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THE INFLUENCE OF FLUID PRESSURE IN GOVERNING FRACTURE GEOMETRY AND MINERAL TEXTURES IN THE PNEUMATOLYTIC LODE SYSTEMS OF SOUTH WEST ENGLAND

C. HALLS, J. W. COSGROVE AND G. S. CAMM

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Cliffs, foreshore and opencast mining operations in south west England provide outstanding exposures of mineral lodes formed during the pneumatolytic stage of hydrothermal evolution in systems originating from the Cornubian granite plutons. The pneumatolytic stage is here defined as the adiabatically regulated transition from the magmatic to hydrothermal states occurring at and immediately below the granite solidus. Variations in the fracture geometry and textures of minerals filling these lode systems are explained in terms of the relationship between the pressure of the fluid in the hydrothermal reservoir and the magnitude of the differential stress under which the rocks are confined. At the early stages of hydrothermal evolution, diffusion of transitional fluids from the surrounding, near-solidus granite into swarms of autogenously generated hydraulic fractures took place under conditions of near-equilibrium saturation for gangue and ore minerals. This contrasts with the later stages of transitional hydrothermal mineralization in composite fault lodes where fault movements were accompanied by adiabatic decrements in pressure and advective transfer of mineralizing fluids as fluid pressures generated in boron rich residual reservoirs within the granite were tapped. Mineralization in this case took place under far from equilibrium conditions.

C. Halls, and J. W. Cosgrove Department of Earth Sciences (THHS), Royal School of Mines, Imperial College of Science Technology and Medicine, London, United Kingdom
G. S. Camm Camborne School of Mines, University of Exeter, Redruth, Cornwall, United Kingdom

INTRODUCTION

Swarms of parallel lodes containing an assemblage of quartz-feldspar-wolframite-cassiterite-muscovite together With variable amounts of loellingite, copper-tin sulphides and molybdenite, with or without topaz, fluorite, apatite and/or accessory tourmaline and with well-defined selvedges of alteration are recognised to be one of the characteristic expressions of the pneumatolytic stage of mineralization in peraluminous, S-type granites. Observations of well-exposed systems in SW England are used to place constraints on the conditions under which the fractures formed and the minerals were deposited

The geometrical regularity and exemplary mineralogy of such greisen-bordered quartz vein systems have attracted the attention of investigators of hydrothermal mineralization in granites since the earliest scientific descriptions were made (e.g. Charpentier, 1778). The characteristic mineral assemblage by which greisen is defined consists of quartz and muscovite (Flett, 1909) formed as a result of pervasive hydrolytic alteration of granite at temperatures between the granite solidus and about 280°C. In fact, the mineral parageneses of veins and altered envelopes in pneumatolytic fracture systems show considerable variation depending on the relative abundance of the elements K, Na, Li, B, F, P and Be in the transitional fluids emanating from the granites concerned. In many cases, swarms of veins can form under conditions spanning the fields of feldspar stability and of greisen alteration (Farmer and Halls, 1993). In SW England, the transitional fluids are not specifically enriched in Be, but there are boron-rich and lithium-fluorine-rich generations of magmato-hydrothermal fluids which produce characteristic tourmaline-rich and topaz-zinnwaldite-fluorite-rich vein mineralogies and alteration envelopes. Investigations of the field relations, mineralogy and petrochemistry of the St Austell pluton (Allman Ward *et al.,* 1982; Manning *et al.,* 1996) have shown that these mineralogically specialised pneumatolytic veins and their alteration envelopes originate from the discrete, chemically specialized intrusive sub-stages of which the pluton is composed. Vein formation and alteration typically take place under physicochemical conditions outside the field of feldspar stability and the replacement of plagioclase, and subsequently K-feldspar, by mica-quartz, tourmaline-quartz or topaz-quartz assemblages is characteristic. The precise conditions governing the formation of boron-rich and fluorine-rich assemblages and the stoichiometry of the metasomatic reactions involved remain to be re-solved, but the geometry of the fracture systems and the textures of mineral growth provide definite constraints on the mechanisms governing the formation of these types of lode systems. The aim of this paper is to present a mechanically constrained model congruent with the fracture geometries and mineral textures observed in the field. For this purpose a model can be defined as ***a representation of a real system, simplified to essentials, which preserves well enough the fundamental relationships of its parts to allow predictions of the way it behaves.***

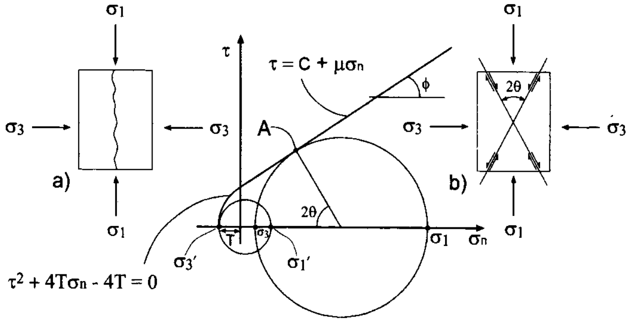

Figure 1. *The graphical expression of the brittle failure envelope combining the Griffith and Navier-Coulomb criteria. The Mohr circles show stress states that would cause a) extensional failure and b) shear failure.*

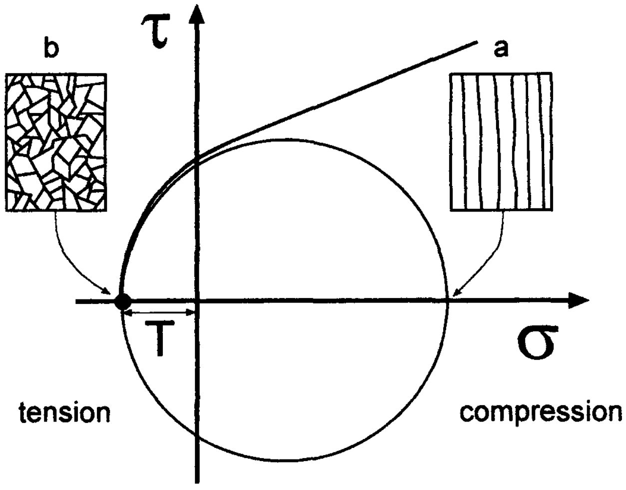

Figure 2. Two Mohr circles representing stress states that would give rise to extensional failure. Stress state 'a' has a relatively large differential stress (approximately 47) and therefore generates extensional fractures which are parallel and which form normal to the least principal stress S_3. The stress represented by Mohr circle 'b' is hydrostatic. The circle therefore is reduced to a point i.e. differential stress is zero, and there is no preferred orientation of the resulting fractures.

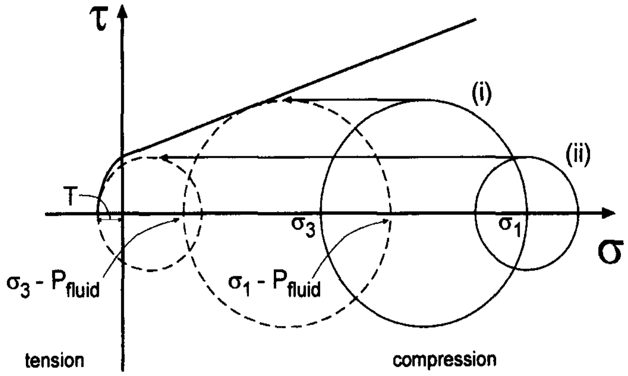

Figure 3. Diagram to illustrate the effect of increasing fluid pressure on the state of compressive stress in a rock. Two states of stress are depicted by Mohr circles (i) and (ii). In stress state (i) the differential stress is relatively large and the circle is brought into contact with the failure envelope in the shear domain. In stress state (ii) the differential stress is low (< 47) and the circle is brought into contact with failure envelope in the extensional domain.

STRUCTURAL CONSTRAINTS

The most explicit feature of greisen vein swarms (sheeted vein systems) in SW England and in other provinces of mineralized granites worldwide is their parallel arrangement. This parallelism, together with the distinctive envelopes of alteration which surround the veins themselves, suggest that the conditions governing their formation are similar, no matter where they are found. In different systems, the frequency of the individual fractures and their dimensions can vary over at least two orders of magnitude (mm to m and m to km), but the patterns of fracturing and alteration show a broad congruence which appears to be scale-independent (see e.g. Wu and Mei, 1982).

Despite the difference of opinion in the older literature concerning the 'passive' as opposed to 'dynamic' origin of such fracture systems (Halls, 1987), their geometrical configuration and the mineral textures in them leave little doubt that the patterns are best explained in terms of hydraulic fracturing. The term 'hydraulic fracturing' is used here to describe fracturing induced by the pressure of any fluid acting within a rock.

To understand how hydraulic fracturing can occur in pneumatolytic systems, the stress conditions governing brittle failure are illustrated in Figure 1. The graph in this figure shows the brittle failure envelope for a typical rock. It is composed of two sections, a straight line representing the Navier/Coulomb criteria for shear failure and a parabolic part representing the Griffith criteria for extensional failure. The Mohr circles on this diagram represent two stress fields. One touches the Navier/ Coulomb portion of the failure envelope and therefore gives rise to shear failure, the condition depicted by Figure lb. The other touches the Griffith portion of the envelope and therefore gives rise to extensional failure, the condition depicted by Figure la.

It can be seen from this diagram that the conditions governing the formation of tensile fracturing in rocks is that the least effective principal stress must equal the tensile strength (T) and that the differential stress (σ_1-σ_3), i.e. the diameter of the Mohr circle, must be small enough for the circle to touch the nose of the parabola (i.e. at $\sigma = -T$, $\tau = 0$). Because the cohesion C is found to be approximately twice the tensile strength, it follows from the geometry of the failure envelope (shown in more detail in Figure 2) that in order to meet these conditions for extensional failure the differential stress must be less than 4T.

It is observed that many of the fractures in typical swarms of parallel greisen veins have opened in the tensile mode (Halls, 1987) and it follows that the conditions under which they formed fall within the range described above. However, extensional fractures do not always occur in regular, parallel arrays. In certain circumstances extensional fracturing develops in random orientations and, if sufficiently developed, brecciation results. Using the brittle failure envelope and the Mohr circle representation of stress shown in Figures 1 and 2, these different fracture geometries can be explained.

It is clear from the above discussion that extensional failure can occur under a range of differential stresses but this range will always be such that (σ_1-σ_3) is < 4T. Two Mohr circles that satisfy this condition are shown on Fig. 2. The larger circle has a differential stress approaching 4T. The smaller circle (the black dot) represents a state of hydrostatic stress. When the stress conditions are not hydrostatic, tensile fractures form parallel to the maximum principal compressive stress a_1, i.e. they open in the direction of the minimum principal stress σ_3, (Figure la). Thus, in the stress state represented by the large Mohr circle in Figure 2, which has a relatively large differential stress, there is a definite direction of easy opening of the extensional fractures, i.e. parallel to σ_3. The fractures would therefore show a marked alignment normal to this direction (Figure 2a). However, for the hydrostatic stress represented by the dot, the differential stress is zero. The normal stress across all planes is the same and there is therefore no preferred orientation for extensional fracturing. The fracturing occurs randomly giving rise to reticular stockworks and/or brecciation, (Figure 2b).

Having defined the conditions under which extensional fractures can form and the factor determining the variations in their spatial organization it is relevant to note that the state of stress in the Earth's crust tends to be compressional and that in the upper, brittle part of the crust (σ_1-σ_3) increases with depth. Under this condition, the state of stress in the crust would plot as a Mohr circle situated to the right of the origin i.e. in the compressive field. This precludes the possibility of extensional failure. This dilemma can be resolved by considering the effect of fluid pressure within the rock. The effect of an increase in fluid pressure on the position of a Mohr circle relative to the failure envelope is shown in Figure 3. Because the outwardly directed fluid pressure opposes the compressive lithostatic stress, s_1 and s_3 are reduced by the same amount. In this way the differential stress is maintained but the Mohr circle is moved towards the failure envelope by an amount equal to the fluid pressure. If the fluid pressure is sufficiently high it will drive the Mohr circle into contact with the envelope and fracturing will occur. This fluid-induced fracturing is termed hydraulic fracturing and it is clear from Figure 3 that either extension (Mohr circle ii, Figure 3) or shear failure (Mohr circle i,

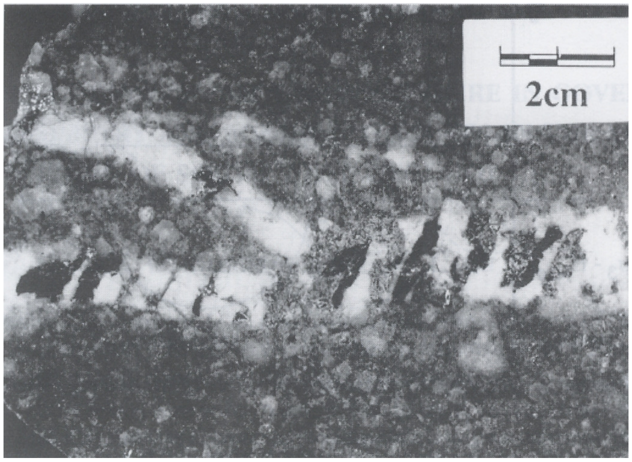

Figure 4. Photograph of a section of greisen vein from Cligga Head. The vein is filled by a parallel syntaxial intergrowth of quartz, wolframite and loellingite crystals which are aligned oblique to the walls of the vein. This can be interpreted as a kinematic indication of hybrid shear/ extension as the vein was opened.

Figure 3) can be induced hydraulically depending on the magnitude of the differential stress.

There are many different situations in which high fluid pressures can be generated in the crust. For example, in lithostatically loaded water/oil-saturated rocks located beneath an impermeable horizon. More pertinent to the present discussion, an increase in fluid pressure takes place in solidifying granite rocks, as the saturated solidus is approached adiabatically or by cooling under static confinement (Niggli, 1920; Burnham and Ohmoto, 1980). The chemical potential energy stored in the water-saturated magma is converted to PAY expansive work as the hydrous fluid exsolves and the fluid pressure in the rock increases (Halls, 1993).

When the internal pressures generated are sufficiently large and the granite is close enough to the solid state to fracture, then extensional hydraulic fractures could be formed under the conditions defined above. Thus the sub-parallel arrays of greisen lodes so typical of the mineralized granite cupolas in Cornwall and elsewhere are inferred to have formed as extensional hydraulic fractures under conditions in which $(\sigma_1\text{-}\sigma_3)$ is equal to or <4T and $P_{\text{fluid}} = \sigma_3 + T$

This mode of fracture development conforms to a well-defined state of differential stress, but the patterns observed in many cases are more complex. From the above discussion it is clear that as the differential stress increases above 4T there will be a change from extensional to shear failure. However, this transition is not abrupt and as the differential stress increases, so the point of contact between the Mohr circle and the failure envelope gradually moves from the point $(\sigma_3 = -T, \tau = 0)$ along the parabola towards the shear failure envelope. During this transition the failure planes will have a component of both extension and shear and therefore this type of failure is termed hybrid (extension/shear) failure. The orientation of these fracture planes with respect to the maximum principal compression direction varies from 0° when $(\sigma_1\text{-}\sigma_3) = 4T$ to ~30° when the differential stress is sufficiently large to cause shear failure. The geometry of the failure envelope determines that such hybrid failure occurs when $\sigma_3 + T > P_{\text{fluid}} > \sigma_3 + 0.8T$ and $(\sigma_1 - \sigma_3)$ lies between 4T and 5.5T (Price and Cosgrove, 1990).

Kinematic evidence from mineral growth textures shows that hybrid fractures of this type have formed in greisen vein swarms at Cligga Head and the Bunny Lode in the St Austell granite as described by Halls (1993). At these localities, parallel-oblique and sigmoid syntaxial intergrowths of quartz and ore minerals fill the veins, demonstrating continuous growth as the fractures opened progressively under a combination of extension and shear (Figures 4 and 5).

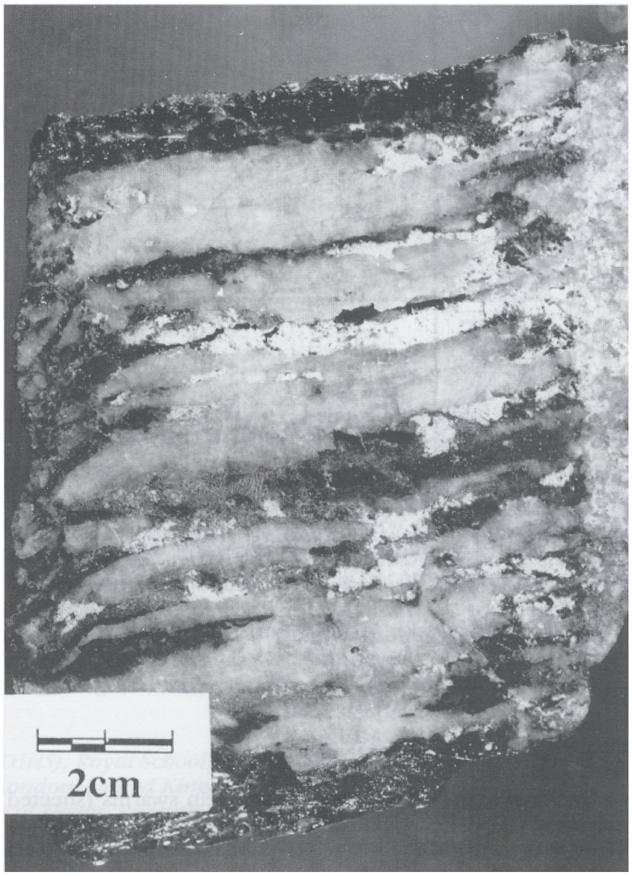

Figure 5. Coarse syntaxial intergowth of quartz, with oxidized iron arsenides, stannite and wolframite filling the vein of the Bunny lode, Gunheath china clay pit, St. Austell. The primary loellingite, stannite and wolframite have been altered to a mixture of scorodite, haematite, turquoise and varlamoffite. The sigmoidal pattern of the syntaxial fibres indicates that varying components of extension and shear displacements occurred during opening.

If the granite solidifies under conditions in which the differential stress in the country rocks is sufficiently large to produce shear failure $(\sigma_1\text{-}\sigma_3) > 6T$, and the increase in fluid pressure generated as the solidus is reached is sufficient to move the Mohr circle into contact with the failure envelope, then shear fractures rather than extensional, or hybrid shear-extension fractures will be formed. In this case the shear fractures produced are also the result of the interaction between the differential confining stress and the internally generated fluid pressure so they are also a type of 'hydraulic' fracturing

The Mohr circle for these stress conditions of higher differential stress will contact the failure envelope in the shear domain regardless of the fluid pressure so the first generation of fractures will be shear fractures (Price and Cosgrove, 1990). If the change in geometry permitted by shear failure leads to a local reduction in the differential stress, then as $(\sigma_1\text{-}\sigma_3)$ enters the range 5.5 - 4T, shear failure will give way to hybrid shear-extension fracturing and, eventually, when $(\sigma_1\text{-}\sigma_3)$ is less than 4T, extensional hydraulic fractures will form. This progression in the mode of fracturing could be expected to occur in any hydrous granite cupola which crystallizes in a field of significant differential stress. A number of the greisen vein swarms in the granite cupolas in SW England appear to show this sequence of evolution.

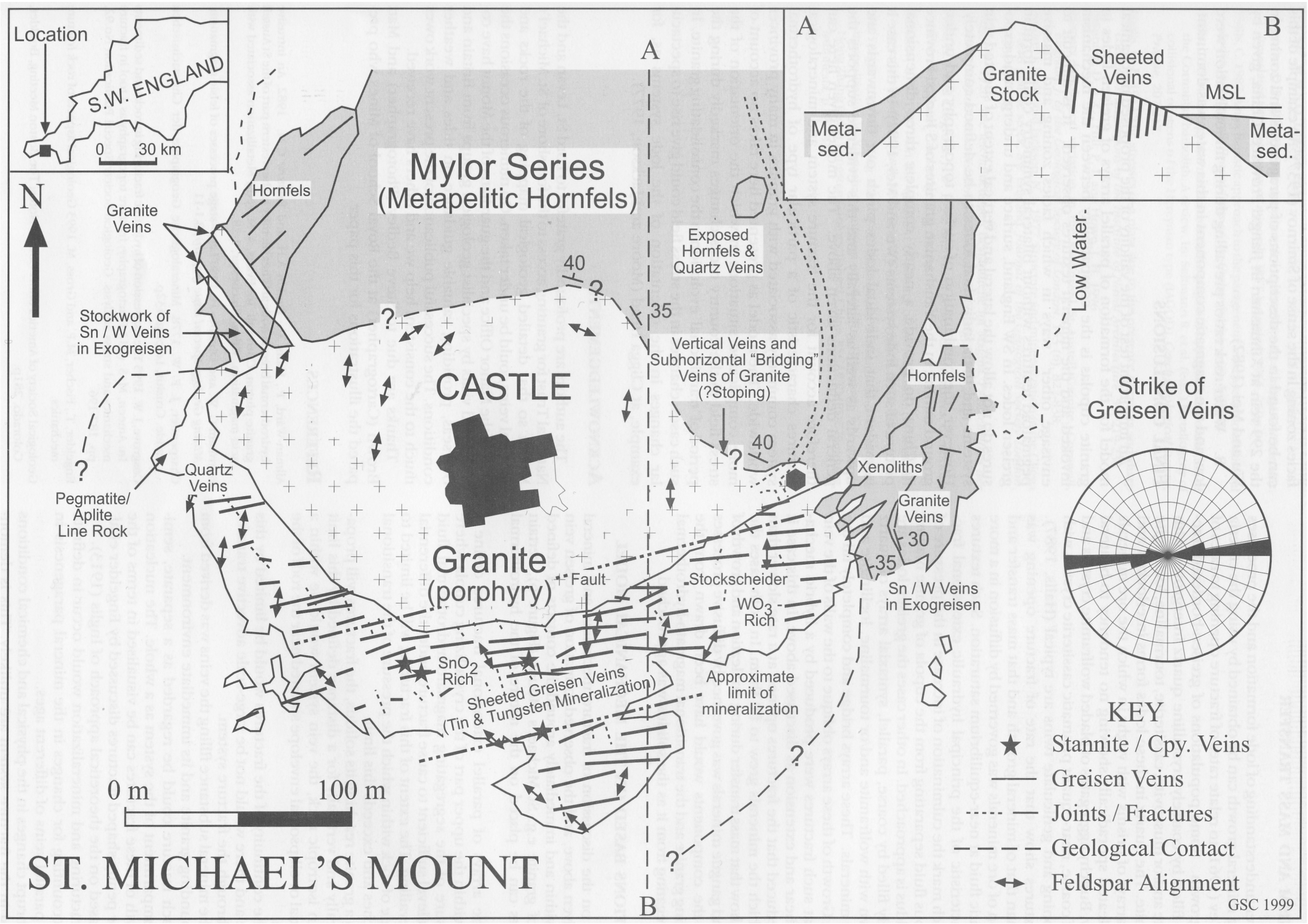

Figure 6. *Geological map of the granite cupola and the envelope of hornfelsed Devonian sediments of the Mylor Formation on St Michael's Mount offshore from Marazion near Penzance. The distribution of the greisen- bordered vein swarm is shown in relation to the contact of the granite cupola and defines the range within which fluid pressures generated in the granite were sufficient to cause hydraulic fracturing.*

MINERAL TEXTURES AS EVIDENCE OF FRACTURE MECHANISM AND MASS TRANSFER

A clearer understanding of lode formation and the processes governing mineral growth can be obtained by using the criteria of Grigor'ev (1961) to relate rates of fracture opening to rates of mineral growth. Some populations of greisen-bordered fractures are filled by coarsely crystalline quartz intergrown with wolframite and/or muscovite, cassiterite, tourmaline, loellingite and stannite. The quartz in these lodes forms interlocked and bridging arrays of prisms with vughs in which the ore minerals have nucleated sporadically showing no tendency to bilateral symmetry. Bunchy aggregates of bladed wolframite crystals and groups of coarse, near-equant prismatic cassiterite crystals with colour zoning and geniculate twins are typical (Halls, 1987). These textures show that the rate of fracture opening was greater than that of mineral growth and that mass transfer and nucleation of ore minerals was governed by diffusion in a more or less static fluid at near-equilibrium saturation. Such textures are characteristic of the principal hydraulic extensional fractures which mark the culmination of increase in the pressure of the hydrous fluid separating from the cupola of granite magma as the solidus is approached. In other cases the greisen lodes are completely filled by coarse, parallel, syntaxial arrays of quartz intergrown with wolframite and/or tourmaline, loellingite and other ore minerals. These arrays bridge and completely fill the fractures. Growth of these arrays oblique to the walls of the vein shows that such fractures were produced by a hybrid mechanism of shear and extension as discussed above. In this case it can be deduced that the fractures opened at a rate slower than that at which the minerals grew to fill them. In both cases the textures show that mass transfer during nucleation and growth of the ore and gangue minerals was governed by diffusive processes and that the components would have been drawn from the surrounding granite and the transitional magmato-hydrothermal fluid segregating from it as the solidus was approached.

DEDUCTIONS BASED ON THE MECHANICAL MODEL

Based on the discussion of fracture mechanics and mineral texture given above, and the observed formation of greisen vein swarms within and immediately around the contacts of defined cupolas of granite e.g. St Michael's Mount (Figure 6), certain constraints can be placed on the nature of the hydrothermal system.

1. The arrays of parallel extensional fractures define a domain within the upper part of the crystallizing cupola where the pressure of the segregating magmato-hydrothermal fluid reached a level sufficient to cause fracture under the differential stress prevailing. The extent of this fracturing will be limited to the volume of rock within which the pressure of the transitional fluid reaches and exceeds this limit.
2. In a granite reaching its solidus, the fractures will propagate laterally and vertically for a distance defined by this limit and, in an isotropic rock, the vein system would lie within a sphaeroidal or ellipsoidal envelope situated near the roof of the intrusion.
3. The continuity of the fractures would be limited by this envelope and there would not be large-scale advective transfer of fluid through the fracture system.
4. The mineral substance filling the veins was derived from the surrounding granite and its immediate environment.
5. Each fracture could be regarded as a separate, semi-closed compartment of the system as a whole. The nucleation and growth of these fractures can be visualised in terms of the model for penny-shaped fractures discussed by Engelder *et al.* (1993) based on the theoretical approach of Inglis (1913).
6. Fracturing and mineralization would occur in definite stages, accounting for changes in the mineral paragenesis in adjacent parallel veins of different ages.
7. Abrupt changes in the physical and chemical conditions prevailing in the fracture system are unlikely. This is demonstrated by the characteristically fluent gradational changes in mineralogy within individual lodes, when zoning is present. In this respect, greisen lode systems provide the ideal example for facies zoning in the sense of Smirnov (1937). An example of this can be found in the descriptions of paragenesis and zoning in the 299 vein at Xihuashan in Jiangxi Province, China, given by Wu and Mei (1982).
8. Water:rock ratios prevailing during mineralization were low and the magmatic component in this water was dominant.

FINAL CONCLUSIONS

An important test of the validity of the proposed mechanical model for the formation of parallel arrays of greisen lodes in granite cupolas is the compatibility between the mechanism invoked and the mineral textures observed. It is difficult to envisage other ways in which facies zoning and massive pegmatoid textures without bilateral symmetry could form in greisen lodes. In SW England, surface and underground exposures do not allow the lateral and vertical extent of sheeted vein systems and their individual lodes to be defined completely. However, the combination of surface topography and underground mining in the Yanshanian granites of S Jiangxi Province in China do provide a nearly complete three dimensional picture of such lode systems (Wu and Mei, 1982). In this case it is evident that individual lodes pinch out downwards and upwards as well as laterally and this evidence supports the general deductions given above. The model given here can therefore account for the fracture system and mineralogical textures characteristic of a particular type of hydrothermal system commonly associated with granites in many provinces worldwide. The model as presented here takes no account of more complicated situations in which the orientation of the stress field in the country rocks changes markedly during the period of 'transitional' evolution in the consolidating granite. In such cases, changes in the stress field could give rise to spectacular changes in the orientation of the lode systems as, for example, at Cligga Head (Moore and Jackson, 1977).

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