THE CHRONOLOGY AND KINEMATICS OF LATE PALAEOZOIC DEFORMATION IN THE NW CONTACT METAMORPHIC AUREOLE OF THE LAND'S END GRANITE

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A structural investigation of coastal exposures between Cape Cornwall and Pendeen Watch, in the NW contact metamorphic aureole of the Land's End Granite, has confirmed a similar deformation chronology as in a reference section around Porthleven. D1 deformation is represented by an ubiquitous bedding-parallel S1 cleavage although F1 folds have not been recognised. D2 deformation is more localised and characterised by open F2 folds that verge WSW to NW and are associated with an ENE to SE dipping S2 crenulation cleavage. These structures are commonly obscured by later deformation and contact metamorphism and have not been described previously. A set of steeply inclined NNW-SSE trending, and subordinate set of moderately SE dipping, post-D2 metamorphic quartz veins formed coevally during an episode of strike-slip deformation prior to, or during, the early stages of D3 deformation. D3 deformation is widespread and represented by F3 folds and a WNW to NW dipping S3 crenulation cleavage; it has been recorded previously as D2 deformation. Two orders of F3 folds are developed; first order folds have a wavelength of up to 50 m, verge ESE, and result in vertical or steeply inclined bedding and S1 cleavage on their short limbs. Second order folds usually have a wavelength of 1 m or less and usually verge ESE, unless on the short limb of first order folds, where they verge WNW. Previously published data, indicating a dominant NW to WNW vergence of F3 folds on the northern flank of the Land's End Granite are incorrect. D3 structures are consistent with formation during the extensional reactivation of large-scale thrust faults. Granite emplacement post-dates all three episodes of ductile deformation but granites and their host rocks are deformed by a late brittle expression of D3 deformation. The Land's End pluton has been accommodated, at the current exposure level, primarily by roof uplift that has resulted in the tilting of D3 and earlier structures to the NW by 40-50°; this may have been accompanied by differential vertical axis rotations of the host rock. The last significant Palaeozoic deformation episode formed F4 folds and S4 cleavage and was a consequence of Mid- to Late Permian ENE-WSW shortening.

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INTRODUCTION

Late Palaeozoic deformation of the Devonian and Carboniferous successions in SW England reflects three principal regional tectonic episodes (e.g. Dearman, 1971; Sanderson, 1973; Leveridge and Hartley, 2006). It is widely accepted that D1 and D2 deformation occurred during Variscan (late Devonian to late Carboniferous) plate convergence and collision whereas D3 deformation relates to a different tectonic regime established prior to, or during, granite emplacement (Turner, 1968; Rattey and Sanderson, 1984; Alexander and Shail, 1995, 1996; Leveridge and Hartley, 2006).

The Land's End Granite and its host rocks provide a suitable location to test the chronology of host rock deformation relative to granite emplacement due to the excellent coastal exposures of these units and their contacts. Relatively little has been published on the chronology and kinematics of deformation within the granite aureole. In part, this may reflect the challenges posed by a locally intense contact metamorphic overprint. The deformation chronology indicated within the aureole on the British Geological Survey Penzance sheet (BGS, 1984), and described in the accompanying memoir (Goode and Taylor, 1988), differs from that proposed in adjacent areas of the Gramscatho Basin (e.g. Smith, 1965, 1966; Rattey and Sanderson, 1984; Alexander and Shail, 1995, 1996). Whilst these latter authors are in broad agreement on the regional deformation chronology outside the aureole, they have differing interpretations of the cause of D3 episode. Rattey and Sanderson (1984) proposed that D3 structures largely developed as a response to vertical shortening brought about by granite emplacement, whilst Alexander and Shail (1995, 1996) proposed a largely pre-emplacement origin during the extensional reactivation of Variscan thrusts.

The purpose of this contribution is to demonstrate that: (i) the regional deformation chronology established by the majority of previous workers outside the Land's End Granite aureole can also be recognized within the NW segment of the aureole. (ii) Ductile D3 deformation within the aureole pre-dates granite emplacement and is kinematically equivalent to D3 deformation outside the aureole. (iii) The accommodation of the Land's End Granite at the present exposure level was achieved largely by post-D3 uplift and tilting of the host rocks. The study is based upon the comparative structural geology of the contact metamorphic aureole on the NW margins of the Land's End Granite and the section around Porthleven on the south coast (Figure 1).

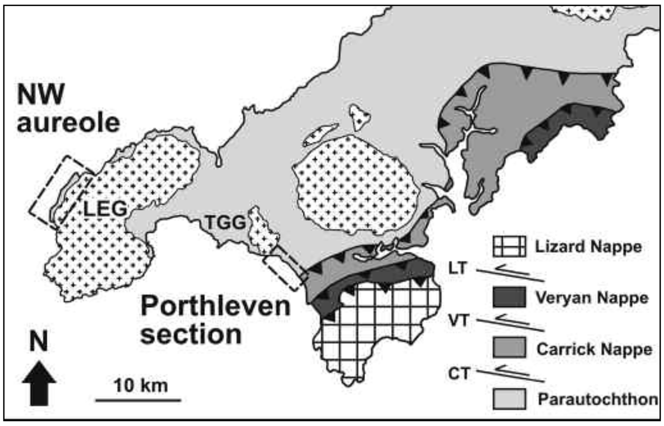


Figure 1. *A simplified geological map of south Cornwall after Leveridge* et al. *(1990) showing the location of the study areas in the NW aureole of the Land's End Granite (LEG) and the Porthleven section to the SE of the Tregonning-Godolphin Granite (TGG). The parautochthonous host rocks to these granites comprises the Mylor Slate Formation which is located structurally below the Carrick Thrust (CT), Veryan Thrust (VT) and Lizard Thrust (LT).*

PREVIOUS WORK

Stratigraphy

The recognition of a major NNW-directed Variscan thrust nappe pile in south Cornwall (Leveridge *et al*., 1984; Holder and Leveridge, 1986; Leveridge *et al*., 1990) has greatly improved the understanding of the stratigraphy and tectonic evolution of the Gramscatho Basin (Figure 1). The inferred trace of the Carrick Thrust occurs at the southern end of the Porthleven section and separates the parautochthonous Mylor Slate Formation from the Portscatho Formation of the Carrick Nappe (Leveridge and Holder, 1985; Holder and Leveridge, 1986). The Portscatho Formation comprises deep marine sandstones and mudstones whilst the Mylor Slate Formation predominantly comprises thinly bedded deep marine siltstones and mudstones, along with basaltic pillow lavas and dolerite sills; its upper part is represented by olistostromes of the Porthleven Breccia Member (Leveridge and Holder, 1985; Leveridge *et al*., 1990). These olistostromes are interpreted to have been sourced primarily from the south during the northwards translation and emergence of the Carrick Nappe (Leveridge and Holder, 1985; Leveridge *et al*., 1990). Palynological data indicate both formations are predominantly Upper Devonian in age, although possibly including some Tournaisian strata (Turner *et al*., 1979; Le Gall *et al*., 1985; Wilkinson and Knight, 1989). The Tregonning Granite is a topaz granite that has been dated by the Rb-Sr whole rock method as 280 ± 4 (2σ) Ma (Darbyshire and Shepherd, 1987), although a $^{40}Ar/^{39}Ar$ zinnwaldite cooling age of 281.0 ± 1.3 (2σ) Ma suggests emplacement was probably a little earlier at 283-284 Ma (Clark *et al*., 1994). The Land's End Granite comprises a variety of textural types of biotite granite dated by the U-Pb monazite method between 277.1 ± 0.4 (2σ) Ma and 274.4 ± 0.4 (2σ) Ma (Chen *et al*., 1993; Clark *et al*., 1994).

Deformation chronology outside the aureole

Outside the contact metamorphic aureole of the Land's End Granite the first detailed investigations of the structural geology of the Mylor Slate Formation were in the Porthleven area. Stone (1962, 1966) identified the polyphase nature of deformation and interpreted the dominant folds as having formed during a regional D2 event. Although two cleavage generations were recognized as predating the 'S2' cleavage, the earliest cleavage was related to 'early (pre-F1) folding' (Stone, 1966) and not incorporated into the regional deformation chronology. Smith (1965, 1966) subsequently identified three principal deformation events in the area around Godrevy and correlated these with the structures around Porthleven, re-assigning the D2 structures of Stone (1962, 1966) to the regional D3 event.

Most subsequent studies largely corroborated this tripartite deformation chronology (D1-D3) for the principal events (Turner, 1968; Dearman, 1971; Sanderson, 1973; Rattey, 1980; Rattey and Sanderson, 1984). A more complex deformation chronology was established further east during remapping of the Falmouth sheet (Leveridge et al., 1990). It was later rationalized within the existing D1-D3 scheme by Alexander and Shail (1995, 1996) who also included the brittle-ductile detachments and brittle SE dipping listric faults described by Shail and Wilkinson (1994) within the D3 event. The proposal by Rattey and Sanderson (1984) of a NW-dipping S2 cleavage and upright D2 Godrevy Antiform was refuted by Alexander and Shail (1995) who considered it a consequence of the misidentification of the NW dipping S3 cleavage as S2.

The consensus, from the above work outside the contact metamorphic aureole, is that these three deformation episodes have an expression in the Gramscatho Basin succession as follows: (1) D1 deformation is ubiquitous and characterised by isoclinal to tight F1 folds that are recumbent or gently inclined to the SSE with an axial planar S1 cleavage that is generally sub-parallel to bedding away from fold hinges. (2) D2 deformation is more partitioned and usually comprises zones of moderately to steeply SSE inclined F2 folds and an associated S2 crenulation cleavage. (3) D3 deformation consists of F3 folds of varying geometry and scale that are commonly SSE verging and have an associated sub-horizontal or NNW dipping S3 crenulation cleavage that locally transposes earlier fabrics. Most previous workers additionally identify at least two post-D3 deformation events (D4 and D5) that resulted in the local development of steeply inclined cleavages and typically upright folds (e.g. Smith, 1965, 1966; Rattey and Sanderson, 1984; Alexander and Shail, 1995, 1996).

Deformation chronology inside the aureole

Little detailed work has been published on polyphase deformation within the contact metamorphic aureole of the Land's End Granite and it was not included in the regional studies of D3 deformation in west Cornwall by Alexander and Shail (1995, 1996). A large amount of structural data for the NW aureole, including sketches of cliff-sections between Botallack and Levant, are contained within the PhD thesis of Jackson (1976). Larger-scale folds of bedding and S1 cleavage, associated with a NW dipping cleavage, were assigned to a D2 event and minor coaxial folds on the steep F2 limbs were assigned to a D3 event. The structural data on the Penzance sheet (BGS, 1984) indicate the widespread occurrence of D3 folds and cleavage in the coastal sections of Mount's Bay and St Ives Bay, including within the contact aureole immediately east of the Land's End Granite around Carbis Bay. However, along the northern and NW aureole of the granite, between St Ives and Cape Cornwall, the dominant folds shown are F2 and associated with a moderately to steeply NW-dipping S2 cleavage. In the accompanying memoir (Goode and Taylor, 1988), F2 folds are represented as S verging and associated with a N dipping S2 cleavage, i.e. they have all the characteristics of F3 folds and S3 cleavage as described by previous workers, and as shown outside the aureole on the Penzance sheet (BGS, 1984). Similar structures at Porthmeor Cove (Exley and Stone, 1982; Stone and Exley, 1984) and Priest's Cove (Salmon and Shail, 1999) have been assigned to the D3 episode. Other workers have suggested that D3 deformation is widespread along the whole northern margin of the Land's End Granite (Rattey and Sanderson, 1984; LeBoutillier, 2002; Kratinova *et al*., 2003). The basis for assigning these structures to the D3 episode is their geometrical similarity with structures outside the aureole. However, there has been no description of regional D2 structures within the aureole and this may explain the apparently anomalous assignation of D2 (BGS, 1984; Goode and Taylor, 1988), in a locally valid deformation chronology, to structures that outside the aureole are classified as regional D3.

Kinematics and timing of deformation relative to granite emplacement

All recent workers agree that regional D1 and D2 structures in south Cornwall were generated by a top sense-of-shear to the NNW during Variscan convergence and collision (e.g. Dearman, 1971; Rattey and Sanderson, 1984; Shail and Alexander, 1995, 1996; Leveridge and Hartley, 2006). Much of the research on the kinematics of post-convergence D3 deformation, and its timing relative to granite emplacement, has been focussed around Porthleven and the Tregonning Granite.

The earliest model was developed by Stone (1962, 1966; his D2) and Smith (1965, 1966); they concluded that D3 structures were generated by pre-granite vertical shortening, possibly due to an increase in super incumbent load following 'sliding'. Turner (1968) attributed the vertical shortening to the rise of the upper surface of the granite batholith, but considered that the resultant D3 fabrics were post-dated by the emplacement of individual cupolas. A similar emplacement-related model was adopted by Rattey (1980) and Rattey and Sanderson (1984) who suggested that small-scale F3 folds typically verged away from the granite margins to define a 'fir tree' interference pattern (Figure 2). It was proposed that this resulted from the superposition of pure shear vertical flattening of the limbs of large-scale upright open antiforms generated above the granite plutons during earlier stages of diapiric emplacement (Figure 2).

An alternative model was proposed by Alexander and Shail (1995, 1996) whereby D3 deformation resulted from the reactivation of major Variscan thrusts in a NNW-SSE post-convergence extensional regime. A top-to-the SSE sense of simple shear, when superimposed on an end-D2 orogenic architecture dominated by SSE dipping elements (bedding, S2 cleavage etc.), resulted in the widespread development of SSE verging folds within the parautochthonous footwall of the Carrick Nappe. Hence granite generation and emplacement, instead of being the cause of D3 deformation, was interpreted as one of its consequences (Shail and Wilkinson, 1994; Shail *et al.*, 2003). Predominantly ESE to SSE verging D3 folds along the northern margins of the Land's End Granite do not appear compatible with the emplacement-related models of Rattey (1980) and Rattey and Sanderson (1984) and have also been interpreted using the extensional reactivation model (Salmon and Shail, 1999; LeBoutillier, 2002; Kratinova *et al.*, 2003). It has been suggested that zones of predominantly NW verging F3 folds, such as to the west of the Tregonning Granite, might be related to vergence reversals during very high strain D3 deformation prior to granite emplacement (Alexander and Shail, 1995, 1996).

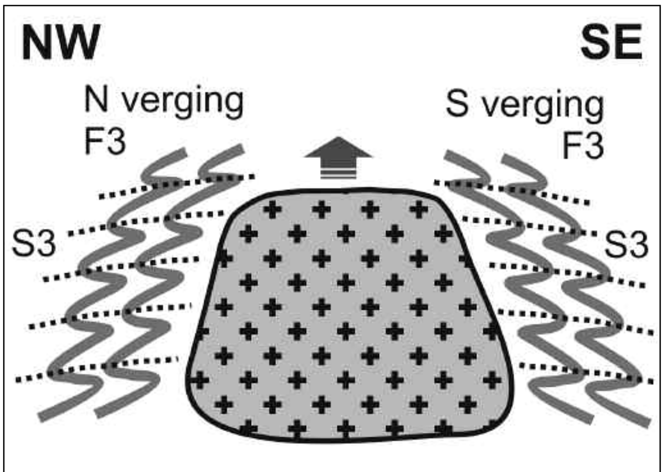


***Figure 2.** A model for emplacement-related D3 deformation after Rattey and Sanderson (1984, figure 6). The forceful (diapiric) emplacement of granite plutons creates broad large-scale antiforms. Vertical shortening during the emplacement process creates predominantly N verging F3 folds on the northern flank of the pluton and predominantly S verging F3 folds on the southern flank of the pluton, together with an approximately horizontal cleavage (S3).*

Field data from the Porthleven section

In order to evaluate the geometry and chronology of deformation in the NW aureole with that outside the aureole, a reference data set was collected from the widely investigated coastal section between Blue Rocks [SW 6489 2333] and Legereath Zawn [SW 6077 2680], on the south side of the batholith. The SE end of the section, from Porthleven to Blue Rocks has not experienced significant contact metamorphism, but to the NW, from Porthleven to Megiliggar Rocks, slatey mudrocks exhibit a progressive change to low-pressure amphibolite facies (biotite-cordierite ± andalusite) hornfels.

D1 structures

D1 deformation occurs throughout the section. The Portscatho Formation at Blue Rocks [SW 6489 2333] exhibits NNW verging tight to isoclinal F1 folds on a 1 to 10 m scale (Figure 3a). S1 is an axial planar spaced cleavage that is bedding-parallel on the fold limbs; no earlier penetrative fabric is observed in the fold hinges. Whilst a S1 slatey cleavage is ubiquitous in the Mylor Slate Formation, few primary folds have been observed and none in the northern end of the section. D1 orientation data are summarised in Figure 4a. F1 fold axes exhibit a range of plunge directions, from NE to ESE, that reflect curvilinear hinges; occasional WSW plunge directions result from D4 refolding. S1 cleavage dips gently to the SSE.

D2 structures

D2 strain is partitioned throughout the section, so that in some areas no structures are developed, whereas elsewhere they may be the dominant element in zones of high D2 strain. Examples of F2 folds in Portscatho Formation sandstones are displayed immediately south of Loe Bar [SW 6437 2414]; they have a shorter wavelength (0.1 – 1 m) than F1 folds, an open to tight style, and generally verge NNW (Figure 3b). The associated axial planar S2 cleavage crenulates the S1 fabric and dips moderately SSE and is commonly associated with a later 'post-D2' generation of subparallel quartz veins (Figure 3c). D2 data are summarised in Figure 4b. F2 folds plunge gently to the ENE and are broadly co-axial with F1 folds; they usually verge NNW, unless on the shorter overturned limbs of larger scale F2 folds where they verge SSE. Facing is to the NNW where folds develop on long 'right way-up' F1 limbs but SSE on the short overturned F1 limbs.

Post-D2 quartz veins

Sub-vertical quartz veins, striking NNW-SSE and up to 0.3 m in width, were observed throughout the section. The mean orientation of a set of seventeen veins was 151°/84° NE. The veins post-date D1 and D2 folds and cleavage, but were buckled during D3 ductile deformation and offset by brittle D3 faults. In the contact aureole, andalusite is often localised in the blackened wallrock of these veins. Approximately S2 parallel quartz veins are common and were also deformed during D3 deformation; in appropriately orientated sections these can be observed to branch from the subvertical NNW-SSE veins.

D3 structures

In the Mylor Slate Formation, zones of ductile D3 deformation are dominant. F3 folds generally verge SSE with short limbs varying in length from 0.05–0.5 m where localised in the hangingwall of extensional faults to several metres in regions of distributed shear (Figure 3d). D3 fold and cleavage orientation data are summarised in Figure 4c. F3 folds predominantly plunge to the ENE, but some to the WSW; S3 cleavage varies from gently NW-dipping at Vellin Gluz [SW 6378 2471] to gently SE-dipping at Western Tye [SW 6326 2512] and sub-horizontal at Megiliggar Rocks [SW 6093 2666]. Further south, in the Portscatho Formation, complex arrays of bedding parallel and listric faults are developed. These are sometimes associated with SSE verging F3 folds and an associated NNW dipping S3 cleavage in their hangingwall that crenulates the SE dipping S2 crenulation cleavage (Figure 3e). Similar bedding parallel fault zones, that have a more brittle expression with well-developed breccia zones and SE dipping Riedel R1 faults in their footwall, occur south of Loe Bar (Figure 3f) and

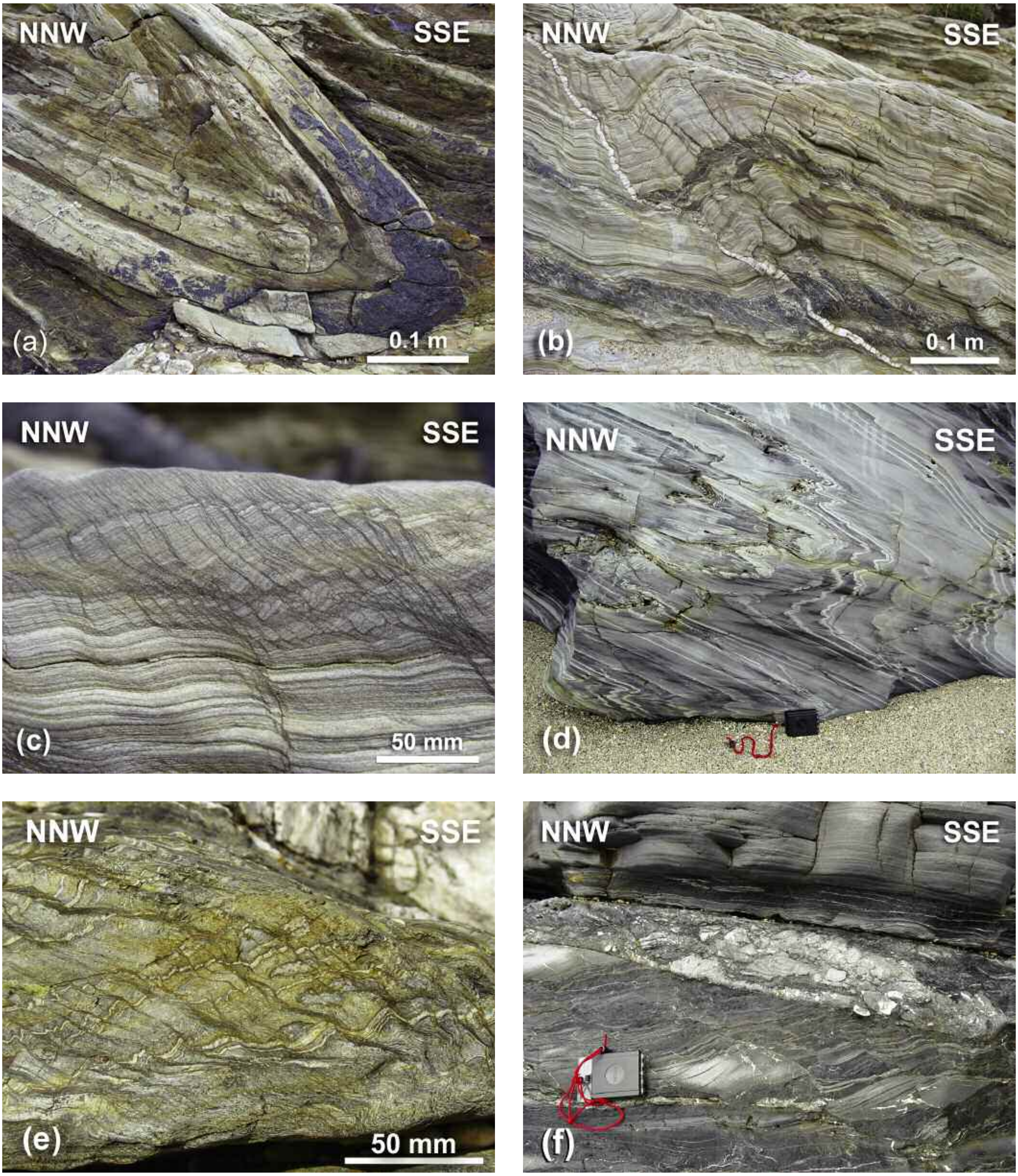


Figure 3. *Examples of D1-D3 structures in the Porthleven section: (**a**) NNW facing F1 fold with axial planar S1 slatey cleavage in mudstones, Portscatho Formation [SW 6460 2367]; (**b**) NNW facing and verging F2 fold with SSE dipping axial planar S2 crenulation cleavage, Portscatho Formation [SW 6457 2374]; (**c**) SSE dipping S2 crenulation cleavage, Portscatho Formation [SW 6457 2372]; (**d**) SSE verging and facing F3 fold, Mylor Slate Formation [SW 6323 2518]; (**e**) SSE dipping S2 crenulation cleavage folded into small-scale SSE verging F3 folds in vicinity of detachment fault, Portscatho Formation [SW 6407 2431]; (**f**) bedding parallel detachment fault (brittle D3) with breccia and synthetic Riedel R1 faults in footwall consistent with a top sense-of-shear to the SSE, Portscatho Formation [SW 6482 2334].*

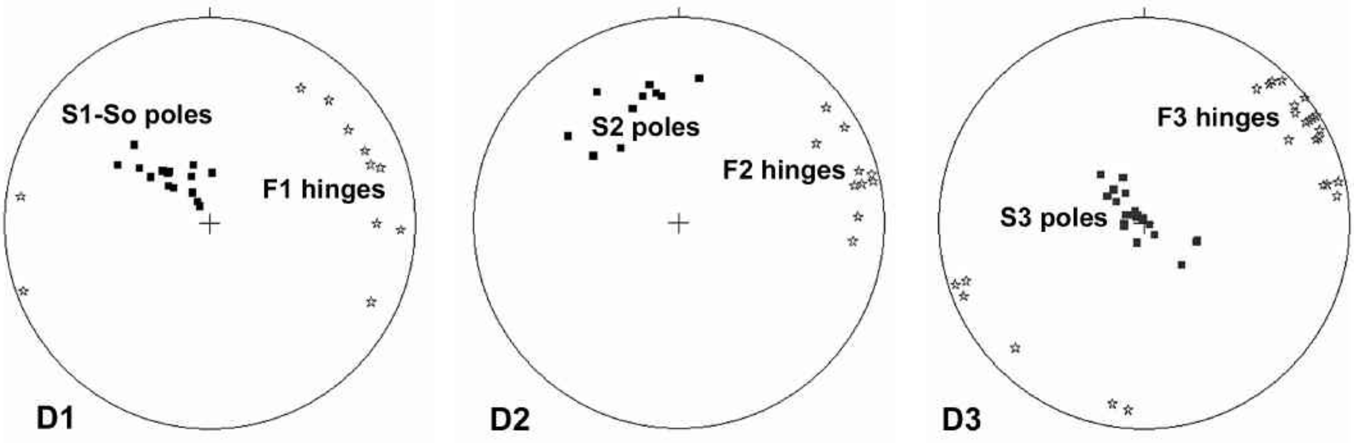


Figure 4. *Equal area lower hemisphere stereograms of cleavage pole (■) and fold hinge (☆) orientation data from the Porthleven section;* ***D1****: S1 (n = 15), F1 (n = 11);* ***D2****: S2 (n = 11), F2 (n = 13);* ***D3****: S3 (n = 23), F3 (n = 26).).*

are compatible with a top-sense-of-shear towards the SSE. All of these structures are post-dated by steeply SSE dipping extensional or dextral-extensional faults.

D4 structures

A fourth phase of ductile deformation is recognized, consisting of large scale open folding of the Mylor Slate Formation at Vellin Gluz and Western Tye, together with small scale tight folding. The F4 folds verge WSW and plunge SSE. The S4 cleavage, which dips steeply ENE, was only clearly discernible at Vellin Gluz (Table 1).

Boundary relations with the Tregonning Granite

F3 folds and S3 cleavage within the Mylor Slate Formation are truncated along a stepped sharp boundary with the upper part of the Tregonning Granite at Legereath Zawn [SW 6077 2680]. There is no evidence of a similar high strain fabric within the granite. The granite sheets, exposed between there and Megiliggar Rocks [SW 6093 2666] are hosted by fractures that are commonly parallel or slightly oblique to the composite S3/S1 fabric and include host rock fragments displaying F3 folds and S3 cleavage.

TECTONIC EPISODE	FOLDING STYLE	MEAN ORIENTATION
D1 Variscan convergence	Tight to isoclinal folds that verge NNW	F1 14/073 n = 11 S1 050/24 SE n = 15
D2 Variscan convergence	Open to tight folds that verge NNW	F2 11/075 n = 13 S2 069/52 SE n = 11
D3 Post-Variscan extension	F3 folds variable, verge SSE	F3 4/058 n = 26 S3 047/4 SE n = 23
D4 ENE-WSW shortening	Large and small scale open folds that verge W	F4 27/164 n = 9 S4 166/48 NE n = 2

Table 1. *Summary D1-D3 structural data, including mean orientations, from the Porthleven section.*

Field data from the Cape Cornwall area

Cape Cornwall is situated on the NW margin of the Land's End Granite (Figure 1). The adjacent areas of Priest's Cove to the south [SW 3520 3165] and Porth Ledden to the north [SW 3535 3200] are classic locations at which the contact relationships between the Land's End Granite and host rock and the internal textural variations in the Land's End Granite can be examined (e.g. Salmon and Shail, 1999; Halls *et al.*, 2001; Müller *et al.*, 2006).

Host rock lithologies and contact metamorphism

The Mylor Slate Formation comprises metasedimentary rocks and metabasic igneous rocks (typically as sills <10 m thickness) and is exposed from Priest's Cove northwards across Cape Cornwall to the Porth Ledden foreshore platform. The metasedimentary rocks indicate low pressure amphibolite facies (biotite-cordierite ± andalusite) contact metamorphism. The sedimentary protolith was dominated by thinly bedded siltstone/very fine-grained sandstone-mudstone couplets in which the siltstone/very fine sandstone is typically 10-20 mm thick and usually accounts for <20% of unit thickness. Contact metamorphism has brought about a grain size inversion, whereby the quartz-dominated metasiltstones/metasandstones underwent relatively minor textural modification, but the growth of biotite and cordierite in the metapelites has resulted in a mean grain size of 1-5 mm. Despite this, structural fabrics pre-dating contact metamorphism have been recognised in metasedimentary rocks across the area.

D1 structures

F1 folds have not been observed. However, a primary cleavage (S1) is recognised throughout the area, with good examples in Priest's Cove to the east of the slipway [SW 3530 3170]. S1 is sub-parallel to bedding, typically dipping between 5° and 20° to the NW at Cape Cornwall and is overprinted by all subsequent structures.

D2 structures

Localised areas of D2 strain, manifested as F2 folds and S2 crenulation cleavage, were recognised primarily in Priest's Cove. F2 folds are open and rounded and have short limb lengths <1 m (Figure 6a). They plunge gently NNW and verge to the WSW. The associated axial planar S2 crenulation cleavage deforms and crosscuts the primary foliation and dips 20-40° to the ENE. These relations are best displayed in the low-lying cliff immediately east of the Priest's Cove slipway [SW 3526 3168] and along the track on the south side of Cape Cornwall. D2 orientation data are summarised in Figure 7.

Post-D2 quartz veins

Post-D2 quartz veins, variably deformed by D3, are present throughout the area. They are very well displayed at the cliff and foreshore platform at the southern end of the Porth Ledden where they strike NNW-SSE and the adjacent wallrock is blackened and commonly contains andalusite.

D3 structures

A third episode of ductile deformation is recognised throughout the Cape Cornwall area. Primary (S1) and secondary (S2) cleavages are refolded by F3 folds and the E dipping S2 crenulation cleavage is cut and deformed by the NW-dipping S3 cleavage (Figure 6b-d). These relationships are also best demonstrated east of the Priest's Cove slipway; a fine example of an ESE verging F3 fold with an axial planar S3 cleavage occurs immediately adjacent to the slipway and includes a boudinaged metabasalt (Figure 6b). Elsewhere, at the western end of Priest's Cove [SW 3480 3175], an east verging F3 fold is defined by a metadolerite sill. Fold geometry varies, although most are open to tight and overturned, with typical wavelengths of 0.1 to 1 m. The folds usually verge ESE and have gently NNE plunging hinges; the axial planar S3 cleavage is widespread (Figure 6c), dipping on average 30-40° to the WSW (Figure 7c). The axial surface of a larger first order F3 fold crops out to the west of the Priest's Cove slipway; WNW verging second order F3 folds are developed on its steeply inclined short limb. The D3 structures are sometimes localised adjacent to bedding-parallel faults but there are insufficient data to independently constrain their kinematics.

Boundary relations with the Land's End Granite

In Priest's Cove the southern boundary of the host rock with the granite is an ESE-trending high angle fault zone that hosts Saveall's Lode, marked by a 0.35 m thick quartz-hematite vein defining the hanging wall of the stoped ground in the cliff. The fault zone can be traced to the low water mark where it intersects and offsets a moderately WSW dipping intrusive boundary between host rock and granite that continues just below low water to the SSE (inferred from the presence of unidirectional solidification textures in the granite). Most of the intrusive boundary between the granite and host rock at Porth Ledden is approximately parallel to the S3 cleavage, dipping 20-30° NW; the northern boundary of the granite is formed by an ESE-trending steeply-dipping mineralized fault. Moderate to steeply dipping granite and aplite sheets – typically <1 m in thickness with a weak modal ENE-WSW strike, crop out in both Priest's Cove and Porth Ledden; they cut across the S3 cleavage and F3 folds and are undeformed by this episode.

Field data from the Botallack area

The Mylor Slate Formation in the vicinity of the Crowns Engine Houses at Botallack [SW 3626 3351] comprises approximately equal proportions of metasedimentary and metabasic igneous rocks; in some areas the latter have been metasomatically altered to produce garnetiferous skarns (e.g. van Marcke de Lummen, 1985). Polyphase deformation has been observed in the coastal exposures adjacent to the engine houses and as far north as Stamps an Jowl Zawn [SW 3622 3400].

D1 structures

A primary foliation (S1) that is parallel to bedding exists throughout the area. No F1 folds have been observed. The combined bedding and foliation S1-S0 fabric has a mean dip of 33° to the NW (Figure 7b).

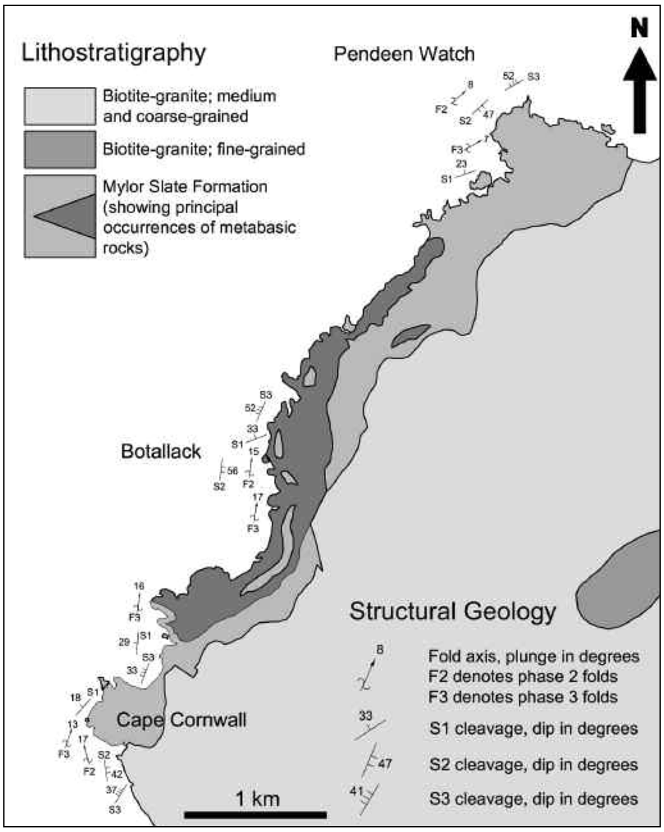


Figure 5. *Summary geological map of the NW aureole of the Land's End Granite showing lithostratigraphical and boundary information (BGS, 1984) and summary structural data from Cape Cornwall, Botallack and Pendeen Watch.*

D2 structures

A second phase of deformation is sporadically observed; it is commonly obscured or modified by the F3 folds and S3 cleavage (Figure 6e). F2 folds are open to tight and overturned, plunge N or NNE, and verge W or WNW; wavelengths are typically around 1 m. An axial planar S2 cleavage dips on average 56° E, with slight variation in proximity to D3 structures (Figure 7b).

D3 structures

D3 structures are dominant throughout the area. First order structures have a wavelength of approximately 50 m and verge to the ESE; they result in localised areas of steeply inclined or vertical bedding and primary foliation, and the reorientation of D2 structures. Second order F3 folds are usually tight and overturned with a wavelength of <1 m; they plunge to the NNE and verge ESE on the long limbs, and WNW on the short steep limbs, of first order F3 folds. The SE dipping S2 crenulation cleavage is locally refolded into a NW dipping cleavage around F3 fold hinges. The S3 cleavage is axial planar to F3 folds, dips moderately WNW, and crenulates the S2 fabric (Figure 6e).

Field data from Pendeen Watch

Coastal exposures between SW 3790 3565 and SW 3835 3595 are exclusively metasedimentary rocks and more distant from the granite contact than previous sites.

D1 structures

A primary bedding-parallel foliation (S1), similar to that elsewhere in the aureole is present and has a mean dip of 23° to the NNW (Figure 7c), although it is locally re-orientated by later structures; no F1 folds were observed.

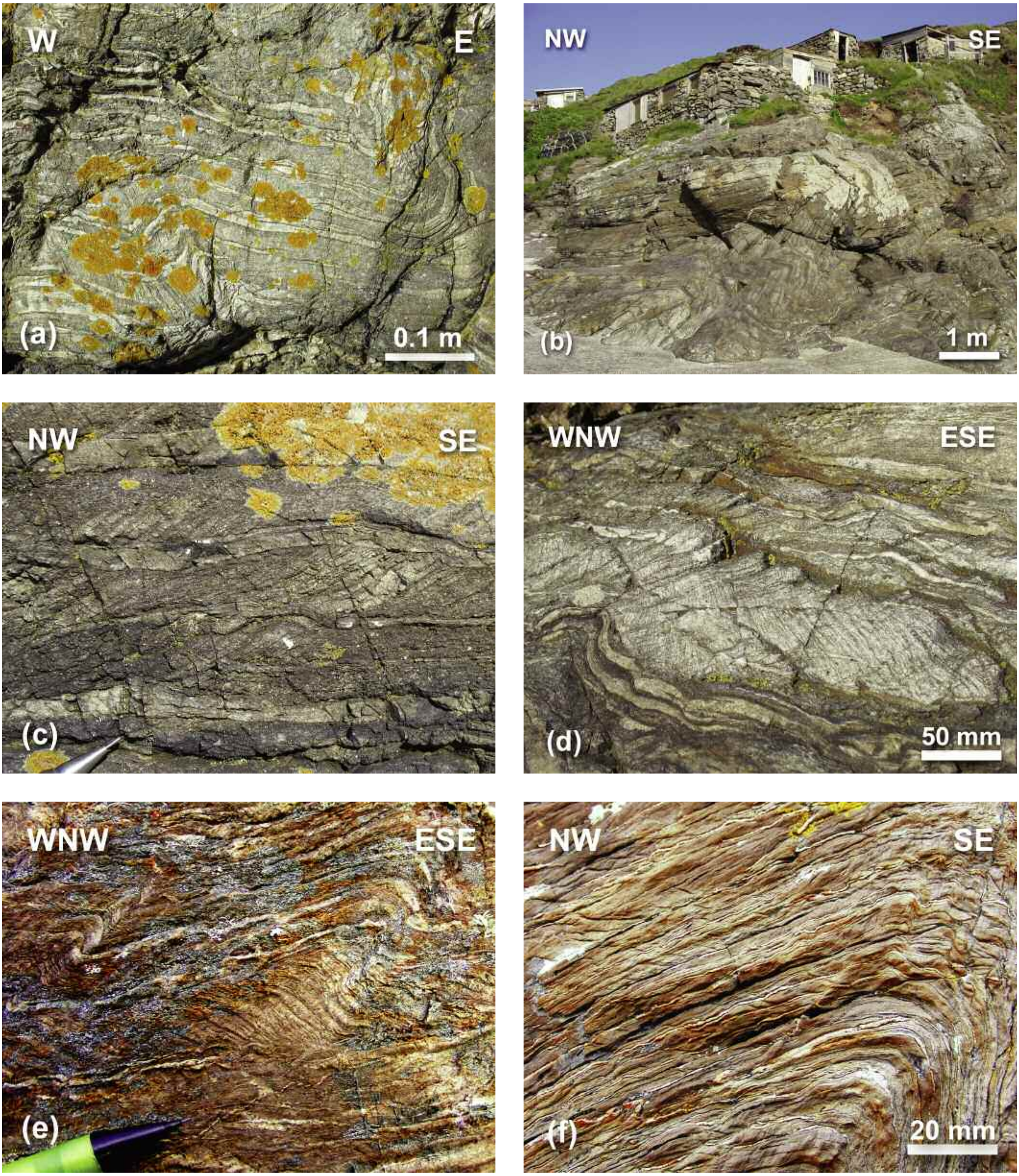


Figure 6. *Examples of D1-D3 structures in the Mylor Slate Formation of the NW contact aureole: (**a**) W verging F2 fold with E dipping axial planar S2 crenulation cleavage, Priest's Cove; (**b**) SE verging F3 fold, Priest's Cove; (**c**) NW dipping S3 crenulation cleavage cutting horizontal composite S1-S0 fabric; contact metamorphism has caused grain size inversion so that the original mudstones are now coarser grained than the subordinate very thinly bedded siltstones (pencil tip is 20 mm long), Priest's Cove; (**d**) WNW dipping S3 crenulation cleavage cuts ESE dipping S2 crenulation cleavage, Priest's Cove; (**e**) ESE dipping S2 crenulation cleavage folded by ESE verging F3 folds (pencil tip is 40 mm long), Botallack Head [SW 3618 3384]; (**f**) Gently SE dipping S2 crenulation cleavage preserved on NW limb of F3 fold with steeply NW dipping axial planar S3 crenulation cleavage, Pendeen Watch [SW 3791 3576].*

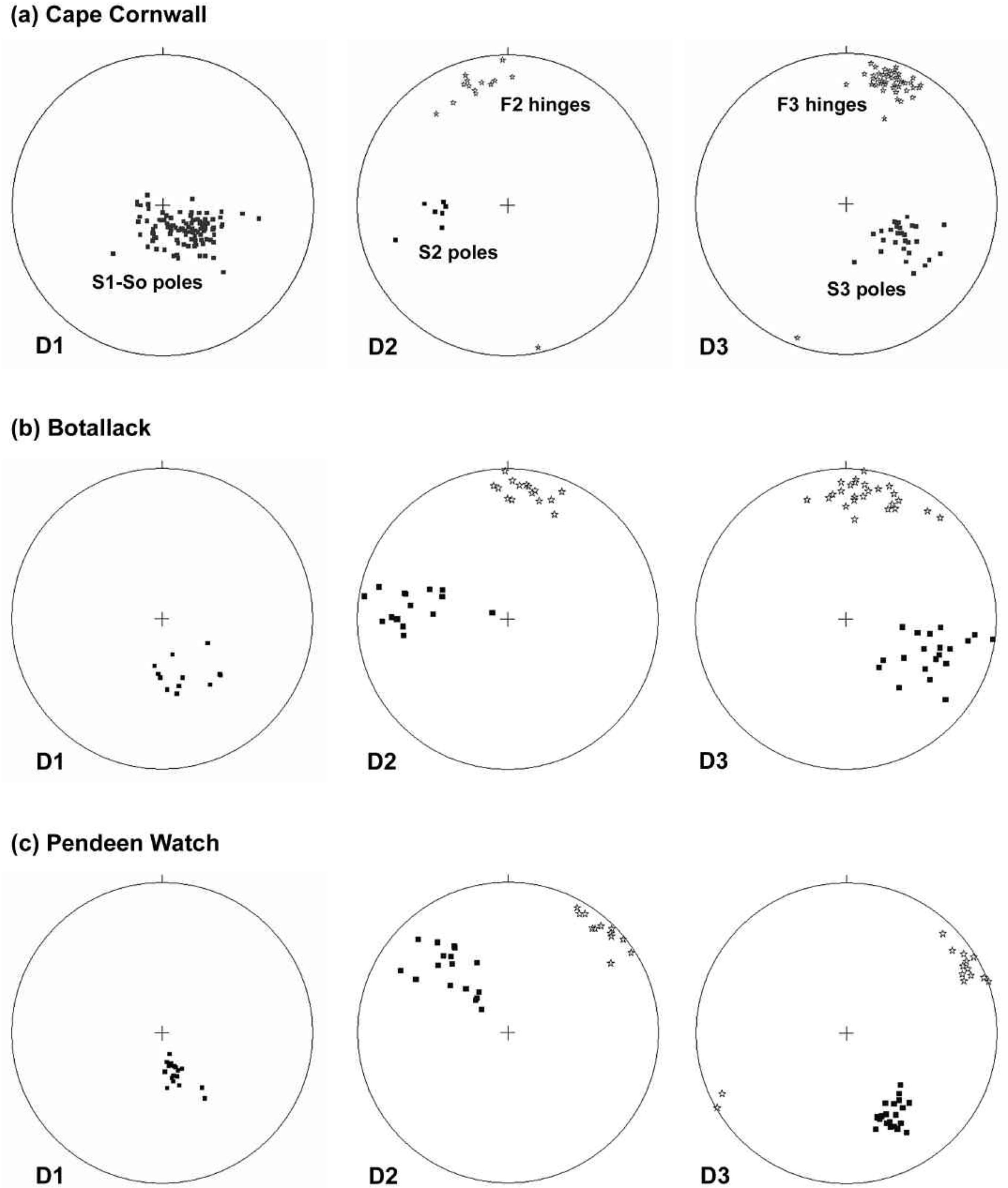


Figure 7. *Equal area lower hemisphere stereograms of cleavage pole (■) and fold hinge (☆) orientation data from the NW contact aureole: (**a**) Cape Cornwall, **D1**: S1-So composite fabric (n = 109); **D2**: S2 (n = 7), F2 (n = 15); **D3**: S3 (n = 29), F3 (n = 60); (**b**) Botallack, **D1**: S1-So composite fabric (n = 12); **D2**: S2 (n = 16), F2 (n = 15); **D3**: S3 (n = 20), F3 (n = 28); (**c**) Pendeen Watch, **D1**: S1-So composite fabric (n = 18); **D2**: S2 (n = 17), F2 (n = 12); **D3**: S3 (n =21), F3 (n = 14).*

D2 structures

D2 deformation occurs in localised high strain zones in the low-lying cliff immediately to the north of the lighthouse. Open F2 folds that plunge to the NE and verge to the NW have a wavelength of approximately 0.2 m to 0.5 m; they have an axial planar S2 crenulation cleavage that dips moderately to the SE (Figure 7c).

D3 structures

Much of the area has a strong D3 overprint, with close to tight F3 folds that plunge to the NE and verge to the SE; the associated axial planar S3 crenulation cleavage dips approximately 52° NW and crenulates both S1 and S2 (Figure 7c). In exposures below the lighthouse, SE verging F3 folds develop on F2 fold limbs and refold the S2 cleavage (Figure 6f).

Porthmeor Cove

Porthmeor Cove [SW 4250 3750] is situated 5 km ENE of Pendeen Watch, towards the western end of the northern contact aureole; the NW and N aureole segments are separated by approximately 3.5 km of granite coastline where no host rocks crop out (Figure 1). This location is well-known due to the small, easily accessible, granite cupola and cross-cutting granite sheets (Stone and Exley, 1984). Data was collected from Porthmeor Point [SW 4255 3790] in the east, to Great Zawn [SW 4210 3735] in the west so that a comparison could be made with the sections in the NW aureole and because of previous brief descriptions of structures assigned to D3 (Exley and Stone, 1982; Stone and Exley, 1984).

D1 and D2 structures

A primary bedding-parallel cleavage (S1) occurs throughout and has a mean dip of 20° NW. F1 folds and D2 structures were not observed.

D3 structures

D3 structures are developed in metasedimentary rocks throughout the area; F3 folds are best observed in the cliff exposures above the Porthmeor cupola [SW 4255 3765]. Typically, F3 folds are tight and overturned and have a wavelength <0.5 m; they verge to the SE and have a mean plunge of 9°/025°. The folds are associated with a NW-dipping axial planar S3 cleavage that crenulates S1 in the hinge areas of F3 folds. Small SE dipping extensional faults (trace lengths <1 m) and SE verging F3 folds above the same bedding-parallel surfaces indicates the development of D3 detachment faults similar to those south of Porthleven (Bar Lodge).

Discussion

Regional deformation chronology

Table 1 summarises the geometry and relative chronology of regional deformation recognised in the Porthleven coastal section. These data are consistent with previous studies that established and refined the D1-D3 deformation chronology (Smith, 1965; Turner, 1968; Rattey and Sanderson, 1984; Alexander and Shail, 1996). Table 2 summarises the geometry and relative chronology of regional deformation established within the NW contact metamorphic aureole of the Land's End Granite and at Porthmeor Cove.

D1 deformation is represented by a ubiquitous bedding-parallel S1 cleavage. F1 folds have not been recognised in the aureole, but the presence of isoclinal folds is implied by the bedding-cleavage relationship and would be consistent with the D1 deformation style outside the aureole (Table 1, see also Smith, 1965; Rattey and Sanderson, 1984). The identification of F1 fold hinges is no doubt hindered by the locally intense D2 and D3 overprint; such deformation, together with textural effects of contact metamorphism, also minimises the occurrence of unambiguous younging criteria that might additionally be used to infer fold axial surfaces.

D2 deformation has been positively identified at Cape Cornwall, Botallack and Pendeen Watch on the basis of refolding relationships between F3, F2 and S1, and cleavage overprinting relationships between S3, S2 and S1. The sections east of the Priest's Cove slipway and around Botallack Head and Pendeen are important locations where D2 structures and their relative chronology with respect to D1 and D3 structures can be established. D2 structures were not identified at Porth Ledden or Porthmeor Cove and this may reflect either the absence of D2 deformation in these areas, due to its partitioned nature, or its obfuscation by D3 deformation and contact metamorphism. F2 folds vary from NNW to NE plunging, WSW to NW verging, and are associated with a moderately ENE to SE dipping S2 crenulation cleavage. ENE to SE verging parasitic F2 folds might be anticipated on the overturned limbs of larger scale F2 folds but have not been observed; it may be that larger scale folds were not generated. However, any such

TECTONIC EPISODE	FOLDING STYLE	CAPE CORNWALL	BOTALLACK	PENDEEN WATCH	PORTHMEOR COVE
D1 Variscan convergence	Folds not observed	S1 048/18 NW n = 109	S1 069/33 NW n = 12	S1 071/23 NW n = 18	S1 077/20 NW n = 18
D2 Variscan convergence	Open folds that verge WSW to NW	F2 17/346 n = 15 S2 353/42 NE n = 7	F2 15/008 n = 15 S2 007/56 SE n = 16	F2 08/043 n = 12 S2 048/47 SE n = 17	Not observed
D3 Post-Variscan extension	Open to tight folds that verge ESE to SE	F3 13/020 n = 60 S3 032/37 NW n = 29	F3 17/009 n = 28 S3 023/52 NW n = 20	F3 07/061 n = 14 S3 061/52 NW n = 14	F3 9/025 n = 13 S3 033/41 NW n = 16

Table 2. *Summary D1-D3 structural data, including mean orientations, from the NW aureole of the Land's End Granite.*

parasitic E to SE verging F2 folds would be optimally orientated for further tightening during D3 deformation, and could have developed into composite F2/F3 SE verging folds in which the S2 cleavage was transposed by the S3 cleavage.

The NNW-SSE and NE-SW trending post-D2 quartz veins described from the Porthleven section are present throughout the NW aureole and are best displayed at the southern end of Porth Ledden. They are variably deformed by D3; depending upon their orientation, and must have formed prior to, or during the early stages of D3 deformation. Several sub-types were recognized in the Porthleven area and assigned to the D3 episode by Wilkinson (1990).

Ductile D3 deformation is widely observed throughout the aureole and in many areas constitutes the dominant expression of deformation. F3 folds plunge gently NNE, are tight and predominantly verge ESE, unless on the overturned limbs of first order F3 folds. The associated axial planar S3 cleavage dips gently to moderately WSW. D3 deformation appears localized in some areas adjacent to bedding-parallel fault zones.

The data presented confirm previous inferences that the predominant folds and cleavages observed within the Land's End Granite aureole formed during the regional D3 event (e.g. Exley and Stone, 1982; Rattey and Sanderson, 1984; Stone and Exley, 1984; Salmon and Shail, 1999; LeBoutillier, 2002; Kratinova *et al.*, 2003). These suggestions were based on the geometrical similarity with D3 structures outside the aureole. However, this study has additionally demonstrated that regional D2 structures are present, albeit commonly overprinted and obscured by D3 and textural changes accompanying contact metamorphism. The deformation chronology and style at Porthleven and in the NW aureole, based on data presented here, are compared with that shown on the Penzance sheet and summarised in the memoir (BGS, 1984; Goode and Taylor, 1988) in Table 3. The SE verging folds and NW dipping cleavage shown in the Land's End aureole and assigned to D2 (BGS, 1984; Goode and Taylor, 1988) are here re-assigned to the regional D3 deformation event in the same manner as for the section between Perranporth and St Ives (Alexander and Shail, 1995). The N verging F3 folds described by Goode and Taylor (1988) were not recognized in this study and their D4 deformation, associated with a subhorizontal cleavage and equivalent to the D3 of Jackson (1976), is interpreted as a high strain manifestation of the regional D3 episode (cf. Alexander and Shail, 1995). The regional D4 episode of deformation, associated with NNW-SSE steeply inclined cleavages (e.g. Smith, 1965, 1966; Rattey and Sanderson, 1984), is confirmed.

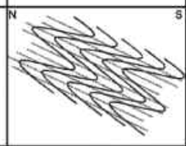
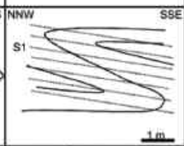
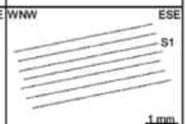
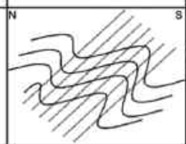
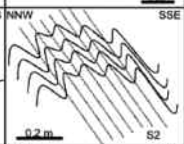
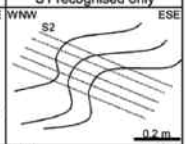
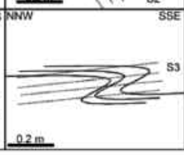
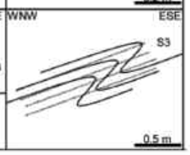
Deformation phase	Penzance Memoir	Porthleven section	Land's End Aureole
D1			 S1 recognised only
D2			
D3			

Table 3. *Summary regional deformation chronology and style for the Porthleven section and Land's End contact metamorphic aureole (this study), compared with that of the second edition Land's End sheet (BGS, 1984) and memoir (Goode and Taylor, 1988).*

Timing of deformation relative to granite emplacement

The main body of the Land's End Granite truncates D3 folds and cleavage in the host rock, and includes arrested xenoliths containing D3 folds and cleavage, at Porth Ledden and Porthmeor Cove (all locations). Minor granite / microgranite intrusive sheets occur widely in the aureole and invariably cut D3 structures and are not folded by D3. Similar relations occur in the aureole of the Tregonning Granite (Stone, 1975; Alexander and Shail, 1996). Granite emplacement post-dated ductile D3 deformation. The steeply inclined NNW-SSE S4 cleavage crenulates contact metamorphic biotites in the aureole of the Tregonning Granite.

Kinematics

Regional D1 and D2 structures are interpreted to have formed during Variscan convergence associated with a dominant top sense-of-shear to the NNW (e.g. Rattey and Sanderson, 1984; Alexander and Shail, 1995, 1996; Leveridge and Hartley, 2006). Kinematic data are not available for D1 structures in the aureole, but the F2 folds have a vergence varying from WSW to NW that is broadly consistent with these studies. Nevertheless, D2 structures within the aureole vary in orientation between each location (Table 2 and Figure 7). D2 structures at Pendeen Watch are closest in orientation to those at Porthleven; there is counterclockwise change in the plunge direction of F2 and dip direction of S2 moving SW from Pendeen Watch to Botallack (~40°) and Cape Cornwall (~55°).

Insufficient data have been collected to fully characterise the kinematics of post-D2 quartz veins. The thicker, steeply inclined NNW-SSE veins have been interpreted by Wilkinson (1990) to have formed in strike-slip shear zones. These thicker veins commonly have thinner moderately SE dipping branches that appear approximately parallel to S2 cleavage in section view (e.g. Figure 3b), but transect S2 cleavage in a counter-clockwise manner by 10-20° in plan view. A tensile origin for these NE-SW striking veins would be possible during dextral movement across the NNW-SSE shear zones as inferred by Wilkinson (1990). Both the NNW-SSE and NE-SW veins were subsequently deformed during D3 and hence must have formed in either a discrete post-D2 regional strike-slip regime that occurred prior to D3, or in a localized strike-slip regime during the early stages of D3. The thicker veins are associated with blackened wall rock hosting andalusite within the contact metamorphic aureoles of the Land's End and Tregonning-Godolphin granites. This association appears anomalous as the veins predate most or all of the D3 deformation and hence granite emplacement and contact metamorphism (see below). The blackened wall rock and andalusite result from a contact metamorphic overprint of a wall rock altered by the migration of high temperature metamorphic fluids during the post-D2 strike-slip event. These metamorphic fluids may reflect peak convergence-related metamorphic conditions at depth; reduction of the Si/Al ratio in the mudrocks of the Mylor Slate Formation predisposed them to localized andalusite formation during later contact metamorphism following granite emplacement.

D3 structures in the aureole are characterised by an NW to WNW dipping S3 cleavage and first order F3 folds that verge E to SE, as do all second order folds on the long limbs of first order structures. The predominance of E to SE verging F3 folds, local vergence reversals being restricted to the short overturned limbs of first order F3 folds, contrasts with the NW verging summary F3 data for the NW and N aureole shown in figure 4 of Rattey and Sanderson (1984). These data invalidate their 'fir tree' model of fold vergence about the Land's End Granite, i.e. small scale F3 structures could not have been superimposed upon pre-existing large-scale antiforms around the granites.

The formation of predominantly E to SE verging F3 folds from SE dipping elements is kinematically consistent with either pure shear vertical shortening (e.g. Stone, 1962, 1966; Smith, 1965, 1966) or by a top-sense-of-shear to the E or SE (Alexander and Shail, 1995, 1996) prior to any post-D3 tilting/rotation. Distinguishing between these models is more challenging in the aureole as independent kinematic indicators for bedding-parallel detachment faults, such as those around Loe Bar, are usually absent. Nevertheless, D3 structures in the aureole are commonly localised in the vicinity of bedding-parallel faults, albeit usually kinematically unconstrained. Some examples, such as at Porthmeor Cove, indicate a complex association of small-scale SE-dipping extensional (Riedel R1) faults and F3 folds / S3 cleavage above bedding parallel faults and are consistent with similar structures outside the aureole and a simple shear rather than vertical shortening origin. Variations in the attitude of S3 cleavage and the inter-limb angles of associated F3 folds, on a metre to decametre scale at a single location, can also be best explained by changes in the intensity of D3 strain generated during a top sense-of-shear to the E to SE. Variations in strain intensity associated with idealised pure shear vertical shortening would modify F3 inter-limb angles but not the cleavage orientation (effects of post-D3 tilting/rotation are minimal at outcrop scale).

Although overprinted by contact metamorphic textural changes the D3 structural styles in the aureole, comprising zones of distributed shear and more localized detachment-related deformation, are similar to those in the Porthleven section. A similar origin involving the development of a top-to-the SSE sense-of-shear during the extensional reactivation of thrust faults that, given contact relations between the granite and host rock, must have occurred prior to granite emplacement (e.g. Alexander and Shail, 1995, 1996). Whilst the Land's End Granite post-dates ductile D3 fabrics, the persistence of a NNW-SSE extensional regime throughout much of its emplacement history is consistent with magmatic state fabrics (Kratinova *et al.*, 2003, in press) and the ENE-WSW trend of the earliest steeply inclined brittle extensional faults and veins (Shail and Wilkinson, 1994; Alexander and Shail, 1995). The absence of a clear ductile expression of this ongoing deformation probably reflects the exhumation and cooling of the host rocks prior to granite emplacement and increasing strain accommodation by brittle faulting. As thin granite / microgranite sheets are also undeformed by ductile D3, the rheological influence of aureole contact metamorphism appears to have been limited.

D3 structures within the aureole vary in orientation between location in a broadly similar manner to D2 structures (Table 2 and Figure 7). F3 hinges at Pendeen Watch are similar in orientation to those at Porthleven; but there is a counter clockwise change in F3 plunge direction between Pendeen Watch and Cape Cornwall (~40°), Botallack (~50°) and Porthmeor Cove (~35°). S3 cleavage in the aureole typically dips ~40-50° NNW to WNW and is markedly different to that at Porthleven. Restoration of this aureole S3 cleavage to the modal horizontal orientation at Porthleven would therefore require a 40-50° tilt to the SE about a horizontal ENE to NNE axis. A similar tilt applied to the aureole S2 cleavage cannot restore all D2 structures to the orientation around Porthleven. One reason for this is the presence of apparent differential vertical axis rotations between locations, described above, of up to 55°. Other factors might include folding of S2 during D3 and the possibility that the S2 in the NW aureole might have developed with a steeper attitude, reflecting lower strain, than at Porthleven. The regional D4 deformation represents an episode of ENE-WSW shortening during the Mid- to Late Permian (Alexander and Shail, 1996; Shail and Alexander, 1997).

Accommodation of the Land's End Granite

Ductile D3 deformation of the host rocks has been shown to predate the emplacement of the Land's End Granite and plays no substantive role in its accommodation. The most obvious consequence of granite emplacement is the NNW to WNW tilting of the S1-S0 and S3 fabrics by ~40-50° relative to those at Porthleven, suggesting that roof uplift during construction or inflation of the pluton was an important mechanism (Figure 8); see also Taylor (2007). Although segmented by higher angle faults, many of the contacts between the granite and the host rocks in the NW aureole are approximately parallel to the S1-S0 and/or S3 fabric and are consistent with such an origin. The vertical axis orientations between aureole locations might be in part related to large-scale open folding accompanying roof uplift and emplacement and that are reflected in the strike variations of the aureole metabasic rocks (Figure 5). Other possibilities include differential block rotations across NW-SE faults prior to granite emplacement, as has been demonstrated elsewhere in the region (e.g. Leveridge and Hartley, 2006), but testing this would require further mapping.

CONCLUSIONS

The regional deformation chronology can be recognised in the NW contact metamorphic aureole of the Land's End Granite. Regional D2 structures, comprising an ENE to SE dipping S2 crenulation cleavage and WSW to NW verging F2 folds have been described for the first time and are consistent with development during a top-sense-of-shear to the NW during Variscan convergence. These structures are commonly obscured by later deformation and the textural effects of contact metamorphism. The 'local' D2 structures, comprising a NW dipping S2 cleavage and SE verging F2 folds, shown in the NW and N aureole in the Land's End sheet and memoir (BGS, 1984; Goode and Taylor, 1988) have been re-assigned here to the regional D3 deformation episode. A set of post-D2 quartz veins, comprising steeply inclined NNW-SSE trending segments up to 0.5 m thick, with thinner moderately SE dipping segments, developed during a discrete episode of post-D2 strike-slip deformation or in the early stages of D3 deformation. Wall rock alteration caused by the migration of metamorphic fluids during that episode may have exerted a favourable compositional influence on the formation of andalusite during later contact metamorphism.

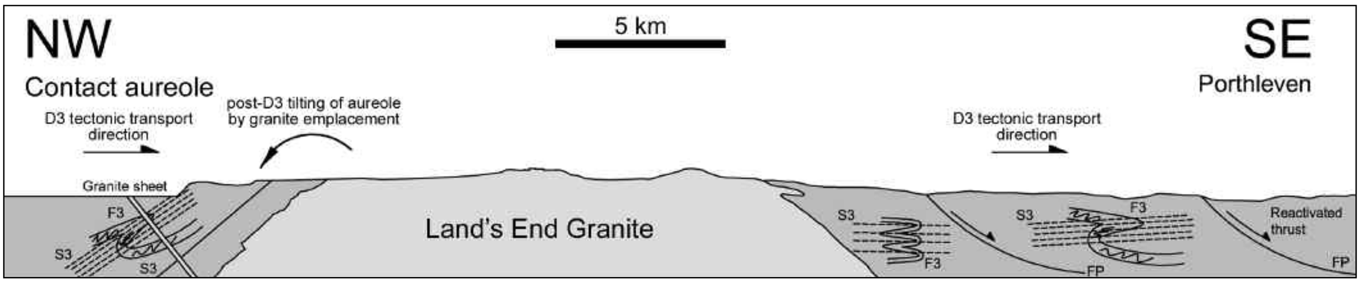


Figure 8. *Summary sketch section summarising the geometry of D3 structures in relation to the granite batholith from the NW aureole and around Porthleven. F3 folds predominantly verge SE on both flanks of the granite but D3 and earlier structures in the NW aureole have been tilted to the NW by roof uplift during granite emplacement.*

D3 structures comprise first order E to SE verging F3 folds and a NW to WNW dipping S3 crenulation cleavage. Some F3 folds may have developed in the vicinity of bedding parallel detachment zones. Overall there is a similarity with the style of D3 structures observed in the Porthleven section. Local vergence reversals of second order folds occur on the steep overturned limbs of these first order structures, but the predominant vergence across the NW aureole is to the E or SE. The suggestion of a dominant NW vergence for F3 folds (Rattey and Sanderson, 1984) along the NW and northern aureole of the Land's End Granite is rejected. Ductile D3 deformation predates granite emplacement and is consistent with formation during a top-to-the SE sense of simple shear developed during the extensional reactivation of large scale thrust faults, although the possibility of a component of pure shear vertical shortening cannot be excluded. The most obvious mechanism for the accommodation of the Land's End Granite was by roof uplift that brought about a NNW to WNW tilting of host rock by ~40-50°. Differential apparent vertical axis rotations between locations in the NW and N aureole may be related to large-scale open folding accompanying granite emplacement and/or pre-granite movements on NW-SE strike-slip faults. Regional D4 deformation, is represented by a steeply dipping NNW-SSE trending F4 folds and S4 cleavage; it postdates the contact metamorphism around the Tregonning Granite and is probably Mid- to Late-Permian and hence marks the latter stages of Palaeozoic deformation.

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