The role of regional tectonics and magma flow coupling versus magmatic processes in generating contrasting magmatic fabrics within the Land's End Granite, Cornwall

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Kratinova, Z., Schulmann, K., Hrouda, F. and Shail, R.K. 2003. The role of regional tectonics and magma flow coupling versus magmatic processes in generating contrasting magmatic fabrics within the Land's End Granite, Cornwall. *Geoscience in south-west England*, **10**, 442-448.

The Lower Permian Land's End Granite intruded Upper Devonian metasedimentary and metavolcanic rocks of the Mylor Slate Formation that had been previously deformed and regionally metamorphosed during Variscan convergence. Structural studies of the host rocks have been used to infer that granite generation and emplacement occurred in response to regional D3 NNW-SSE extension of moderately thickened crust. Detailed field mapping along the northwestern margin of the granite reveals complex magmatic fabrics defined by K-feldspar and biotite. Close to the pluton margins, a gently NW or SE dipping magmatic foliation is defined by the preferred orientation of K-feldspar and biotite. Further from the pluton margin, the foliation dips moderately NW or SE, or occurs in steeply dipping NW-SE trending zones with very strong fabrics. Magmatic foliations tend towards parallelism with the margins of stoped blocks over a distance of one to several metres, but there is no evidence that the blocks deform a previously formed magmatic fabric. The Land's End Granite exhibits low degrees of anisotropy of magnetic susceptibility (AMS) and biotite is the carrier. The AMS foliation generally dips gently to the NW or SE and contains two, near-orthogonal lineations that trend ENE-WSW and N-S. The variations in magnetic lineation orientation correlate with the intensity of the macroscopic feldspar fabric. In zones where the feldspar fabric is strongly developed, the AMS has a NW plunging lineation, whereas in zones where the feldspar fabric is weak, the AMS has a NE plunging lineation. There is close correspondence between the orientation of the AMS fabrics and D3 structures within the Mylor Slate Formation. However, it is possible that there was only partial coupling between the granite magma and extensional deformation of the host rock. Stoped blocks and host rock irregular contacts exert a significant control on fabric orientation.

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Introduction

Magmatic fabrics comprise the foliations, lineations and associated microstructures that form by crystal alignment in the presence of a melt. Such fabrics may represent a combination of different flow regimes, complex displacement paths and the variable behaviour of passive and active particles (Paterson *et al.*, 1998). Multiple magmatic fabrics have been described in many plutons (e.g. Blumenfeld and Bouchez, 1988; Schulmann *et al.*, 1997). Various explanations are proposed, including differential rotation of minerals with different axial ratios during non-coaxial deformation (Blumenfeld and Bouchez, 1988), formation of orthogonal foliations of minerals with contrasting axial ratios during coaxial flow (Ježek *et al.*, 1996; Schulman *et al.*, 1997), and multiple processes operating during the evolution of a magma chamber (Paterson *et al.*, 1998).

The interpretation of magmatic fabrics is partially dependent upon the timing of their formation relative to chamber construction and regional deformation (Paterson *et al.*, 1998). In near surface to mid-crustal plutons the timing of magmatic fabric development can be evaluated by assessing its relationship to stoped blocks (Fowler and Paterson, 1997; Paterson and Miller, 1998). Paterson *et al.* (1998) proposed a model for magmatic fabric development based upon the degree of coupling between the host rock and granite. Their scheme provides a framework against which the relative contribution of internal magma chamber processes and regional strain can be assessed. The role of regional and local tectonic strains in governing the emplacement of, and fabric development in, magmas has been the focus of considerable recent research (e.g. Hutton, 1997).

Anisotropy of magnetic susceptibility (AMS) analysis is a common method, providing a quantitative description of crystalline fabrics, which has recently been applied to the mapping of magmatic fabrics (e.g. Bouchez, 1997). If the sampling is detailed enough and the magnetic mineralogy is known, than the AMS technique allows the determination of magmatic fabric variations at outcrop scale.

Although the occurrence of magmatic fabrics within the Cornubian Batholith, particularly those defined by feldspar phenocrysts, is well known, relatively little has been published since the work of Ghosh (1934) on the Carnmenellis Granite (Figure 1), with the exception of very recent work by Mintsa Mi Nguema *et al.* (2002). The degree of coupling between magma flow and regional tectonics, and the relative timing of fabric formation with respect to final chamber construction, are poorly constrained. The purpose of this paper is to describe the field relationships and magmatic fabrics along the northwestern margin of the Land's End Granite and evaluate the control(s) upon fabric development. The new data presented here are part of an ongoing study to assess the relative contribution of regional tectonics and internal magmatic processes in the development of the magmatic fabrics within the Land's End Granite. The orientation of the magmatic fabric has been investigated using the shape-preferred orientation (SPO) of igneous minerals (K-feldspar, biotite) and by the anisotropy of magnetic susceptibility (AMS) technique.

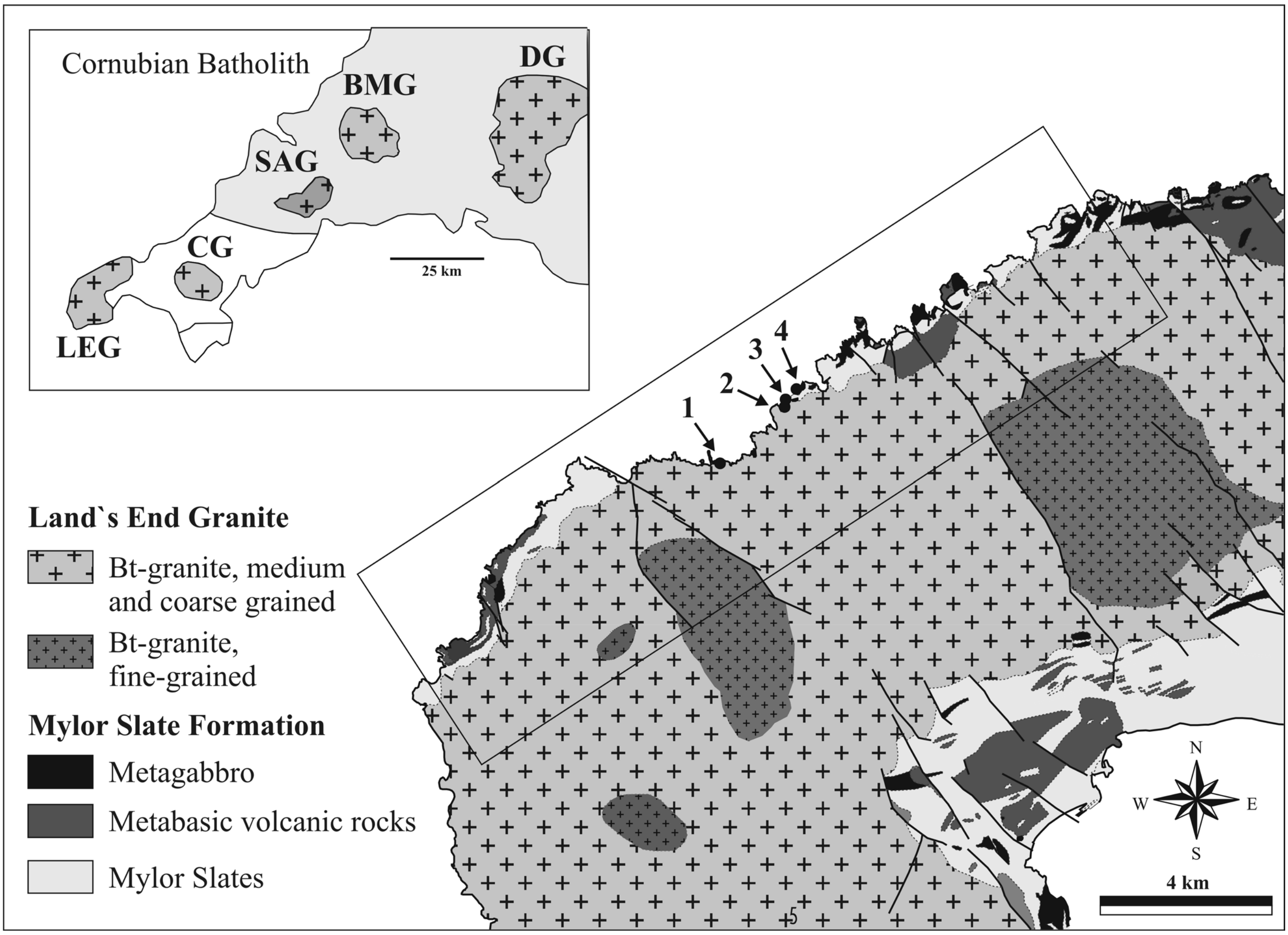

Figure 1. *Simplified geological map of the Land's End Granite (after British Geological Survey, 1984). Inset shows the Gramscatho Basin (no ornament) and the principal plutons of the Cornubian Batholith: Dartmoor Granite (DG), Bodmin Moor Granite (BMG), St Austell Granite (SAG), Carnmenellis Granite (CG) and Land's End Granite (LEG). The box corresponds to the study area represented in more detail in Figure 2. Four localities were investigated using the AMS method (1, Wolf Rocks; 2, Halldrine Cliff; 3, cliff between Halldrine Cove and Great Zawn; 4, Great Zawn).*

GEOLOGICAL SETTING

South Cornwall represents the westernmost part of the Variscan basement massif in SW England (Figure 1). The Gramscatho Group comprises deep marine sedimentary and volcanic rocks of Devonian age that accumulated in the Gramscatho Basin during rifting and the early stages of Variscan convergence (Holder and Leveridge, 1986; Isaac *et al.*, 1998). These successions subsequently underwent thrust-related burial, deformation and low-grade regional metamorphism during the Carboniferous as a consequence of Variscan convergence (Andrews *et al.*, 1998; Warr *et al.*, 1991). Towards the end of the Carboniferous, there was a change to an extensional tectonic regime that was associated with widespread magmatism, mineralization and the development of sedimentary basins (Dearman, 1970; Hawkes, 1981; Watson *et al.*, 1984; Shail and Wilkinson, 1994).

The Cornubian Batholith represents a suite of peraluminous, S-type (Chappell and White, 1974) and anatectic granites (Booth and Exley, 1987; Ghosh, 1934). It is markedly composite at a variety of scales and has been assembled through successive intrusions of texturally different magma batches (e.g. Hawkes and Dangerfield, 1978; Dangerfield and Hawkes, 1981; Hill and Manning, 1987; Salmon, 1994). The age of emplacement, determined by U-Pb dating of magmatic monazite, spans some 20 Ma, ranging from 293 ± 1.3 Ma for the Carnmenellis Granite to 274.5 ± 1.4 Ma for the Land's End Granite (Chen *et al.*, 1993; Chesley *et al.*, 1993). The granites are approximately coeval with a range of mantle-derived intrusive and extrusive igneous rocks (e.g. Floyd *et al.*, 1993) and studies of enclaves suggest there may have been mingling between the two (Stimac *et al.*, 1995). Geochemical data indicate a predominantly crustal origin for the granites with a minor, but variable, mantle-derived component (Floyd *et al.*, 1993; Darbyshire and Shepherd, 1994; Stone, 1997, 2000).

The Land's End Granite (Figure 1), is exposed in cliffs up to 90 m high around the coast of West Penwith and intrudes intensively deformed Upper Devonian rocks of the Mylor Slate Formation (Goode and Taylor, 1988). The pluton comprises two predominant types of granite, coarse-grained porphyritic granite and fine-grained granite (Reid and Flett, 1907; Dangerfield and Hawkes, 1981; Booth and Exley, 1987; Goode and Taylor, 1988; Salmon, 1994; Powell *et al.*, 1999; Halls *et al.*, 2001). Different textural types within the fine-grained granite have been recognised according to the amount of phenocrysts (Salmon and Powell, 1998). In general, the mineralogy consists of quartz, alkali-feldspar (orthoclase), plagioclase, biotite, cordierite and accessory minerals (monazite, zircon, tourmaline and muscovite). Abundant microgranitoid enclaves, attributed to an origin by magma mingling (e.g. Vernon *et al.*, 1988), are present in both textural types (Stimac *et al.*, 1995). Emplacement models suggested for the Land's End Granite include diapiric ascent of a single magma, accompanied by contamination, differentiation and metasomatism (Booth and Exley, 1987; Goode and Taylor, 1988; Rattey and Sanderson, 1984) and/or multiple intrusion of discrete magma pulses (Powell *et al.*, 1999).

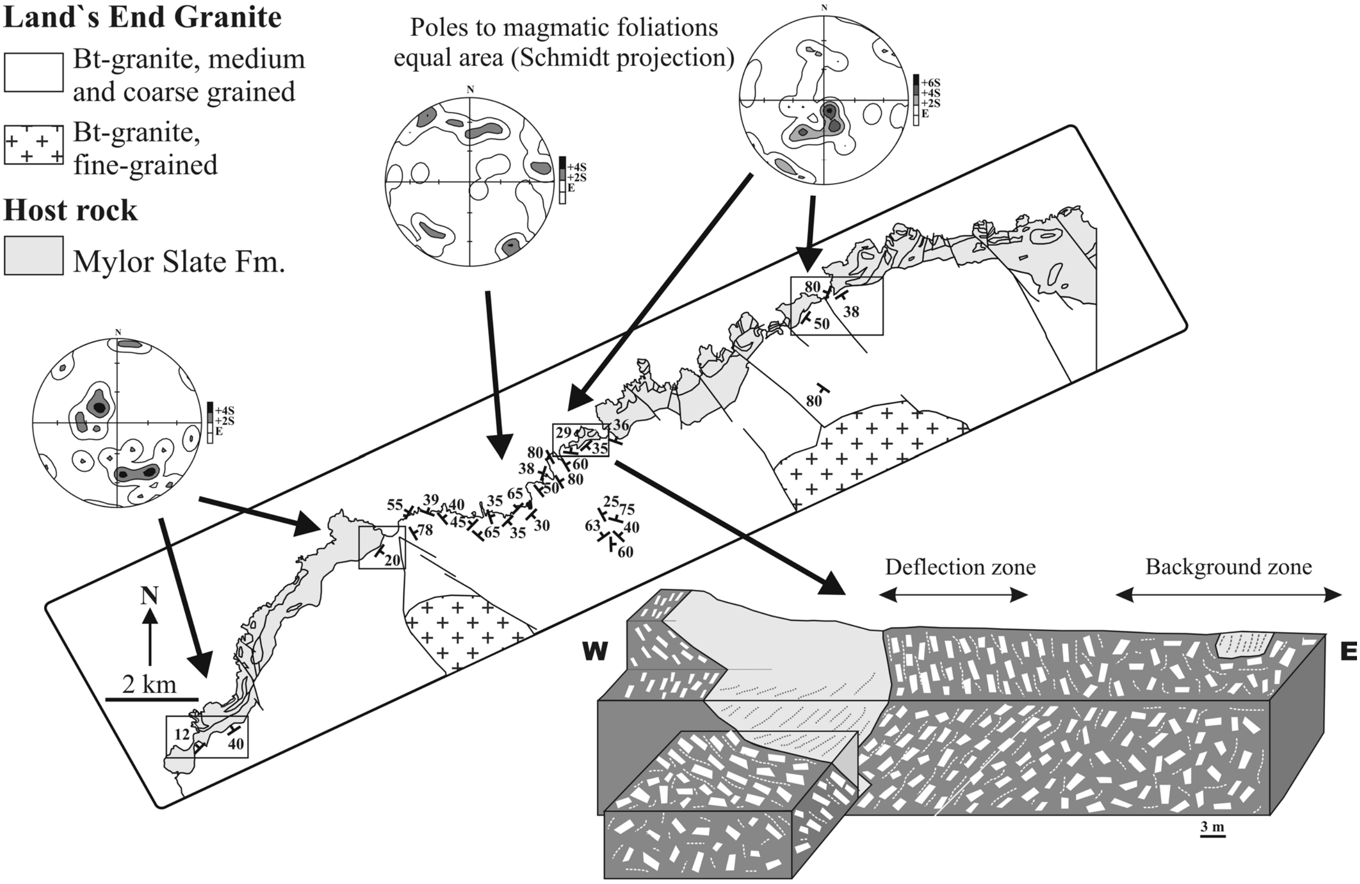

Figure 2. Structural map of the study area. Lower hemisphere stereograms show poles to magmatic foliations (see text). The schematic cross-section represents the magmatic fabric in the vicinity of a stoped block between Halldrine Cove and Great Zawn.

HOST ROCK DEFORMATION

The Mylor Slate Formation comprises intercalated metasedimentary and metabasic rocks that are intensively deformed and were affected by low-grade regional metamorphism and later thermal contact metamorphism in the vicinity of the Land's End Granite (Goode and Taylor, 1988). Detailed structural investigations in south Cornwall have indicated two episodes of deformation (D1 and D2) associated with Variscan convergence. These are generally represented by NNW-verging folds and SSE-dipping cleavages that formed in a thrust regime with a top sense-of-shear to the NNW (e.g. Rattey and Sanderson, 1984). D3 folds and cleavage were interpreted by Rattey and Sanderson (1984) to have developed during the subsequent diapiric emplacement of the granite and supposedly exhibit a "fir tree" geometry similar to that described by Pitcher and Berger (1972). One of the requirements of their model is that folds to the south of the batholith generally verge to the SSE (unless on the overturned limb of a larger-scale structure), whilst those to the north generally verge to the NNW.

However, recent work in south Cornwall suggests that most ductile D3 strain predates, and is not spatially related to, the granites (Alexander and Shail, 1995, 1996; Salmon and Shail, 1999). F3 folds along the northern margin of the batholith, including the Land's End Granite, generally verge to the SSE, similar to those along the southern margin. D3 deformation cannot be attributed to granite emplacement and the diapiric model of Rattey and Sanderson (1984) is rejected (Alexander and Shail, 1995, 1996; Salmon and Shail, 1999). Instead, D3 deformation is interpreted as having initiated during the latest Carboniferous in response to NNW-SSE extension of the previously thickened crust. F3 folds generally verge SSE and S3 cleavage dips NNW or is horizontal; both are usually compatible with formation by a top sense-of-shear to the SSE, developed during thrust fault reactivation. These ductile fabrics are overprinted by ENE-WSW striking extensional faults and tensile fractures, and NNW-SSE strike-slip faults, that indicate continued NNW-SSE extension during exhumation of the country rocks and granite emplacement (Alexander and Shail, 1995, 1996). These brittle structures are developed in the granites as well as the country rock and are often mineralised (e.g. Moore, 1975). Collectively, these data have been interpreted as indicative of granite generation and emplacement occurring within a latest Carboniferous to early Permian NNW-SSE extensional tectonic regime (Shail and Wilkinson, 1994; Alexander and Shail, 1995, 1996; Shail and Alexander, 1997).

MAGMATIC FABRICS

The magmatic fabric was investigated along the northwest margin of the Land's End Granite between St Just and Zennor (Figure 1). The main textural variety studied is a medium to coarse-grained, porphyritic biotite granite containing variable proportions and sizes of feldspar phenocrysts; grainsize terminology follows Dangerfield and Hawkes (1981). The dominant magmatic fabric in the porphyritic granite is sub-horizontal and strongly developed. It is defined by the preferred orientation of subhedral alkali-feldspar phenocrysts and biotite within the coarse-grained groundmass. In the north-eastern and south-western parts of the section, close to the contact with the Mylor Slate Formation, the foliation defined by feldspar phenocrysts dips gently to the NW or SE (Figure 2). However, in the central part of the section, where the host rock is absent, the feldspar foliations dip moderately NW or SE, or form wide NW-SE trending zones of steep and intense feldspar fabrics (Figure 2). Adjacent to stoped blocks of the Mylor Slate Formation the magmatic foliations and lineations become parallel to block margins within one to several metres from the contact (Figure 2).

The magmatic fabric also varies in direction and intensity in the deeper parts of the intrusion in a manner that appears to be

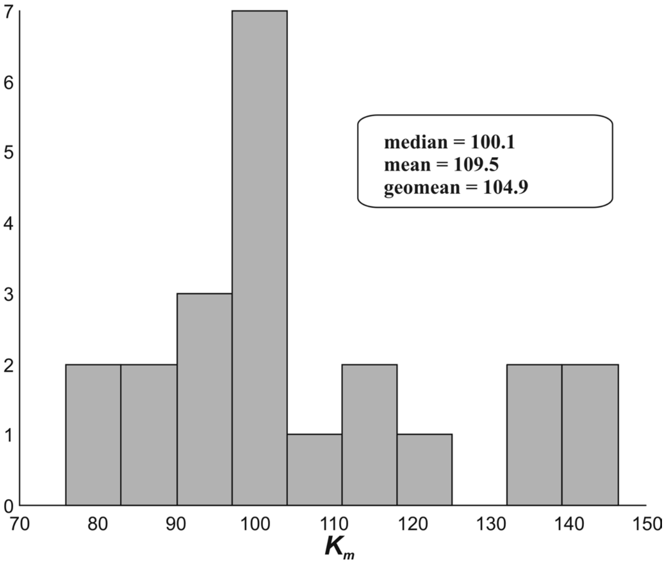

Figure 3. *Histogram showing the bulk magnetic susceptibility (K_m) values, where* $K_m = (k_1 + k_2 + k_3)/3$.

related to variations in K-feldspar crystal size and abundance. Locally, transitions from subhorizontal to subvertical planar fabrics are observed at outcrop scale. However, this fabric is locally disturbed by semi-circular metre-scale patterns defined by the K-feldspar SPO. These curved zones of K-feldspar fabrics are often not continuous and produce complex interference patterns at outcrop scale. Aplite and pegmatite sheets and subvertical tourmaline-quartz veins cut magmatic fabrics within the porphyritic granite.

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY (AMS)

The magmatic fabric data was complemented by a detailed magnetic susceptibility study. Four profiles (Figure 1) were selected and a total of 400 samples were obtained using a portable drilling machine. An average of seven cores were obtained from each sample site. Low field anisotropy of magnetic susceptibility (AMS) was measured with the KLY-3S Kappabridge (Jelinek and Pokorny, 1997). The data were statistically evaluated using the ANISOFT program package (Hrouda *et al.*, 1990). AMS is a petrophysical technique for investigating the preferred orientation of magnetic minerals in rocks. It is represented by symmetric second rank susceptibility tensor whose principal directions often correlate to the principal directions of the finite strain tensor (Hrouda, 1993). In order to determine the contribution of particular minerals to the bulk rock susceptibility, variations of the bulk susceptibility with temperature were analyzed on powder specimens using the CS-3 apparatus and KLY-3S Kappabridge (Parma and Zapletal, 1991).

Results of AMS

The mean bulk magnetic susceptibility (K_m) of the samples is relatively low, ranging from 75 x 10^{-6} to 146 x 10^{-6} SI (Figure 3). The thermomagnetic curve for a representative sample has a hyperbolic profile from its initial parts up to temperatures of 500°C and indicates a more marked decrease in magnetic susceptibility in the vicinity of 560-570°C as the Curie temperature is approached (Figure 4). These results suggest that the AMS is principally controlled by the magnetocrystalline anisotropy of biotite. The magnetic fabric has a very low degree of anisotropy, P' = 1.025, characteristic of the weak alignment of magnetic particles. The magnetic foliation generally dips gently to the NW or SE and contains two orthogonal magnetic lineations that trend NW-SE and NE-SW (Figure 5a, b). The variations in magnetic lineation trend correlate with the intensity of the macroscopic feldspar fabric. In zones where the feldspar fabric is strongly developed, the AMS has a NW plunging lineation, whereas in zones where the feldspar fabric is weak, the AMS has a NE plunging lineation (Figure 5a, b). We also observe variations in the shape of the AMS ellipsoid from neutral to oblate for zones of strong feldspar fabrics to slightly prolate to oblate for zones marked by weak feldspar fabrics. As the AMS fabric is carried by biotite, the AMS lineation can be interpreted as a zone axis of biotite fabric.

Similar variations in lineation trend and shapes of the AMS ellipsoid are observed in the vicinity of the host rocks and stoped blocks of the Mylor Slate Formation, which is dismembered by extensional faults (Figure 5b). Two types of margins are recognized, one is represented by extensional faults and the other is parallel to the regional fabric of the Mylor Slate Formation. The granite adjacent to extensional faults shows narrow zones of fault-parallel magmatic AMS fabrics. Wider zones of parallelism are developed between the granite fabric and that in the host rock and are characterized by NNE-SSW lineations.

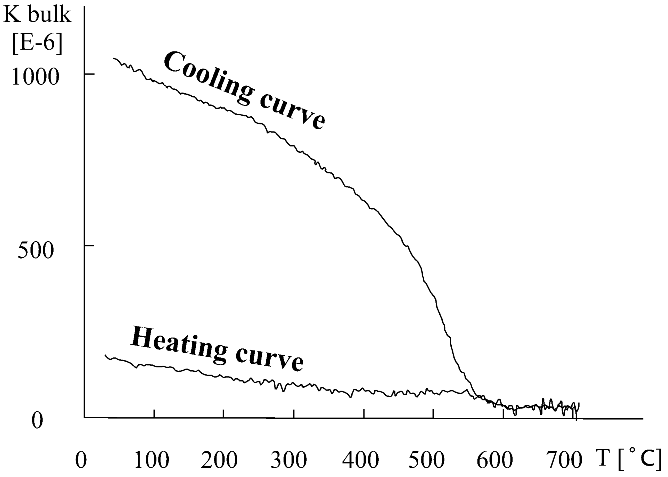

Figure 4. *Magnetic susceptibility versus temperature plot showing the hyperbolic heating curve characteristic of biotite as the magnetic carrier.*

DISCUSSION

Along the northwestern margin of the Land's End Granite, the medium- to coarse-grained porphyritic granite has an AMS fabric characterized by a gently N dipping foliation and sub-horizontal lineations that trend either N-S or E-W (Figure 6). There are also variations in the shape of the AMS ellipsoid associated with changes in the direction of the magnetic lineation. These variations correlate with the intensity of the mesoscopic feldspar fabric and with the distance from the host rock margin, or stoped blocks, of the Mylor Slate Formation. The possible role of: (i) regional deformation, and (ii) host rock contacts and stoped blocks in generating these magmatic fabrics are evaluated below.

Magmatic fabrics developed during regional deformation

Previous studies indicate that the ductile fabrics associated with D3 deformation of the Gramscatho Basin succession developed prior to the intrusion of the Cornubian Batholith and were associated with latest Carboniferous-Lower Permian regional NNW-SSE extension of the previously thickened crust (Alexander and Shail, 1995, 1996). As crustal thinning and exhumation progressed, these ductile fabrics were overprinted by brittle structures formed in the same NNW-SSE extensional regime, that are also present in the granites (Shail and Wilkinson, 1994; Alexander and Shail, 1995, 1996). Granite generation and emplacement therefore appear to have been synchronous with regional NNW-SSE extension (Shail and Wilkinson, 1994).

Comparison of host rock structures in the Mylor Slate

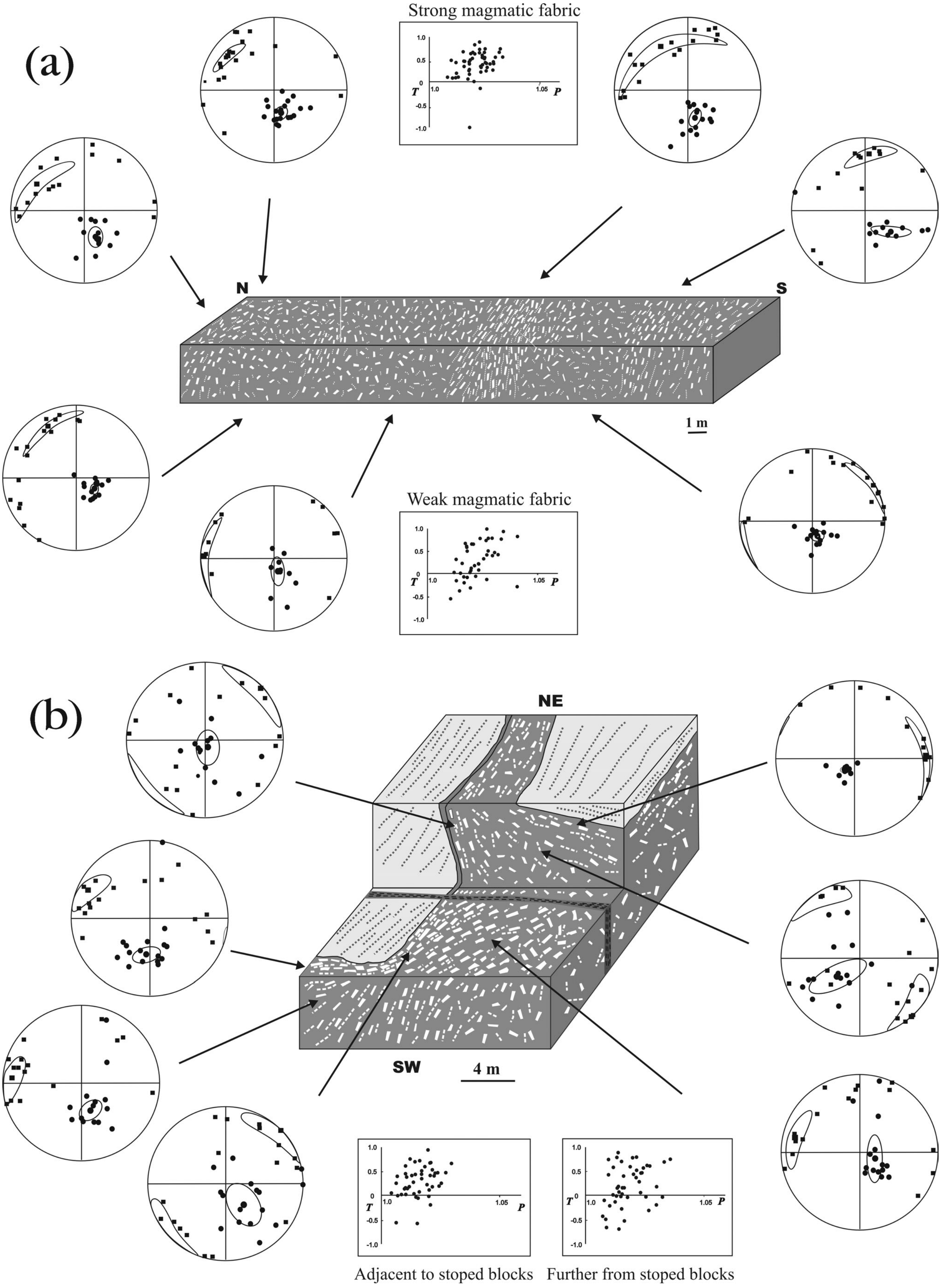

Figure 5. *Schematic profiles showing the anisotropy of magnetic susceptibility data with respect to: (a) the intensity and orientation of the magmatic fabric (top), and (b) the presence of stoped blocks of Mylor Slate Formation (bottom). Lower hemisphere Schmidt stereograms summarize the orientation of poles to the magnetic foliation (circles) and magnetic and lineations (squares). P' and T parameters are defined after Jelinek (1981):* $P' = \exp 2\,[(y_1 - y) + (y_2 - y) + (y_3 + y)]$, $T = 2 \ln (k_2/k_3)/(k_1/k_3) - 1$, $y_1 = \ln k_1$, $y_2 = \ln k_2$, $y_3 = \ln k_3$, $y = (y_1 + y_2 + y_3)/3$. *If* $1\ {}^{3} \geq T > 0$, *the magnetic fabric is planar, if* $-1 \leq T < 0$, *the magnetic fabric is linear.*

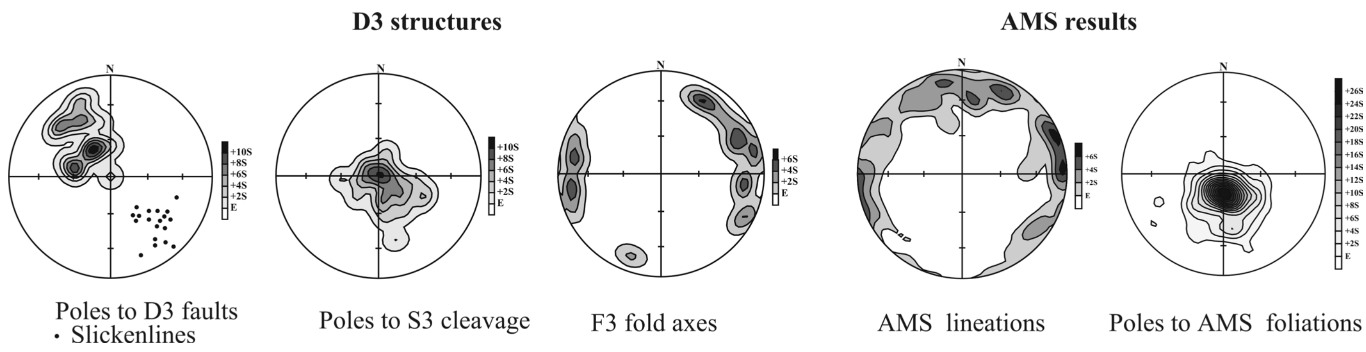

Figure 6. *Lower hemisphere Schmidt stereograms summarizing the orientation of D3 structures in the host rock (after Shail and Alexander, 1997) and the AMS fabric data from the Land's End Granite presented in this study.*

Formation with magmatic fabrics in the Land's End Granite reveals a near parallelism of the S3 cleavage and the AMS foliation (Figure 6). Moreover, F3 fold axes are parallel to the principal maximum of AMS lineations, and slickenlines developed on brittle D3 faults are close in orientation to the secondary maximum of AMS lineations (Figure 6). However, since the later (brittle) D3 structures developed in the Mylor Slate Formation are not penetrative, it is difficult to interpret the geometrical coincidence between them and the AMS fabrics in terms of complete coupling between host rock and granite. It is possible that there was only partial coupling between the crystal 'mush' of incompletely crystallized granite and the host rock, such that extensional deformation only partially influenced the magmatic fabric. Nevertheless, a recent combined AMS and anisotropy of anhysteric remanence (AAR) study of the Carnmenellis Granite interpreted the dominant NW-SE magnetic lineation in terms of regional NW-SE stretch of the magma during emplacement (Mintsa Mi Nguema *et al*., 2002)

The perpendicular AMS lineations could be interpreted in terms of combined pure and simple shear strain with a vertical shortening axis and an elongation axis parallel to the simple shear direction (resulting in plane strain AMS fabrics), alternating with zones of flow dominated by non-coaxial flattening (resulting in oblate AMS fabrics), as described by Schulmann *et al*. (1997).

Magmatic fabrics developed adjacent to host rock contacts and stoped blocks

Paterson and Miller (1998) have demonstrated metre-scale deflections of magmatic fabrics around stoped blocks that they interpreted as having formed due to the higher effective viscosity of the latter. This study has also highlighted metre-scale deflections of the magmatic fabric in the Land's End Granite around stoped blocks of the host rock. These deflections are characterized by changes in the orientation of the AMS foliations and lineations, and an increased oblatness of the AMS ellipsoid, with respect to main granite fabric. The AMS fabric in the granite further from the contact with stoped blocks is typically associated with a plane strain AMS ellipsoid geometry and different orientations of the main magnetic directions relative to the granite fabric close to the stoped block. We have not observed zones of complex fabrics around the stoped blocks studied that could be interpreted as a deflection of a previously formed fabric. In contrast, the fabrics wrap around studied blocks in a manner similar to that described by Paterson and Miller (1998). In agreement with these authors, we suggest that the crystal-rich magmas of the Land's End Granite recorded strain during or after final chamber construction. In order to further evaluate the magmatic fabrics, numerical modelling of the deflection of flow lines around rigid particles as proposed by Ježek *et al.* (1999, 2002) should be employed in future.

ACKNOWLEDGEMENTS

We are grateful to the British Geological Survey, Jon Brookes and the National Trust and Camborne School of Mines for support during fieldwork and data collection. The financial support of grant No. EK43-203653 is acknowledged. Constructive and thorough reviews by Scott Paterson and Stan Salmon helped to improve the manuscript and are kindly acknowledged.

REFERENCES

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

ALEXANDER, A.C. and SHAIL, R.K. 1996. Late- to post-Variscan structures on the coast between Penzance and Pentewan, south Cornwall. *Proceedings of the Ussher Society*, **9**, 72-78.

ANDREWS, J.R., ISAAC, K.P., SELWOOD, E.B., SHAIL, R.K. and THOMAS, J.M. 1998. Variscan structure and regional metamorphism. In: SELWOOD, E.B., DURRANCE, E.M. and BRISTOW, C.M. (eds), *The Geology of Cornwall.* Exeter University Press, Exeter, 82-119.

BLUMENFELD, P. and BOUCHEZ, J.L. 1988. Shear criteria in granite and migmatite deformed in the magmatic and solid states. *Journal of Structural Geology,* **10**, 361-372.

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

BOUCHEZ, J.L. 1997. Granite is never isotropic: an introduction to AMS studies of granitic rocks. In: BOUCHEZ, J.L., HUTTON, D.H.W. and STEPHENS, W.E. (eds), *Granite: from segregation of melt to emplacement fabrics.* Kluwert Academic Publishers, Dordrecht, 95-113.

BRITISH GEOLOGICAL SURVEY 1984. *Penzance. England and Wales Sheet 351/358*. Solid and Drift Geology. 1:50,000. British Geological Survey, Nottingham.

CHAPPELL, B.W. and WHITE, A.J. 1974. Two contrasting granite types. *Pacific Geology*, **8**, 173-174.

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 mineralization in the Cornubian batholith, southwest England. *Journal of the Geological Society, London,* **150**, 1183-1191.

CHESLEY, J.T., HALLIDAY, A.N., SNEE, L.W., MEZGER, K., SHEPHERD, T.J. and SCRIVENER, R.C. 1993. Thermochronology of the Cornubian batholith in southwest England: implication for pluton emplacement and protracted hydrothermal mineralization. *Geochimica and Cosmochimica Acta,* **57**, 1817-1835.

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. 1994. Nd and Sr isotope constraints on the origin of the Cornubian batholith, SW England. *Journal of the Geological Society, London,* **151**, 795-802.

DEARMAN, W.R. 1970. Some aspects of the tectonic evolution of South-West England. *Proceedings of the Geologists' Association,* **81**, 483-491.

FLOYD, P.A., EXLEY, C.S. and STYLES, M.T. 1993. *Igneous rocks of South-West England.* Chapman and Hall, London.

FOWLER, T.K. and PATERSON, S. R. 1997. Timing and nature of magmatic fabrics in plutons from structural relations around stoped blocks. *Journal of Structural Geology*, **19**, 209-224.

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

GOODE, A.J.J. and TAYLOR, R.T. 1988. *Geology of the area around Penzance.* Memoir of the British Geological Survey, Sheets 351/358 (England and Wales).

HALLS, C., JINCHU, Z. and YUCHENG, L. 2001. Field evidence for discrete episodes of intrusion during the emplacement of the Land's End pluton. Results from detailed mapping and observation of the Porth Ledden coastal section. *Geoscience in south-west England*, **10**, 221-222.

HAWKES, J.R. 1981. A tectonic "watershed" of fundamental consequence in the post-Westphalian evolution of Cornubia. *Proceedings of the Ussher Society,* **5**, 128-131.

HAWKES, J.R. and DANGERFIELD, J. 1978. The Variscan granites of south-west England: a progress report. *Proceedings of the Ussher Society,* **4**, 158-171.

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.

HOLDER, M.T. and LEVERIDGE, B.E. 1986. A model for the tectonic evolution of south Cornwall. *Journal of the Geological Society, London,* **143**, 125-134.

HROUDA, F. 1993. Theoretical-Models of Magnetic-Anisotropy to Strain Relationship Revisited. *Physics of the Earth and Planetary Interiors*, **77**, 237-249.

HROUDA, F., JELINEK, V. and HRUSKOVA, L. 1990. A package of programs for statistical evaluation of magnetic anisotropy data using IBM-PC computers (abstract). EOS *Transactions of the American Geophysical Union*, 1289.

HUTTON, D.H.W. 1997. Syntectonic granites and the principle of effective stress: a general solution to the space problem. In: BOUCHEZ, J.L., HUTTON, D.H.W. and STEPHENS, W.E. (eds), *Granite: from segregation of melt to emplacement fabrics.* Kluwert Academic Publishers, Dordrecht, 189-197.

ISAAC, K.P., SELWOOD, E.B. and SHAIL, R.K. 1998. Devonian. In: SELWOOD, E.B., DURRANCE, E.M. and BRISTOW, C.M. (eds), *The Geology of Cornwall.* Exeter University Press, Exeter, 31-64.

JELINEK, V. 1981. Characterisation of the magnetic fabrics of rocks. *Tectonophysics*, **79**, 63-67.

JELINEK, V. and POKORNY, J. 1997. Some new concepts in technology of transformer bridges for measuring susceptibility and anisotropy of rocks. *Physics and Chemistry of the Earth*, **22**, 179-181.

JEŽEK, J., SAIC, S., SEGETH, K. and SCHULMANN, K. 1999. Three-dimensional hydrodynamical modelling of viscous flow around a rotating ellipsoidal inclusion. *Computers and Geosciences,* **25**, 547–558.

JEŽEK, J., SCHULMANN, K. and SEGETH, K. 1996. Fabric evolution of rigid inclusions during mixed coaxial and simple shear flows. *Tectonophysics*, **257**, 203-221.

JEŽEK, J., SCHULMANN, K. and THOMPSON, A.B. 2002. Strain partitioning parameters in front of an obliquely convergent indenter. In. BERTOTTI, G., SCHULMANN, K. and CLOETINGH, S. (eds), *Continental collision and the tectonosedimentary evolution of forelands.* European Geophysical Society, Special Publication Series, **1**, 145-165.

MINTSA MI NGUEMA, T., TRINDADE, R.I.F., BOUCHEZ, J.L. and LAUNEAU, P. 2002. Selective thermal enhancement of magnetic fabrics from the Carnmenellis granite (British Cornwall). *Physics and Chemistry of the Earth,* **27**, 1281-1287.

MOORE, J.M. 1975. A mechanical interpretation of the vein and dyke systems of the S.W. England orefield. *Mineralium Deposita,* **10**, 374-388.

PARMA, J.A. and ZAPLETAL, K. 1991. CS-1 apparatus for measuring the temperature dependence of low-field susceptibility of minerals and rocks (in cooperation with KLT-2 Kappabridge), Geofyzika, Brno.

PATERSON, S.R. and MILLER, R.B. 1998. Stoped blocks in plutons: paleo-plumb bobs, viscometers, or chronometers? *Journal of Structural Geology*, **20**, 1261-1272.

PATERSON, S.R., FOWLER, T.K., SCHMIDT, K.L., YOSHINOBU, A.S., YUAN, E.S. and MILLER, R.B. 1998. Interpreting magmatic fabric patterns in plutons. *Lithos*, **44**, 53-82.

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

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.

RATTEY, P.R. and SANDERSON, D.J. 1984. The structure of SW Cornwall and its bearing on the emplacement of the Lizard Complex. *Journal of the Geological Society, London*, **141**, 87-95.

REID, C. and FLETT, J.S. 1907. *The geology of the Land's End District.* Memoir of the British Geological Survey, Sheets 351/358 (England and Wales).

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. *Proceedings of the Ussher Society,* **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.

SHAIL, R.K. and ALEXANDER, A.C. 1997. Late Carboniferous to Triassic reactivation of Variscan basement in the western English Channel: evidence from onshore exposures in south Cornwall. *Journal of the Geological Society*, London, **154**, 163-168.

SHAIL, R.K. and WILKINSON, J.J. 1994. Late- to post-Variscan extensional tectonics in south Cornwall. *Proceedings of the Ussher Society*, **8**, 162-270.

SCHULMANN, K., JEZEK, J. and VENERA, Z. 1997. Perpendicular linear fabrics in granite: markers of combined simple shear and pure shear? In: BOUCHEZ, J.L., HUTTON, D.H.W. and STEPHENS, W.E. (eds), *Granite: from segregation of melt to emplacement fabrics.* Kluwert Academic Publishers, Dordrecht, 159-176.

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. 1997. A geochemical dichotomy in the Cornubian batholith. *Proceedings of the Ussher Society,* **9**, 206-210.

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

VERNON, R.H., ETHERIDGE, M.A. and WALL, V.J. 1988. Shape and microstructure of microgranitoid enclaves, indicators of magma mingling and flow. *Lithos*, **22**, 1-11.

WARR, L.N., PRIMMER, T.J. and ROBINSON, D. 1991. Variscan very low-grade metamorphism in southwest England: a diastathermal and thrust-related origin. *Journal of Metamorphic Geology,* **9**, 751-764.

WATSON, J., FOWLER, M.B., PLANT, J.A. and SIMPSON, P.R. 1984. Variscan-Caledonian comparisons: late orogenic granites. *Proceedings of the Ussher Society,* **6**, 2-12.