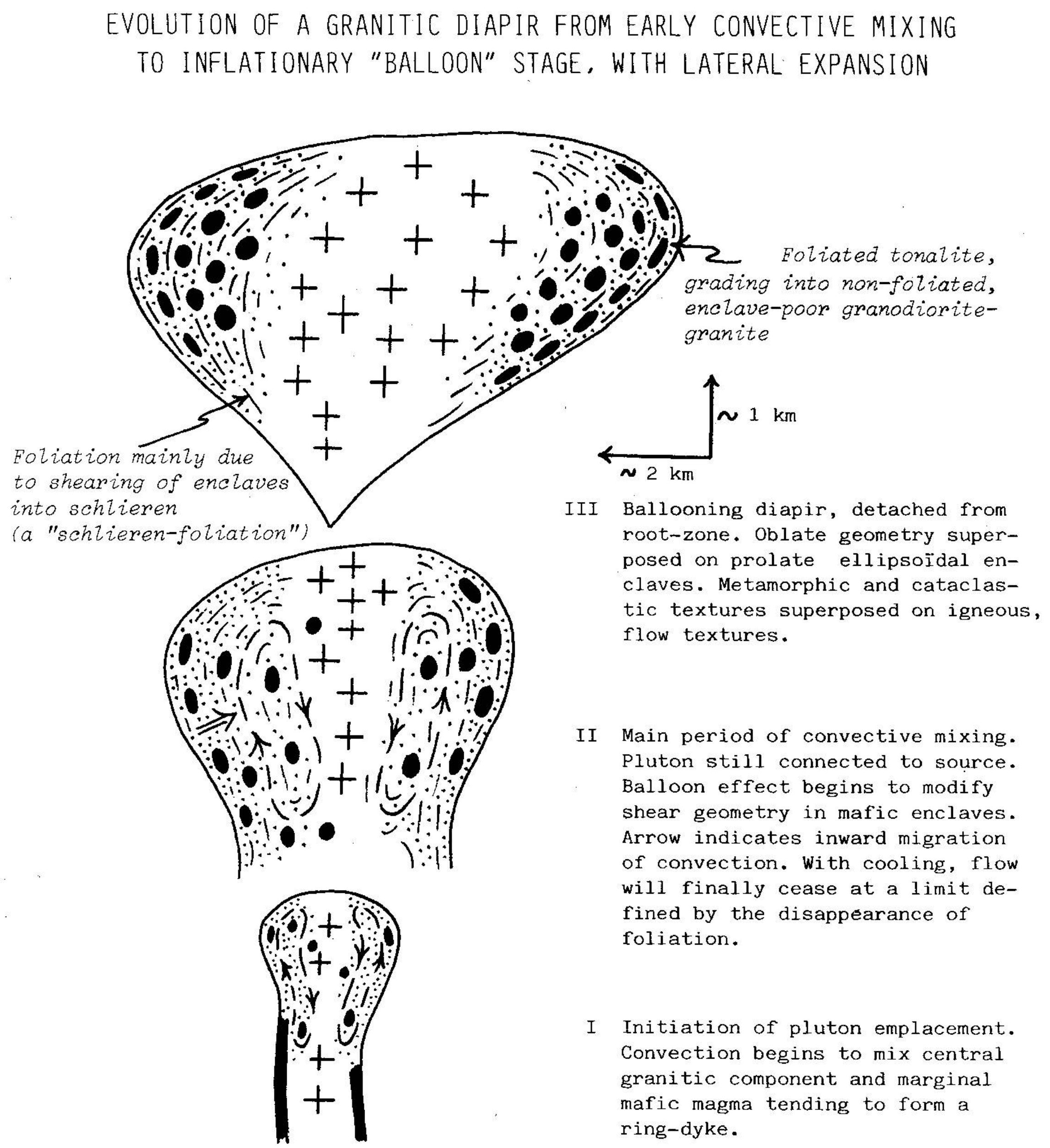


Fig. 7 Evolution of a granitic diapir from early convective mixing to the inflationary, balloon stage, with lateral expansion:
This cartoon attempts to illustrate, in three steps, the transition from a rising pluton, in which convective mixing is the dominant process, to a situation in which the pluton ceases to migrate upwards, but expands laterally, as if inflated like a balloon. Distinct structures are formed through convection (shearing of enclaves produces schlieren and igneous banding) and inflation (flattening deforms enclaves into oblate ellipsoids-see text).
Variations depend on a host of factors: a) initial conditions of composition, temperature, and therefore viscosity; b) rate at which the body cools, which will determine how long the convective system will operate, and how far into the pluton it will migrate before ceasing to be active; c) how far the pluton travels, and therefore d) the type of crust it traverses and finally comes to rest in (the "balloon" stage may coincide with the arrival of the pluton into the brittle crust, in which the capacity for upward migration of the mush is greatly reduced); e) interaction with the crust (for instance cooling through incorporation of crustal water); f) moment of detachment from root-zone, which will determine the amount of material supplied from the anatectic source, and from the basaltic feeder-dykes; g) others...
Note that the visible enclaves with the flattening geometry may represent only the last increment of basic liquid injection, as they are not drawn out into schlieren. This could explain why they rarely exhibit prolate forms.

This is therefore an alternative hypothesis to models in which a single magma undergoes differentiation within a magma chamber. Although acid and basic liquids may be derived from separate sources, the model may be applicable when they have a common origin. Acid differentiates of a basic magma may be intruded by late pulses of basic liquids, with the same result.

To conclude, it may be necessary to reassess compositional zonations in certain granitic plutons, where the margins are dioritic and contain mafic inclusions, in terms of a bimodal system in which mixing through vigorous convection has occurred between a ring-dyke of gabbroic composition and a core of acid magma, and to question fractional crystallization of a single magma as the dominant process for the variation and pattern of composition. The spectrum of relationships between a well-individualised basic ring-dyke and a zoned batholith with gradational features is the expression of a transition from commingling to pervasion, from mere juxtaposition of contrasted magmas to mixing, leading to and resulting in the production of homogeneous hybrids.

Acknowledgements

I thank my colleagues François Bussy and Philippe Thélin for many interesting discussions on this subject. I am also indebted to L.S. Hollister for a critical review of the manuscript.

References

AKAAD, M.K. (1956): The Ardara granitic diapir of County Donegal, Ireland, Q.J. Geol. Soc. Lond., 112, p. 263–288.

ANDRÉ, F. (1983): Pétrologie structurale et Pétrogenèse des Formations plutoniques septentrionales du Massif des Ballons (Vosges, France). Thèse Univ. Nancy, 3e Cycle, 247 p.

BALK, R. (1937): Structural behaviour of igneous rocks. Mem. Geol. Soc. Am. 5, 177 p.

BARRIÈRE, M. (1976): Flowage differentiation: limitation of the "Bagnold effect" to the narrow intrusion. Contrib. Mineralogy and Petrology, 55, p. 139–145.

BARRIÈRE, M. (1977): Le complexe de Ploumanac'h (Massif armoricain). Thesis Univ. Bretagne occidentale (Brest), 291 p.

BARTLETT, R.W. (1969): Magma convection, temperature distribution, and differentiation. Am. J. Sci., 267, p. 1067–1082.

BATEMAN, P.C., CLARK, L.D., HUBER, N.K., MOORE, J.G., and RINEHART, C.D. (1963): The Sierra Nevada batholith – a synthesis of recent work across the central part. U.S. Geol. Surv. Prof. Pap. 414-D, 46 p.

BATEMAN, P.C., and NOKLEBERG, W.J. (1978): Solidification of the Mount Givens granodiorite, Sierra Nevada, California. J. Geol., 86, p. 563–579.

BATEMAN, P.C., and CHAPPELL, B.W. (1979): Crystallization, fractionation and solidification of the Tuolumne Intrusive Series, Yosemite National Park, California. Geological Society of America Bull., 90, p. 465–482.

BERGER, A.R., and PITCHER, W.S. (1970): Structures in granitic rocks: a commentary and a critique on granite tectonics. Proc. Geol. Assoc. 81, p. 441–461.

BERTHELSEN, A. (1970): Globulith: a new type of intrusive structure, exemplified by metabasic bodies in the Moss area, SE Norway. Norges Geologiske Undersogelse Nr. 266, p. 70–85.

BEST, M.G. (1982): Igneous and metamorphic petrology. W.H. Freeman and Co., New York, 630 p.

BISHOP, A.C. (1963): Dark margins at igneous contacts: a critical study with special reference to those in Jersey, Channel Islands. Proc. Geol. Ass. Lond., 74, p. 289–300.

BLAKE, D.H., ELWELL, R.W.D., GIBSON, I.L., SKELHORN, R.R., and WALKER, G.L.P. (1965): Some relationships resulting from intimate association of acid and basic magmas. Q.J. Geol. Soc. Lond., 121, p. 31–49.

CLOOS, H. (1925): Einführung in die tektonische Behandlung magmatischer Erscheinungen (Granittektonik). I. Spezieller Teil. Das Riesengebirge in Schlesien. Bau, Bildung und Oberflächengestaltung. 194 p. Borntraeger, Berlin.

DEBON, F. (1980): Genesis of the three concentrically-zoned granitoid Plutons of Cauterets-Panticosa (French and Spanish Western Pyrenees). Geol. Rund., 69/1, p. 107–130.

DREWES, H., FRASER, G.F., SNYDER, G.L., and BARNETT, H.F., JR. (1961): Geology of Unalaska Island and adjacent insular shelf, Aleutian Islands, Alaska. Bull. U.S. Geol. Surv., 1028-S, p. 583–676.

DUCHESNE, J.C., and MAQUIL, R. (1981): Evidence of syn-intrusive deformation in South-Norwegian anorthosites (abstract). Terra Cognita, Special Issue, p. 94.

EMELEUS, C.H. (1982): The Central Complexes, in "Igneous Rocks of the British Isles", D.S. Sutherland (Ed.), John Wiley and Sons, Ltd., p. 369–414.

FRIDRICH, C.J., and MAHOOD, G.A. (1984): Reverse zonging in the resurgent intrusions of the Grizzly Peak cauldron, Sawatch Range, Colorado. Geological Society of America Bull. 95, p. 779–787.

HILDRETH, W. (1981): Gradients in silicic magma chambers: implications for lithospheric magmatism. Jour. Geophys. Res., 86, p. 10153–10192.

HOLDER, M.T. (1979): An emplacement mechanism for post-tectonic granites and its implications for their geochemical features. In "Origin of Granite Batholiths: Geochemical Evidence" (Atherton, M.P., and Tarney, J., Eds.). Shiva Publishing Ltd., p. 116–133.

IRVINE, T.N. (1979): Rocks whose composition is determined by crystal accumulation and sorting. In H.S. Yoder, Jr. (Ed.), The Evolution of the Igneous Rocks: Fiftieth Anniversary Perspectives. Princeton University Press, p. 244-306.

KING, R.F. (1966): The magnetic fabric of some Irish granites. Geol. J., 5, p. 43-66.

KOMAR, P.D. (1976): Phenocryst interactions and the velocity profile of magma flowing through dikes or sills. Geological Society of America Bull., 87, p. 1336-1342.

MARRE, J. (1973): Le complexe éruptif de Quérigut. Pétrologie, structurologie et cinématique de mise en place. Thèse d'Etat, Toulouse, 536 p.

MARRE, J. (1982): Structurologie des granitoides. Bur. Rech. Géol. Min., série "manuels et méthodes".

MCBIRNEY, A.R. (1984): Igneous Petrology. Freeman, Cooper and Co., 504 p.

MCBIRNEY, A.R. and NOYES, R.M. (1979): Crystallization and layering of the Skaergaard intrusion. J. Petrology, 20, p. 487-554.

NICKEL, E., KOCK, H., and NUNGASSER, W. (1967): Modellversuche zur Fliessregelung in Graniten. Schweiz. Min. Petr. Mitt., 47, p. 399-497.

PERFIT, M.R., BRUECKNER, H., LAWRENCE, J.R., and KAY, R.W. (1980): Trace element and isotopic variations in a zoned pluton and associated volcanic rocks, Unalaska Island, Alaska: a model for fractionation in the Aleutian calcalkaline suite. Contrib. Mineralogy and Petrology, 73, p. 69-87.

PETERSEN, J.S. (1987): Solidification contraction: another approach to cumulus processes and the origin of igneous layering. In: I. Parsons (Ed.) "Origins of Igneous Layering", (NATO-ASW), p. 1-22.

PHILLIPS, W.J. (1965): The deformation of quartz in a granite. Geol. J., vol. 4/2, p. 391-414.

PITCHER, W.S., and BERGER, A.R. (1972): The Geology of Donegal. A study of Granite. Emplacement and Unroofing. Wiley-Interscience, John Wiley and Sons, Inc., p. 435.

RAMSAY, J.G. (1985): Structures des batholites granitiques. Emplacement mechanics of a granite diapir in the Chindamora batholith, Zimbabwe. Unpublished ms for course on "Granitoides et Roches associées.", University Lausanne, March 1985.

VON RAUMER, J.E. (1967): Kristallisation und Gefügebildung in Mont-Blanc-Graniten. Schweiz. Min. Petr. Mitt., 47/2, p. 499.-580.

REID, J.B., JR., EVANS, O.C., and FATES, D.G. (1983): Magma mixing in granitic rocks of the central Sierra Nevada, California. Earth and Planet. Sci. Lett., 66, p. 243-261.

REYNOLDS, D.L. (1954): Fluidization as a geological process, and its bearing on the problem of the intrusive granites. Am. J. Sci., 252, p. 577-613.

ROOBOL, M.J. (1971): Some relations between common acid-basic associations. Geol. Mag., 108 (6), p. 525-531.

SHAW, H.R. (1965): Comments on viscosity, crystal settling, and convection in granitic magmas. Am. J. Sci., 263, p. 120-152.

SHAW, H.R. (1974): Diffusion of H_2O in granitic liquids. In Geochemical Transport and Kinetics, A.W. Hofmann et al. (Eds.), Carnegie Inst. Wash., Washington D.C., Publ. 634, p. 139-170.

SPARKS, R.S.J., HUPPERT, H.E., and TURNER, J.S. (1984): The fluid dynamics of evolving magma chambers. Proc. Royal Soc. London, v. 310A, p. 511-534.

STEWART, D.B. (1956): Ann. Rep. Dir. Geophys. Lab., Carnegie Inst. Washington Year Book, 55, p. 194-195.

SWANSON, S.E. (1986): Textural and mineralogic zoning in the Rocklin pluton, Western Sierra Nevada, California, USA. Inter. Min. Assoc. Abstr. Program 14th General Meeting, p. 243.

TURNER, F.J., and VERHOOGEN, J. (1960): Igneous and metamorphic petrology. 2nd ed. New York: McGraw-Hill, 694 p.

TUTTLE, O.F., and 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. Geological Society of America Memoir, 74, 153 p.

VERNON, R.H. (1984): Microgranitoid enclaves in granites-globules of hybrid magma quenched in a plutonic environment. Nature, 309, p. 438-439.

VISONÀ, D. (1986): Chilled margins and commingling of magmas in the Bressanone (Brixen) Hercynian granodiorites (Eastern Alps, Northern Italy). Chemical Geol., 56, p. 33-44.

WAGER, L.R., and DEER, W.A. (1939): Geological Investigations in East Greenland. Part III. The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland. Medd. om Gronland, 105, n. 4, p. 1-352.

WICKHAM, S.M. (1987): The segregation and emplacement of granitic magmas. Q. J. Geol. Soc. Lond., 144, p. 281-297.

WILCOX, R.E. (1944): Rhyolite-basalt complex on Gardiner River, Yellowstone Park, Wyoming. Geological Society America Bull., 55, p. 1047-1080.

WILLIAMS, H., and MCBIRNEY, A.R. (1979): Volcanology. San Francisco: Freeman, Cooper and Co., 397 p.

WINDLEY, B. (1965): The role of cooling cracks formed at high temperatures and of released gas in the formation of chilled basic margins in netveined intrusion. Geol. Mag., 102, p. 521-530.

Manuscript received December 9, 1987; revised manuscript accepted February 16, 1988.