

COLUMNAR, BRANCHING AND CURVED FELDSPAR GROWTH IN THE ST MICHAEL'S MOUNT GRANITE, CORNWALL.

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The St Michael's Mount Granite is well-known for its spectacular Sn-W mineralisation and greisenisation. The primary textural and mineralogical variations in the granite are less well-known. A marginal biotite granite is succeeded by a tourmaline muscovite granite and a central porphyritic granite. A banded granite zone with comb-layering, occurs near the outer edge of the tourmaline muscovite granite. The banding is interpreted as a frozen-in record of sinuous, advancing fronts of *in-situ* crystallisation in a solidifying magma with branching K-feldspars growing in towards the magma. The position of the banded zone in the stock is related to the temperature gradient and corresponding undercooling. Local kinetic controls were important in the processes involved in the formation of banding and grain-size variations. Columnar and branching K-feldspars grew far from equilibrium but once established acted as 'seed' crystals for continued rapid growth.

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INTRODUCTION

St Michael's Mount lies approximately 4 km east of Penzance and 1 km south of Marazion [SW 515 298]. It is managed by the National Trust and the collection of rock samples is prohibited. The locality is well known for its granite hosted tin-tungsten mineral veins with greisenised granite borders (e.g. Dominy *et al.*, 1995). However the textural variations of the granites that predate the greisenisation are less well documented.

The northern part of the island (Figure 1) is made up of marine pelites and semi-pelites of the Devonian Mylor Slates Formation, regionally metamorphosed to lower greenschist facies during the Variscan Orogeny. In the south-west of the island these have been intruded by a small granite stock with the formation of andalusite and biotite in a narrow contact metamorphic aureole. The marginal parts of the intrusion contain areas of biotite granite and these pass into tourmaline muscovite granite which forms the major part of the intrusion. A zone of banded granite is sometimes present close to the outer edge of the tourmaline muscovite granite. Hosking (1953) notes this curious granite variant characterised by crudely orientated "fleur-de-lys" feldspar aggregates on the southern foreshore of the Mount but did not comment further on its possible origin, although in 1954 he proposed that this type of pegmatite was formed before the final solidification of the granite. Halls (1987) uses the St Michael's Mount Granite as one example of crystallisation textures at internal contacts that mark sub-stages in the magmatic evolution of composite plutons but does not give any specific field descriptions. This paper describes some of the main features of the banded zone and suggests that the banding represents a frozen-in record of advancing *in-situ* crystallisation fronts in a solidifying magma. The variations in mineralogy and grain size may be explained largely in terms of kinetic controls on the crystallisation of an undercooled peraluminous silicic magma.

THE ST MICHAEL'S MOUNT GRANITE

The narrow contact aureole and low-grade thermal metamorphism indicate a small, high level intrusion. If the exposed contact is part of a regular circular intrusion then the total surface area of the stock would be only 0.1 km². Granite-country rock contacts are sharp and straight with dykes penetrating out from the granite. Dykes at the eastern contact (too small to be shown on Figure 1) trend east-west and have irregular sinuous contacts. The presence of angular xenoliths of hornfels in the dykes suggests stoping as the method of emplacement. The north-west contact dips nearly vertically northwards. Here dyke

emplacement was mostly by joint dilation, resulting in several northward-tapering near-vertical dykes striking 140° (Figures 1 and 3).

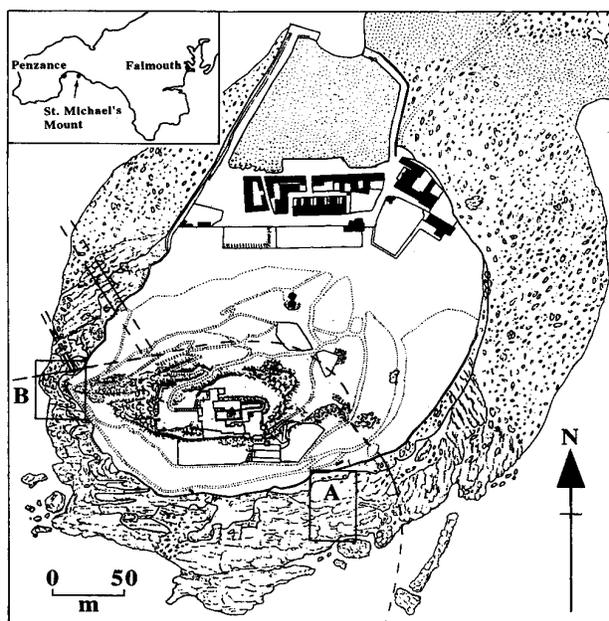


Figure 1. Map of St Michael's Mount.

Granite occurs south-west of contact shown by solid and broken (inferred) line. Granite dykes above B also shown by dashed lines. A: Area of Figure 2. B: Area of Figure 3.

Detailed study of selected peripheral parts of the St Michael's Mount intrusion has revealed variations in both texture and mineralogy within the granite. Although there is nearly 100% rock exposure on the foreshore, boulders, barnacles, algae and lichen often obscure textural detail and this together with the limited amount of exposure inland makes a comprehensive study of the intrusion difficult.

The biotite granite is a medium- (1-5mm) to coarse-grained (>5mm) leucocratic rock which weathers to a light orange colour. It is without obvious megacrysts and contains prominent biotite clusters up

to 3mm in size. The biotite granite is only found in marginal areas of the stock. However it does not form a continuous zone next to the contact but occurs as patches which merge into the tourmaline muscovite granite. On the north-west foreshore the relationships between the two phases may be observed in boulders. Veins of tourmaline muscovite granite cut across the biotite granite. The tourmaline muscovite granite forms the main part of the exposed intrusion, except for a small central area of granite porphyry, 20 m in diameter near the steps on the south-west foreshore.

The tourmaline muscovite granite is a leucocratic, grey-white weathering rock. It exhibits a wide range in grain size and also in the proportions of feldspar megacrysts. The presence of tourmaline and muscovite may be observed at outcrop together with variable amounts of K-feldspar, plagioclase and quartz. Petrographic descriptions (Davison, 1920; Hosking, 1953; Moore, 1977) indicate that the plagioclase is albite and that accessory minerals include biotite, topaz and apatite. Moore (1977) gives nine chemical analyses of unaltered St Michael's Mount Granite but with no indication of the granite types analysed. It may be concluded from these analyses that the bulk composition is that of a peraluminous silicic granite with significant concentrations of boron, fluorine, phosphorus and lithium.

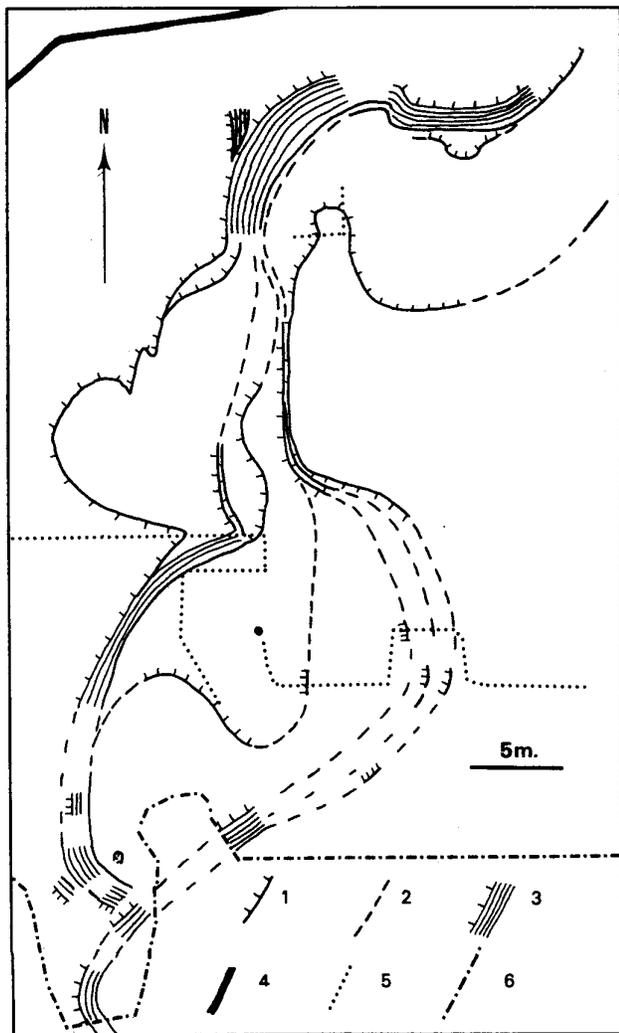


Figure 2. Map of part of south-east foreshore (area A on Figure 1). Greisens and veins have been omitted for clarity. Key: 1: One or two parallel bands with K-feldspars at high angles to bands. Ticks denote direction of branching. 2: Inferred trace of bands (partly obscured). 3: More than two parallel bands with K-feldspars branching in direction of ticks. 4: Sea wall. 5: 2 m vertical rock step. 6: Springs low-tide mark.

The granite has four joint sets, one horizontal and three vertical which trend at about 160°, 050° and 070°. Greisen bordered mineral veins occur within the last two sets. The mineralogy of the veins and greisen borders has been described (Davison, 1920; Hosking, 1953 and Moore, 1977). Moore (1977) estimates that the greisens contain over 13% modal topaz.

THE BANDED GRANITE ZONE

The banded granite zone occurs within the tourmaline muscovite granite near its outer edge. The indications are that it forms an arcuate zone broadly related to the shape of the contact of the granite stock. The zone is variable in detail and contrasting features may be observed in two main areas of the foreshore (A and B on Figure 1) near to the south-east and north-west contacts.

The South-East area, A. (Figure 2).

Banding is continuous over an exposed distance of at least 50 m in a zone up to 25 m wide. Greisen veins cut across the banding, often at a high angle, up to 90°. Sometimes relict features of the banding may be observed where the granite has been greisenised. Therefore the banding was formed before the greisenisation occurred. The banding is composed of regular and irregular differences in grain size and mineral proportions. Bands range from less than 5 mm to 100 mm in width and are often sub-vertical. Boundaries between bands may be sharp or gradational. On the large scale the bands are broadly parallel to the contact of the granite stock but in detail they are sinuous and form embayments. Bands appear to intersect and bifurcate. The number of bands developed varies along strike.

Some bands, particularly those less than 10 mm in width, may be almost monomineralic and consist mainly of millimetre-scale quartz or of K-feldspar. Individual crystals appear to have grown from a bounding surface of the band and quartz especially may have a dendritic habit. Other bands are relatively enriched in fine-grained (<1 mm) tourmaline needles. Textures vary from uniformly fine-grained within a single band to medium- or coarse-grained and porphyritic within other bands. Coarser-grained bands often have fine-grained patches irregularly distributed within them. Individual millimetre-scale bands can be traced for no more than several metres.

A prominent feature of the banding is the occurrence of large, elongate curving K-feldspars at a high angle to the banding. The size of the K-feldspar crystals is variable and their spacing varies from isolated to dense (Figures 6 and 7). A high proportion appear to originate at bounding surfaces between bands and may persist through one or more bands. The crystals flare, that is increase in width, along their length and may show small angle branching. The crystals at a given location, where seen on horizontal sections, all flare and branch in the same general direction approximately towards the assumed centre of the granite stock. Around the sides of the embayments traced out by the banding there are marked deviations from this direction and here the crystals branch towards the centre of the embayments. The constant feature is that the K-feldspars are always at a high angle to the banding.

Figure 7 shows well defined small scale banding with a sparser development of large K-feldspars at a high angle to the banding. Although it appears that there are millimetre scale K-feldspars forming almost monomineralic bands there are comparatively few larger crystals. The few large crystal structures are disproportionately elongate. The small scale banding shows undulations and disruptions at the points where these crystals intersect the banding.

The north-west area B (Figure 3).

In this area banding and branching K-feldspars are only sporadically developed but some of the occurrences are particularly impressive. Branching feldspars occur in biotite granite adjacent to the contact. This is the only locality where they have been found not immediately associated with the tourmaline muscovite granite.

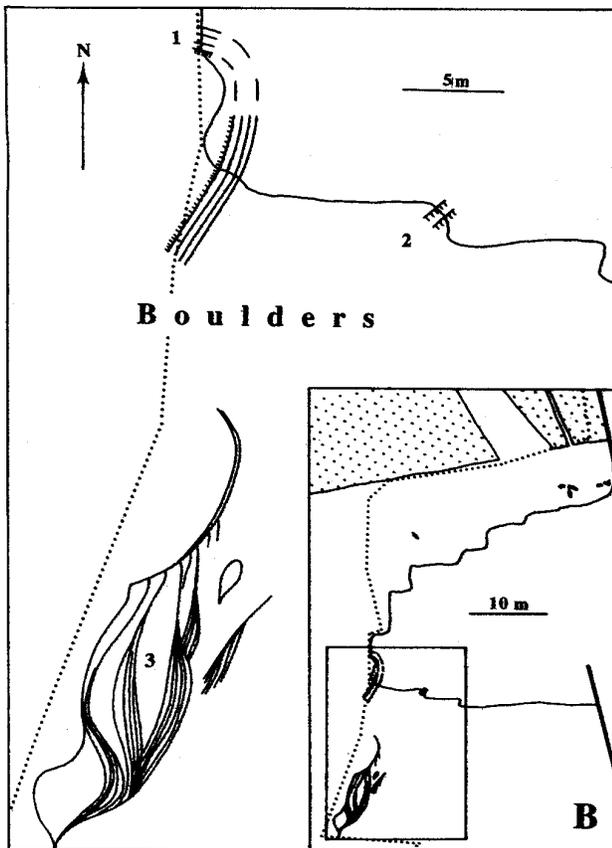


Figure 3 Map of north-west contact area (Area B on Figure 1). Inset whole of B; Main diagram part of B enlarged as indicated in inset.

Stipple: metasedimentary rocks. Blank: granite. Lines at 1, 2 and 3 indicate nature of fine-scale banding in granite. Direction of K-feldspar branching shown by ticks. Dotted line: High-tide mark.

They are impersistent and have a variety of growth directions. Farther south, (locality 1, Figure 3) on a 3 m high cliff face facing to the west, banding is present on a number of scales and with differing textures. Large feldspars occur in the finer-grained bands and flare and branch to the south-west. These structures, individually up to 100 mm in length, curve gently upwards and several together form regular trains, 0.5 m long and oblique to the banding (Figure 8). Several examples (Figure 4) have high-angle dendritic branches. 5 m farther south, feldspars branch to the north-west. The banding forms an arc concave to the west but may only be traced over a distance of about 10 m. Banding and south-eastward branching feldspars occur in the cliff at locality 2. In three dimensions, the upward curving feldspars have a form rather like a hand, palm-upwards, with outstretched curving fingers. On horizontal surfaces many of the K-feldspar crystals have an almost square cross-section where the "forgers" have been cut through.

At locality 3, (Figure 3), intricate banding of a different nature may be observed in the granite. This banding forms a series of intersecting elliptical arcs on both horizontal and vertical rock faces over an area of 20 m². Bands are often only a few millimetres thick and appear dark. The banding is simply a reflection of regular variations in grain size of the granite. Sometimes millimetre scale monomineralic bands of either orientated feldspar or quartz have grown from the bounding surfaces of the dark bands. This crystal growth is on the concave side of the arcs.

ORIGIN OF THE BANDED GRANITE ZONE

Moore and Lockwood (1973) introduced the term comb-layering to describe banded igneous rocks with elongate large crystals that

have grown at a high angle to the banding. These textures are found in a wide variety of igneous rock compositions including ultrabasic (Donaldson, 1977), diorites and granodiorites (Moore and Lockwood, 1973), alkaline cumulates (Petersen, 1985), and silicic granites (Carten *et al.*, 1988). The balance of opinion is that they are the result of magmatic crystallisation processes although some authors require a coexisting fluid phase. None of the authors make any reference to the possibility that all the associated textures together could have been formed from post-solidification metasomatic activity and, therefore, presumably considered it too unlikely to merit discussion.

Shannon *et al.* (1982) interpret the banding as a series of time-markers recording the migration of crystallisation fronts. Banding is broadly parallel to contacts of intrusions and branching crystals grow *in-situ* from substrates at the solidification fronts and branch inwards towards the magma. Following this model, the comb-layering of the south-eastern area of the St Michael's Mount Granite can be interpreted as a series of crystallisation fronts that generally moved inward from the walls of the intrusion (Figure 2). However from the traces of the banding, it is apparent that different parts must have moved inwards at different rates, and as a result, a series of embayments were formed and subsequently infilled. Figure 4 is a reconstruction based on the form of the fronts at a particular instant. If this explanation is accepted, then the banded granite, at least, crystallised inwards and it is worth emphasising that at the present level of exposure it was far from being the final part of the stock to solidify.

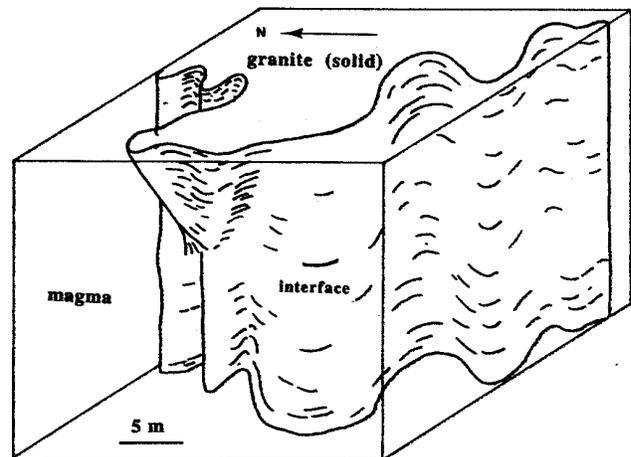


Figure 4. Snapshot of the form (highlighted by dashed lines) of a solidification front for the south-east area, reconstructed from the map of the banding (Figure 2).

DEVELOPMENT OF TEXTURES IN THE BANDED GRANITE ZONE.

Study of textures in igneous rocks can reveal information about the processes and their controls that may have operated during crystallisation. It is becoming increasingly apparent that crystallisation of magmas is often largely a kinetic problem concerning the apparent stability of phases in the system (Swanson, 1977; Kirkpatrick, 1981; London, 1992). Many of the features of the banded granite zone are indicative of the importance of kinetic controls on their crystallisation.

Undercooling, grain nucleation and growth rates

Undercooling may be defined as the difference between the liquidus temperature and the actual temperature of a magma. The liquidus for the bulk composition of the magma is unlikely to be the same as the liquidus that applies locally where crystallisation is taking place (Kirkpatrick, 1981). Figure 5 shows a schematic relationship between a local liquidus temperature, (T_{liquidus}), and actual temperature, (T_{actual}), at a magma-solid interface.

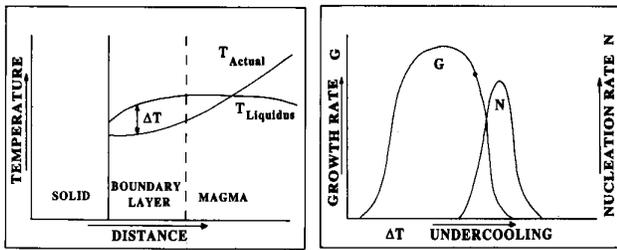


Figure 5. Simplistic representations of (left) undercooling as difference between liquidus temperature and actual temperature at a solid-liquid boundary layer, and (right) relationship between growth rate, nucleation rate and undercooling. Based on Kirkpatrick, 1981.

Undercooling is a measure of difference and changes in it may be achieved by changes in either T_{actual} or $T_{liquidus}$, or both. For example, changes in $T_{liquidus}$ at constant magma temperature may result from changes in the composition of the liquid of the boundary layer caused by build up of rejected components from the solid being unable to diffuse rapidly away from the interface. Changes in cooling rate could cause changes in T_{actual} . Rates of nucleation and of grain growth vary, (Figure 5), with the degree of undercooling (Fenn, 1977).

Magma composition, level of intrusion and rate of cooling

The bulk composition of the St Michael's Mount Granite magma is fairly close to that of a minimum melt (Moore, 1977). Consequently relatively small local changes in composition caused by partial crystallisation and low rates of diffusion in the highly silicic magma might alter the stable liquidus phases. The magma contains high concentrations of boron and fluorine which together with an uncertain water content would lower the bulk liquidus temperature and so permit intrusion to higher levels in the crust before solidification. The lower temperatures would have the general effect of lowering diffusion rates. Rates of cooling, however, and hence undercooling

might be greater than in granites with lower volatile contents. The location of the banded zone in the stock is almost certainly related to the general influence of temperature gradient and corresponding rate of undercooling. As the magma continued to crystallise inwards, these critical general conditions together with the magma composition, must have changed and the more "normal" textures of the tourmaline muscovite granite replaced those of the banded zone.

Fine-grained textures

Fine-grained granitic textures may be formed at relatively high degrees of undercooling. That is with a high nucleation rate for the crystallising phases but a low growth rate (Figure 5). The alternations of fine-grained banding in comb-layering have been explained in terms of pulses of fluid exsolution from magmas (e.g. Halls, 1987). However it is not clear whether the St Michael's Mount magma was fluid-saturated when the banded granite solidified. Manning (1985) states that the south-west England granite magmas were not generally water-saturated and only became saturated at the very final stages of crystallisation. As has already been pointed out, the banded granite zone was not the final part of the St Michael's Mount stock to crystallise and it may not have reached fluid saturation. A further problem is that the fine-grained textures, besides occurring repetitively in bands of finite length, also occur as patches of the order of 10 mm in diameter within coarser-grained textures. Very localised causes of the undercooling would be required to account for these features.

Monomineralic banding

Millimetre scale monomineralic bands of quartz and of K-feldspar have nucleated on the bounding surfaces of bands. Nucleation on a surface is easier than completely within a liquid. Local liquidus conditions must have changed, probably as the result of diffusional difficulties resulting in constitutional undercooling (Kirkpatrick, 1981) where a boundary layer of rejected components builds up and as a result the liquidus temperature is lowered. Dendritic quartz growth on surfaces is described by Swanson and Fenn (1986).



Figure 6. K-feldspar comb-layering on near-horizontal section, (pencil about 150 mms) southeast foreshore, (Area A), near sea wall. Crystals nucleate from a point, often a bounding surface, and all flare and branch in the same general direction

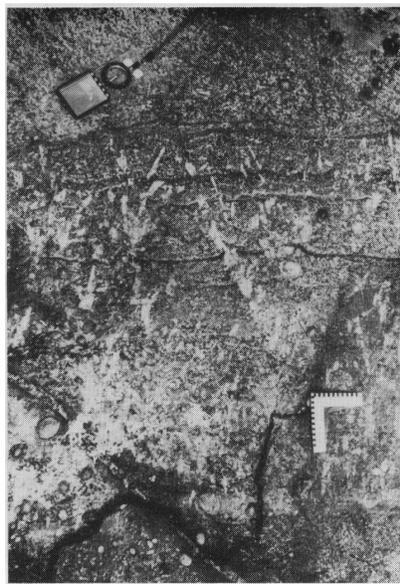


Figure 7. Banding and K-feldspar growth, horizontal section, (scale marked every 5 mm), south-east foreshore (Area A). Once established K-feldspar persists through several bands. Note the association of irregularities in the banding with presence of K-feldspars.

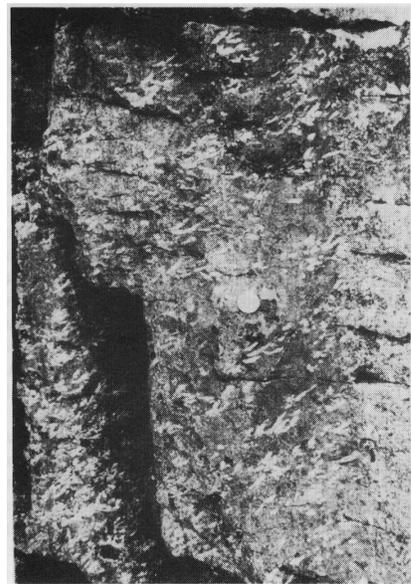


Figure 8. Vertical banding and trains of feldspar growths with variations in scale and texture, (coin 25 mm in diameter; locality 1, Figure 3)

Growth of large branching K-feldspars

A number of features indicate that normal nucleation of K-feldspar was often difficult. The monomineralic bands are seen to have required a substrate for nucleation. Those crystals in the monomineralic bands with the most favourable orientation for growth grew more rapidly than their neighbours. Once they protruded from the boundary layer into the magma the undercooling was greater (Figure 5) and they continued to grow. From their size, growth rates must have been high and almost self-perpetuating once the crystals outgrew the boundary layer. Thus moderate undercoolings must have been likely for the crystallisation of K-feldspars and this together with low rates of nucleation led to high growth rates and the development of branching forms (Fenn, 1977; Lofgren and Donaldson, 1975). Where K-feldspars protruded into the magma they could act as seed-crystals and continue to grow metastably forming the columnar crystals that cause irregularities in the thin mineral bands through which they persisted (Figure 7).

The flare of the K-feldspar crystals may be interpreted in terms of changing relative growth rates on different faces. This could be the result of changes in the mechanism of growth as undercooling changes (London, 1992). The curvature of the crystals has been interpreted as deflecting in a moving magma (e.g. Moore and Lockwood, 1973), but Lofgren and Donaldson (1975) reported that curved crystals may be grown under static conditions in experimental charges.

CONCLUSIONS

New observations at St Michael's Mount have revealed the presence of a banded granite zone. Using the evidence of branching crystal growth in comb-layers, the banded granite zone is interpreted as a series of frozen-in crystallisation fronts which reveal the variations in rate of solidification and development of embayments between solid and magma. Compositional banding, grain size variations and growth of large columnar and branching K-feldspars was controlled by differing rates of undercooling which depended on the general temperature gradient and rate of cooling but particularly on local variations in composition and rates of diffusion. There is no clear evidence that the magma was water-saturated or that the controls necessarily included the release of exsolved fluid.

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