Insights into the formation of the Isles of Scilly Pluton

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The Isles of Scilly granite is one of the oldest plutons of the Cornubian granite batholith. The relatively isolated and scattered nature of the Isles of Scilly mean that the pluton has not been subjected to the same level of study as mainland plutons. Mapping and re-examination of selected areas of the pluton have been undertaken and confirm that it is made up of a series of discrete intrusive bodies. A number of granite types are recognised, most being varieties of coarse-grained granite. These are intruded by fine- and medium-grained granites, as sub-horizontal and sub-vertical sheets and dykes. Contact relationships vary from undulose to planar and sharp to protrusive and in many cases indicate that adjoining granites were present as coexisting magmas. Sub-rounded and irregularly-shaped granitic enclaves provide further evidence for this. Country rock xenoliths are rare and concentrated in a few localities. Elvan dykes have contact relationships which suggest that the host granite was not completely solid when the elvans were emplaced. This is at odds with interpretations elsewhere in the batholith. Both high-angle and gently-dipping faults are present, some indicating a period of extensional deformation.

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Introduction

Almost all granites are composite bodies, although some are more composite than others. Some plutons consist of a small number of separate granite bodies (e.g. England, 1992; Castro and Fernandez, 1998; Cruden, 1998), others are made up of a large number of individual granites (e.g. Bons *et al*., 1999) while most lie somewhere in between. The presence of multiple granite intrusions suggests two possible processes during pluton formation. Either there is continuous production of granite melt which then separates and ascends in a series of 'pulses'; or the melt is produced in batch fashion, with each batch segregating and ascending before the next is produced. Castro and Fernandez (1998) suggested that melts extracted rapidly from the source will be more heterogeneous than those extracted more slowly. Many granite plutons have elliptical to circular map outlines, regarded in the past as evidence of diapiric ascent and emplacement (Buddington, 1959; Ramberg, 1970). Many are annular bodies, consisting of a series of roughly concentrically-zoned granite bodies, usually with the youngest in the centre (e.g. Phillips, 1956; Pitcher and Berger, 1972; Bateman and Chappell, 1979; Brown *et al*., 1979; Tindle and Pearce, 1981). A number of plutons have been shown to be tabular in form and interpreted as being emplaced by a process of either lopolithic or laccolithic inflation (Corry, 1988; Hogan *et al*., 1998; Jackson and Pollard, 1988; Cruden, 1998).

Much research and debate over recent years has concentrated on the subjects of ascent and emplacement. Discussions on magma ascent have largely focussed upon the relative importance of the processes of diapirism and dyking, with dyking now regarded by many as the principle process (e.g. Hutton, 1992, 1996; Petford *et al.*, 1993; Petford, 1996; Clemens, 1998). Research into emplacement mechanisms has highlighted the importance of fractures, faults and shear zones in facilitating final emplacement as well as magma ascent (e.g. Hutton, 1982, 1988; Castro, 1986; Clemens and Mawer, 1992; D'Lemos *et al*., 1992; McCaffrey, 1992; Castro and Fernandez, 1998; Vigneresse and Bouchez, 1997; Bons *et al.*, 1999). Such granites may display a sheet-like structure, although the close similarity of melts being emplaced may make this difficult to discern on the ground (Hutton, 1996; Clemens, 1998). Furthermore, if initial emplacement is followed by inflation, or bulbous growth, the final form of the pluton may not be obviously sheet-like (Brun *et al.*, 1990; Clemens, 1998). In a re-assessment of a number of granites with spherical and/or annular form, Paterson and Vernon (1995) returned to the idea of magma ascent by diapirism, postulating a 'nested diapir' model in place of ballooning.

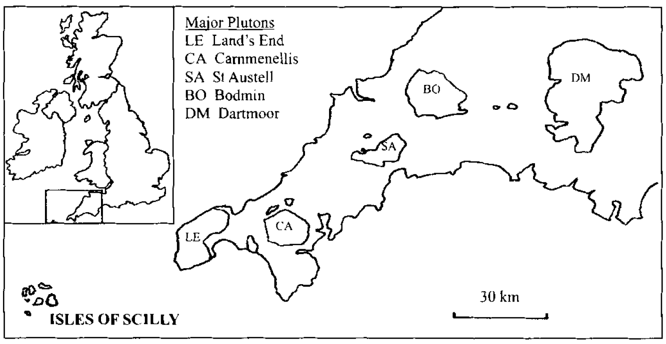

Figure 1. The major plutons of the Cornubian batholith.

The Isles of Scilly comprise approximately 55 islands and lie *c.* 40 km west-south-west of Land's End (Figure 1). The islands comprise the north-western two-thirds of an oval shaped body (Barrow, 1906). At *c.* 290 Ma (Clark *et al.*, 1993; Chen, 1994) the Isles of Scilly pluton is one of the oldest plutons in the Cornubian batholith, as well as being one of the largest at *c.* 200 km^2 (Hawkes *et al.*, 1986). All of the islands consist of granite, no large remnants of the country rocks survive. The larger islands are capped by predominantly Pleistocene drift deposits.

Compared to the considerable amount of work carried out on other Cornubian plutons, the Isles of Scilly remain relatively unscrutinized. Work on the islands has been intermittent, but sporadic publications (Carne, 1850; Statham, 1859; Barrow, 1906; Osman, 1928; Hawkes *et al.*., 1986; Stone and Exley, 1989) have resulted in a general understanding of the geology. Barrow (1906) described the Isles of Scilly pluton as having a core of fine-grained non-porphyritic granite surrounded by porphyritic coarse-grained granite. Although mapping reveals this to be superficially the case, it presents rather a simplistic view of the pluton's formation and the variety and juxtaposition of the granites which it comprises. A number of separate granites have now been identified in the Isles of Scilly pluton, primarily on the basis of textural differences (Mullis, 2001). These differences are often subtle but are sufficient in most cases to allow the individual granites concerned to be delineated as separate intrusive bodies.

Although the plutons of the Cornubian batholith have long been known to be composite bodies (e.g. Reid and Flett, 1907; Ghosh, 1934; Dangerfield and Hawkes, 1981; Stone, 1987), only a few studies have hinted at their true complexity (Hill and Manning, 1987; Knox and Jackson, 1990; Manning *et al.*, 1996). Research on the Land's End pluton has shown it to be much more complex than was previously appreciated, with abundant evidence that it is made up of a large number of discrete granite intrusions, many of which are dyke or sheet-like in form (Salmon, 1994; Salmon and Powell, 1998; Powell *et al.,* 1999). Study of internal contacts within the Land's End Granite has allowed local emplacement chronologies, and emplacement styles, to be established (Powell *et al.,* 1999; Salmon and Shail, 1999) and similar internal contacts have also been identified within the Isles of Scilly pluton.

Clearly, field studies form the basis for much of the study of granites, particularly with regard to the processes of ascent and emplacement. The close association of a relatively large number of individual granites indicates a piecemeal process of emplacement and pluton growth, though this interpretation might be compromised by processes of differentiation. The form and texture of the individual granites can give important clues as to the mechanisms of magma ascent and final emplacement. Detailed study of internal contacts can establish emplacement chronologies and provide information regarding the physical state of the adjoining magmas when they were juxtaposed. The latter might be used to suggest the relative elapsed times between successive intrusions. In this paper the preliminary findings, based primarily on field observations, of this ongoing study are presented.

The granites of the Isles of Scilly

The pluton consists of coarse, medium and fine-grained biotite granites (CGG, MGG, FGG respectively, see Table 1). Mineralogically, the rocks are typical biotite-granites, with accessory minerals that include pinitised cordierite, tourmaline, andalusite, monazite, apatite, ilmenite, zircon, uraninite and anatase (this study and Hawkes *et al.*, 1986). Following the recognition by Barrow (1906) of two predominant granite types in the pluton, Osman (1928) described two separate coarse-grained granites, one with orthoclase phenocrysts, the other comprising "…not quite so coarse…" granite. Osman (1928) described the "rather fine-grained granite" as younger than, and underlying, the coarse granites and sending dykes and sills into them. Osman (1928) also described a "marginal [later] intrusion of fine-grained granite" occurring on St. Mary's between Porthloo and Carn Morval (Figure 2). Dangerfield and Hawkes (1981) pointed out that much of the granite described by Barrow (1906) and Osman (1928) as fine-grained is, in fact, medium-grained granite. Exley and Stone (1982) used a different granite classification scheme and described the islands as consisting of Type B (coarse-grained megacrystic) and Type C (fine-grained) biotite granites. In their geochemical study, Stone and Exley (1989) describe four granite types which basically equate to those of earlier workers. Stone (2000) described the Isles of Scilly pluton, along with the other early plutons of the Cornubian batholith, as having a "fairly simple ring-type structure."

A: Grain-size descriptors (after Dangerfield and Hawkes, 1981).	
Fine-grained granite	Mean groundmass grain size <1mm
Medium-grained granite	Mean groundmass grain size 1 – 2mm
Coarse-grained granite	Mean groundmass grain size >2mm
B: Descriptive terms for feldspar phenocryst abundance (modified after Goode and Taylor, 1988).	
Abundantly-porphyritic	>10% phenocrysts
Moderately-porphyritic	5 – 10% phenocrysts
Sparsely-porphyritic	< 5% phenocrysts

Table 1. *Descriptive terms used in text.*

In this study, four main granite types are identified, based on a combination of grain-size and phenocryst abundance. These are coarse-grained granites with abundant, moderately-abundant or sparsely-abundant phenocrysts, together with non-porphyritic medium-grained granite (for definitions of terms see Table 1). Local variations of each type are present. In addition, these granites are intruded by many fine and medium-grained granite sheets. In all cases the predominant phenocryst phase is orthoclase, which varies in size, shape and orientation from one granite to another. Orthoclase phenocrysts are tabular and up to 40 mm in length, though more commonly 15-25 mm. This places the granites in the "small megacryst" variant of Dangerfield and Hawkes (1981). Although variable, in most of the granites the feldspar phenocrysts are subhedral. Euhedral pinitised cordierite is also present as a phenocryst phase, with crystals up to *c.* 8 mm in length, though it varies in abundance from one granite to another. Quartz is rarely present as phenocrysts, more often as aggregates of single grains.

Early workers (e.g. Barrow, 1906; Osman, 1928) remarked on the distinct sub-parallel alignment of the feldspar phenocrysts. Barrow (1906) interpreted this as due to fluxion movements during injection and noted that the lines of fluxion undulate and are often vertical. This study also notes the importance of the feldspar orientation and interprets it to be due to magmatic flow. Phenocryst alignment is often deflected round enclaves, but is not generally deflected by intrusive sheets. However, it is unlikely that the gross structure is due to flow within a single large intrusive body. Rather, the marked changes in orientation are interpreted, especially if accompanied by other textural evidence, to indicate the presence of separate intrusive bodies

In places, phenocrysts are concentrated in elongate, abundantly-porphyritic pods or streaks. These are usually less than 10 cm wide, and have the same orientation as the phenocrysts in the surrounding granite. There is no field evidence as to the origin of such features. Powell *et al.* (1999) described similar phenomena in the Land's End pluton, though generally on a larger scale than in the Isles of Scilly. A possible origin as syn-plutonic dykes was suggested, with contact zones between similar granites or magmatic-state shearing as possible alternative mechanisms. The appearance of some of the concentrations on St. Mary's suggests an origin as magmatic enclaves of abundantly-porphyritic granite which have been stretched or streaked out by flow movement of the enclosing magma.

Enclaves are present in the Isles of Scilly granites, but are not common. They fall into two distinct categories as defined by Stimac *et al.* (1995): non-igneous enclaves and enclaves of an igneous origin. The non-igneous variety, i.e. pelitic country-rock xenoliths, are rare over most of the islands, but local concentrations are present in the south-west of St. Mary's and south-west of St. Agnes. There are two broad sub-divisions of igneous enclave. The first are mafic microgranular enclaves (Stimac *et al.*, 1995), many of which equate to the "oval patches" of Barrow (1906) and the Stage 1 "basic inclusions of microgranite" described by Osman (1928). They were observed during this study on Great Ganilly and south-west St. Mary's. Most country-rock and microgranular enclaves are elongate or ovoid, less than 30 cm long, with their long axes aligned sub-parallel to phenocryst orientation. Salmon (1994) interpreted similar phenomena in the Land's End pluton as evidence that the phenocryst orientation is primary and due to alignment during magma movement.

The second, and by far the most common, type of igneous enclave comprise distinct bodies of granite recognisable elsewhere in the pluton. Many of these equate to the 'Type 1' granite enclaves of Stone and Exley (1989). They are common throughout the pluton, and vary in size from a few centimetres to several metres in diameter. These enclaves are usually sub-rounded or irregular in outline with contacts that vary from sharp and protrusive to gradational (see below). In places, however, angular or sub-angular granite enclaves are present (e.g. within medium-grained granite sheets at Gap Point), indicating a greater degree of crystallization when disrupted by incoming magma.

Internal granite contacts

The study of internal contacts between constituent granites can give valuable insights into the mode of emplacement, the relative age of adjoining granites and also the physical (or crystallization) state of the two granites when they came together. Barrow (1906) found, in general, no sharp contacts between his two main granite types, and therefore interpreted the contacts as gradational ("… a gradual passage.."). A similar interpretation has been made in other Cornish plutons (e.g. Booth and Exley, 1987). The nature of contacts between granites is controlled primarily by the physical state of the earlier magma when the later one is emplaced. This is largely controlled by the degree of crystallization of the magma, which in turn controls its *effective* viscosity (see Salmon, 1994, and Powell *et al.*, 1999, for brief discussions). At around 65% crystallization (i.e. with *c.* 35% melt remaining) the magma begins to behave as a solid and will take a shear strain (Arzi, 1978; van der Molen and Paterson, 1979). This is due to interlocking of the crystal matrix. The point at which it occurs is known as the critical melt fraction. Below the critical melt fraction (i.e. with <35% melt remaining) the magma will 'break' in an angular manner. Three principle types of internal contact have been recognised during the current study: gradational, sinuous or irregular, and planar.

Gradational contacts exist at a number of localities within the pluton, often between fine-grained granite enclaves and a coarser-grained host. The gradation is usually manifested by a gradual change in feldspar phenocryst abundance (Figure 3a). This suggests a degree of physical interaction and mixing between the two magmas. For this to take place both magmas must be above their respective critical melt fractions (i.e. with >35% melt remaining). As one magma is intruded into the other, shearing and turbulence effects along the interface between them will promote mixing and phenocrysts from one magma will become incorporated as xenocrysts into the other. If one of the magmas is non-porphyritic the gradation in phenocryst abundance will be apparent (Figure 3a), but if both are porphyritic the gradational contact may not be so obvious and may be overlooked in the field.

Irregular or sinuous contacts indicate that the earlier granite magma was still above its critical melt fraction (i.e. >35% melt remaining) when the later magma was emplaced (Figure 3b). However, in some instances the earlier granite appears to have been so close to the critical melt fraction, that it was able to maintain its textural integrity whilst still producing irregular contacts. In many such cases the contact is discordant to the magmatic state fabric (i.e. phenocryst alignment) in the earlier granite (Figure 3c). Such contacts again give important information as to the emplacement chronology. The behaviour of magmas that are very close to their critical melt fraction may differ depending on the nature of the external stress, or even on different time scales (Mahood and Carnejo, 1992). This means that if another magma is emplaced quickly and forcibly, the earlier magma may fracture in a brittle manner, but if intrusion is more sluggish or continuous it may deform in a ductile manner, producing sinuous contact relationships. More highly-irregular contacts are also present (Figure 3d) and suggest that the two coexisting magmas were well above their critical melt fraction.

Planar contacts occur predominantly between sub-horizontal or sub-vertical sheets and the enclosing granite. The sheets are usually fine or medium-grained granite (occasionally composite) and occur throughout the pluton. Sheets may bifurcate, anastomose and, where several sheets are present, cross-cut each other. Very good examples occur around Gap Point on St. Mary's. Thin sub-vertical sheets are usually cross-cut by thicker sub-horizontal sheets. When examined in detail, most of the planar contacts are seen to be protrusive in nature. The term 'protrusive' is used to describe a contact at which crystals, particularly phenocrysts, belonging to one (or both) of the granites protrude across the contact into the other (Porter, 1997). Such a contact indicates that the earlier magma was below its critical melt fraction but still not completely solid (*c.f.* Figure 3b). As fractures propagate in response to the incoming magma, the crystal matrix is forced apart, leaving an interface which is irregular on the crystal scale, with existing crystals protruding into the new magma. Knife-sharp contacts, in which crystals of the earlier granite are cross-cut, are rare.

At the north-eastern end of St. Mary's is a planar contact between two medium-grained granites which are texturally very similar. The contact is marked by distinctive *stockschieder* feldspar megacrysts. These nucleated on a pre-formed substrate, the crystal matrix of the earlier granite, and grew into the newer magma. The two adjoining granites are so similar that, if the contact was not exposed or observed, they could be taken as the same intrusion.

Granites of the main islands

Most of the larger islands have been mapped to some degree as part of this study. A number of granites have been identified and in a number of localities, contacts between individual granites have been observed. Due to the drift cover that occupies much of the land away from the coastal strip, mapping has necessarily been confined to the rocky foreshores. For localities referred to in the text, see Figure 2.

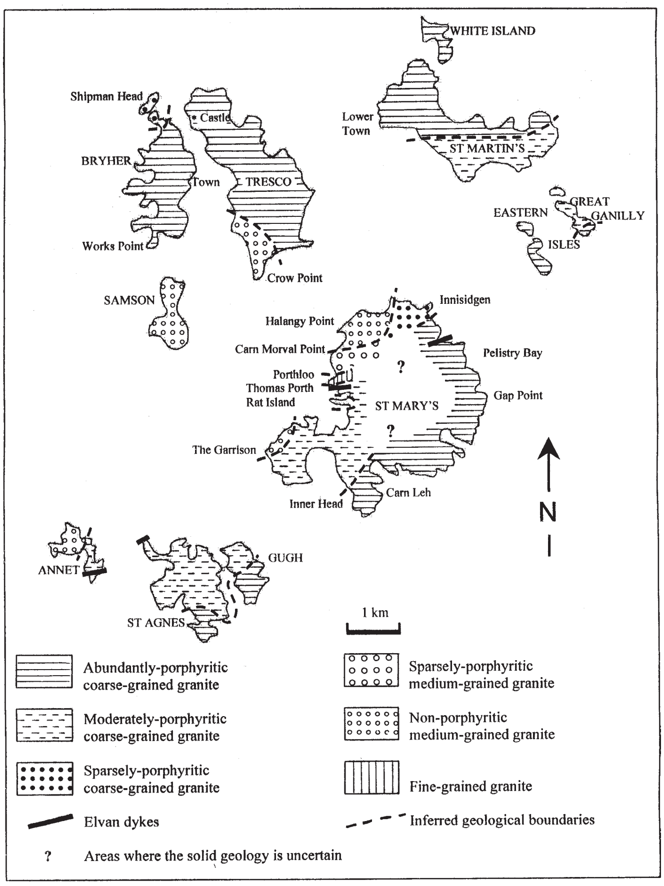

Figure 2. *The geology of the larger islands of the Isles of Scilly pluton.*

St. Mary's

This is the largest island, and has many of the most important features found throughout the pluton. Around Rat Island and occupying foreshore exposures to the east as far as Thomas Porth are outcrops of moderately-porphyritic coarse-grained granite. Sub-rounded enclaves of coarse-grained granite with abundant phenocrysts are common and a number of narrow N-S striking fine-grained granite dykes are present. At the north end of Thomas Porth is a distinctively different moderately-porphyritic coarse-grained granite which has stubby, euhedral phenocrysts. This also contains phenocrysts of pinite, but they are not common. The contact between these two granites is not exposed. At

Porthloo is yet another moderately-porphyritic coarse-grained granite which is intruded by an elvan dyke. Just to the north of this are exposures of fine-grained granite which are predominantly non-porphyritic. Continuing to the north the rock changes to sparsely-porphyritic medium-grained granite which is intermingled with moderately-porphyritic coarse-grained granite. Phenocrysts in the medium-grained granite are fairly randomly oriented, those in the coarse-grained granite, which is reminiscent of that at Rat Island, have a N-S alignment. Contacts between the two are sharp and sinuous (Figure 3c), and are discordant to the phenocryst alignment in the coarse-grained granite. The contact relationships indicate that, although both were present as coexisting magmas, the medium-grained granite postdates the coarse-grained granite. The sparsely-porphyritic medium-grained granite continues to the north and is cut by a number of planar fine-grained granite sheets, several of which have distinct tourmaline schlieren parallel to their margins. The sheets dip to the north and strike approximately E-W. Intrusions of similar fine-grained granite, also with tourmaline schlieren, occur in the moderately-porphyritic coarse-grained granite body at the north end of Thomas Porth, though they are disrupted in the manner of syn-plutonic intrusions. If these two very similar examples of fine-grained granite belong to the same pulse of intrusion, it can be inferred that the moderately-porphyritic coarse-grained granite at Thomas Porth is younger than the sparsely-porphyritic medium-grained granite north of Porthloo. Approximately 100 m south of Carn Morval Point is another headland, the top of which is occupied by a small body of moderately-porphyritic coarse-grained granite. In this area are a large number of sub-horizontal sheets of fine-grained granite, usually between 10 and 30 cm thick. Most are planar, but a number of the thinner ones are sinuous. The greater degree of sinuosity indicates a greater proportion of melt remaining in the enclosing granite, suggesting that the thin sinuous sheets were emplaced prior to the thicker, planar sheets. Sheets of medium-grained granite are also present. Within fifty metres north of Carn Morval Point the rock changes to medium-grained granite which is predominantly non-porphyritic, although the contact is not exposed. At Halangy Point is the internal planar contact between two similar medium-grained granites described above. The non-porphyritic medium-grained granite continues round the north coast, until, in the region of Bar Point, the rock changes to sparsely-porphyritic coarse-grained granite, the contact being obscured. South of Innisidgen a body of abundantly-porphyritic coarse-grained granite is present, although again the contact is not exposed. This granite continues to the south, with local variations in grain size and feldspar abundance, which may represent separate pulses of magma emplacement. Around the southern shore of Pelistry Bay, the abundantly-porphyritic coarse-grained granite has stubby, subhedral to euhedral phenocrysts with a NE-SW orientation. Pinitised cordierite megacrysts up to 8 mm long are common. Further south, around Gap Point, the phenocryst orientation is less well defined and the granite is intruded by numerous sub-horizontal sheets striking *c.* E-W. These consist predominantly of non-porphyritic fine-grained granite, some being medium-grained. In some cases, both occur within the same composite sheet, the contact between them being generally planar and distinct. Cross-cutting relationships and anastomosing sheets are present. Similar abundantly-porphyritic coarse-grained granite continues to the south as far as Inner Head, with intermittent exposures of moderately-porphyritic coarse-grained granite at Carn Leh Cove. The coast from Inner Head round The Garrison back to Rat Island consists of is moderately-porphyritic coarse-grained granite, with a large body of non-porphyritic medium-grained granite being present northeast of The Garrison.

St. Agnes and Gugh

Both of these islands consist entirely of varieties of coarse-grained granite. Gugh is divided roughly in half, with moderately-porphyritic coarse-grained granite occupying the northern half and abundantly-porphyritic coarse-grained granite in the south. The contact is not seen, but appears to strike *c.* NE-SW. Most of St. Agnes consists of the same moderately-porphyritic coarse-grained granite as on Gugh, with the abundantly-porphyritic granite being present around the southern-most part of the island. Areas of sparsely-porphyritic coarse-grained granite are present within the moderately-porphyritic coarse-grained granite, but it is unclear whether these are enclaves or separate intrusions. Along parts of the west coast of St..Agnes, numerous granite enclaves, most of which are fine or medium-grained, are present within the moderately-porphyritic coarse-grained granite. Sub-angular pelitic xenoliths are also found in this area. A body of red, very fine-grained granite is present on the north coast of St. Agnes. This appears dyke-like, striking *c.* NE-SW, and contains subrounded or elliptical enclaves of the surrounding moderately-porphyritic coarse-grained granite. An elvan dyke is present at the north-western tip of St. Agnes.

Annet

Annet was not visited during this study because of seasonal restrictions. Basically, it consists of two granites, separated by a contact that strikes *c.* NNE-SSW. The granite to the west has been previously mapped as fine or medium-grained granite, that to the east as coarse-grained granite (Hawkes *et al.*, 1986).

Samson

Time constraints meant that this island was only briefly visited. Northern and central areas were examined and found to be predominantly non-porphyritic medium-grained granite, with occasional orthoclase phenocrysts in a few localities.

Bryher

Bryher is a complex island both in terms of the granites present and the contact relationships between them. The dominant granite on the island is a distinctive abundantly-porphyritic coarse-grained granite, in which the proportion of phenocrysts is often much greater than 10% (Figure 3b). The northern tip of the island is sparsely-porphyritic coarse-grained granite and isolated bodies of this alternate with the abundantly-porphyritic coarse-grained granite down the northern stretch of the east coast. Phenocrysts in the abundantly-porphyritic granite are oriented *c.* NNW-SSE. Opposite Tresco Castle, dykes of non-porphyritic fine-grained granite cut the coarse granite. The dykes are up to 80 cm wide, strike *c.* NE-SW and appear to extend across to Tresco. To the south is a N-S trending dyke of fine-grained granite with enclaves of moderately-porphyritic coarse-grained granite. Just south again is an E-W trending composite dyke, consisting of two slightly different pulses of fine-grained granite, and containing elongate, sub-rounded enclaves of the abundantly-porphyritic coarse-grained granite. In the area to the north and south of the town, bodies of both sparsely-porphyritic and moderately-porphyritic coarse-grained granite are intermingled with the abundantly-porphyritic granite. Where contacts are exposed they are lobate, sinuous or irregular, indicating that the granites were present as coexisting magmas. Numerous fine-grained granite enclaves occur within the coarse-grained granites and enclaves of sparsely-porphyritic granite occur within abundantly-porphyritic coarse-grained granite. The southern half of the east coast is predominantly abundantly-porphyritic coarse-grained granite, with smaller exposures of medium-grained granite around the south-east corner of the island and at Works Point. The stretch of coast from here round the SW corner of the island is occupied by both abundantly-porphyritic and sparsely-porphyritic coarse-grained granite which again appear to be the product of intermingled coexisting magmas. Phenocrysts in the abundantly-porphyritic granite are orientated predominantly N-S, those in the sparsely-porphyritic granite are E-W. Fine-grained granite enclaves are present in the moderately-porphyritic coarse-grained granite. All of these rocks are cut by planar fine-grained granite dykes, up to 15 cm wide, which strike *c.* NW-SE and dip to the SW. The west coast of Bryher comprises abundantly-porphyritic coarse-grained granite as far as Great Mussel Rock, just south of the northern tip of the island. At Great

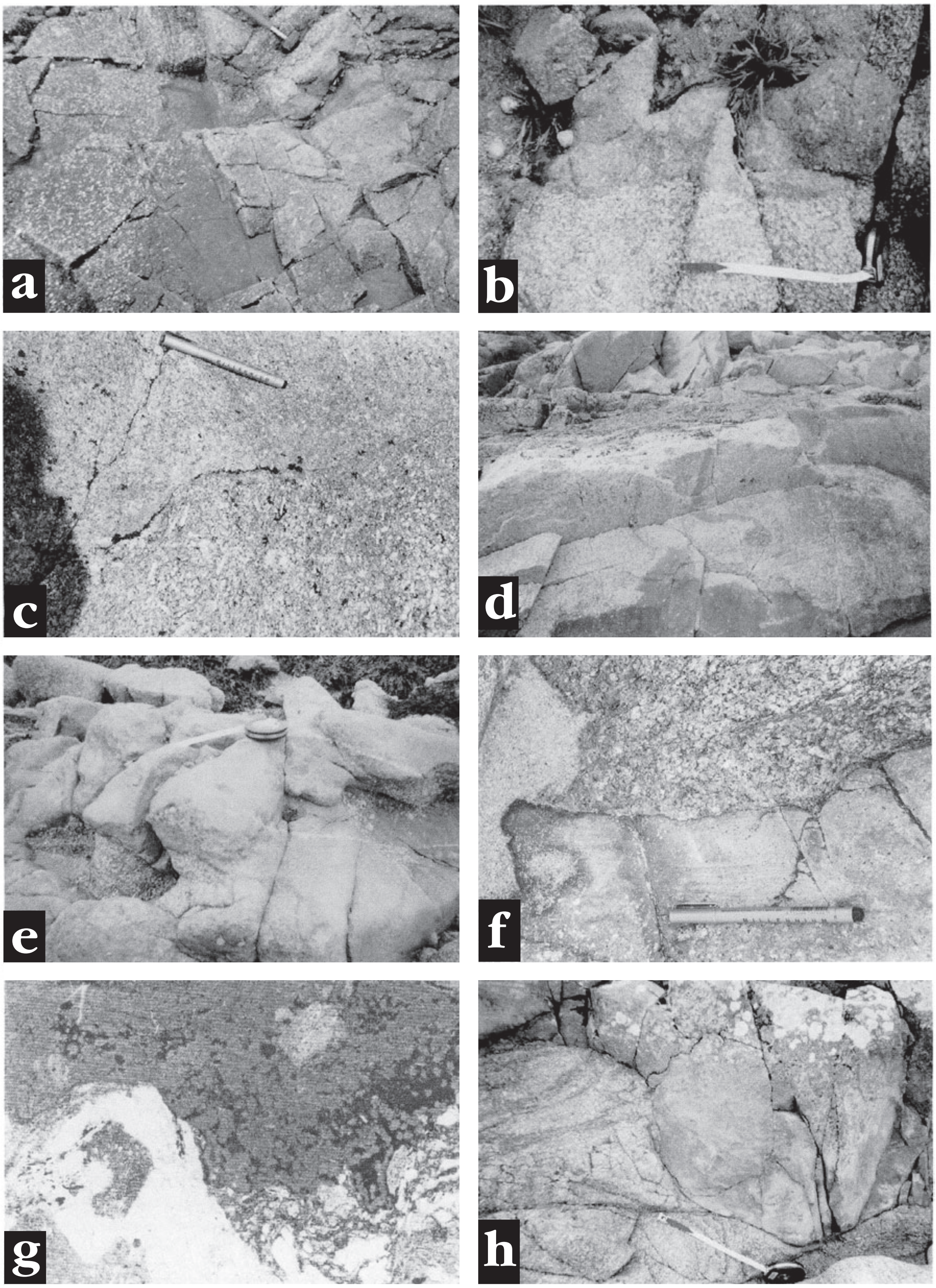

Figure 3. *(a) gradational contact between a sparsely-porphyritic fine-grained granite enclave (centre) and surrounding moderately-porphyritic coarse-grained granite, St Martin's; (b) sinuous contact between abundantly-porphyritic coarse-grained granite (bottom) and sparsely-porphyritic coarse-grained granite, Bryher; (c) sinuous contact between moderately-porphyritic coarse-grained granite (bottom) and sparsely-porphyritic medium-grained granite. The contact is discordant to the phenocryst alignment in the coarse-grained granite, indicating that this predates the medium-grained granite, St Mary's; (d) highly-irregular contacts between abundantly-porphyritic coarse-grained granite (pale, centre) and sparsely-porphyritic coarse-grained granite (darker) indicating that the two came together as coexisting magmas. Round 'blob' in right foreground is c. 25 cm across; (e) fine-grained granite dyke with irregular enclaves of the surrounding abundantly-porphyritic coarse-grained granite, White Island; (f) irregular contact between elvan (bottom) and coarse-grained granite, Porthloo, St Mary's; (g) photo-micrograph showing the contact between elvan (the dark material) and granite. Note the intimate nature of the contact, with small granitic clots enclosed within the elvan, suggesting physical mixing along the interface. The shadowy crystal towards the top may be a xenocryst from the granite; (h) sub-rounded apophysis of elvan (top and right) intruding abundantly-porphyritic coarse-grained granite, Watermill Cove, St Mary's.*

Mussel Rock, the contact between this and the sparsely-porphyritic granite is exposed. It is highly irregular in places (Figure 3d), indicating crystallization from co-existing magmas. The two granites are intimately co-mingled, with small enclaves of abundantly-porphyritic granite within sparsely-porphyritic granite and larger enclaves of sparsely-porphyritic granite within the abundantly-porphyritic granite.

Tresco

The granites of Tresco share the complexity of those on Bryher. The island consists predominantly of abundantly-porphyritic coarse-grained granite. Phenocryst orientation is predominantly E-W, though with local variations of NE-SW and NW-SE. It is not clear whether these local variations represent undulations in phenocryst orientation in the main body of granite or indicate discrete pulses of intrusion. Within the abundantly-porphyritic coarse-grained granite are isolated, predominantly sub-rounded, masses and enclaves of sparsely-porphyritic coarse-grained granite, moderately-porphyritic coarse-grained granite and sparsely-porphyritic fine-grained granite. Where contacts are seen they are undulose, sinuous or irregular, suggesting that all of these granites were present as coexisting magmas. The southwest coast comprises a body of non-porphyritic medium-grained granite within which are isolated areas that are moderately porphyritic. Fine-grained granite dykes striking *c.* NE-SW are present, being particularly concentrated in the area around the castle. Just north of the harbour, midway up the west coast, is a dyke-like body of sparsely-porphyritic coarse-grained granite that strikes *c.* NE-SW and is *c.* 2 m wide. Within the dyke are sub-rounded enclaves of abundantly-porphyritic coarse-grained granite with contacts that are sharp and sinuous, locally irregular.

St. Martin's and White Island

The northern half of St. Martin's consists predominantly of abundantly-porphyritic coarse-grained granite in which the phenocrysts are orientated NE-SW. Within this are a number of large bodies or enclaves of coarse-grained granite which are sparsely-porphyritic. One of these is present halfway along the north coast, between Great Bay and Wine Cove. The enclave is irregular in shape, indicating that the two granites were present as coexisting magmas. In places, enclaves of fine-grained granite which are elongate, sub-rounded and range in size up to *c.* 20 cm are present. A body of moderately-porphyritic coarse-grained granite occupies the southern part of the island. The feldspar phenocrysts in this granite have a greater range of sizes than is typical in other granites of the islands, ranging from 1 cm up to 4 cm with the majority being 1 to 2 cm.

Many fine-grained granite dykes, ranging in thickness from 5 cm to *c.* 2 m wide, are present on St. Martin's, predominantly within the abundantly-porphyritic coarse-grained granite of the northern part of the island. Strikes vary from NE-SW to NW-SE. The dykes often bifurcate, some are anastomosing. The paucity of dykes in the southern moderately-porphyritic granite suggests that it postdates the northern abundantly-porphyritic granite, within which they are common. This suggestion is lent some credence by exposures just south of the quay at Lower Town, where a series of sparsely-porphyritic fine-grained granite enclaves occur within the moderately-porphyritic coarse-grained granite. The enclaves range in size from *c.* 5 cm up to *c.* 2 m and are sub-rounded or irregular in outline. Contacts are mostly sharp, but some are gradational (Figure 3a). The enclaves are aligned NE-SW over a distance of *c.* 10 m and have the appearance of a syn-plutonic dyke which has broken up during emplacement.

White Island consists predominantly of the same abundantly-porphyritic coarse-grained granite as that on St. Martin's. Two fine-grained granite dykes are present at the southern end. One strikes *c.* NE-SW and is *c.* 1.5 m wide. This has margins that are macroscopically planar but on the cm scale are undulose and protrusive. Rounded or irregular enclaves of the host granite are present within the dyke (Figure 3e). The relationships indicate that the dyke was emplaced while the abundantly-porphyritic coarse-grained granite was incompletely solid. The other dyke strikes *c.* NW-SE and has contact relationships which are much more sharp and angular, suggesting that it post-dates the NE-SW trending dyke. At the north-eastern tip of White Island is a body of sparsely-porphyritic coarse-grained granite which underlies the abundantly-porphyritic granite with a sub-horizontal undulose contact. Distinct, closely-spaced joints in the sparsely-porphyritic granite are parallel to the contact and are not present in the abundantly-porphyritic granite into which the sparsely-porphyritic granite appears to be intrusive.

The Eastern Isles - Great Ganilly and Great Arthur

Great Ganilly and Nornour consist predominantly of moderately-porphyritic coarse-grained granite which is very similar to that which occupies the southern half of St. Martin's. The Arthurs consist of abundantly-porphyritic coarse-grained granite. Little Ganilly was not visited. Around the southern tip of Great Ganilly is abundantly-porphyritic coarse-grained granite, contacts between this and the moderately-porphyritic granite are undulose and gradational over a few cms. The contacts indicate that they were present as coexisting magmas. A number of fine-grained granite dykes are present, orientated *c.* NW-SE or N-S.

ELVAN DYKES

In early works (e.g. Barrow, 1906; Osman, 1928) only two elvan (granite porphyry) dykes are described in the islands, both on St. Marys. Hawkes *et al.* (1986), however, indicated the presence of two more, on Annet and St. Agnes, and suggested that, although strikes, dips and thicknesses vary, they may all represent a single fissure filling displaced by faulting. The elvans have a pink or grey, fine-grained groundmass with phenocrysts of alkali-feldspar, quartz, pinite and biotite. The dykes all have chilled margins, up to 2 m wide, with distinct flow banding and phenocrysts up to 3 mm. Phenocryst size and abundance continue to increase from the inner edge of the chilled margin to the centre of the dyke. The most abundant and largest phenocrysts are alkali-feldspars, which have inclusions of biotite and quartz. In the main body of the dykes these are up to 3 cm in size, but commonly less than 1 cm. They show a preferred orientation, parallel to the contacts of the dyke, which is interpreted as a flow alignment. All of the phenocryst phases are euhedral, with some quartz being present as crystal aggregates.

Contact relationships between the St. Mary's elvans and adjoining granite are informative. They are sharp and macroscopically planar or undulose, but on the cm scale are often irregular (Figure 3f). Microscopically, the contact is seen to be highly irregular, with evidence of small-scale physical mixing (Figure 3g). In places, subrounded apophyses of the elvan extend into the adjoining granite (Figure 3h). Locally-derived granite enclaves are common within the elvan chilled margins. They are usually sub-rounded or irregular in outline, often with protrusive contacts. The relationships indicate that the adjacent granite was not completely solid when the elvans were emplaced.

Elsewhere in the batholith, elvans cross-cut, and therefore post-date, the coarse granites (Exley and Stone, 1982; Hawkes *et al.*, 1986; Selwood *et al.*, 1998). The general interpretation seems to be that the elvans represent a single, and very late, magmatic episode (Alderton, 1993; Exley *et al.*, 1983; Hawkes *et al.*, 1975; Hawkes *et al.*, 1986; Floyd *et al.*, 1993). Henley (1974) suggested that the elvans were emplaced 15 – 20 Ma after the granites. Darbyshire and Shepherd (1985) re-analysed the Rb/Sr ages produced by Hawkes *et al.* (1975) for the Brannel and Wherry elvans and arrived at ages of 270±3 Ma and 282±6 Ma respectively. However, Chen *et al.* (1993) distrust these ages, particularly the latter, pointing out that the Wherry elvan cannot be shown to postdate the granite in that area. Goode (1973) describes the elvans as part of a post-granite dyke phase of activity. Goode and Taylor (1980) suggested that the elvans are of a similar age to breccia pipes (which contain both elvan and granite clasts) and postdate consolidation of the granites. Exley and Stone (1982) reported various lines of evidence that could closely-link the elvans with the granites, although Exley *et al.* (1983) suggested that the elvans could be feeder dykes for post-orogenic rhyolitic volcanoes. Alderton (1993) proposed that the elvans were produced by potassium enrichment of biotite granite magmas as their geochemical and REE patterns are similar to the associated granites; and Hall (1970), following his study of the Hingston Down elvan, suggested that the parent magma of the elvans is of "normal" granitic composition. Having studied the Praa Sands elvan and others, Stone (1968) concluded that the elvans were derived from biotite granite magma by a process of alkali ion-exchange. Hawkes *et al.* (1975) found marked variation in $^{87}Sr/^{86}Sr$ initial ratios, suggesting a heterogeneous source.

If most elvans do indeed represent the last magmatic activity in the batholith as a whole, the observations at Porthloo and Watermill Cove, St. Mary's, represent a departure from the norm, as these elvans appear to be contemporaneous with one of the oldest granites in the batholith. A more likely explanation is that each individual pluton has its own late elvan phase, representing the last magmatic activity of that particular period in the batholith's formation. This would suggest that the elvans are related to the late fine-grained granite magmas of each pluton, explaining why elvans are not seen cutting fine-grained granites. If this is the case, the fact that the elvan and coarse-grained granite at Porthloo appear contemporaneous would not be quite so remarkable. Further research on the Cornish elvans is clearly overdue.

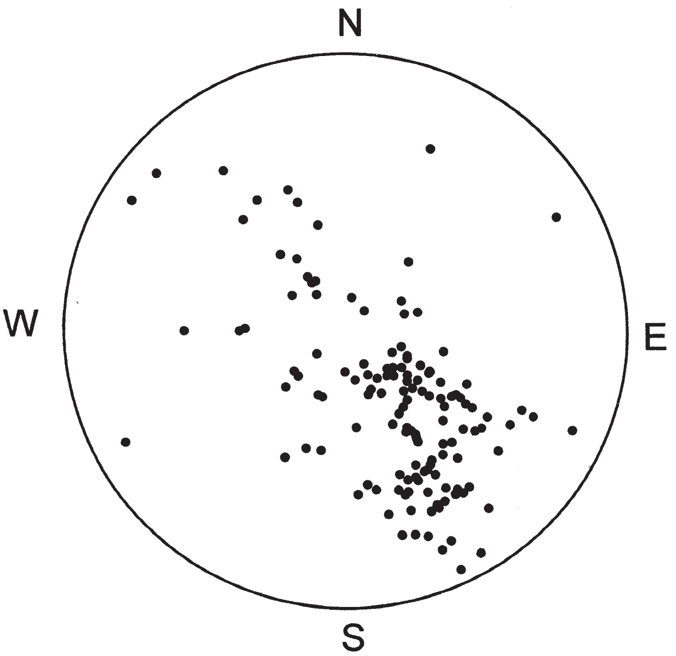

Figure 4. *Stereographic projection showing poles to fault planes.*

Structures

Early workers described post-emplacement structures present in the pluton. Barrow (1906) reported "greisen lines" which trend ENE-WSW and "low-hade planes" with no greisen. Osman (1928) paid particular attention to the structures, reporting NNW-SSE trending strike-slip faults and low-hade thrust planes, which he interpreted as being associated with the emplacement of the 'Stage 3 fine granite'. Hawkes *et al.* (1986) reported reddening of the granite associated with ENE trending structures. The current study has identified two sets of steeply-dipping faults and a set of sub-horizontal or gently-dipping (angle of dip <20°) faults.

Examples of gently-dipping faults are present at Gap Point (St. Mary's), the north-eastern outcrops of White Island and in the gully between the north end of Bryher and Shipman Head. Greisen-bordered veins are present throughout the pluton, with good examples on Great Ganilly and an anastomosing system of greisen veins on the south side of Nornour. The predominant set of faults, that includes the gently-dipping ones, strikes *c.* NE-SW and mostly dips NW, with a minor set, which strikes *c.* NW-SE and is sub-vertical (Figure 4). Most of the faults have quartz and tourmaline infills, indicating the presence of magmatic or magmatic-hydrothermal fluids during deformation. A number are associated with fine-grained granite sheets, but it is unclear whether the fine-grained granite predates the deformation and simply represents a plane of weakness, or whether intrusion of the magma accompanied shearing. Slickensides are present on many surfaces and indicate that in most cases the shearing was oblique-slip. In places, the granite above and below gently-dipping fault planes has been deformed, with phenocrysts rotated into, and out of, the plane of shear. This suggests that brittle faulting overprinted ductile shear zones that developed either late in the magmatic state or whilst the granite was just below its solidus. On many gently-dipping faults, the various indicators describe a dextral sense of shear, mostly with 'top to the south-east' movement, although a number around Gap Point, St Mary's, have 'top to the north-west' movement, with sinistral shear. Moderately-dipping quartz veins are present in the hanging walls of some gently-dipping faults, e.g. at Gap Point, St Mary's.

Gently-dipping faults have not been recognised in all of the plutons of the batholith. None have been reported from the Land's End Granite, but similar gently-dipping structures, termed "quartz floors", have been documented in the Carnmenellis Granite at South Crofty Mine (Owen, 1981). These represent one of the earliest fracturing events in the granite and have infills of quartz ± feldspar ± tourmaline ± wolframite ± arsenopyrite ± cassiterite ± chalcopyrite and dip gently to the SSE (Owen, 1981). Although there is little published kinematic information, unpublished data indicate that some of these structures are gently-dipping extensional faults (Shail *pers. comm.* 2001). Elsewhere in south Cornwall, gently-dipping faults have been shown to be extensional and post-date Variscan contractional deformation (Shail and Wilkinson, 1994; Alexander and Shail, 1995). Observations of cross-cutting relationships in a number of localities indicates several phases of faulting (Table 2) and shows that some of the dominant NE-SW set are late. The dominant fine-grained granite dyke trend within the pluton is also NE-SW, as is that of quartz veins (many, admittedly, associated with shear planes), suggesting a period of NW-SE extension during and immediately following the emplacement of most of the coarse granites. Work on the significance of these structures is ongoing.

Relative Age	Infill	Orientation
Oldest	Greisen ± quartz ± tourmaline	NE-SW
	quartz ± tourmaline	NW-SE
	quartz ± tourmaline	E-W
Youngest	quartz ± tourmaline	NE-SW

Table 2. *Relative ages of infills and orientations of faults.*

Summary

Re-mapping of the Isles of Scilly pluton has confirmed that it is made up of a number of distinct, relatively small, individual granites. This is in contrast to earlier interpretations which described the pluton as comprising two predominant granite types. In essence, however, the earlier interpretations were correct, as all of the granites identified by the current study comform broadly to the classifications used by previous workers. Differences between the individual granites are often subtle. This means that contacts between them, if exposed, are easily overlooked. However, a number of internal contacts between granites have been identified indicating that the pluton is complex and composite. Contact relationships reveal that a number of the granites were present as coexisting magmas. Because of the greater degree of crystallization required to produce them, planar contacts suggest somewhat longer time-gaps between successive intrusions.

The coarse-grained granites which make up Bryher, the greater part of Tresco and the northern half of St. Martin's all appear to belong to the same intrusion. They are abundantly-porphyritic and contain numerous enclaves, some several metres across, of both moderately-porphyritic and sparsely-porphyritic coarse-grained granite. Contact relationships suggest that both predate the abundantly-porphyritic granite but that all three were present as coexisting magmas. The fact that fewer enclaves occur in the abundantly-porphyritic granite which occupies the southern half of the east coast of Bryher may indicate that this represents a separate and slightly later pulse of the same magma. There are also instances, such as on the west coast of Tresco and near Lower Town on St. Martin's, where large bodies of fine-grained granite appear to be intrusive into the abundantly-porphyritic granite, when the latter was still in a magmatic state. The northern tip of Bryher is occupied by a larger body of sparsely-porphyritic coarse-grained granite. Contacts are very intimate and intermingled, with each granite containing enclaves of the other. It appears that the sparsely-porphyritic granite is intrusive into the abundantly-porphyritic granite. A similar situation occurs at the north end of White Island, where sparsely-porphyritic granite also appears to post-date abundantly-porphyritic granite, although relationships here suggest that the latter was at a more advanced stage of crystallization, possibly solid. The southern half of St. Martin's, together with Great Ganilly, are occupied by moderately-porphyritic coarse-grained granite which has a distinctive range of phenocryst sizes. Dykes of fine-grained granite which cut the northern abundantly-porphyritic granite do not intrude the moderately-porphyritic coarse-grained granite, suggesting that the latter is the younger of the two.

St. Mary's has the largest number of different granites. Much of its eastern half is occupied by abundantly-porphyritic coarse-grained granite, although local variations in phenocryst abundance and orientation suggest that it may comprise more than one phase of intrusion. The western half of St. Mary's contains a number of different granites, each recognisable as an individual intrusion. Much of the north-western coast has fine and medium-grained granites which were originally mapped as part of the fine-grained granite 'core'.

The abundantly-porphyritic coarse-grained granite which occupies the southern parts of St. Agnes and Gugh is similar to that in the southern part of St. Mary's, and may represent extensions of it. However, the moderately-porphyritic coarse-grained granite which occupies the northern part of these islands appears dissimilar to that around the Garrison and Rat Island on St. Mary's.

Numerous dykes and sub-horizontal sheets cut the coarser-grained granites. These are predominantly of fine-grained granite with some, notably those around Gap Point on St. Mary's, being of medium-grained granite. In places, cross-cutting relationships indicate that the dykes post-date the sub-horizontal sheets. Early workers interpreted the fine-grained granite dykes as offshoots of the fine-grained granite 'core', but as the fine-grained granite 'core' is, in fact, medium-grained, this interpretation appears untenable. Although contacts are sharp, most are protrusive, indicating that the host granites were not completely solid when the dykes and sheets were emplaced.

Elvan dykes intrude the coarse-grained granites but never the finer varieties. This is the same situation as reported in the rest of the batholith where their relationship with fine-grained granites is usually described as "uncertain". This could be taken as evidence that the elvans predate, or are of similar age as, the fine-grained granites. In the Isles of Scilly pluton this would lend support to the evidence that the elvans (certainly those on St. Mary's) were emplaced before the host coarse granites were completely solid.

CONCLUSIONS

The Isles of Scilly pluton was built up in a piecemeal fashion by the successive emplacement of numerous small batches of granite magma. A similar process of multiple intrusion has been identified by recent work on the Land's End pluton, one of the youngest plutons of the Cornubian batholith. As the Isles of Scilly pluton is one of the oldest, it would appear that such a process spans the formative life of the batholith. This contradicts some early models for the formation of the batholith, which postulated the successive emplacement of a relatively small number of large diapiric masses which then differentiated *in-situ* to produce the granite varieties present. However, few of the larger granite bodies are distinctly sheet-like and, although structural evidence suggests that the granites were emplaced during a period of extensional faulting, evidence for the actual mechanism of emplacement is, as yet, inconclusive.

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REFERENCES

ALDERTON, D.H.M. 1993. Mineralization associated with the Cornubian granite batholith. In: PATTRICK, R.A.D. and POLYA, D.A. (eds), *Mineralization in the British Isles*. Chapman and Hall, London, 270-354.

ALEXANDER, A.C. and SHAIL, R.K. 1995. Late Variscan structure on the coast between Perranporth and St. Ives, Cornwall. *Proceedings of the Ussher Society*, **8**, 398-404.

ARZI, A.A. 1978. Critical phenomena in the rheology of partially melted rocks. *Tectonophysics*, **44**, 173-184

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 Bulletin*, **90**, 465-482.

BARROW, G. 1906. *The geology of the Isles of Scilly*. Memoir of the Geological Survey of England and Wales.

BONS, P.D., ELBURG, M.L., STEBBING, N., PARNELL, C. and SOESOO, A. 1999. The Mr Curly multi-lenticular granitoid complex, Western Australia. *Conference abstracts, Fourth Hutton Symposium on the Origin of Granites,* Clermont-Ferrand, France.

BOOTH, B. and EXLEY, C.S. 1987. Petrological features of the Land's End Granite. *Proceedings of the Ussher Society*, **6**, 439-446.

BROWN, G.C., CASSIDY, J., TINDLE, A.G. and HUGHES, D.J. 1979. The Loch Doon granite: an example of granite petrogenesis in the British Caledonides. *Journal of the Geological Society, London*, **136**, 745-753.

BRUN, J.P., GAPAIS, D., COGNE, J.P., LEDRU, P. and VIGNERESSE, J.L. 1990. The Flamanville granite (northwestern France): an unequivocal example of a syntectonically expanding pluton. *Geological Journal*, **25**, 271-286.

BUDDINGTON, A.F. 1959. Granite emplacement with special reference to North America. *Geological Society of America Bulletin*, **70**, 671-747.

CARNE, J. 1850. On the Geology of the Islands of Scilly. *Transactions of the Royal Geological Society of Cornwall*, **7**, 140-154.

CASTRO, A. 1986. Structural pattern and ascent model in the Central Extremadura batholith, Hercynian belt, Spain. *Journal of Structural Geology*, **6**, 633-645.

CASTRO, A. and FERNANDEZ, C. 1998. Granite intrusion by externally induced growth and deformation of the magma reservoir, the example of the Plasenzuela pluton, Spain. *Journal of Structural Geology*, **20**, 1219-1228.

CHEN, Y. 1994. *Geochronological relationships in the Cornubian metallogenetic province, southwest England.* Unpublished PhD thesis, Queens University, Kingston, Ontario.

CHEN, Y., CLARK, A.H., FARRAR, E., WASTENEYS, H.A.H.P., HODGSON, M.J. and BROMLEY, A.V. (1993). Diachronous and independent histories of plutonism and mineralisation in the Cornubian Batholith, southwest England. *Journal of the Geological Society, London*, **150**, 1183-1191.

CLARK, A.H., CHEN, Y., FARRAR, E., WASTENEYS, H.A.H.P., STIMAC, J.C., HODGSON, M.J., WILLIS-RICHARDS, J. and BROMLEY, A.V. 1993. The Cornubian Sn-Cu(-As,W) metallogenetic province: produce of a 30 M.Y. history of discrete and concomitant anatectic intrusive and hydrothermal events. *Proceedings of the Ussher Society*, **8**, 112-116.

CLEMENS, J.D. 1998. Observations on the origins and ascent mechanisms of granitic magmas. *Journal of the Geological Society, London*, **155**, 843-851.

CLEMENS, J.D. and MAWER, C.K. 1992. Granitic magma transport by fracture propagation. *Tectonophysics*, **204**, 339-360.

CORRY, C.E. 1988. *Laccoliths: mechanisms of emplacement and growth*. Geological Society of America Special papers, **220**.

CRUDEN, A.R. 1998. On the emplacement of tabular granites. *Journal of the Geological Society, London*, **155**, 853-862.

DANGERFIELD, J. and HAWKES, J.R. 1981. The Variscan Granites of south-west England: additional information. *Proceedings of the Ussher Society*, **5**, 116-120.

DARBYSHIRE, D.P.F. and SHEPHERD, T.J. 1985. Chronology of granite magmatism and associated mineralization, SW England. *Journal of the Geological Society, London*, **142**, 1159-1177.

D'LEMOS, R.S., BROWN, M. and STRACHAN, R.A. 1992. Granite magma generation, ascent and emplacement within a transpressional orogen. *Journal of the Geological Society, London*, **149**, 487-490.

ENGLAND, R.W. 1992. The genesis, ascent and emplacement of the Northern Arran granite, Scotland: implications for granite diapirism. *Geological Society of America Bulletin*, **104**, 606-614.

EXLEY, C.S. and STONE, M. 1982. Petrology of the granites and minor intrusions. In: Sutherland, D.S. (Ed.), *Igneous Rocks of the British Isles*. John Wiley and Sons, Chichester, 293-302.

EXLEY, C.S., STONE, M. and FLOYD, P.A. 1983. Composition and petrogenesis of the Cornubian granite batholith and post-orogenic volcanic rocks in southwest England. In: HANCOCK, P.L. (Ed.), *The Variscan fold belt in the British Isles*. Adam Hilger, Bristol, 153-177.

FLOYD, P.A., EXLEY C.S. and STYLES M.T. 1993. *Igneous Rocks of Southwest England*. Chapman and Hall, London.

GOODE, A.J.J. 1973. The mode of intrusion of Cornish elvans. *Report of the Insitute of Geological Sciences No. 73/7.*

GOODE, A.J.J. and TAYLOR, R.T. 1980. Intrusive and pneumatolytic breccias in south-west England. *Report of the Insitute of Geological Sciences No. 80/2.*

GHOSH, P.K. 1934. The Carnmenellis Granite: its petrology, metamorphism and tectonics. *Quarterly Journal of the Geological Society, London*, **90**, 240-276.

HALL, A. 1970. The composition of Cornish quartz-porphyry ("elvan") dykes. *Proceedings of the Ussher Society*, **2**, 205-208.

HAWKES, J.R., HARDING, R.R. and DARBYSHIRE, D.P.F. 1975. Petrology and Rb/Sr age of the Brannel, South Crofty and Wherry elvan dykes, Cornwall. *Bulletin of the Geological Survey of Great Britain No. 52.*

HAWKES, J.R.; DANGERFIELD, J. and WHEATLEY, C.W. 1986. A geological field guide to the Isles of Scilly, Cornwall. *Mineralogy and Petrology Report No. 86/35.* British Geological Survey, Keyworth.

HENLEY, S. 1974. Geochemistry and petrogenesis of elvan dykes in the Perranporth area, Cornwall. *Proceedings of the Ussher Society*, **3**, 136-145.

HILL, P.I. and MANNING, D.A.C. 1987. Multiple intrusions and pervasive hydrothermal alteration in the St. Austell Granite, Cornwall. *Proceedings of the Ussher Society*, **6**, 447-453.

HOGAN, J.P., GILBERT, M.C. and PRICE, J.D. 1998. Magma traps and driving pressure: consequences for pluton shape and emplacement in an extensional regime. *Journal of Structural Geology*, **20**, 1155-1168.

HUTTON, D.H.W. 1982. A tectonic model for the emplacement of the Main Donegal granite, NW Ireland. *Journal of the Geological Society, London*, **139**, 615-631.

HUTTON, D.H.W. 1988. Granite emplacement mechanisms and tectonic controls: Inferences from deformation studies. *Transactions of the Royal Society of Edinburgh*, **79**, 245-255.

HUTTON, D.H.W. 1992. Granite sheeted complexes: evidence for the dyking mechanism. *Transactions of the Royal Society of Edinburgh*, **83**, 377-382.

HUTTON, D.H.W. 1996. The 'space problem' in the emplacement of granite. *Episodes*, **19**, 114-119.

JACKSON, M.D. and POLLARD, D.D. 1988. The laccolith-stock controversy: new results from the southern Henry Mountains, Utah. *Geological Society of America Bulletin*, **100**, 117-139.

KNOX, D.A. and JACKSON, N.J. 1990. Composite granite intrusions of SW Dartmoor, Devon. *Proceedings of the Ussher Society*, **7**, 246-251.

MAHOOD, G.A. and CORNEJO, P.C. 1992. Evidence for ascent of differentiated liquids in a silicic magma chamber found in a granitic pluton. *Transactions of the Royal Society of Edinburgh*, **83**, 63-69.

MANNING, D.A.C., HILL, P.I. and HOWE, J.H. 1996. Primary lithological variation in the kaolinized St Austell Granite, Cornwall, England. *Journal of the Geological Society, London*, **153**, 827-838.

McCAFFREY, K. 1992. Igneous emplacement in a transpressive shear zone: Ox Mountains igneous complex. *Journal of the Geological Society, London*, **149**, 221-235.

MULLIS, S.J.L. 2001. *The formation and emplacement of the Isles of Scilly Pluton*. Unpublished MSci thesis, University of Derby.

OSMAN, C.M. 1928. The granites of the Scilly Isles and their relation to the Dartmoor granites. *Quarterly Journal of the Geology Society, London*, **84**, 258-292.

OWEN, M.C. 1981. *The evaluation of a tungsten orebody at South Crofty tin mine, Cornwall*. Unpublished MSc thesis, Camborne School of Mines.

PATERSON, S.R. and VERNON, R.H. 1995. Bursting the bubble of ballooning plutons: a return to nested diapirs emplaced by multiple processes. *Geological Society of America Bulletin*, **107**, 1356-1380.

PETFORD, N. 1996. Dykes or diapirs? *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **87**, 104-114.

PETFORD, N., KERR, R.C. and LISTER, J.R. 1993. Dike transport of granitoid magmas. *Geology*, **21**, 845-848.

PITCHER, W.S. and BERGER, A.R. 1972. *The Geology of Donegal: A study of granite emplacement and unroofing.* Wiley, New York.

PHILLIPS, W.J. 1956. The Criffell-Dalbeattie granodiorite complex. *Journal of the Geological Society, London*, **138**, 221-239.

PORTER, R. 1997. *A study of the dykes from Porthoustock Point to Godrevy Cove, the Lizard, Cornwall.* Unpublished BSc thesis, University of Derby.

POWELL, T., SALMON, S., CLARK, A.H. and SHAIL, R.K. 1999. Emplacement styles within the Land's End granite, West Cornwall. *Geoscience in south-west England*, **9**, 333-339.

RAMBERG, H. 1970. Model studies in relation to intrusion of plutonic bodies. In: NEWALL, G. and RAST, N. (eds), *Mechanisms of Igneous Intrusions*. Seel House Press, Liverpool, 261-286.

REID, C. and FLETT, J.S. 1907. *Geology of the Land's End District*. Memoir of the Geological Survey of Great Britain.

SALMON, S. 1994. Mingling between coexisting granite magmas within the Land's End granite - preliminary observations. *Proceedings of the Ussher Society*, **8**, 219-223.

SALMON, S. and POWELL, T. 1998. Variation in the fine-grained granites of the Land's End Pluton. *Geoscience in south-west England*, **9**, 157-164.

SALMON, S. and SHAIL, R.K. 1999. Field excursion to examine the granites in the area between Cape Cornwall and Porth Nanven, West Penwith, 3rd January 1999. *Geoscience in south-west England*, **9**, 391-393.

SELWOOD, E.B., DURRANCE, E.M. and BRISTOW, C.M. 1998. *The Geology of Cornwall.* University of Exeter Press, Exeter.

SHAIL, R.K. and WILKINSON, J.J. 1994. Late- to post-Variscan extensional tectonics in south Cornwall. *Proceedings of the Ussher Society*, **8**, 262-270.

STATHAM, F.T. 1859. On the Geology of the Scilly Isles. *Geologist*, **2**, 12-27.

STIMAC, J.A., CLARK, A.H., CHEN, Y. and GARCIA, S. 1995. Enclaves and their bearing on the origin of the Cornubian batholith, southwest England. *Mineralogical Magazine*, **59**, 273-296.

STONE, M. 1968. A study of the Praa Sands elvan and its bearing on the origin of elvans. *Proceedings of the Ussher Society*, **2**, 37-42.

STONE, M. 1987. Geochemistry and origin of the Carnmenellis pluton, Cornwall: further considerations. *Proceedings of the Ussher Society,* **6**, 454-460.

STONE, M. 2000. The early Cornubian plutons: a geochemical study, comparisons and some implications. *Geoscience in south-west England*, **10**, 37-41.

STONE, M. and EXLEY, C.S. 1989. Geochemistry of the Isles of Scilly pluton. *Proceedings of the Ussher Society*, **7**, 152-157.

TINDLE, A.G. and PEARCE, J.A. 1981. Petrogenetic modelling of in situ fractional crystallization in the zoned Loch Doon pluton, Scotland. *Contributions to Mineralogy and Petrology*, **78**, 196-207.

VAN DER MOLEN, I. and PATERSON, M.S. 1979. Experimental deformation of partially melted granite. *Contributions to Mineralogy and Petrology*, **70**, 299-318.

VIGNERESSE, J.L. and BOUCHEZ, J.L. 1997. Successive granitic magma batches during pluton emplacement: the case of Cabeza de Araya (Spain). *Journal of Petrology*, **38**, 1767-1776.