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MINGLING BETWEEN COEXISTING GRANITE MAGMAS WITHIN THE LAND'S END GRANITE - PRELIMINARY OBSERVATIONS

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The Land's End Granite consists of coarse-grained granite (CGG) which is feldspar-megacrystic to varying degrees. Within this are isolated bodies of fine-grained granite (FGG), also variably megacrystic. Contacts are commonly obscured, leaving the exact relationship between the two granite types uncertain. However, excellent granite-granite contacts are displayed on sea cliffs in the area around Tol-Pedn-Penwith. Fine-grained granite forms sub-rounded enclaves, ranging from the sub-metre to the 100-metre-plus scale, within the CGG. Contacts between the granites are sharp, distinct and undulose. Apophyses from the CGG intrude the FGG, producing lobate margins. Megacrysts within both granites impinge upon the contact, indicating that they were present prior to the two magmas coming together. These, and other, contact relationships indicate that the two granites were present contemporaneously as magmas.

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LOCALITY AND GEOLOGICAL SETTING

The Land's End Granite occupies the majority of the peninsula of West Penwith (Figure 1) and is the most westerly mainland exposure of the Cornubian Batholith. The granite was intruded into Devonian metasedimentary rocks of the Mylor Formation, associated with which is a series of meta-volcanic rocks (Goode and Taylor, 1988). Around the coast of West Penwith the granite is exposed in cliffs which are up to 90 m high. In many places these give generally excellent, though localised, three-dimensional exposure. Away from the coast, granite outcrop is much more sporadic.

The Cornubian granites have been classified according to their mineralogy and grain size, the criteria used in this paper being those summarised by Dangerfield and Hawkes (1981). The Land's End Granite consists of two predominant granite types, a coarse-grained facies and a fine-grained facies. The coarse-grained granite (CGG) has a groundmass with an average grain size of greater than 2.0 mm and the groundmass of the fine-grained granite (FGG) has an average grain size of less than 1.0 mm. A medium-grained variety has also been recognised.

The majority of the Land's End Granite comprises CGG, within which are a number of isolated bodies of FGG. A similar situation exists within other Cornubian granite plutons (e.g. Hawkes and Dangerfield, 1978; Dangerfield and Hawkes, 1981). The relationship between the two granites is commonly obscured in outcrop. In the Land's End granite the FGG was initially described as Intruding the CGG (Reid and Flett, 1907) and has also been described as a series of flat-lying, sheet-like enclaves within the CGG (Goode and Taylor, 1988).

Booth (1968) described the Land's End Granite as having a medium to fine-grained core which, in places, has broken through or veined a coarse-grained porphyritic envelope. However, the composite nature of the pluton was not thought attributable to the emplacement of separate intrusions, but to late stage K-metasomatism. Exley and Stone (1982) suggested that the FGG's are enriched in K_2O (relative to the CGG) and were thus unlikely to have been produced by magmatic processes. They attributed the origin of the FGG to metasomatic processes which took place either *in-situ* or prior to emplacement. However, whole-rock compositions in Booth and Exley (1987) do not indicate any significant enrichment of K_2O in FGG over CGG (5.80 wt% and 5.61 wt% respectively). Booth and Exley (1987) describe the FGG as occurring beneath the CGG, with intrusive contact relationships being exposed in places. The intrusive relationships are interpreted as being due to remobilization of parts of a fine-grained core. It is suggested (*ibid*) that the Land's End pluton originated with the emplacement of a single magma having a

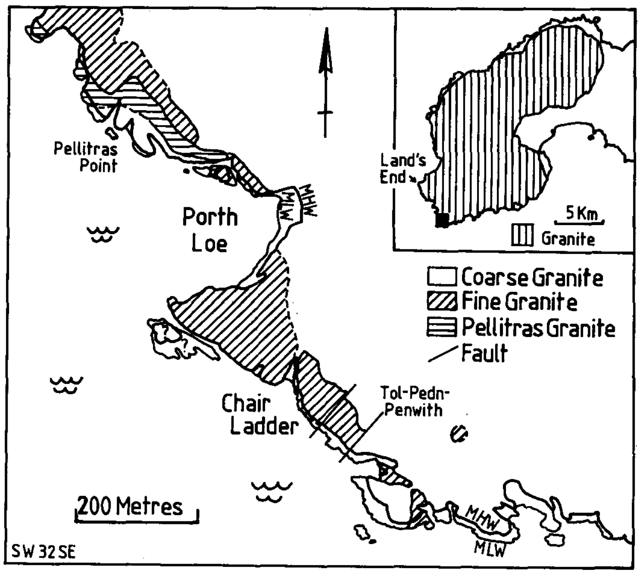

Figure 1. Geological map of the area around Tol-Pedn-Penwith.

composition approximating to the ternary minimum in the "granite" system. Subsequent metasomatic and differentiation processes produced the various granite facies now present.

Darbyshire and Shepherd (1985) concluded from isotopic and other evidence that the FGG and CGG should be considered as separate phases. More recent investigations (Chen *et al*., 1993; Clark *et al*., 1993) have produced emplacement ages for the CGG (Lamorna Quarry, SW 452 243) and FGG (Castle an Dinas, SW 487 348) of 274.5±1.4 Ma and 277.1±0.6 Ma respectively. Muscovite cooling ages are 4 to 5 m.y. younger and overlap, suggesting that the older FGG may still have been incompletely crystallized when the CGG was emplaced. Clark *et al*. (1993) suggest that there are several separate coarse-grained facies present within the Land's End pluton. Observations by the present author concur with this view and suggest that the same also applies to the FGG's. Chesley *et al*. (1993) produced emplacement ages which are in broad agreement with those cited above and went on to suggest that the FGG mass at Castle an Dinas is a roof pendant of an earlier igneous phase.

Although the difference in emplacement ages between the CGG and FGG is relatively small, it has some significance when considering the development of the Land's End pluton. The emplacement ages support the view that the pluton consists of a number of separate magmatic intrusions.

Both the CGG and FGG contain biotite and muscovite and commonly contain tabular alkali-feldspar megacrysts ranging in length up to 12 cm. The abundance of feldspar megacrysts is variable throughout both facies. The megacrysts commonly display a preferred orientation, in places aligned sub-parallel to the margins of the granite. Megacryst alignment is variable, with swirls, perturbations and local concentrations, and can often be seen to be deflected around enclaves. The patterns suggest alignment by flow and that in turn suggests that the megacrysts were present in the magma while it was still capable of ductile flow.

The status of the alkali-feldspar megacrysts in the Cornubian granites has long been a matter for debate, with interpretations often being contradictory. The megacrysts have mostly been interpreted as being metasomatic or formed by post-magmatic processes (Stone and Austin, 1961; Exley and Stone, 1964, 1982; Booth, 1968; Hawkes, 1968; Booth and Exley, 1987; Exley and Edmondson, 1993). These interpretations rest on textural and structural evidence and phenomena such as megacrysts cutting across granite-aplite contacts and megacrysts within xenoliths. Whilst it is not the purpose of this paper to enter too deeply into the megacryst debate, it should be pointed out that similar lines of evidence have elsewhere been interpreted as being due tomagmatic processes and such megacrysts interpreted as phenocrysts (e.g. Hibbard, 1981; Vernon, 1986; Clark *et al.,* 1993).

Megacryst alignment has been interpreted as being due to alkali-feldspar replacement of flow-orientated magmatic plagioclase crystals (Booth, 1968; Hawkes, 1968). This interpretation was refuted by Stone and Exley (1969) who suggested that nucleation and initial growth of alkali-feldspars occurred below the present crustal level and that the growing crystals became orientated during emplacement in a solid medium. Another interpretation, which seems to have been generally disregarded, is that the megacrysts are in fact phenocrysts which became aligned due to magmatic flow during and following emplacement. This interpretation has been placed upon aligned megacrysts in the Carnmenellis pluton by Leveridge *et al.* (1990) who agreed with Ghosh (1934) that the alkali-feldspar megacrysts are magmatic phenocrysts.

MAGMA MIXING AND MAGMA MINGLING

A magma is here defined as a mixture of liquid (melt) and crystals. Gas bubbles and xenoliths may also be present. If two or more magmas are brought together they can interact in a number of ways. Firstly they may mix to form a new "hybrid" magma. In order for mixing to occur the two magmas must have the same, or very similar, viscosities at the temperature at which the system finally equilibrates (Sparks and Marshall, 1986). A strong viscosity contrast will inhibit mixing, but can be overcome by prolonged and vigorous mechanical stirring. Stagnant magmas, even those with similar viscosities, will not mix. Some chemical exchange may still take place, by the processes of diffusion and/or fluid infiltration, leading to modification of magma compositions. Convection can be produced by density contrasts between adjacent magmas and if strong enough may promote mixing. If mixing does not take place the magmas survive as separate entities with stable interfaces between them. Lithologies produced in this way, by the coming together of two or more contemporaneous magmas, are often referred to as "mixed-rocks" or "mixed-magma complexes", but these terms are misnomers. The magmas have not mixed and the process should more correctly be referred to as "magma mingling".

Magma mingling is most commonly observed between coexisting magmas of contrasting composition, e.g diorite and granite; descriptions of mingling between granitic magmas being much less common. Relationships typical of magma mingling are now well known (e.g. Blake *et al.,* 1965; Walker and Skelhorn, 1966) and the phenomenon has been widely reported (e.g. Wiebe, 1974; Barbarin, 1988; Cook, 1988). Typical relationships include the following:

1. Fine-grained margins in basic rocks, interpreted as chilled margins.
2. Lobate, undulose or crenulate contacts.
3. Enclaves of basic rock occurring within acid rock. The enclaves are usually sub-rounded or irregularly-shaped, with crenulate, fine-grained, margins.
4. Pipes and apophyses of acid rock intruding basic rock.
5. Sinuous net-veining of basic rock by acid rock.

FIELD OBSERVATIONS

Detailed mapping has recently been carried out along a stretch of coastline c. 4.5 km south-east of Land's End, in the area around Tol-Pedn-Penwith (SW 365 216, Figure 1). Three granite types have been recognised in this area. Most of the area consists of CGG within which are a number of enclaves of FGG. Crosscutting both the CGG and FGG is an irregularly shaped sheet-like intrusion of non-megacrystic granite. Within a few metres of its top and bottom margins this granite is fine-grained with an aplitic texture. Common throughout are small interstitial or radiating dusters of tourmaline. The granite changes gradationally inwards until, in its centre, it is medium to coarse-grained with an anhedral granular texture. No enclaves of any kind have been observed within it. Metre-scale enclaves of similar granite are present elsewhere within

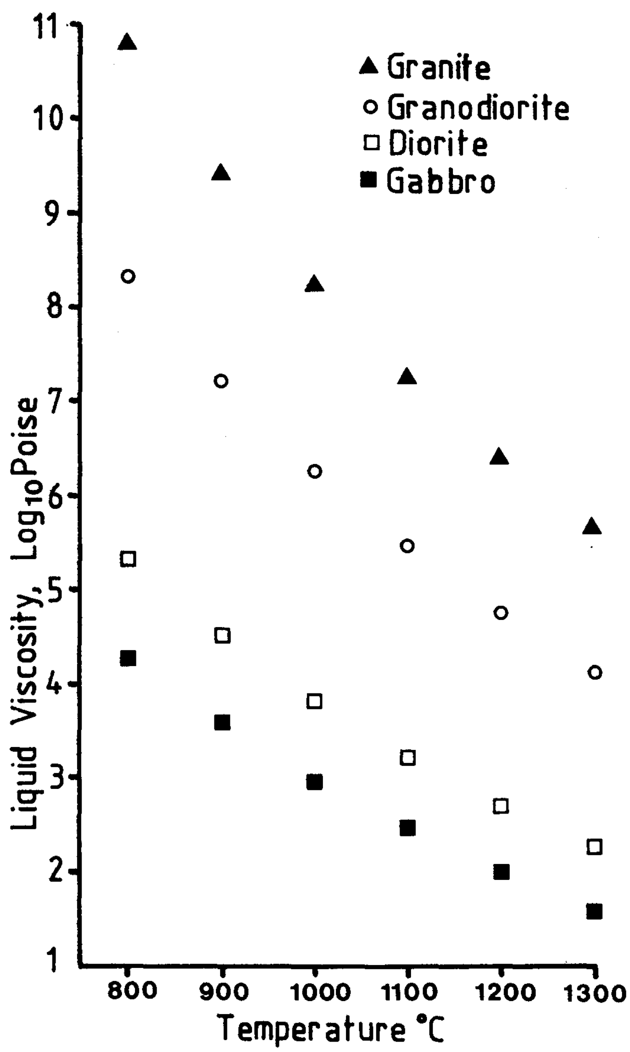

Figure 2. The effects of temperature and chemical composition on the viscosity of silicate liquids (modified from Salmon, 1992).

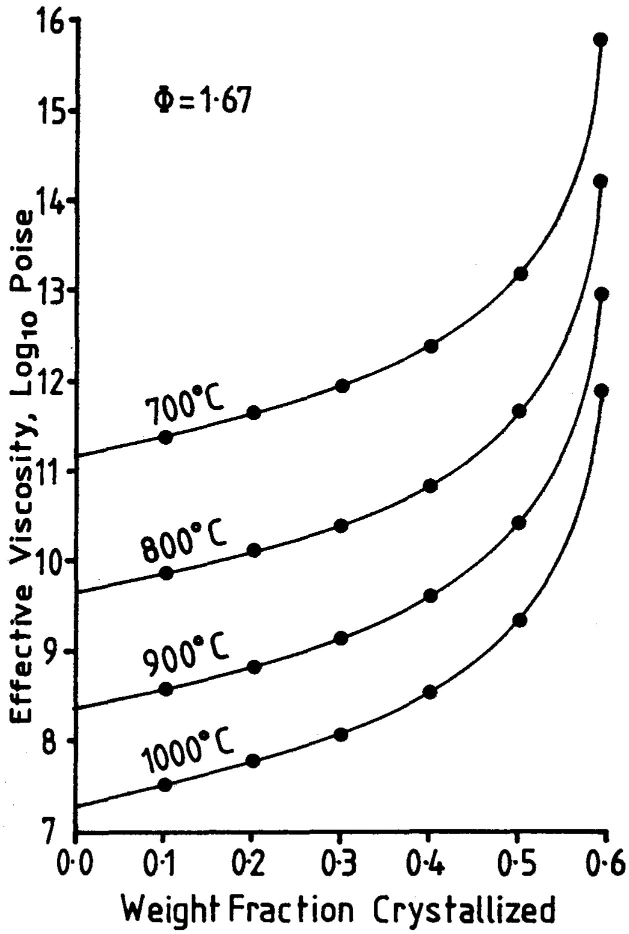

Figure 3. . Variation in the effective viscosity of magmas with temperature and weight fraction of crystallization. The composition used in calculations was that of the coarse-grained granite, given in Booth and Exley, 1987

the FGG. In the interests of clarity, and as the granite does not conform strictly to any of the subdivisions of Dangerfield and Hawkes (1981), it will be referred to as the Pellitras Granite (PELG).

The CGG contains tabular alkali-feldspar megacrysts up to 9 cm in length. The abundance of megacrysts is variable, but is normally between 15% and 20% of the whole rock. Dense concentrations of megacrysts occur in places. Megacrysts usually display a preferred orientation, the attitude of which varies throughout the rock. The groundmass is coarse-grained, locally medium-grained, with a generally anhedral granular texture.

The FGG contains a number of megacryst phases. Alkali-feldspar megacrysts have approximately the same size and distribution range as in the CGG. Close to contacts with CGG some alkali-feldspar megacrysts have a thin reddish rim. Quartz megacrysts are generally sub-rounded and up to 8 mm across. Biotite megacrysts are subhedral to euhedral and up to 4 mm across. The groundmass is slightly darker in colour than that of the CGG. Areas with medium-grained groundmass are found in a few places. The FGG in this area is distinctly different to that observed in Castle an Dinas quarry [SW 487 348].

The FGG occurs as a series of enclaves which are wholly enclosed within the CGG. The enclaves range in size from c. 10 cn in diameter to c. 300 x 50 m in area. The base of the FGG can be observed along the foot of the cliffs and on cliff faces, allowing the vertical extent of the larger enclaves to be estimated. At Chair Ladder, on the south side of Porth the cove [SW 364 219] and around Pellitras Point (Figure 1) the FGG enclaves appear to be up to 45 m deep.

Contacts between CGG and FGG are sharp and distinct with no grain size variation in either granite. Interfaces between CGG and the larger bodies of FGG are irregular and lobate on the metre or multi-metre scale. Along the top of the Chair Ladder cliffs the interface appears to be much more planar. Apophyses of CGG intrude the base of the FGG. Some of these are pipe-like, with a circular cross-section (Plate 1A). The CGG in many apophyses is densely megacrystic with some smaller apophyses being pegmatitic. In places, dense concentrations of alkali-feldspar megacrysts occur immediately below the FGG along sub-horizontal interfaces. Smaller enclaves of FGG are generally sub-rounded or rounded (Plate 1B) with undulose, and in some cases crenulate, margins. The alignment of megacrysts in the CGG is deflected around the margins of some smaller FGG enclaves.

Alkali-feldspar megacrysts within the FGG impinge upon the contact (Plate 1C). Partially covering some of these megacrysts is a thin rind of FGG groundmass. These relationships indicate that the megacrysts were present within the FGG magma when the two magmas came together. The same phenomena occur with megacrysts in the CGG, but with less frequency. The size and abundance of megacrysts is often markedly different in adjoining granite faciees (e.g. Plate 1C).

The granites contain three types of enclave (besides FGG in CGG). The first are angular meta-sedimentary rock fragments, usually less than 15 cm long. The other two types are mafic, fine-grained and equigranular with sub-rounded outlines. Some of these contain alkali-feldspar megacrysts and may also contain smaller megacrysts of quartz and biotite. No alkali-feldspar megacrysts have been observed within meta-sedimentary endaves. Elongate meta-sedimentary enclaves are commonly aligned parallel to the orientation of alkali-feldspar megacrysts in the enclosing granite. This is further evidence that the alignment was brought about by flow movements within the magma.

The upper surface of the PELG is in contact with FGG and can be seen to cut across individual alkali-feldspar megacrysts within it (Plate 1D). The surface is relatively planar in places but undulates so that it dips in a north to north-east direction at between 12° and 38°. The base of the granite is similarly undulatory and is in contact with CGG. At its south-eastern end the PELG dips away very steeply to the south-east into the CGG. The relationships suggest that, although the CGG and FGG were not solid when the Pellitras granite was intruded, they were substantially crystallized.

DISCUSSION

Contact relationships between the CGG and FGG are typical of those commonly found between coexisting magmas, indicating that the two came together as coexisting magmas. There is no field evidence to suggest that any mixing took place between them. As the compositions of the two granites are similar (Booth and Exley, 1987) the fact that no mixing appears to have taken place is somewhat unexpected. A major deterrent to magma mixing is a viscosity contrast between the magmas involved. Viscosity of a silicate liquid is controlled mainly by temperature and chemical composition (Figure 2), with the amount of SiO_2 being the most important chemical factor (Shaw, 1972). Density is also controlled by temperature and composition. In the case of coexisting magmas of contrasting composition, e.g. gabbro and granite, physical and chemical factors come into play and almost always result in magma mingling rather than mixing. In the case of two magmas of similar composition, such as two granites, there should be little or no chemical inhibition to mixing. This suggests that coexisting granite magmas should almost always mix and produce hybrids and may explain the paucity of descriptions of granite mingling in the literature. The main difficulty lies in recognising such hybrids. This is a topical area of research and debate and it is possible that many granites have such a hybrid origin.

The viscosity calculations of Shaw (1972) take no account of the presence of crystals, in other words they give *liquid* viscosities.

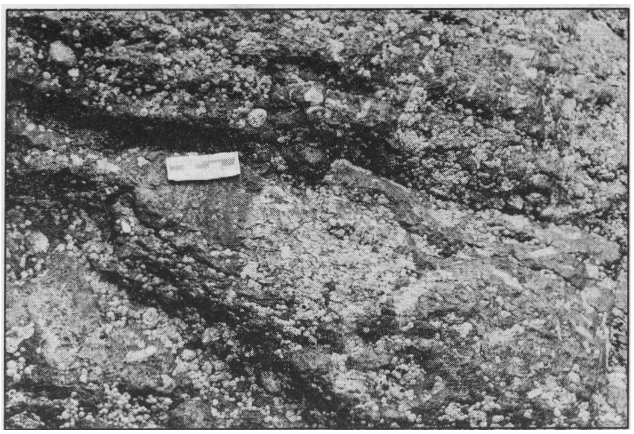

Plate 1A. Cross-section of a cylindrical apophysis of underlying coarse-grained granite intruding fine-grained granite, foot of Chair Ladder cliffs. The apophysis is c. 14 cm across.

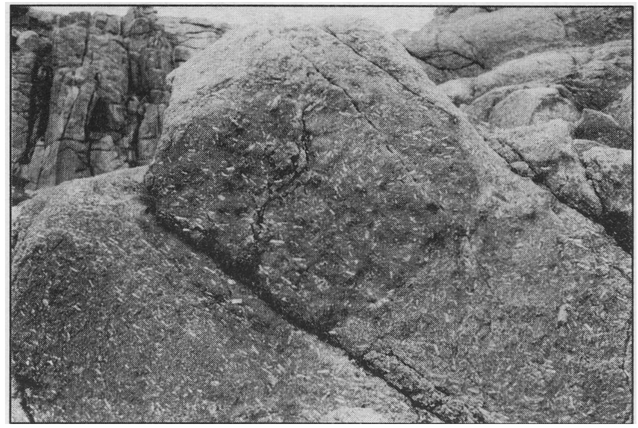

Plate 1B. Rounded enclave of fine-grained granite within coarse-grained granite, south-east of Chair Ladder. The enclave is c. 1.75 m across.

Plate 1C. Contact between fine-grained granite (above) and coarse-grained granite, south side of Porth Loe. Note that megacrysts within the fine-grained granite impinge on the contact, and that the megacrysts in the fine-grained granite are generally larger and more abundant than in the coarse-grained granite.

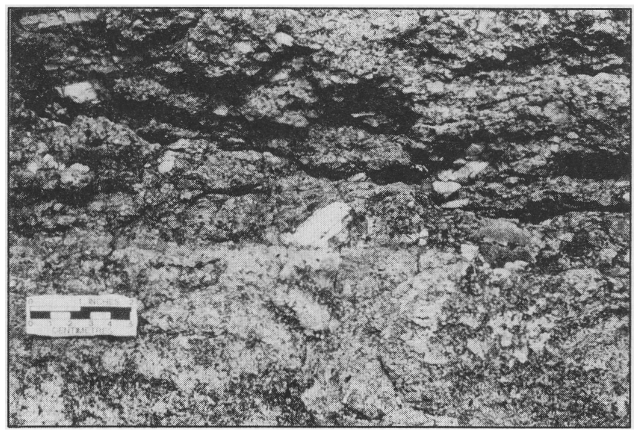

Plate 1D. Upper surface of the Pellitras granite in contact with fine-grained granite, above Pellitras Point. The Pellitras granite cuts across alkali-feldspar megacrysts in the fine-grained granite.

Calculation of the viscosity of a mixture of liquid plus crystals, the effective viscosity, can be carried out using the following formula from Roscoe (1952):

$$\eta_E = \eta_L[1 - (\Phi X)]^{-2.5}$$

where η_E is the effective viscosity, η_L is the liquid viscosity, X is the volume fraction of solid particles (or the weight fraction of crystallization) and Φ is constant for an assumed size and shape of solid particles. At any given temperature, the effective viscosity of the magma increases with the weight fraction of crystals present (Figure 3). If the solid particles are uniform spheres, Φ = 1.35, but a closer approximation to natural lavas occurs if is set to 1.67 (Marsh, 1981). With X = 0.6 and Φ = 1.67 the effective viscosity becomes infinite. In other words, at 60% crystallization the magma starts to behave as a solid and will take a shear strain (Sparks and Marshall, 1986; Wickham, 1987).

So, although the *liquid* viscosity of the two granites was very similar, their effective viscosities may have been dissimilar enough to inhibit mixing between them. If this is so, it suggests that the two granite magmas had crystallized to different degrees when they came together (it is unlikely, in any case, that a true granite *liquid* ever exists). An alternative scenario is that the effective viscosities were similar, but conditions within the magma chamber were so stagnant that the magmas simply sat quietly side by side while cooling and crystallizing. This explanation is somewhat at odds with evidence of flow within the magmas provided by megacryst and xenolith alignment. The presence of apophyses of CGG rising up into the base of the FGG suggests some density contrast between the two magmas, although local concentrations of residual liquid beneath the interface may have contributed to this. A small density contrast should be enough to bring about convection, but this may have been sluggish. Although the effective viscosities of the two magmas were similar, the fact that both were highly viscous anyway may have been enough to slow convection and inhibit mixing.

Although the magmas do not mix, the presence of residual liquid in one or both means that the magmas may still interact chemically. This can occur by diffusion, but as this process is driven primarily by compositional gradients it may not be very strong in adjacent magmas of similar composition. Chemical interaction can also occur by fluid infiltration, i.e. the physical movement of residual liquid from one magma into the other. This process does not depend on compositional gradients and has the capacity to affect larger volumes of magma than diffusion alone (Salmon, 1992). The reddish-coloured rims present on alkali-feldspar megacrysts close to contacts may be due to reaction and thus indicate some chemical exchange between the two magmas.

It is quite common to find distinct contrasts in megacryst size and abundance either side of an interface between two granites (e.g. Plate 1C). If the megacrysts had been produced by late-stage metasomatic processes, it is to be expected that these processes would have acted uniformly throughout the rock, at least on a local scale. The fact that they do not appear to have done so suggests a different origin for the megacrysts.

If the megacrysts are in fact phenocrysts, such local variations in size and abundance can be readily explained by slightly different crystallization rates in adjoining coexisting magmas.

CONCLUSIONS

The Land's End Granite consists predominantly of coarse-grained granite. Contained within this are a number of dissimilar bodies of fine-grained granite which may have different origins and relative ages. In the area around Tol-Pedn-Penwith are enclaves of fine-grained granite. These have contact relationships with the enclosing coarse-grained granite which indicate that the two came together as coexisting magmas during formation of the pluton. The FGG may have been present as a discrete magma before being taken up by the CGG immediately prior to emplacement. Alternatively, the FGG may have been intruded into the CGG magma. Either way the presence of alkali-feldspar megacrysts impinging on the contact indicates that the megacrysts were present when the magmas came together. This and other evidence appears to be contrary to earlier interpretations that the megacrysts were formed by late-stage, post-magmatic processes, and suggests that the megacrysts are in fact phenocrysts.

The survival of the two granites as discrete, contemporaneously magmatic entities appears to be an unusual occurrence. It may have been due to a difference in effective viscosity caused by variations in the proportion of crystal phases present in the two magmas, the presence of megacrysts/phenocrysts being a contributory factor. Alternatively the high viscosity of the two magmas may have been sufficient to inhibit mixing between the two magmas in the absence of any strong convective stirring.

There is some evidence of compositional modification close to contacts between CGG and FGG resulting in reaction rims on megacrysts. This may have been brought about by infiltration or exchange of residual liquids. The effects of such chemical exchanges are currently being investigated.

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