Lotus Quarries to Drungans Burn

[NX 897 685]–[NX 907 665]

W.E. Stephens

Introduction

The Criffel pluton

The Criffel pluton is an outstanding example of a granitic pluton that exhibits strong concentric zonation. This zonation has been well characterized in terms of petrology, geochemistry and structure. The origin of such zonation in granitic plutons has been the subject of controversy for many decades, and this pluton has contributed significantly to that debate. Criffel is also an important pluton because it lies close to the postulated suture line resulting from the closure of the Iapetus Ocean. It was emplaced soon after this closure, around 397 Ma ago (Halliday *et al.,* 1980) into low-grade greywackes and pelites of Silurian (Llandovery to Wenlock) age.

The original survey of the pluton mapped the external boundaries of the pluton but did not distinguish different facies (Horne *et al.,* 1896). Petrological zonation was first demonstrated by Phillips (1956) in developing the idea of Macgregor (1937) who showed that the western part of the pluton consists of multiple phases of granite. Phillips also produced the first detailed map of the whole pluton and its aureole, and this remains the most detailed geological study of the area. Stephens and Halliday (1980), Stephens *et al.* (1985) and Stephens (1992) focused on the petrological and petrogenetic aspects and refined the two-fold classification of Phillips. Five more-or-less concentric zones based on the dominant mafic mineralogy are now recognized (Figure 8.32); from the least to the most evolved these are clinopyroxene-biotite-hornblende (CBH) granodiorite, biotite-hornblende (BH) granodiorite, biotite (B) granite, muscovite-biotite (MB) granite, and biotite-muscovite (BM) granite. The pluton and host rocks are also notable for their mineralization (Gallagher *et al.,* 1971; Braithwaite and Knight, 1990), including uranium and other rare minerals.

Zonation of granitic plutons is a very common feature, but no consensus exists for its origin. Models to explain zonation include, among others, fractional crystallization, multi-pulse intrusions, magma mixing, variable degrees of restite separation, and contamination by assimilation. An isotopic study of zonation of the Criffel pluton demonstrated for the first time that closed-system process alone could not account for such zonation, at least in this pluton (Halliday *et al.,* 1980; Stephens and Halliday, 1980). Crystals and melts may separate in a closed system from a parental magma in various ways; by crystal settling or wall-rock accumulation, by the separation of entrained restite, or by filter-pressing processes. The system becomes open when the parental magma is contaminated in some way, either by assimilation of wall rock during ascent or emplacement, or by the mingling and ultimately mixing with a different magma. The only way of confidently distinguishing open and closed systems is by means of isotopic ratios; these parameters change little during closed-system processes but will disclose the open-system interaction of two magmas or magma + wall rock if these initially have significant isotopic differences. This methodology was first successfully applied to demonstrating the importance of open system processes at Criffel.

In terms of the widely used I- and S-type classification of granites (Chappell and White, 1974) Criffel is somewhat enigmatic. The early, outer hornblende-bearing facies (CBH and BH granodiorites) are undoubtedly I-types (derived from meta-igneous source rocks). The last, innermost member, the BM granite, has affinities with S-types (derived from metasedimentary source rocks), although it does not entirely fit in all of its features. The intermediate zones, the B and MB granites, are transitional in their characteristics. The pluton also provided mafic microgranular enclaves (igneous-textured xenolithic inclusions) for a study by Holden *et al.* (1987) which was the first to show that such enclaves can retain a Nd isotopic memory of a mantle or mantle-like source. The implications are either that mantle-derived material became involved in the crustal melting event (Holden *et ed.,* 1987) or that primitive magmas became incorporated into the granitic magma around the time of emplacement, as has been demonstrated elsewhere (Castro *et al.,* 1990).

There are numerous analogous zoned plutons worldwide, especially in cordilleran batholiths such as the Sierra Nevada Batholith in California, and in almost every Phanerozoic orogenic belt. The importance of Criffel is not just that it was the first in which some of the important isotopic observations were made, but also because the nature of its zonation straddles the key I-type and S-type classification that has been widely applied since it was proposed in the mid-1970s (Chappell and White, 1974). Most plutons in Andean cordilleran settings belong to the I-type category and are believed to be the products of deep crustal melts (Chappell and Stephens, 1988) although some argue for a small or even a significant proportion of mantle material (DePaolo *et al.,* 1992). Either way, I-types represent the melting of an igneous protolith and are generally characterized by metaluminous bulk compositions and the presence of hornblende and titanite. In contrast, S-type granites are typical of continent–continent collision orogens and are common in the Himalayas and the Hercynian of Europe. These granites are the products of melting metasedimentary protoliths leading to very different compositional and mineralogical characteristics, including peraluminous bulk composition, reflected in the presence of peraluminous minerals such as cordierite and muscovite.

The studies of Phillips and co-workers on this pluton have been important in terms of emplacement mechanisms and magma chamber dynamics (Phillips, 1956; Phillips *et al.,* 1981, 1983; Holder, 1983). Several features such as enclave and mineral foliations, a steepening of the country rocks, and rotation of envelope fabrics into parallelism with the pluton margin, are suggestive of diapiric emplacement. However, as the amount of marginal deformation is very limited, Phillips *et al.* (1981) argued that emplacement was principally by stoping, and that convection in the magma was the cause of the primary mineral alignments and foliations. In discussion of their paper, Holder (1983) argued that the same features could be better explained by pluton ballooning. In an attempt to resolve the issue of the role of diapirism, Courrioux (1987) measured strain trajectories, strain gradients, and quartz fabrics over the whole pluton, which showed diapirism to have been the dominant emplacement mechanism for the second, inner magma pulse, and also possibly for the first.

The pluton is represented by two GCR sites: the Lotus Quarries to Drungans Burn site illustrates the main rock types and the concentric zoning; and the Millour to Airdrie Hill site exposes the outer contact and marginal zones, which contain abundant mafic-rich enclaves of structural and petrogenetic importance.

The Lotus Quarries to Drungans Burn GCR site

This site provides a section through the main components of the Criffel zoned pluton. Lotus Quarry is located within granodiorites close to the northern contact, and represents one end of a traverse in which there is a rapid petrological variation through the other facies to the two-mica granites to be found in the vicinity of Drungans, near the evolved centre of the pluton (Stephens, 1992) (Figure 8.32). This variation takes place over the whole pluton (Stephens and Halliday, 1980), but the gradient of change is steepest in this traverse; SiO_2 increases by about 10% over approximately 2 km, or roughly 1% SiO_2 every 200 m (Figure 8.33). This site has been selected as it offers the shortest traverse over all the major plutonic zones (i.e. steepest gradient of change) with reasonable exposure.

Description

The site is described from north to south, being the logical progression from least to most evolved members of the pluton (Figure 8.32). Exposure is quite good on the northern flanks of Lotus Hill to Lotus Quarry, but less good southwards towards Drungans Burn; the effects of forestry are to obscure some outcrops while creating others in road cuttings.

In and around Lotus Quarry the grey, foliated granodiorites of the CBH facies are exposed. As is the norm for this pluton the foliation dips outwards, in this case quite steeply at about 70° to the NW The granodiorites are similar petrographically to those described more fully at the Millour and Airdrie Hill GCR site, and here also there are mafic enclaves lying in the foliation plane. The clinopyroxene is invariably included within amphibole, often in apparent reaction relationship. South of the quarry for about 300 m the granodiorite evolves to a clinopyroxene-free facies of biotite-hornblende granodiorites. The next zone inwards is normally the biotite granite facies but this is cut out in this area. Southwards, almost as far as Drungans, is the zone of muscovite-biotite granites. On Lotus Hill, a contact between this facies and the hornblende granodiorites can be located to within a few metres and the sharp junction is preserved in local boulders. This is important evidence that the pluton was emplaced as multiple pulses of magma.

Small knolls in the field west of Drungans cottage consist of the biotite-muscovite granite facies, but exposure is too poor to establish its relationship with the muscovite-biotite granite. The abundant large crystals of muscovite in the BM granite are magmatic on the basis of their igneous textures (Figure 8.35) and these are well seen in exposures at Drungans. About another 1.5 km SW of Drungans, on the northern end of Long Fell ridge, is the evolved core of the pluton in which muscovite is dominant with very little biotite present. In fact, biotite is normally extensively chloritized in this facies.

The contrast between the two ends of the traverse is illustrated in (Figure 8.34) a, b, in which the grey, strongly foliated CBH granodiorite with mafic enclave is compared with the structurally more isotropic pink BM granite with abundant alkali feldspar and very few mafic minerals.

Interpretation

In order to understand the origins of zoning and the implications for the petrogenesis of such plutons it is essential to integrate the field data with the geochemistry. In this traverse the only evidence for an internal contact has been found between the MB granite and the BH granodiorite. Internal contacts between facies variations within the granodiorites (CBH to BH granodiorites) and within the granites (B to MB to BM granites) have never been located and it is presumed that these are gradational. However the sharp MB granite-BH granodiorite contact (which in places cuts out the B granite) shows that the granites were emplaced as a later magmatic pulse after the granodiorites had largely or entirely consolidated. This is consistent with the structural evidence for diapiric intrusion of the inner pulse discussed under the Millour and Airdrie Hill GCR site. The excision of the biotite granite leads to steepening of the compositional gradient in the region of the GCR site but elsewhere in the pluton even this boundary appears to be transitional, as described by Stephens and Halliday (1980).

Whole-rock geochemical variations along the traverse are best exemplified by SiO_2, which increases from about 62–72% (Figure 8.33), with very tightly bunched contours. At the same time, all other major oxides except K_2O decrease significantly, as do most trace elements except Rb which increases significantly. Most notable are the changes in isotopic ratios determined by Halliday *et al.* (1980) and Halliday (1984), with initial $^{87}Sr/^{86}Sr$ ranging from 0.7052 to 0.7073, ■Nd ranging from –0.6 to –3.1, and $\delta^{18}O$ ranging from 8.5 to 11.9‰ (all expressed as variations from outer to inner facies).

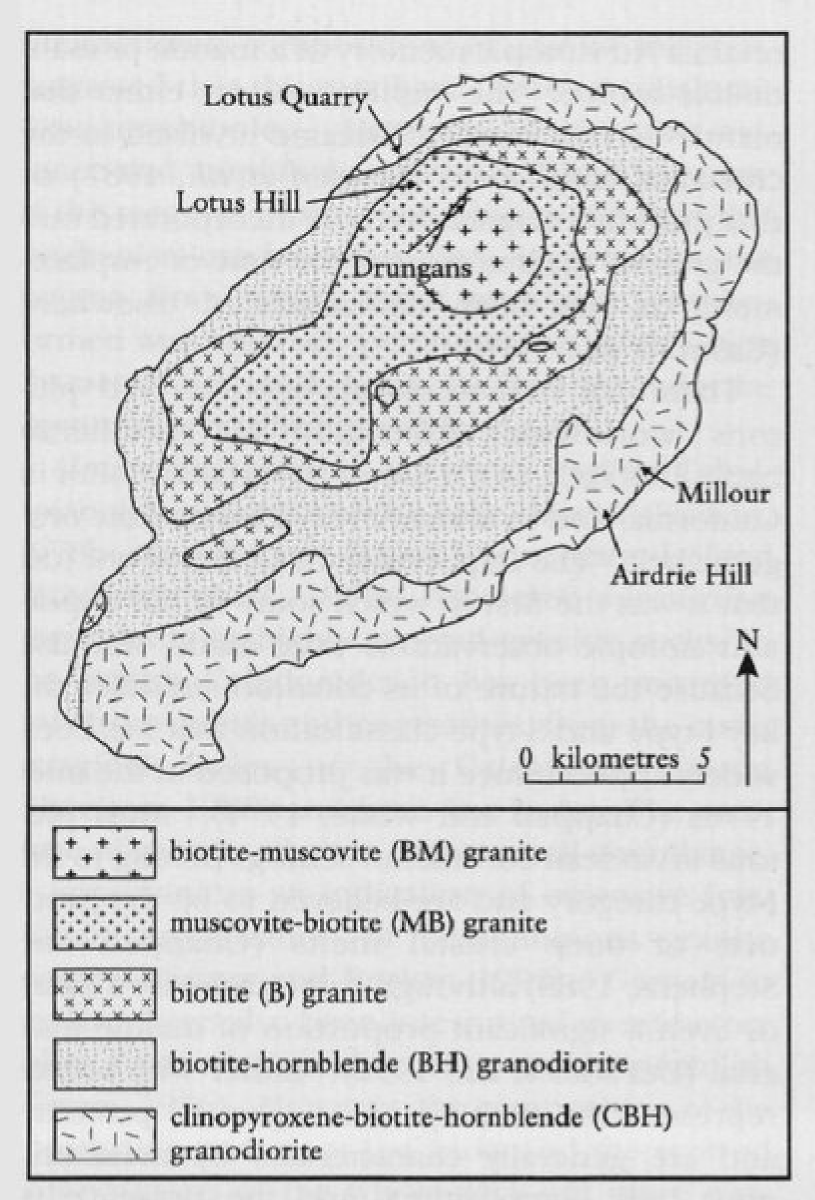
The varieties of outer granodiorite fit all the criteria for I-type granites (Chappell and White, 1974), including the presence of hornblende, metaluminous bulk compositions, and appropriate levels of the Sr, Nd and oxygen isotope ratios. The inner BM granites, however, depart from the I-type classification and have strong affinities with the S-types in most important respects, especially their peraluminous compositions and evolved isotopic compositions, including values of $\delta^{18}O$ well above 10‰. These granites are not unequivocally S-types, but nor are they I-types and are perhaps best described as transitional S-types.

The I-type to S-type zonation in a fairly regular concentric structure is unusual and its origin is not well understood. The Outer I-type granodiorites are generally similar' to I-types worldwide and have an origin dominantly in a relatively juvenile lower crust. The S-type characteristics of the most evolved inner granites can be correlated with the local Silurian greywackes, and it is likely that these have melted to provide the innermost magmas, although this must have happened at considerable depth given that there is no evidence for local melting. How these two melting events led to an organized zoned pluton is not clear; Stephens (1992) has suggested that the control was rheological, but it is possible that the inner pulse hybridized with the outer to produce the intermediate zones, although this would seem to be precluded by the fact that the outer granodiorites were largely crystallized when the granites were intruded (Courrioux, 1987).

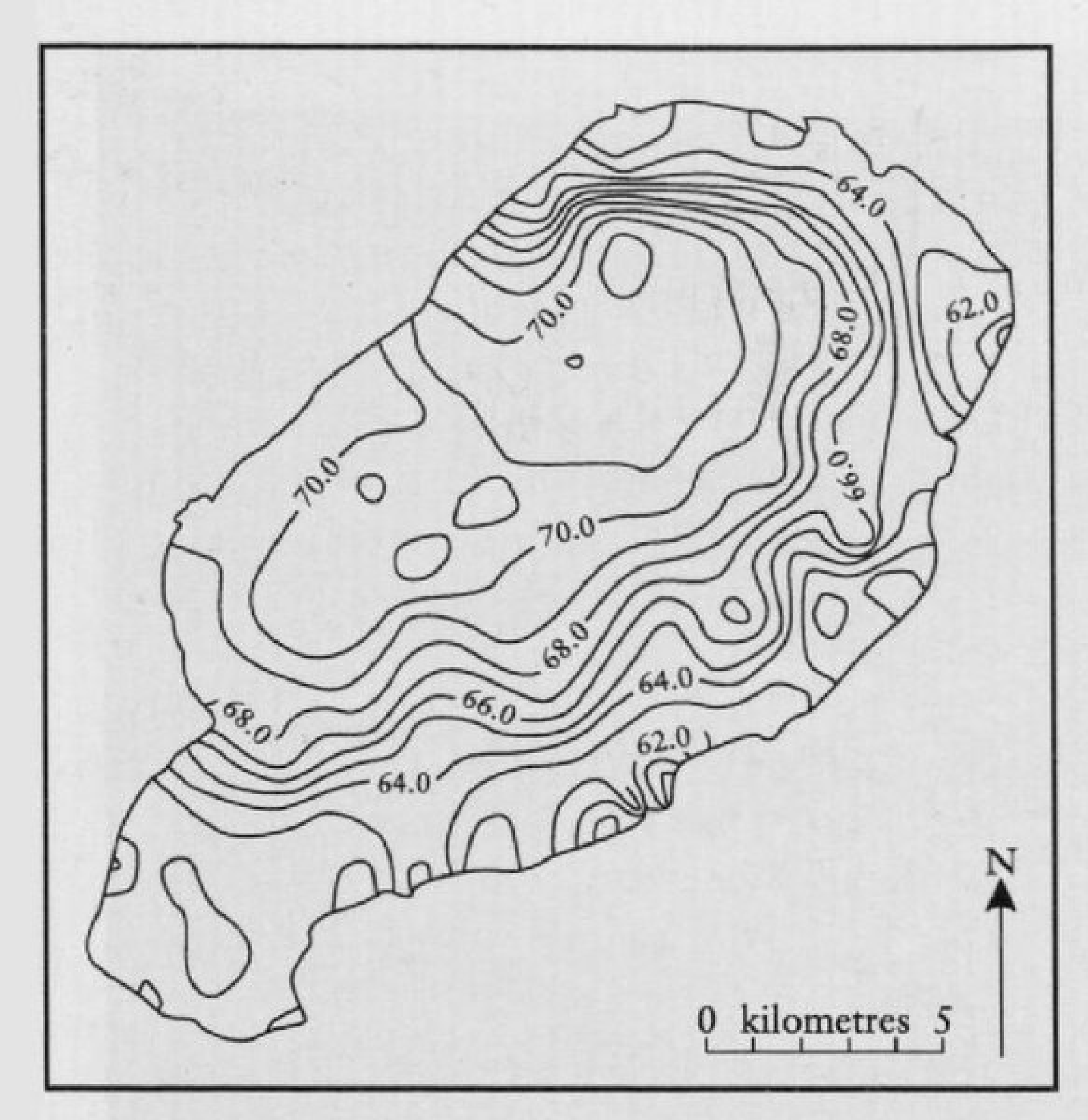
Conclusions

The notion that originally homogeneous magmas differentiate to form diverse rock types is central to igneous petrology, and the products take many forms. In granites, such differentiation often takes the form of a zoned pluton, of which the Criffel pluton represents one unusual variety (I-type to S-type) which requires multiple pulses of magma derived dominantly from different sources (protoliths). The Lotus Hill to Drungans traverse is of international importance in this context. It provides a compact summary of this type of zonation and has contributed to detailed published studies of the observed variations as well as to some of the first discussions of the likely causes of such zonation. The contrasts in isotopic ratios between the zones make it especially likely that this pluton will be important in generating and testing new models for such zonation.

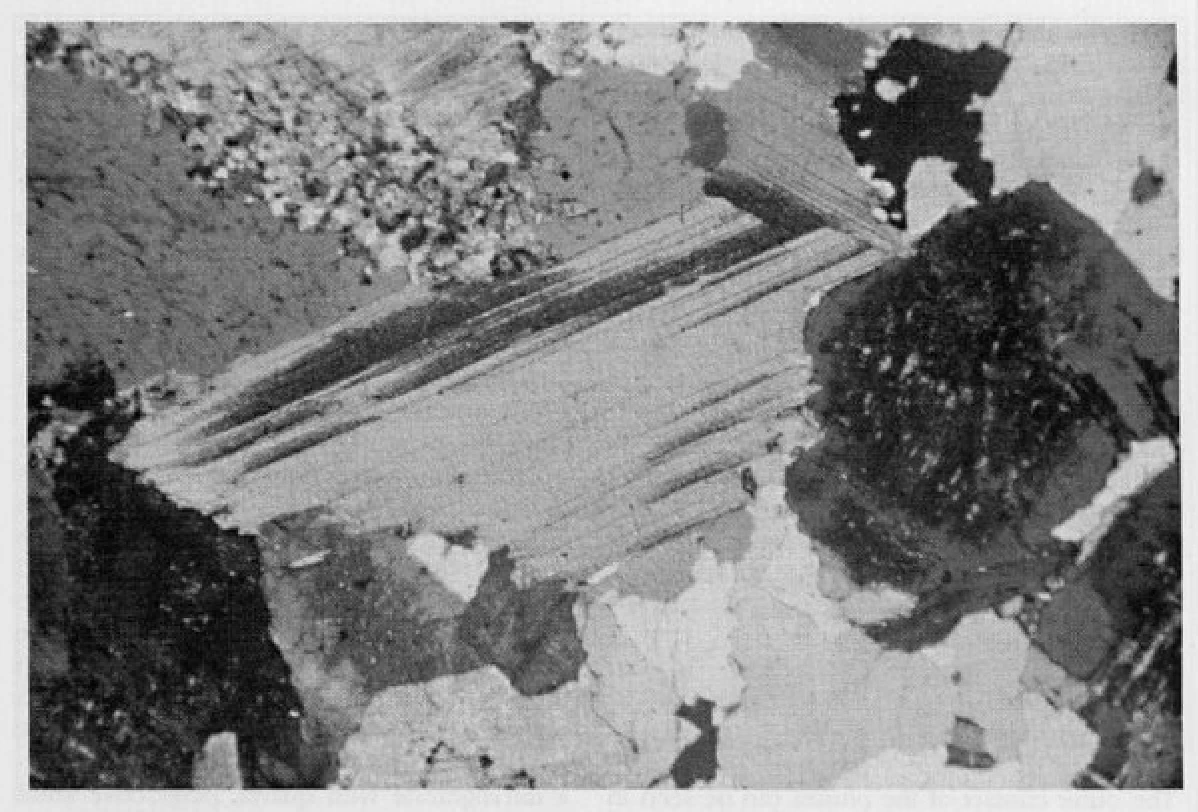
References



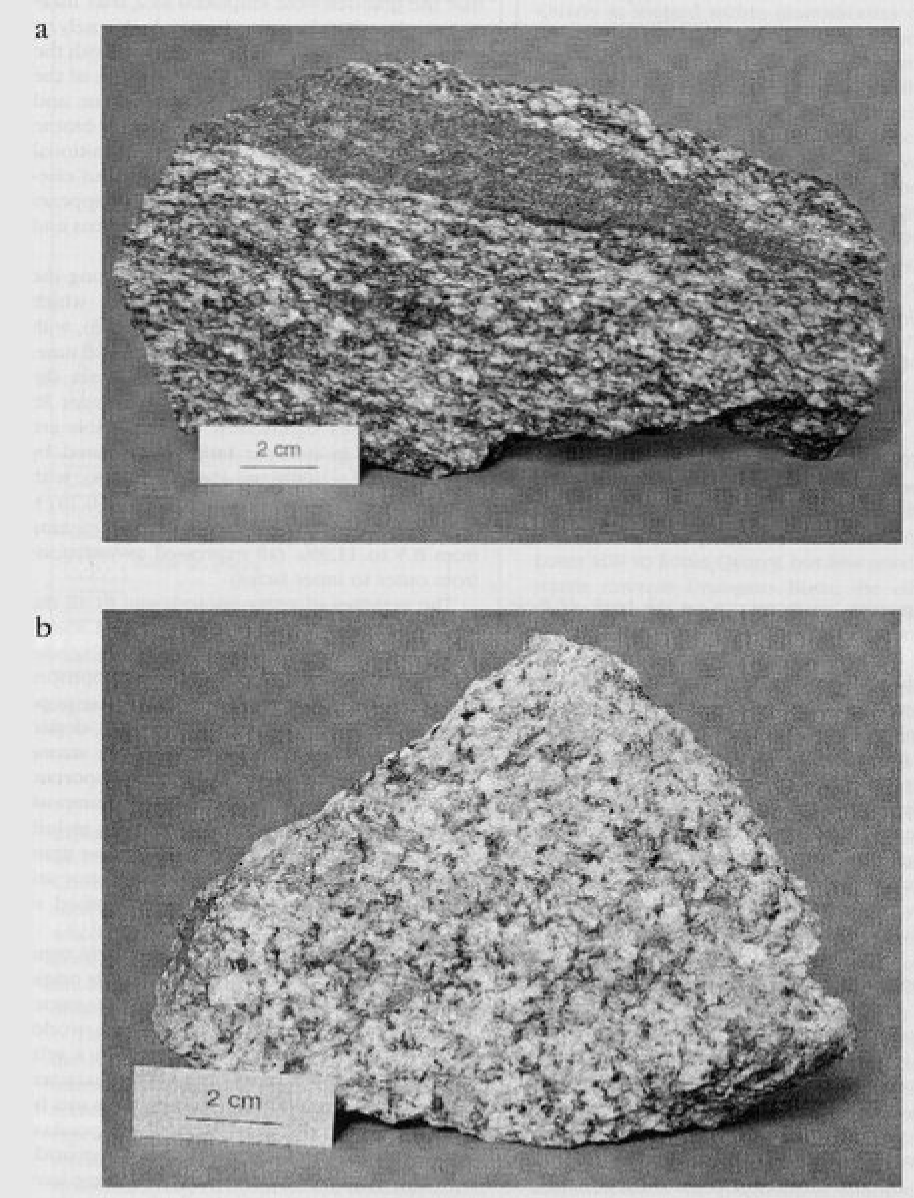
(Figure 8.32) Map showing the principal petrological facies of the Criffel pluton.



(Figure 8.33) Contour map of SiO_2 variation in the Criffel pluton.



(Figure 8.35) Photomicrograph of the biotite-muscovite granite from the Criffel pluton. (Photo: W.E. Stephens.)



(Figure 8.34) (a) Typical clinopyroxene-biotite-hornblende granodiorite, with enclave from the margin of the Criffel pluton. (b) Biotite-muscovite granite from the interior of the Criffel pluton. (Photos: W.E. Stephens.)