LATE VARISCAN STRUCTURES ON THE COAST BETWEEN PERRANPORTH AND ST. IVES, CORNWALL

A. C. ALEXANDER AND R.K. SHAIL

Structural mapping of the coast between Perranporth and St. Ives has shown that two generations of north-north-west verging Variscan convergence related structures (D1 and D2) are post-dated by a diverse range of structures showing top to the south-east sense of shear. These D3 structures are represented by the coeval development of ductile zones of distributed shear, brittle-ductile detachments and brittle south-east dipping listric extensional faults. Lithology of the pre-existing anisotropy controls both the extent and the geometry of these structures. Extensional exhumation is suggested by the progressively more brittle nature of post-D2 deformation. D3 deformation probably represents the late orogenic extensional reactivation of thrust faults. Subsequent north-north-west dipping faults appear synchronous with granite emplacement. A period of east-north-east—west-south-west shortening occurred prior to the development of steep, commonly mineralized, faults which indicate renewed north-north-west—south-south-east extension. The infill of the north-north-west—south-south-east striking cross-course faults relates to later approximately east-west extension. This study suggests that following Variscan convergence there is a period of late-orogenic extension both pre-dating and synchronous with granite emplacement and mineralization.

A.C. Alexander and R.K. Shail, Camborne School of Mines, University of Exeter, Redruth, Cornwall, TR15 3SE

INTRODUCTION

Structural interpretations of coastal sections in south Cornwall have concentrated, until recently, on the early Variscan convergence history (e.g. Smith, 1965; Rattey and Sanderson, 1982; 1984). However, interest in late orogenic processes has introduced scope for further field based study (e.g. Holdsworth *et al.,* 1993; Shail and Wilkinson, 1994). Much of this recent work has been carried out on south coast localities, notably near Porthleven, where south verging folds and complex fault arrays can be related to the extensional reactivation of thrusts (Shail and Wilkinson, 1994). Similar south verging folds can be seen on the north coast, but have been attributed to backthrusting (Leveridge *et al.,* 1990). A reinvestigation of these, and other structures, as part of this study suggests that they can be interpreted in terms of extensional tectonics.
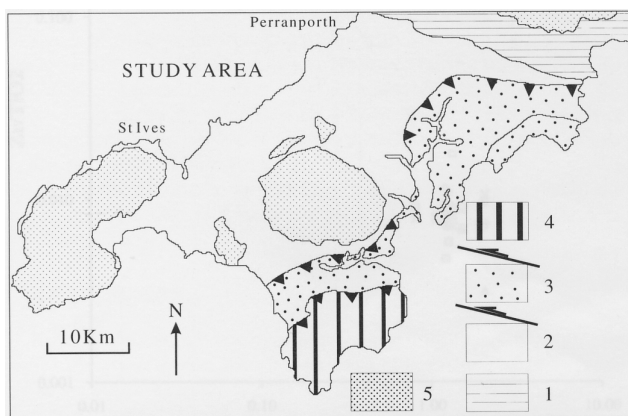

Figure 1. Simplified geological map of south Cornwall, showing study area. (1) Meadfoot Group; (2) Parautochthonous Gramscatho Group and Mylor Slate Formation; (3) Allochthonous Gramscatho Group; (4) Lizard ophiolite Complex; (5) Granites.

THE VARISCAN EVOLUTION OF SOUTH CORNWALL

Basin evolution and Variscan convergence

The study area (Figure 1) lies to the south of the Start-Perranporth Line (Holdsworth, 1989a) and comprises low grade ?mid-Emsian to late Famennian metasediments originally deposited in the Gramscatho Basin (Leveridge *et al.,* 1990). Variscan convergence brought about closure of this basin by the earliest Carboniferous (Wilkinson and Knight, 1989) and was associated with the emplacement of thrust nappes, including the Lizard ophiolite, towards the north-north-west (Rattey and Sanderson, 1984; Leveridge *et al.,* 1984). This gave rise to thrust related burial and regional pumpellyite-actinolite facies metamorphism (Barnes and Andrews, 1981). The associated D1 and D2 structures generally verge and face towards the north-north-west (e.g. Rattey and Sanderson, 1984).

The change from bulk contraction to extension

Several authors have noted a change from bulk contraction to bulk extension between the formation of D2 structures and the sequential emplacement of the Cornubian batholith (e.g. Hawkes, 1981; Shail and Wilkinson, 1994). Certain post-D2 structures indicate vertical shortening pre-dating final granite emplacement (Turner, 1968). Most workers have termed these structures D3 and relate them to strains created by the rising batholith (e.g. Turner, 1968; Rattey and Sanderson, 1984). However Leveridge *et al.* (1990) have recently suggested that post-D2 structures exposed along the north coast can be related to a D3 backthrust event, whilst the D3 structures of previous workers are interpreted as reflecting later (D5) extensional reactivation. D4 of Leveridge *et al.* (1990), which represents continued north-northwest directed thrusting was not recognised in this study. It seems likely that regional extension had probably initiated by the latest Carboniferous as polymetallic mineralization in the Carn Brea granite, hosted by steeply dipping extensional faults, is dated at 286 Ma (Chen *et al.,* 1993; ^{40}Ar-^{39}Ar muscovite).

[SW 5544 3889] and Godrevy Head [SW 5800 4325]. Commonly the overturned limbs of these folds are shortened with a strong to transposing subhorizontal axial planar cleavage. At Droskyn Point [SW 7513 5430] and Chapel Porth [SW 6967 4955] the folds are much tighter and recumbent, with a gently dipping, and often transposing axial planar S3 cleavage (Figure 3a). D3 folding is either restricted to narrow zones of high strain or to diffuse areas of distributed homogenous shear. In many cases the margins of the fold envelopes dip moderately or steeply south-eastwards, subparallel to the S2 cleavage, or are bounded by extensional faults. Top to the south-east slip on the S2 cleavage often brings about extension of S1. In some high strain zones small scale north-south trending folds are developed. These show an inconsistent crosscutting relationship with the dominant southwards verging folds and give rise to complex dome and basin interference patterns.

Detachments

In many cases F3 folds are localized in the immediate hanging-wall of bedding-parallel brittle detachment surfaces (Figure 3b). At Porthcadjack Cove [SW 6413 4479] a detachment system includes a lateral ramp and a culmination antiform. F3 folding is essentially confined to within 2 m or so of the detachment surface. The folds themselves are highly non-cylindrical, often with bifurcating hinges, and are overturned towards the south-east (Figure 2b). In this example the maximum short limb length is only 0.3 m or less, although at nearby Burney Deadman's Cove [SW 6125 4309] short limbs may be up to a metre or so within thicker sandstone units. Cleavage at these localities is generally poorly developed, and where observed is often a spaced domainal fabric. A set of folds with near orthogonal axes in the hanging wall shows an inconsistent cross-cutting relationship with the south-eastwards verging folds. Domal interference patterns have been recorded. The development of secondary synthetic extensional faults associated with the detachments indicate a dominant top to the south-east sense of displacement. East to north-east dipping sigmoidal quartz-chlorite veins, up to 0.5 m thick, are found along parts of the north coast section. These veins cross-cut the S3 cleavage, but are folded in much the same way as the S2 parallel quartz, except that folds verge in the direction of vein dip. The veins are cross-cut by D3 detachment surfaces and so are probably in part synchronous with the D3 deformation.

Brittle south-east dipping listric faults

The development of listric and predominantly low angle south-east dipping (10°-60°) extensional faults is common along the north coast section. Secondary fractures and slickenline lineation data again reflect a consistent south-eastwards displacement sense (Figure 2c). They cross-cut all previously described structures and often bring about hangingwall rotation. The hangingwalls of some of the low angle faults show F3 folding, particularly in the areas where previously ductile D3 deformation has been recorded, e.g. Trevellas Porth [SW 7257 5199]. However there is a general lack of earlier ductile and semi-ductile D3 structures between Bassets Cove [SW 6384 4420] and Derrick Cove [SW 6191 4296]. Here, south-eastwards directed displacement is reflected predominantly by listric normal faults, often including minor brittle secondary conjugate fractures (Figure 3c), which locally show extension in the order of 50% or more. Poorly developed folds and cleavage are still seen in some hangingwalls.

Post-D3 structures

Late cleavages

A diverse range of structures post-dates the main D3 deformation, including gentle folds, cleavages and later faults. Two main cleavages can be recognized cross-cutting and crenulating D3 structures. An early steep north-north-west—south-south-east trending crenulation cleavage is cross-cut by a similar east-west

trending fabric (e.g. Rattey and Sanderson, 1984). Two sets of broad open to gentle symmetric upright folds have axes which parallel these trends. Both the D3 brittle listric faults and the east to north-east dipping quartz-chlorite veins have also been deformed by these folds. Locally the development of additional minor intersection lineations has been observed.

Late faulting

Late north-north-west dipping faults consistently post-date D3 detachments and south-east dipping listric faults. These faults often develop in fairly broad zones, within which extension values across minor faults reach nearly 50%. The faults commonly show listric profiles and dip at angles between 30° and 60° (Figure 2d). Minor asymmetric close folds in the hangingwalls of these faults verge in the direction of dip. The related spaced cleavage is generally poorly developed. At Trevellas Porth [SW 7267 5224] a fault dipping at around 40° to the north-north-west hosts an elvan dyke (Figure 3d), whilst another fault with the same orientation hosts a breccia dyke. At Chapel Porth [SW 6967 4955] a similar intrusive breccia shows abundant interstitial pyrite and has been substantially chloritized. Many low angle north dipping faults on the foreshore at Bassets Cove [SW 6367 4411] show intensely hydrofractured quartz-rich breccias.

A further set of faults (Figure 2d) consistently cross-cut all previous structures, along the north coast section. These are generally steeper structures, greater than 45° in dip, dipping either to the north-north-west or south-south-east, although in places they may be difficult to distinguish from the lower angle north dipping faults. These fault zones vary greatly in width with some containing cataclasite up to a metre thick, and are commonly mineralized with an association of quartz, chlorite and various sulphides (especially pyrite, chalcopyrite, sphalerite and galena). Some faults show an association of quartz, calcite and possible siderite. There is often evidence for crack-seal quartz textures suggesting repeated fluid pressure cycling. Slickenline data from these faults generally show dominantly dip-slip displacement, although many faults show minor sinistral and dextral slip components. A further set of north-north-west—south-southeast trending steep faults (cross-courses) are commonly found in restricted zones, for example at Porthcadjack Cove [SW 6414 4465], where dilational quartz-filled fractures cross-cut an earlier steeply south-east dipping fault. The main infill textures show dominantly dilational behaviour and evidence for fluid pressure cycling.

DISCUSSION

Comparison with previous work

South verging folds have been previously described by Smith (1966) and Rattey and Sanderson (1984) from the north coast section and interpreted in terms of D2 deformation. Rattey and Sanderson (1982, 1984) inferred that the change in vergence of their minor F2 folds defined a major upright F2 fold which they termed the Godrevy Antiform. However, not only is such an upright structure incompatible with the general style of D2 deformation but it is clear from this study that south-east verging folds and fabrics consistently post-date north-north-west verging F2 folds and fabrics. The Godrevy antiform is therefore rejected. The sub-horizontal nature of S0/S1 along much of the north coast is also somewhat anomalous. It may reflect the position of an original thrust flat during early deformation, or suggest rotation of previously inclined structures during later faulting. The latter interpretation is preferred here since the rotation of both D2 and D3 structures by south-east dipping late D3 faults has been recorded. The close association between detachments and south verging folds was first noted by Smith (1966) who remarked on the similarities with gravity-driven thrusts. The same association was described by Leveridge *et al.* (1990) and used as evidence for D3 backthrusting. However, these structures appear to be coeval with the development of zones of distributed shear and in
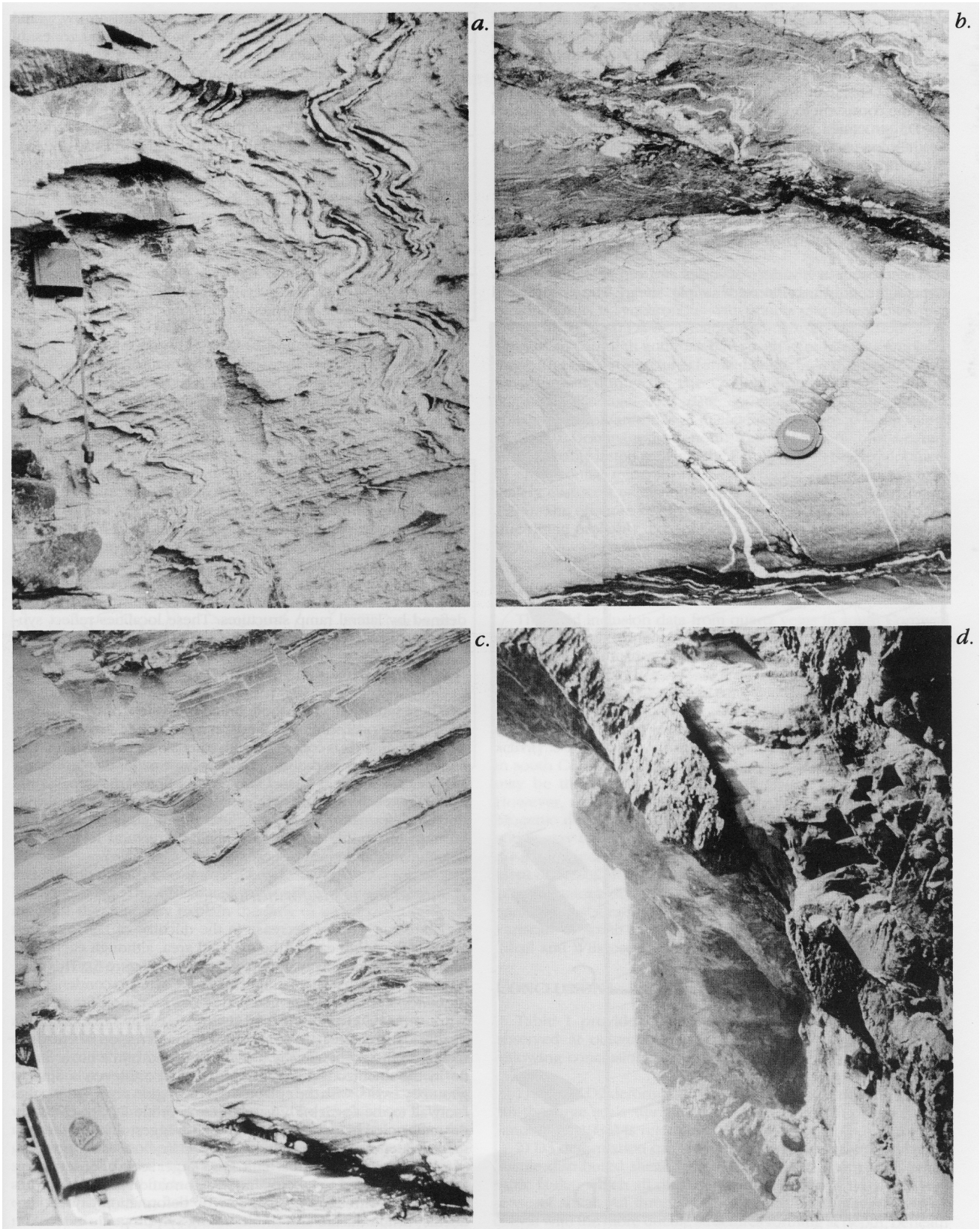
Figure 3. Field photographs of structures showing: (a) Tight recumbent F3 folds, from Droskyn Point [SW 7513 5430] with a low angle strong S3 crenulation cleavage in a zone of high distributed shear strain, folding both S2 and S2 parallel quartz veins. (b) Minor F3 folds developing on both a gently north dipping bedding plane and a low angle south dipping brittle fault, from Bassets Cove [SW 6384 4420]. Note that the moderately south dipping S2 cleavage and S2 parallel quartz veins are folded. (c) Minor D3 brittle south dipping extensional faults, at Bassets Cove [SW 6364 4410]. (d) Moderately low angle north-north-west dipping fault hosting a 6-8m thick elvan dyke, at Trevellas Forth [SW 7267 5224].

part coeval with the brittle south-east dipping listric faults, suggesting that D3 reflects bulk extension. Turner (1968) interpreted F3 recumbent folds with gently dipping S3 axial planar cleavages in terms of vertical shortening during granite emplacement. However the consistent top to the south-east sense of shear indicated by D3 structures mitigates against a simple flattening model. Furthermore, such a shear sense is unlikely to have developed on the northern margin of the granite batholith.

Interpretation of D3 structures

1) Zones of distributed shear

These occur at a variety of scales and can be interpreted in terms of southwards-directed simple shear. The nature and orientation of the

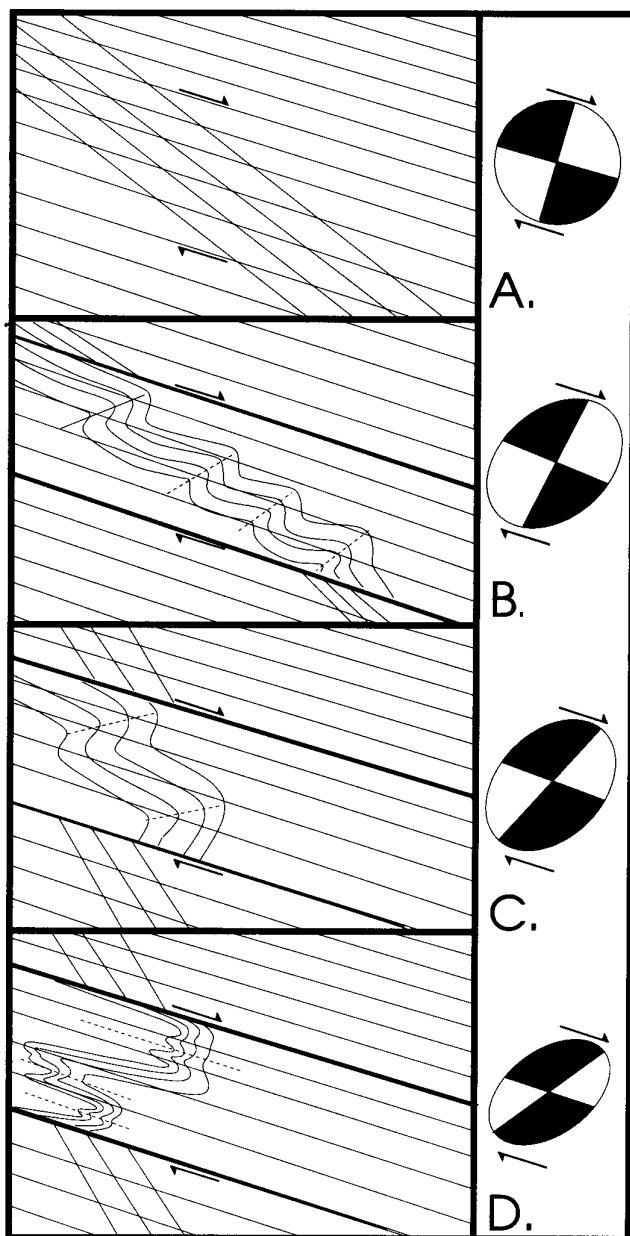*Figure 4. Shear zone model for the development of F3 folds with increasing strains. The steeper fabric may represent either S2 cleavage or bedding. Figure 4d shows the situation where the overturned limb of the fold enters the extensional field of the finite strain ellipsoid and is stretched, giving rise to an apparent change in vergence.*

dominant pre-existing S0/S1 anisotropy would result in south-east dipping bedding-parallel D3 shear zones. In such a system the moderately south-east dipping S2 cleavage, if present, would undergo folding, since it lies in the shortening field of the finite strain ellipsoid (Figure 4a,b). Bedding will not deform whilst it remains parallel to shear zone boundaries. However, if shear zones develop at a lower angle than bedding, or when localised sticking occurs, then bedding will also undergo folding of this style. With increasing shear strain the folds become tighter and the axial plane and associated cleavage will rotate into the same orientation as the shear zone margins, the folds becoming recumbent (Figure 4c,d). The shorter overturned limbs of these folds would soon enter the extensional field of the incremental strain ellipsoid and would be stretched, resulting in the development of neutral and even opposing vergence (e.g. Ramsay *et al.*, 1983). The overall geometry and extent of these zones is likely to be governed by lithology and strain rates.

2) Detachments

These structures show features similar to those developed in thrust terrains (Leveridge *et al*.,1990). The hangingwall folds are likely to have formed during down-dip sticking of movement on the detachment (e.g. Holdsworth, 1989b). Translation of bedding planes towards the south-east is indicated not only by fold vergence but also by synthetic Riedel shears and tensile fractures. There is much evidence for the development of minor F3 folds above more competent units where no prominent brittle detachment surface has yet developed. Prior to fault-block rotation these low angle structures would probably have dipped at low to moderate angles to the south-east, indicating a normal displacement. The development of orthogonal folds in the hangingwall may reflect translation of material into a constrictional zone, defined by lateral ramp structures. These localities reflect synchronous brittle extensional faulting and ductile folding.

3) Brittle south-east dipping listric faults

These faults reflect the more brittle equivalent of D3 deformation, and the overprinting of these on more ductile structures with similar kinematics is consistent with extensional exhumation. The fault zones developed during D3 may have major displacements in the order of 100 m or so. One section of coast displays mainly brittle D3 structures and as such may reflect extension coeval with ductile deformation at depth. Subsequent faulting may have brought this brittle region to a similar structural level as the detachments and shear zones.

A model for D3 deformation

There is a general decrease in the ductility of D3 structures towards the south-east of the mapped area, although each style of structure is in no way mutually exclusive (Figure 5). This may be simplified in that later faulting may have acted to condense this sequence into its present geometry. The metamorphic map of Warr *et al.* (1991) and Robinson *et al.* (1994) shows that the more ductile D3 structures are dominant within the region of epizonal metamorphism whereas the detachments and brittle listric faults lie in the anchizonal area (Figure 6). At Porthleven a similar geometry exists, with the epizonal ductile region representing the footwall to the Carrick Thrust with more brittle D3 structures in the anchizonal hanging-wall. This could suggest that the detachment-related structures on the north coast lie close to the position of a major reactivated thrust fault. On a larger scale of observation D3 may be related to heterogenous deformation associated with backslip on thrusts. The division of deformation styles into ductile, brittle-ductile and brittle during syn-orogenic extension has been described previously by Carmignani and Kligfield (1990) from the Apennines of Italy and Froitzheim (1992) from the Austroalpine nappes in Switzerland. In the Apennines the inter- pretation is based on a metamorphic core complex model (Carmignani and Kligfield, 1990). However in south Cornwall the metamorphic
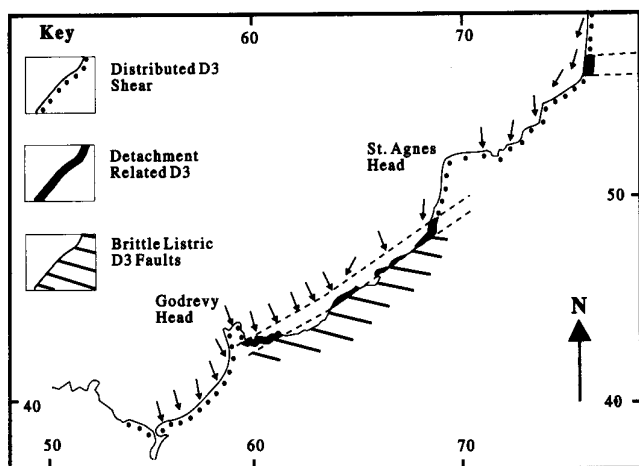
Figure 5. Summary diagram of all three dominant D3 deformation styles. Note the decrease in ductility towards the south-east. The arrows represent the mean top sense of movement determined from fold vergence, synthetic extensional faults and slickenline data. The continuation of the zones of detachment is uncertain due to poor inland exposure.
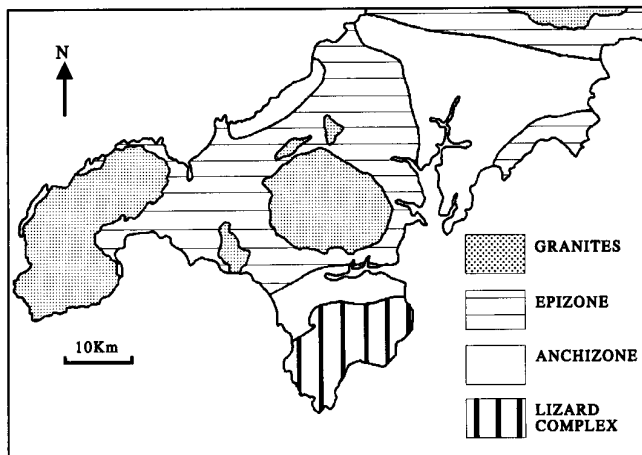

Figure 6 -The metamorphic grade map of south Cornwall (modified after Robinson et al., 1994; Warr et al., 1991), showing the strong correlation between the localities of distributed D3 shear and epizone grade rocks.

grades do not vary greatly between the upper and lower sections. The distributed nature of the deformation over much of the area may explain the lack of any sudden jump in metamorphic grades.

Interpretation of late faulting, cleavages and folds

Some of the low angle north-north-west dipping fault zones are considered to have substantial displacements, again of the order of 100 m or more, although a lack of marker horizons does not allow accurate measurement of separation. The orientation of these faults relative to the main batholith axis, as well as the association with elvan dykes, breccia dykes and hydrofracture veins all suggest an origin related to granite emplacement. These may have developed in response to continued extension after the granite intruded and pinned movement on the south-east dipping structures. The north-north-west—south-south-east steep cleavage and associated folds suggests that a regime of approximately east-west shortening had developed, apparently post-dating the north-north-west dipping fault set. Hobson and Sanderson (1983) note that the development of this set of folds is widespread over much of south-west England and may be very important during late Variscan evolution. Post-dating these structures

are a number of steep mineralized faults which reflect continued north-northwest—south-south-east extension. Minor strike-slip components to these faults may reflect a gradual change in the stress regime before dominant east-north-east—west-south-west extension developed with the cross-course infills.

Timing of earliest extension

Recent dating of the many granite plutons, elvans and mineralized lodes has allowed the relative dating of many of the later faults. Mineralization hosted by faults (lodes) began during the earliest Permian (e.g. Chen *et al*, 1993). Final emplacement of the Tregonning-Godolphin Granite post-dates D3 deformation (Turner, 1968). Specimens from the north coast indicate that cordierite and other thermal metamorphic spots appear to have grown mimetically along the S3 cleavage and one sample shows a cordierite spot overgrowing a low angle south dipping minor extensional fault (displacement < 3 mm). If the development of low angle north dipping faults is synchronous with granite emplacement, which seems likely, then D3 deformation pre-dates the intrusion of the Cornubian batholith and may have even controlled its emplacement. The earliest structures formed under bulk extension would have formed during the late Carboniferous, and are probably Stephanian in age. This date correlates well with orogenic collapse in the Variscides of mainland Europe (e.g. Malavielle *et al.*, 1990). Dominant north-north-west—south-south-east extension probably lasted well into the Permian, with the development of cross-course mineralization reflecting a change to approximately east-west extension during the Triassic (Scrivener *et al.*, 1994). The offshore basins began to develop in the Permian but true rifting probably did not begin until the Triassic (e.g. Evans, 1990).

Orogenic collapse versus critical crustal wedge

The fluid inclusion data from quartz veins in south Cornwall trace an overall exhumation history from Dl to D3 (Harvey *et al*, 1994). The exhumation during convergence can be explained in terms of erosion and/or extension near the top of a critical wedge (e.g. Harvey *et al.*, 1994; Shail and Wilkinson, 1994). Orogenic collapse (e.g. Dewey, 1988) causes both extension and a rapid rise in the heat flow to the base of the lithosphere. Magmatic activity is therefore likely to accompany extension, as is the case in south Cornwall. Platt (1993) suggests that the thermal history may be the only way to tell between the two mechanisms. However, magmatism is equally likely to occur during the lateorogenic development of far-field tensional deviatoric stresses, which may have acted in constructive interference with gravity driven collapse (e.g. Ziegler, 1993). The synchronous develop-ment of latest Carboniferous and Permian extensional structures, potassic volcanicity, granite emplacement and the limited devel-opment of offshore basins points to the interpretation of the late Variscan of south Cornwall as representing orogenic collapse (Shail and Wilkinson, 1994).

CONCLUSIONS

Table 1 provides a brief summary of the main structures observed at outcrop between Perranporth and St. Ives. The following conclusions have been reached:

1) Dl and D2 deformation of previous workers are re-affirmed, but the large scale upright F2 Godrevy Antiform of Rattey and Sanderson (1984) is rejected.

2) D3 deformation can be sub-divided into three main styles-ductile distributed shear, brittle-ductile detachments and brittle listric faults, which all display a dominant top to the south-east sense of shear. All three styles of deformation may have been coeval with the more ductile structures forming at depth, beneath more brittle detachments and extensional faults. Post-D2 deformation becomes progressively more brittle with time, reflecting extensional exhumation. D3 extension may have allowed the emplacement of the Cornubian batholith, and possibly initiated during the Stephanian.

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RELATIVE CHRONOLOGY		STRUCTURES & ORIENTATIONS	BULK KINEMATICS & INTERPRETATION
D1		F1 Folds verge & face NNW	NNW-SSE shortening during
D1		S1 Dips gently SSE	Variscan convergence &
D2		F2 Folds verge NNW	thrust nappe
D2		S2 Dips moderately SSE	emplacement
D3	Distributed shear	F3 Folds verge SSE S3 Dips moderately NNW	NNW-SSE late orogenic extension, possibly reactivating major thrust faults and pre-dating granite emplacement
D3	Detachments	Synthetic extensional faults dip and displace to SSE	NNW-SSE late orogenic extension, possibly reactivating major thrust faults and pre-dating granite emplacement
D3	Brittle Listric Faults	Extensional faults dip SSE Slickenlines plunge SSE	NNW-SSE late orogenic extension, possibly reactivating major thrust faults and pre-dating granite emplacement
LATE	Brittle Listric Faults	Extensional faults dip NNW Slickenlines plunge NNW	NNW-SSE extension coeval with granite emplacement
LATE	Crenulation Cleavage	Steep cleavage strikes NNW-SSE	ENE-WSW shortening
LATE	Steep Faults & Lodes	Steep, often mineralized, faults dip NNW or SSE	NNW-SSE extension and minor strike-slip
LATE	Crosscourse Faults	Steep faults strike NNW-SSE	ENE-WSW extension

Table 1. Summary deformation history and interpretations for the coast between Perranporth and St. Ives, south Cornwall.

3) North-north-west dipping faults, cross-cut all earlier D3 structures and are probably related to granite emplacement, which would have pinned movement on the south-east dipping structures. Subsequent extension would occur on these later faults. A period of east-west shortening is followed by the development of mineralized faults, reflecting north-north-west-south-south-east extension. Cross-course mineralization is associated with approximately east-west extension.

4) The extensional structures, igneous activity and basin evolution in south Cornwall are consistent with a model for gravity driven orogenic collapse possibly aided by regional deviatoric tensional stresses.

ACKNOWLEDGMENTS

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