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LATE-TO POST-VARISCAN EXTENSIONAL TECTONICS IN SOUTH CORNWALL

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Faults which post-date Variscan contractional deformation are ubiquitous in south Cornwall. Three broad geometric/kinematic types can be defined. The first type comprises low angle (dip <45°) extensional faults which exhibit listric or ramp and flat geometries and may display complex arrangements of secondary faults and folds in their hangingwalls. In some instances they host elvans and "mainstage" magmatic-hydrothermal lodes (more rarely lamprophyres). The second type are moderate to high angle (dip >45°) extensional faults which generally offset earlier low-angle faults; they frequently host elvans and "mainstage" magmatic-hydrothermal lodes. The third type are high-angle faults which usually exhibit dominant strike-slip displacement, offset all previous faults and are often associated with base metal mineralization. Collectively these structures exerted a strong control on granite emplacement, mineralization and the development of offshore sedimentary basins. The approximately coeval association of potassic volcanicity, granite magmatism, extensional faulting and sedimentary basin development was probably a consequence of late Carboniferous to early Permian collapse of previously thickened lithosphere.

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INTRODUCTION

South Cornwall represents one of the most internal onshore sectors of the Variscan orogen in the UK. The majority of field-based structural studies in the area, in common with those throughout the Upper Palaeozoic massif of south-west England, have principally investigated the geometries and kinematics of structures associated with Variscan contractional deformation (e.g. Rattey and Sanderson, 1984; Leveridge *et al.,* 1984; 1990). In contrast, relatively few recent studies have focused attention on the ubiquitous late- to post-Variscan structures. This contribution provides a preliminary assessment of the geometries, kinematics and timing of these structures, their relationship to magmatism and mineralization, and their possible origins and implications for the tectonic evolution of the area.

VARISCAN TECTONICS OF SOUTH CORNWALL

The Meadfoot Group crops out along the north-eastern margin of the study area (Figure 1) and comprises a late Siegenian to mid-Emsian assemblage of mixed siliciclastic/carbonate shallow marine sediments. The Gramscatho Group crops out throughout the remainder of the area and represents the deep-marine, predominantly siliciclastic, mid-Emsian to late Famennian infill of the most southerly of a series of sedimentary basins formed within south-west England during the Devonian and early Carboniferous (Holder and Leveridge, 1986). The Gramscatho Basin probably initiated in response to Devonian rifting; the generation of oceanic crust is confirmed by the Lizard Complex ophiolite (Bromley, 1979). The development of an "A-type" subduction zone at the southern margin of the basin during the Upper Devonian (e.g. Floyd *et al.,* 1991) brought about its closure by the earliest Carboniferous and significant crustal shortening across south-west England (e.g. Shackleton *et al.,* 1982).

Mainstage Variscan deformation

The last decade has seen the synthesis of detailed structural observations, new palaeontological data, offshore seismic data and BGS re-mapping into a regional model (Leveridge *et al.,* 1984; Holder and Leveridge, 1986; Leveridge *et al.,* 1990). The evidence presently available indicates that the boundaries between certain lithostratigraphic units must represent thrust faults (Figure 1). Mesoscopic deformation and low-grade regional metamorphism compatible with large-scale thrusting occurs throughout the area (Warr *et al.,* 1991). F1 and F2 folds generally verge and face to the north-north-west and are associated with locally intense cleavage development. Bedding, S1 and S2 all usually dip to the south-south-east; there are no major areas of overturned strata. M1 mineral lineations, where present, normally plunge down the dip of S1. The east-south-east—west-south-west trending Start-Perranporth Zone approximately coincides with the northern margin of the basin; here, D1 and D2 structures possess orientations and geometries that are compatible with formation in a dextral transpressional regime (Holdsworth, 1989a).

Late- to post-Variscan deformation

Published work concerning the late- to post-Variscan structures exposed along coastal sections in south Cornwall is relatively sparse. Brief descriptions occur in Shackleton *et al.* (1982), Hobson and Sanderson (1983), Coward and Smallwood (1984), Leveridge *et al.* (1990), and in preliminary work by Holdsworth *et al.* (1993). More detailed descriptions occur in the unpublished PhD thesis of Turner (1968). Similar structures have received more attention in North Cornwall and Devon through the work of Freshney (1965), Dearman and Freshney (1966), Freshney *et al.* (1972), and have been mentioned more recently by Warr (1988; 1989). All these studies indicate that extensional faulting occurred relatively late during Variscan evolution, the so-called "Great Reversal" of Dearman (1970) or "tectonic watershed" of Hawkes (1981).

Magmatism and mineralization

A complex sequence of late- to post-orogenic magmatism and mineralization occurs throughout the region (e.g. Bromley, 1989; Willis-Richards and Jackson, 1989; Jackson *et al.,* 1989; Alderton, 1993; Floyd *et al.,* 1993). Geochronological studies (Chesley *et al.,* 1993; Chen *et al.,* 1993) confirm that granite intrusion and mainstage lode development spanned some 25-30 Ma from approximately 294 Ma. Highly potassic mantle-derived magmatism is represented by lamprophyres; these are approximately coeval with the earliest granites (Leat *et al.,* 1987).

LATE- TO POST-VARISCAN DEFORMATION IN SOUTH CORNWALL

Extensional structures within the metasediments

Pentire Point East/Polkerris Beach

On the north coast at Pentire Point East [SW 7805 6161], moderately southward-dipping slates and sandstones, which define the limbs of north-verging and facing F1 folds, are deformed by shear bands indicating top sense of movement to the south-west.

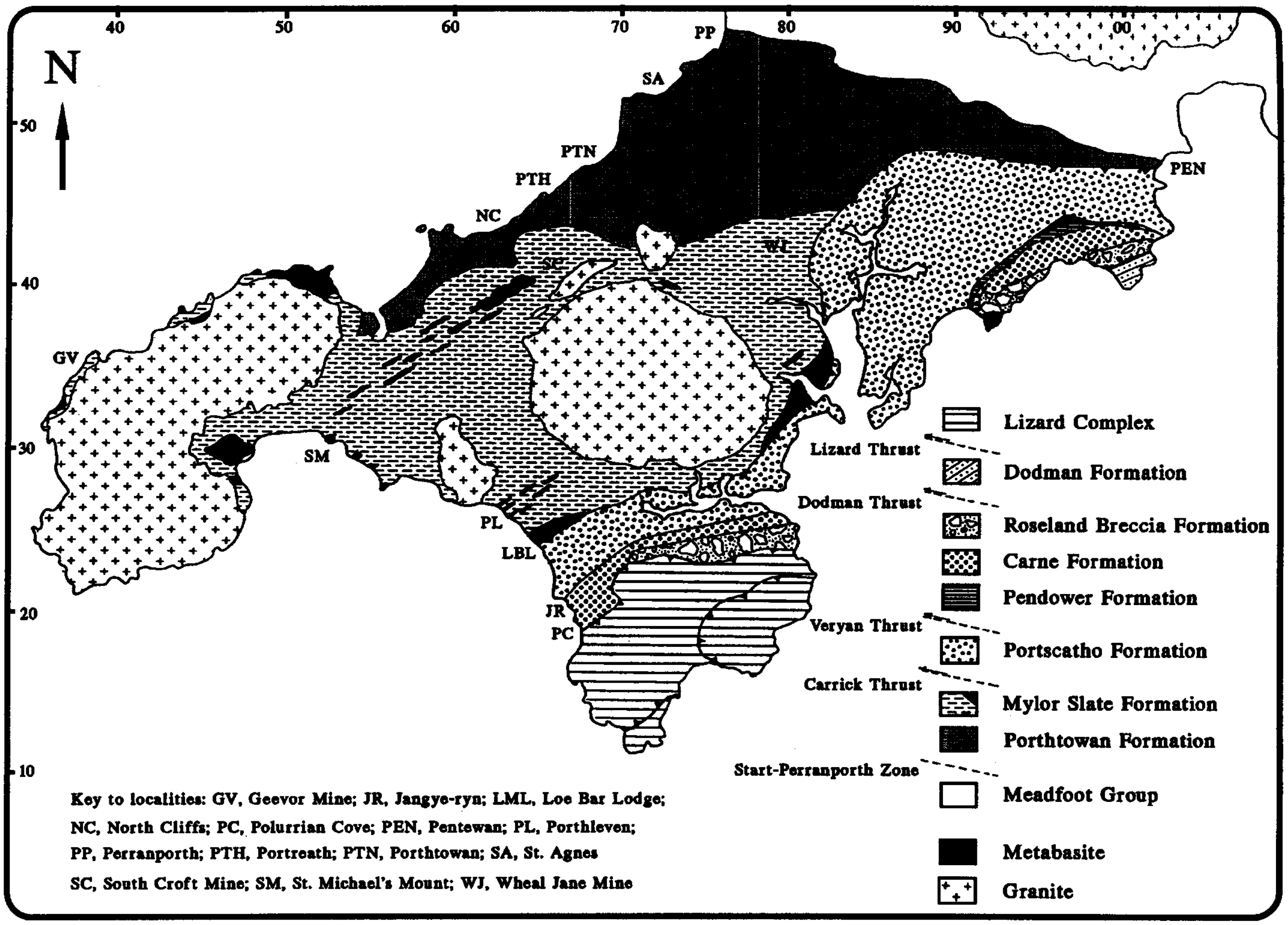

Figure 1. Simplified Upper Palaeozoic geology of south Cornwall (modified after Leveridge et al., 1990). Principal locations mentioned in text marked.

In some instances, these shear bands also indicate a dextral component of displacement (conjugate sinistral shear bands are occasionally observed). The shear bands are localized in zones adjacent to southward-dipping low-angle (dip <45°) extensional faults, which possess a small dextral slip component. Secondary southward-verging folds, with or without an associated cleavage, are developed in the hangingwalls of some faults. Similar structures can be observed on the south coast on the north-west side of Polkerris Beach [SX 0900 5227]. At both locations, low-angle fault zones are displaced by higher-angle faults.

Trevaunance Cove/Porthtowan/North Cliffs

Moderate to high angle (dip >45°) north-west and south-east-dipping extensional faults occur throughout the entire north coast section south-west of Pentire Point East. They are particularly well exposed around Trevaunance Cove [SW 7216 5160], between Porthtowan [SW 6916 4817] and Chapel Porth [SW 6970 4950], and along the North Cliffs [SW 6250 4316]. These higher angle faults post-date bedding-parallel faults which exhibit south-south-east-verging folds and associated north-north-west-dipping secondary cleavages in their hangingwalls and local footwall extension. These low-angle faults possess a similar geometry to those exposed along the south coast, but present data cannot resolve whether they developed during regional extension or as a consequence of the localized backthrusting described from the north coast by Leveridge *et al.* (1990).

Porthleven to Gunwalloe

Palaeontological, structural, sedimentological and offshore seismic evidence is broadly compatible with significant Variscan thrust faulting having taken place along, or close to, the boundary between the Mylor Slate Formation and the Portscatho Formation (Leveridge *et al.,* 1984; Leveridge and Holder, 1985; Edwards *et al.,* 1989). However, the contact between the Mylor Slate Formation and the overlying Portscatho Formation along this section is formed by a moderately south-east-dipping extensional fault at Loe Bar Lodge [SW 6400 2433]. It therefore seems probable that the Carrick Thrust has been cut out by late-or post-Variscan extension (Leveridge and Holder, 1985), in a similar manner as the Lizard Boundary Thrust farther to the south at Polurrian Cove (e.g. Barnes and Andrews, 1984). Intuitively, any major, possibly extensionally reactivated structure would be expected to pass through the Bar and continue along the line of the Helford River. Onshore seismic data obtained 10 km eastwards along strike show south-east-dipping reflectors in approximately such a position (Jones, 1991).

Towards the north-west end of the section, at Porthleven, spectacular south-south-east-verging post-D2 folds associated with an intense, locally transposing, cleavage fabric were formerly visible prior to coastal defence works. These folds continue to the margin of the Tregonning Granite and have been assigned to D3 by Turner (1968) and D5 by Leveridge *et al.* (1990). Farther south-east along this section numerous faults are observed which strike approximately east-north-east—west-south-west and dip at low or moderate angles to the south-south-east. Fault zones exhibit listric or ramp and flat geometries and are often associated with complex arrangements of secondary faults and folds (Figure 2a). Considerable quartz-veining is localized within, and adjacent to, many of these fault zones, suggesting widespread availability of fluids during deformation. Synthetic secondary faults and bedding offsets, together with slickenline and slickenfibre lineation data indicate dominant dip-slip

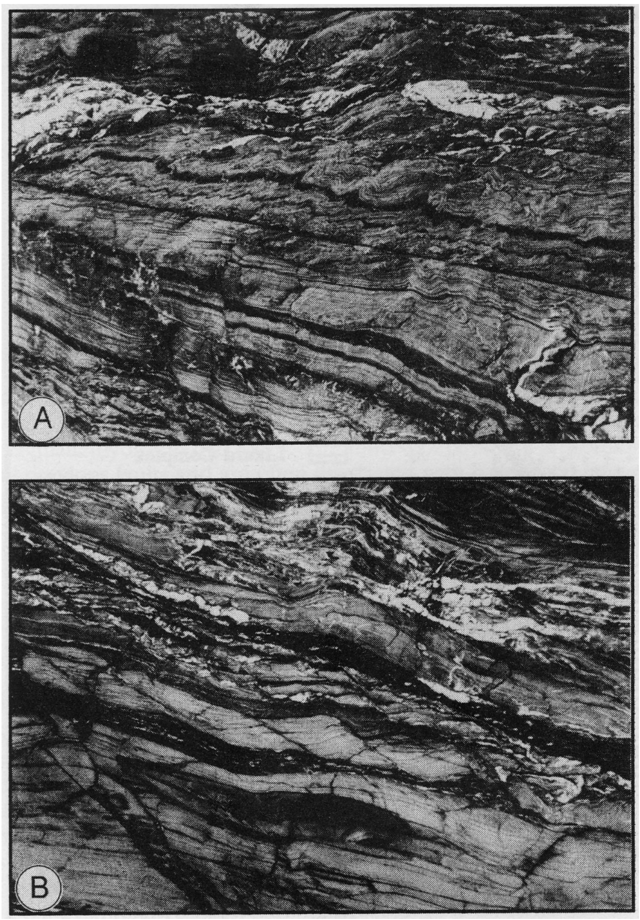

Figure 2. Field photographs of structures described in text: (a) Low angle detachments; prominent example (centre) associated with SE-verging folds in hangingwall and synthetic extensional faults in footwall [SW 6479 2338] Field of view 2m, looking NE. (b) SE-dipping Blue Rock "Thrust" (top left to bottom right). Well developed synthetic extensional faults indicate top sense of shear down dip to the SE. Pencil for scale (centre), looking NE [SW 6472 2347]

extensional displacements of approximately 0.1 to 10 m, occasionally with a slight dextral component (Figure 3). It is difficult to constrain larger magnitude displacements due to limited vertical exposure (generally 10-15 m) and the absence of suitable markers.

Synthetic secondary extensional faults bound small planar rotational fault blocks within the fault zone and probably initiated as synthetic Riedel shears and tensile fractures. Potential dilatant sites created by the rotation of these small-scale fault blocks, above approximately planar detachments, appear to have been filled by plastic flow of mudstone and precipitation of quartz. The "Blue Rock Thrust" [SW 6472 2347], defined on the basis of palynology and D2 strain intensification by Wilkinson and Knight (1989), displays excellent examples of synthetic secondary faults indicating down-dip top to the south-east sense of shear (Figure 2b). If this structure originated as a thrust fault, it now exhibits extensional reactivation. Secondary folds, with or without secondary cleavage, are observed in the hangingwalls of many detachments; they consistently exhibit a sense of vergence to the south-south-east (generally down-dip relative to the fault with which they are associated). In some instances, secondary synthetic extensional faults and folds are observed above the same detachment. Propagation of successive generations of low-angle faults may truncate or fold earlier formed detachments and their associated structures.

Higher angle faults along the section also strike approximately east-north-east and dip south-south-east, although some north north-west-dipping antithetic faults do occur (Figure 3). Again, dip-slip extensional displacements predominate and a small dextral component is sometimes present. Fault zones generally exhibit a planar geometry and may be associated with substantial breccia, chloritized gouge, and quartz-veining, e.g. Caca-stull Zawn [SW 6359 2482]. Higher angle faults usually cut across lower angle faults, although some may represent ramps to predominantly low-angle structures. Rare high angle north-north-west-striking faults are also observed; slickenlines and slickenfibres generally pitch at less than 45°S, indicating a dominant strike-slip component. The orientation of these slickenlines is, in some cases, identical to those on immediately adjacent east-north-east-striking faults, suggesting that the two faults, at least in part, may have moved synchronously.

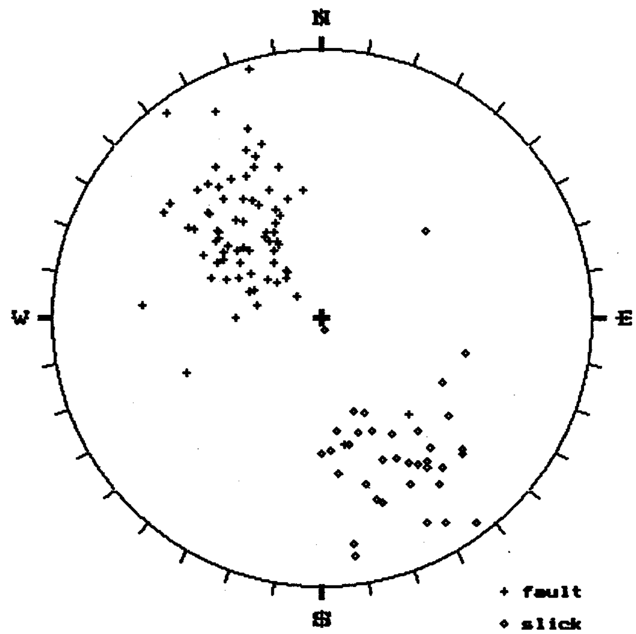

Figure 3. Equal area lower hemisphere stereogram showing fault poles and associated slickenline data for the Loe Bar Lodge to Gunwalloe coastal section.

Extensional faulting, magmatism and "mainstage" mineralization

Lamprophyres represent a volumetrically insignificant expression of late Variscan magmatic activity, and are generally badly weathered. The only example included in this study crops out on the northern side of Holywell Bay [SW 7670 5988], where a 2-3 m thick dyke is intruded into one of a series of moderately south-dipping extensional fault zones within the Meadfoot Group slates. This data implies that lamprophyre intrusion was either synchronous with, or post-dated faulting.

The relationship between granite intrusion and extensional faulting is difficult to directly constrain due to modification of many granite-country rock boundaries by stoping late in the emplacement history. The elongate surface form of the Carn Brea Granite has long been used to imply at least a localized structural control on emplacement by east-north-east—west-south-west striking faults (e.g. Dines, 1956). Magmatic fabrics within the granites have received only limited attention; most workers note a marked north-north-west-plunging lineation defined by alkali feldspar megacrysts (e.g. Ghosh, 1934). A tectonic control on megacryst alignment within the Carnmenellis granite has been discounted by Leveridge *et al.* (1990).

The distribution of elvan dykes within the region is shown in Figure 4. A 6-8 m thick east-north-east-trending elvan dyke dipping 40° north-north-west is spectacularly exposed in the cliffs to the east of Trevaunance Cove. It parallels some of the extensional faults in the immediate vicinity and appears to postdate minor low-angle extensional faults in its footwall. Subsurface studies at Wheal Jane (Rayment *et al.,* 1971) and Mount Wellington (Kettaneh and Badham, 1978) indicate elvans occupying similar low- or moderately north-north-west-dipping fault zones. To the north of Pentewan, a complex arrangement of elvan sills and dykes are observed in coastal outcrop [SX 0260 4757]. The dyke feeding these sills is clearly intruded along, and also deformed by, a moderately north-north-east-dipping extensional fault. All these occurrences imply that elvan emplacement was synchronous with, or post-dated the development of associated extensional faults, as has been previously inferred by Goode (1973).

Early granite-related mineralization is associated with pegmatites, greisen-bordered veins and tourmaline breccias (e.g. Chesley *et al*., 1993). These structures are usually interpreted as hydraulic fractures propagated through a carapace of previously crystallized granite by magmatic-hydrothermal fluids (Bromley and Holl, 1986; Halls, 1987); as such, most are purely dilational, but high temperature ductile shear is recorded in some cases (Alderton, 1993).

The majority of Cu-Sn production has been derived from "mainstage" polymetallic quartz-tourmaline-chlorite-sulphide-fluorite lodes. These are generally hosted by steeply dipping east-north-east–west-south-west striking faults (Figure 4), which possess complex kinematic and paragenetic histories (e.g. Hill and MacAlister, 1906; Collins, 1912; Bromley and Holl, 1986; Halls, 1987; Farmer, 1991). Net displacements are generally extensional and modest, up to several 10's of metres or less (e.g. Taylor, 1966), although displacements of up to 100m or so occur across some lodes. In the Camborne-Redruth and St. Agnes areas, the majority of lodes dip north-north-west and are cut by later south-south-east-dipping 'caunter lodes" which are also generally mineralized. Anomalous lode orientations include the "Great Flat lode" in the Camborne-Redruth district which dips 30° south (Dines, 1956), and the steeply-dipping "mainstage" lodes with a dominant north-west south-east strike in the St. Just mining district (Garnett, 1966).

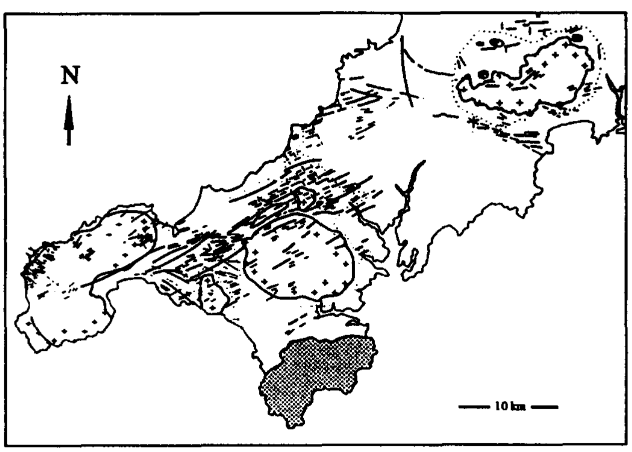

Figure 4. Distribution of elvans (thick lines), lodes (thin lines) and cross-courses (dashed lines) in south Cornwall (modified from Hosking, 1962).

Faults displacing "mainstage" mineralization

The elvans, greisen-bordered veins/tourmaline breccias and mainstage lodes are displaced by at least two subsequent fault sets. The first of these strike east-north-east west-south-west to east-south-east–west-north-west and may be considered as non-mineralized caunter lodes or "slides" (terminology is highly variable); they generally bring about extension and have been described in some detail from the St. Agnes district (e.g. Davies, 1880). Particularly good north-south cross-sections across Wheal Kitty and Penhalls Mine are reproduced in Dines (1956). These indicate that "slides" dipping 60° south-south-east bring about 15-20% extension of earlier mainstage lodes hosted by moderate-to low-angle fault zones.

The second set of faults are represented by north-west-south-east to north-south-striking subvertical "cross-courses" (Figure 4) which commonly exhibit dextral strike-slip displacements and are both structurally and paragenetically late, being either non-mineralized or hosting low-temperature base-metal mineralization (e.g. Hill and MacAlister, 1906; Collins, 1912; Dearman, 1963). They occur widely throughout the area and have already been described from the Porthleven section. Vertical quartz-filled structures of this type can also be observed cutting moderately southwards dipping extensional faults on Perran Beach [SW 7580 5540], at Porthcadjack Cove [SW 6410 4466], where the 'Great Cross-course" is exposed, and at St. Michael's Mount, where north-west south-east trending vertical quartz-filled tensile fractures post-date east-north-east–west-south-west-striking greisen-bordered sheeted veins. Some authors have suggested that north-west-south-east-striking faults existed prior to mainstage mineralization (e.g. Garnett, 1961; Kettaneh and Badham, 1978), whilst Bristow (1989) has argued that similar faults delimit intrusive episodes within the St. Austell composite pluton. Coward and Smallwood (1984) postulated that north-west-south-east-trending structures within the basement originated as tear faults during Variscan thrusting.

Fluid inclusion studies

The widespread availability of fluids throughout Dl, D2 and subsequent extensional deformation is represented by multiple generations of quartz veining along the coastal section from Porthleven to Jangye-ryn. Fluid inclusions within these veins have been described in detail by Wilkinson (1990a); their characteristics are summarized in Table 1. The first post-compression phase of fluid activity occurred synchronously with the emplacement of the Tregonning-Godolphin granite and formed variably oriented quartz veins in the metamorphic aureole. These contain distinctive H_2O-CO_2-N_2 -salt fluid inclusions (Wilkinson 1990b) which may be partly of magmatic origin but also contain a significant component derived from the metasedimentary country rocks (Wilkinson, 1991). Similar "aureole-type" fluids are recorded in quartz-filled microfractures cross-cutting earlier D1/D2 veins adjacent to low-angle extensional, or extensionally reactivated structures, e.g. the Blue Rock "Thrust" and may imply that extensional deformation occurred synchronously with emplacement of the granite.

Fluids mobilised in the later east-north-east-trending high-angle extensional faults cutting the same metasediments are quite different,

Deformation event	Fluid type	Fluid Temperature	Fluid Pressure
Peak pumpellyite-actinolite regional metamorphism, brittle-ductile thrusting (D_1)	H_2O + 2 weight % CO_2 = 2 weight % NaCl equivalent	330-300°C	3.5-2.9 kbar
Late, brittle thrusting (D_2)	H_2O + = 10 weight % CO_2 + 1-7 weight % NaCl equivalent	300-270°C	2.9-1.2 kbar
Contact metamorphism, low angle brittle-ductile extension	$H_2O + CO_2 + N_2 + CH_4$ + 1-40 weight % NaCl equivalent	440-200°C	1.0-0.5 kbar
ENE-WSW to NE-SW high angle, brittle extensional faulting	H_2O + 0-6 weight % NaCl equivalent	≈200°C	<0.5 kbar
NNW-SSE to NS subvertical strike-slip and oblique-slip lauding	H_2O + 27 weight % NaCl + $CaCl_2$ equivalent	≈440°C	<0.5 kbar

Table 1. *Summary of fluid types associated with deformation events*

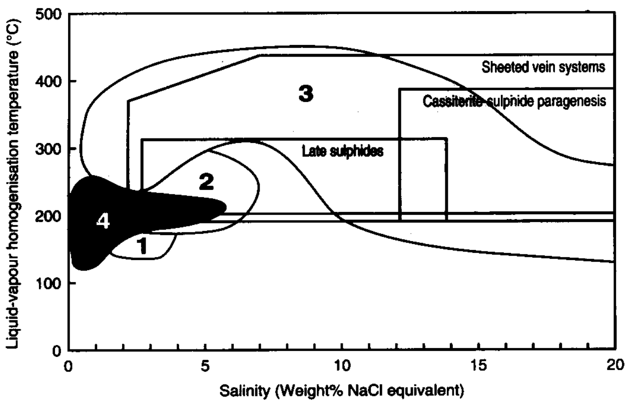

Figure 5. Homogenisation temperature-salinity diagram for fluid inclusions in quartz from *Southwest England. Shaded fields represent data from Wilkinson (1990a): 1. Syn D_1 veins; 2. Syn-D_2 veins;* 3. *Syn- to post D_3 veins (Wilkinson, 1990b); 4. Veins associated with brittle, high angle extensional faults. For comparison are shown for mineralised structures: wolframite/cassiterite/sulphide mineralised greisen-bordered sheeted vein systems (Jackson et al., 1977; Charoy, 1981; Shepherd et al., 1985); cassiterite/sulphide lodes (Jackson et al., 1982; Shepherd et al., 1985; Farmer, 1991); and late sulphide veins (Shepherd et al., 1985).*

being lower temperature, dilute, H_2O-rich solutions, comparable with the "end-member" fluids responsible for the paragenetically late cassiterite-polymetallic sulphide-chlorite paragenesis observed in granite-hosted lodes (Figure 5). Stable isotopic data indicate that these fluids are evolved meteoric waters (Wilkinson, 1990a). There is evidence in the Porthleven area that such fluids infiltrated north-south-trending "cross-course" faults and mixed with high salinity brines associated with the low temperature base metal paragenesis (Wilkinson, 1990a). This suggests synchronous dilation of both structures, consistent with kinematic indicators already described, and implies that the late phase of tin mineralization was coincident with the influx of basinal brines. This is in agreement with fluid inclusion data from Wheal Pendarves and South Crafty (Scrivener *et al.,* 1986) and the Kit Hill-Gunnislake district further east (Shepherd and Scrivener, 1987). Such fluids are geochemically comparable with highly evolved basinal brines, and were probably derived from Permo-Triassic sediments to the south (Gleeson and Wilkinson, 1993), indicating several kilometres of sediment had accumulated by this time.

Timing of extension

Field evidence suggests that lamprophyres, elvans and mainstage mineralization can all be hosted by extensional faults of variable orientation, and therefore implies faulting was synchronous with, or predated these infills. A selection of previously published geochronological data is shown in Table 2. The late Stephanian K-Ar determination for the Chyweeda lamprophyre [SW 612 326] implies a similar minimum age for extensional faulting in Holywell Bay *if* all south Cornish lamprophyres are approximately coeval. This may not be unreasonable as a mean K-Ar age of 295.2±2.6 Ma (late Stephanian) for similar highly potassic southwest England lavas is quoted by Hawkes (1981).

The earliest development of mainstage polymetallic lodes is in the Carn Brea Granite at approximately 287 Ma. Since these are hosted by steeply-dipping extensional faults it provides another minimum age constraint on fault initiation, occurring some 7 Ma after granite emplacement and 2 Ma after elvan intrusion. Our own fluid inclusion data suggest that low-angle extensional faults along the Porthleven to Gunwalloe section must have been active since at least the emplacement of the Tregonning Granite at 281.5±1.3 Ma. Mainstage lodes within the Land's End Granite are some 20 Ma younger than those in the Carnmenellis Granite (Chen *et al.,* 1993; Chesley *et al.,* 1993) and show evidence for overprinting hydrothermal events at approximately 220-210 Ma, 170-160 Ma and less than 75 Ma. The two earlier events probably possess regional significance since they are also represented by low-temperature adularia-zeolite hydrothermal assemblages in the ultramafic rocks of the Lizard Complex (Halliday and Mitchell, 1976; Seager *et al.,* 1978).

Repeated reactivation of east-north-east-west-south-west and north-north-west-south-south-east-striking Variscan basement faults dominated the post-Carboniferous tectonic evolution of the Western Approaches Basin (e.g. Day *et al.,* 1989; Evans, 1990; Hillis and Chapman, 1992). Although widespread alluvial sedimentation did not commence until early Triassic rifting (Evans, 1990), seismic, aeromagnetic and borehole data suggest that late Carboniferous to Permian lavas plus subordinate interbedded conglomerates and breccias rest unconformably on Variscan basement throughout much of the Melville sub-basin (Chapman, 1989; Evans, 1990). A thick sediment-dominated package of similar age may be preserved in the Plymouth Bay Basin if bright reflectors at 2.8 s TWTT represent volcanics coeval with those further west and in Devon (Pint *et al.,* 1987). It is probable that the distribution of these volcanics and sediments was controlled by localized extension commencing during the latest Carboniferous (Harvey *et al.,* 1994), whilst Triassic rifting may have influenced the 220-210 Ma hydrothermal overprint recorded at Geevor and the Lizard.

Locality/lithology	Method	Mineral	Age(Ma)	Source
Chyweeda lamprophyre	K-Ar	phlogopite	292.9±3.4	[1]
Carnmenellis Granite	U-Pb	monazite	293.7±0.4	[2]
South Crofty elvan	Ar-Ar	muscovite	288.7±-0.7	[3]
South Crofty lode	Ar-Ar	muscovite	286.2±0.5	[2]
Tregonning Granite	Ar-Ar	zinnwaldite	281.5±1.6	[4]
Land's End Granite	U-Pb	monazite	274.5±-0.7	[2]
Bostraze sheeted vein	Ar-Ar	muscovite	271.20.8	[2]
Geevor lode	K-Ar/Ar-Ar	clays	225-215	
			170-160	
			570	[5]
Lizard veins	K-Ar/Ar-Ar	adularia	220-210	
			170-160	[6,7]

Sources: (1) Goode and Taylor (1988); (2) Chen *et al. (1993);* (3) Chesley *et al.* (1993); (4) Clark *et al.* (1993); (5) Jackson *et al.* (1982); (6) Halliday and Mitchell (1976); (7) Seager *et al.* (1978)

***Table** 2. Previously published geochronological data*

DISCUSSION

Distribution, geometries, kinematics and timing of extension

The structures we have described are of regional extent and post-date D1 and D2 fabrics. They brought about extension relative to the palaeohorizontal and, at least locally, shortening relative to the layering (e.g. Wheeler and Butler, 1993). Although rotation of thrust faults could produce low angle extensional geometries (e.g. Andrews *et al.,* 1988), such a mechanism is incompatible with the present attitude and regional context of D1 and D2 structures and therefore discounted. The concensus of geochronological and offshore stratigraphic evidence implies that regional extension of Variscan basement in south Cornwall must have *initiated* by the latest Carboniferous. Three broad geometric/kinematic fault types have been described:

1) Low angle (dip <45°) extensional faults which exhibit listric or ramp and flat geometries and may display complex arrangements of secondary faults and folds in their hangingwalls. In some instances they may host lamprophyres, elvans and "mainstage" magmatic-hydrothermal lodes (e.g. Wheal Jane, Wheal Kitty).

2) Moderate to high angle (dip >45°) extensional faults which generally offset earlier low-angle faults; they frequently host elvans and "mainstage" magmatic-hydrothermal lodes but also include the caunter lodes and slides.

3) High-angle "cross-course" faults which usually bring about dextral strike-slip displacement of all previous faults and are often associated with base metal mineralization.

Mechanisms of extension

Fluid inclusions in quartz-chlorite veins formed during Variscan compression in south Cornwall have been studied by Wilkinson (1990a). These inclusions provide information on the chemistry of fluids mobilised during peak regional metamorphism and thrust-nappe emplacement (syn-D1) and during the subsequent, more brittle, D2 compression. In combination with mineral assemblage, vitrinite reflectance and mineral chemistry data, they also enable constraints to be placed on the Variscan pressure-temperature evolution of the Cornish crust (Table 1), including the post-peak metamorphic history (Harvey *et al.,* 1994). The data suggest that lithologies which underwent peak metamorphism during D1 subsequently experienced some 7 or 8 km of syn-compressional, and at least 1 km of post-compressional exhumation by the time the Tregonning granite was emplaced.

It is clear from seismic studies (e.g. Day and Edwards, 1983; Leveridge *et al.* 1984) that south Cornwall formed part of a large-scale Variscan crustal thrust wedge. Syn-compressional exhumation through such a wedge during continued convergence following syn-D1 underplating could be brought about by erosion and/or extension of overlying parts of the wedge (e.g. Platt, 1993). Post-compressional exhumation indicates that convergence had ceased or that the presently exposed metasediments may have moved into a region of dominant extension higher within the orogenic wedge, with or without continued erosion. This latter part of the exhumation history may be represented by the south-south-east-verging D3 ductile deformation of Turner (1968), which might have developed during early extensional reactivation of the Carrick Thrust (Leveridge *et al.,* 1990).

The low-angle top to the south-south-east extensional fault zones described from the Porthleven section during this study probably represent a slightly later (Turner, 1968), and relatively brittle expression of the same process (e.g. Holdsworth *et al.,* 1993). The acute angle of bedding to fault plane cut-off suggests that the low angle of these fault zones is primary and has not developed by subsequent rotation. High fluid pressures during deformation and the marked anisotropy of the rock mass probably contributed to the propagation and reactivation of such low angle extensional structures. The vergence of secondary folds within these fault zones is usually down the dip of the underlying detachment, and hence also largely controlled by the orientation of pre-existing anisotropy (generally bedding, S1 cleavage, or an earlier thrust). Folds probably formed as a consequence of localized compression related to "sticking" on the detachment during this down-dip movement (e.g. Holdsworth 1989b). The amount of extension accommodated by these low angle faults is difficult to assess due to the paucity of suitable markers, especially across structures with potentially large displacements. However, estimates from small-scale displacements over distances up to 20 m indicate approximately 5-20% extension.

The orientation of the east-north-east—west-south-west-striking moderate to high angle faults hosting lamprophyres (rare), elvans, "mainstage" mineralization (lodes and caunter lodes), and their non-mineralized equivalents is explained reasonably well by the stress trajectory model (σ_1 vertical, σ_3 north-northwest—south-south-east) of Moore (1975). These structures generally cross-cut earlier low angle faults, and it can be implied from the geochronological data (Table 2) that this broad regime of *dominant* north-north-west—south-south-east extension must have persisted from about 293 Ma (Chyweeda lamprophre) or 287 Ma (South Crofty mainstage lodes) to perhaps 275 Ma or later. Early greisen-bordered veins (e.g. St. Michael's Mount) probably formed in a similar stress regime, but endogranitic mineralized pegmatites (e.g. "quartz floors" at South Crofty) may have been influenced by localized intra-pluton stresses (Bromley, 1989).

Estimates of extension across mainstage lodes have not been performed, but it is clear from the foregoing discussion of the St. Agnes district that post-lode "slides" in that area brought about as much as 15-20% extension. Some degree of planar-rotational behaviour may have occurred. The change in dominant orientation of extensional structures between the western (Land's End, Carnmenellis) and eastern (St. Austell, Bodmin, Dartmoor) sectors of the batholith probably reflects contrasting orientations of pre-Devonian basement fabrics across the Start Perranporth Zone. The approximately coeval association of latest Carboniferous to early Permian potassic volcanicity, granite magmatism, extensional faulting and the development of sedimentary basins was probably brought about by lithospheric extension during orogen collapse (Dewey, 1988). The likely applicability of such a mechanism to the Variscides of mainland Europe has been recently highlighted (e.g. Ménard and Molnar, 1988; Echtler and Malavieille, 1990). The high-angle "cross-course" faults which usually bring about dextral strike-slip displacement of all previous structures and are associated with base metal mineralization reflect a change in the large-scale stress regime which may have taken place post 275 Ma. This is compatible with the large-scale model of Arthaud and Matte (1977).

Implications

Variscan contractional deformation, stratigraphy and low-grade regional metamorphism

The kinematics of late- to post-Variscan fault displacements are of paramount importance. In particular, low angle faults cannot be presumed to either originate as thrusts or to preserve net contraction. Recognition of significant extension could well change our perception of the stratigraphy in south Cornwall and elsewhere in south-west England. It is also possible that major late- to post-Variscan extensional faults may exhibit lower metamorphic grades in their hangingwalls than they do in their footwalls.

Generation, transport and emplacement of lamprophyres and granites

The consensus of evidence indicates a dominant crustal origin for the Cornubian batholith (Floyd *et al.,* 1993), although a variable mantle-derived component is increasingly realized through studies of geochemistry, enclaves and isotope systematics (Leat *et al.,* 1987; Clark *et al.,* 1993). In addition, relatively uncontaminated mantle-derived melts, as represented by the lamprophyres, were intruded at about the same time as the early granites (Leat *et al.,* 1987). Convection processes below tectonically thickened lithosphere potentially provide an elegant petrogenetic solution to the contemporaneity of crustal- and mantle-derived melts, as well as possibly driving gravitational collapse (e.g. Dewey, 1988; Platt and England, 1993). In such cases, partial melting in both the asthenospheric/lithospheric mantle (lamprophyres) and the lower crust (granites) may be driven by increased heat flow and/or adiabatic decompression. Mixing would clearly be possible, but granite formation primarily by fractionation and contamination of significant volumes of mantle-derived magma is not required. Arguments rejecting crustal partial melting on the basis of unreasonably high geothermal gradients in 27-30 km thick crust (e.g. Shackleton *et al.,* 1982; Watson *et al., 1984)* are flawed since, prior to extension, the Variscan crust probably attained a thickness of 40 km (D1 fluid inclusion characteristics, Table 1).

The base of the Cornubian batholith appears to be approximately planar, is located at 10-12 km depth and corresponds in part to the regional R2 reflector of Brooks *et al.* (1984). Granite emplacement in the relatively brittle upper crust might have been achieved by east-north-east-west-south-west dip-slip extensional faults and north-west-south-east-trending strike-slip faults acting coevally above this mid- crustal décollement to create rhomboidal "pull-aparts" of varying geometries and dimensions (e.g. Paterson *et al.,* 1991). These could be incrementally infilled with dyke transported magma (e.g. Petford *et al.,* 1993), although the final geometry of the intrusion may have been modified by high-level stoping.

Various estimates of emplacement depth for currently exposed parts of the Cornubian batholith have been made. Charoy (1986) suggested final crystallization of the Carnmenellis granite occurred at pressures of 2-2.5 kbar. Fluid inclusion data presented in this study (Table 1) suggest aureole fluids around the Tregonning granite equilibrated at 0.5-1.0 kbar. On the basis of metamorphic aureole phase relationships, Floyd (1971) suggested intrusion of the Land's End granite took place at approximately 1 kbar, whilst the fluid inclusion data of Jackson *et al.* (1982) requires a hydrostatic head of 2.8 km during sheeted vein formation. One way to account for the apparent dichotomy in emplacement depths between these two granites is that some 20 Ma of continued exhumation occurred between intrusion of the Carnmenellis granite (293 Ma, Chen *et al.,* 1993) and the Land's End granite (274 Ma, Chen *et al.,* 1993). The implied syn-emplacement exhumation rate of approximately 0.2 mm yr^{-1} is compatible with estimates for exhumation during D1-D2 deformation through to granite intrusion (Harvey *et al.,* 1994).

Mineralization

The creation of a widespread network of fracture and fault related dilatant sites to host early and mainstage vein mineralization was ultimately controlled by the same tectonic processes that brought about granite petrogenesis and emplacement, i.e. lithospheric collapse following crustal thickening. The anomalous orientation of mainstage mineralization in the St. Just district could reflect the relatively late evolution of the Land's End granite (Table 2) during a period when the stress regime had changed from σ_1 being approximately vertical to horizontal (330°), e.g. Arthaud and Matte (1977). Descriptions of mainstage mineralization at Geevor occurring in approximately contemporaneous normal and reverse faults (Garnett, 1966) are compatible with development in a strike-slip fault zone. Lower temperature "cross-course" type base metal mineralization across south Cornwall took place in a similar stress regime; north-west-south-east striking faults and fractures providing suitable pathways for fluids derived, primarily, from adjacent offshore basins.

Development of offshore basins

The late Carboniferous to early Permian tectonic evolution of parts of the Western Approaches Basin may be best explained in terms of lithospheric collapse prior to late Permian or Triassic rifting (e.g. Harvey *et al.,* 1994). Onshore exposures in south Cornwall provide an analogue of the pre-existing Variscan basement template of dominant east-north-east-west-southwest and north-north-west-south-south-east striking faults in these offshore regions. Re-activation and/or propagation of new structures during Mesozoic rifting and inversion may have been minimized in south Cornwall due to the buttressing effect of the Cornubian batholith.

CONCLUSIONS

Extensional faults are ubiquitous in south Cornwall. They exerted a strong control on magmatic-hydrothermal mineralization, the development of offshore sedimentary basins and possibly granite emplacement. The approximately coeval late Carboniferous to early Permian association of potassic volcanicity, granite magmatism, extensional faulting and sedimentary basin development was probably brought about by the collapse of previously thickened lithosphere as has been previously implied by Hawkes (1981) and Dewey (1988). As such these extensional faults represent an intrinsic part of Variscan evolution.

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REFERENCES

ALDERTON, D.H.M. 1993. Mineralization associated with the Cornubian Granite Batholith. In: *Mineralization in the British Isles.* Eds: R.A.D. PATTRICK and DA. POLYA, Chapman and Hall, London, pp 270-354.

ANDREWS, J.R., BARKER, A.J. and PAMPUN, C.F. 1988. A reappraisal of the facing confrontation in north Cornwall: fold- or thrust-dominated tectonics? *Journal of the Geological Society, London,* **145**, 777-788.

ARTHAUD, F. and MATTE, P. 1977. Late Palaeozoic strike-slip faulting in southern Europe and northern Africa: Result of a right-lateral shear zone between the Appalachians and the Urals. *Bulletin of the Geological Society of America,* **88**, 1305-1320.

BARNES, R.P. and ANDREWS, J.R. 1984. Hot or cold emplacement of the Lizard Complex? *Journal of the Geological Society, London,* **141**, 37-40.

BRISTOW, C.M. 1989. The Fal Valley lineaments. *Journal of The Camborne School of Mines,* **89**, 34-41.

BROMLEY, A.V. 1979. Ophiolitic origin of the Lizard Complex. *Journal of The Camborne School of Mines,* **79**, 25-38.

BROMLEY, A.V. 1989. *Field Guide. The Cornubian Orefield.* Sixth International Symposium on water-rock interaction (Malvern, UK). International Association of Geochemistry and Cosmochemistry, 111p.

BROMLEY, A.V. and HOLL, J. 1986. Tin mineralization in southwest England. In: *Mineral Processing at a crossroads.* Eds: BA. WILLS and R.W. BARLEY. NATO ASI Series, 117, Martinus Nijhoff, Dordrecht, pp 159-262.

BROOKS, M., DOODY, J.J. and AL-RAWI, F.R.J. 1984. Major crustal reflectors beneath SW England. *Journal of the Geological Society, London,* **141**, 97-103.

CHAPMAN, T.J. 1989. The Permian to Cretaceous structural evolution of the Western Approaches Basin (Melville sub-basin), UK. In: *Inversion Tectonics.* Eds: MA. COOPER and G.D. WILLIAMS, Special Publication of the Geological Society, London, **44**, 177-200.

CHAROY, B. 1981. Post-magmatic processes in southwest England and Brittany. *Proceedings of the Ussher Society,* **5**, 101-115.

CHAROY, B. 1986. The genesis of the Cornubian Batholith (South-West England): the example of the Carnmenellis Pluton. *Journal of Petrology,* **27**, 571-604.

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: Implications for pluton emplacement and protracted hydrothermal mineralization. *Geochimica et Cosmochimica Acta,* **57**, 1817-1835.

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

COLLINS, J.H. 1912. Observations on the west of England mining region. *Transactions of the Royal Geological Society of Cornwall* **14**, 1-638.

COWARD, M.P. and SMALLWOOD, S. 1984. An interpretation of the Variscan tectonics of SW Britain. In: *Variscan Tectonics of the North Atlantic Region.* Eds: D.H.W. HUTTON and D.J. SANDERSON. Special Publication of the Geological Society, London, **14**, 125-129.

DAVIES, A.T. 1880. The phenomena of heaves or faults in the mineral veins of Saint Agnes, *Cornwall. Reports and Proceedings of the Miners' Association of Cornwall and Devon for the year 1879,* Lake & Company, Falmouth, 12-33.

DAY, GA. and EDWARDS, J.W.F. 1983. Variscan thrusting in the basement of the English Channel and SW Approaches. *Proceedings of the Ussher Society,* **5**, 432436.

DAY, GA., EDWARDS, J.W.F. and HILLIS, R.R. 1989. Influences of Variscan structures off southwest Britain on subsequent phases of extension. *In: Extensional tectonics and stratigraphy of the North Atlantic margins.* Eds: A.J. TANKARD and H.R. BALKWILL, Memoir of the American Association of Petroleum Geologists, **46**, 425-432.

DEARMAN, W.R. 1963. Wrench-faulting in Cornwall and South Devon. *Proceedings of the Geologists' Association,* **74**, 265-287.

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

DEARMAN, W.R. and FRESHNEY, E.C. 1966. Repeated folding at Boscastle, North Cornwall, England. *Proceedings of the Geologists' Association,* **77**, 199-215.
DEWEY, J.F. 1988. Extensional collapse of orogens. *Tectonics,* **7**, 1123-1139.
DINES, H.G. 1956. The metalliferous mining region of south-west England. *Economic Memoir of the Geological Survey of Great Britain.*
ECHTLER, H. and MALAVIEILLE, J. 1990. Extensional tectonics, basement uplift and Stephano-Permian collapse basin in a late Variscan metamorphic core complex (Montagne Noire, Southern *Massif* Central). *Tectonophysics,* **177**, 125-138.
EDWARDS, J.W.F., DAY, GA. and LEVERIDGE, B.E. 1989. Thrusts under Mount's Bay and Plymouth Bay. *Proceedings of the Ussher Society,* **7**, 131-135.
EVANS, C.D.R. 1990. *United Kingdom offshore regional report the geology of the western English Channel and its western approaches.* British Geological Survey, HMSO, London.
FARMER, C.B. 1991. Paragenetic evolution of the composite lodes at South Crofty Mine, Cornwall, U.K. *PhD. Thesis, Imperial College, University of London.*
FLOYD, P.A. 1971. Temperature distribution in the Land's End granite aureole, Cornwall. *Proceedings of the Ussher Society,* **2**, 335-351.
FLOYD, P.A., SHAIL, R., LEVERIDGE, B.E. and FRANKE, W. 1991. Geochemistry and provenance of Rhenohercynian synorogenic sandstones: implications for tectonic environment discrimination. In: *Developments in Sedimentary Provenance Studies. Eds:* A.C. MORTON, S.P. TODD and P.D.W. HAUGHTON. Special Publication of the Geological Society, London, **57**, 173-188.
FLOYD, P.A., EXLEY, CS. and STYLES, M.T. 1993. Igneous rocks of South-West England. Chapman and Hall, London.
FRESHNEY, E.C. 1965. Low-angle faulting in the Boscastle area. *Proceedings of the Ussher Society*, **1**, 175-180.
FRESHNEY, E.C., McKEOWN, M.C. and WILLIAMS, M. 1972. *Geology of the coast between Tintagel and Bude.* Memoir of the British Geological Survey, Sheet 322 (England and Wales).
GARNETT, R.H.T. 1961. Structural control on mineralization in South-West England. *Mining Magazine,* 105, 329-337.
GARNETT, R.H.T. 1966. Relationship between tin content and structure of lodes at Geevor mine, Cornwal. *Transactions of the Institution of Mining and Metallurgy,* **75**, B1-B22.
GHOSH, P.K. 1934. The Carnmenellis Granite: Its petrology, metamorphism and tectonics. *Journal of the Geological Society*, London, **90**, 240-276.
GLEESON, S.A. and WILKINSON, J.J. 1993. Geochemical evolution of basinal brines and base metal mineralization, South Cornwall, U.K. *Polska Akademie Nauk Archiwum Mineralogiczne,* **49**, 85.
GOODE, A.J.J. 1973. The mode of intrusion of Cornish elvans. *Report of the Institute of Geological Sciences,* No. 73/7, 8pp.
GOODE, A.J.J. and TAYLOR, R.T. 1988. *Geology of the country around Penzance.* Memoir of the British Geological Survey, Sheet 351/358 (England and Wales).
HALLIDAY, A.N. and MITCHELL, J.G. 1976. Structural, K-Ar and ^{40}Ar-^{39}Ar age studies of adularia K-feldspars from the Lizard Complex, England. *Earth and Planetary Science Letters,* **29**, 227-337.
HALLS, C. 1987. A mechanistic approach to the paragenetic interpretation of mineral lodes in Cornwall. *Proceedings of the Ussher Society,* **6**, 548-554.
HARVEY, M., STEWART, S., WILKINSON, J.J., RUEFUL, A. and SHAIL, R.K. 1994. Tectonic evolution of the Plymouth bay Basin. *Proceedings of the Ussher Society,* **8**, 271-278.
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.
HENWOOD, W.J. 1843. On the metalliferous deposits of Cornwall and Devon. *Transactions of the Royal Geological Society of Cornwall* **5**, 1-386.
HILLIS, R.R. and CHAPMAN, T.J. 1992. Variscan structure and its influence on post- Carboniferous basin development, Western Approaches Basin, SW UK Continental Shelf. *Journal of the Geological Society,* London, **149**, 413-417.
HOBSON, D.M. and SANDERSON, D.J. 1983. Variscan deformation in Southwest England. In: *The Variscan Fold Belt in the British* Ed: P. L.HANCOCK, Hilger, Bristol, pp 108-129.
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.
HOLDSWORTH, R.E. 1989a. The Start-Perranporth Line: a Devonian terrane boundary in the Variscan orogen of SW England. *Journal of the Geological Society,* London, **146**, 419-421.
HOLDSWORTH, R.E. 1989b. Late brittle deformation in a Caledonian ductile thrust wedge: new evidence for gravitational collapse in the Moine Thrust sheet, Sutherland, Scotland. *Tectonophysics,* **170**, 17-28.
HOLDSWORTH, R.E., BUTLER, C.A., SHALL, R.K. and STEELE, SA. 1993. Late stage gravity collapse structures in mountain belts: examples from Palaeozoic orogens in the British Isles. *In:Late orogenic extension in mountain belts.* BRGM, **219**, 9091.
JACKSON, N.J., MOORE, J. McM. and RANKIN, A.H. 1977. Fluid inclusions and mineralization at Cligga Head, Cornwall, England. *Journal of the Geological Society, London,* **134**, 343-349.
JACKSON, N.J., HALLIDAY, A.N., SHEPPARD, S.M.F. and MITCHELL, J.G. 1982. Hydrothermal activity in the St. Just mining district, Cornwall. In: *Metallization associated with acid magmatism Ed:* A.M.EVANS, John Wiley and Sons, London, 137-179.
JACKSON, N.J., WILLIS-RICHARDS, J., MANNING, D.A.C. and SAMS, M.S. 1989. Evolution of the Cornubian Ore Field, Southwest England: Part II. Mineral Deposits and Ore-Forming Processes. *Economic Geology,* **84**, 1101-1133.
JONES, R.H. 1991. A seismic reflection survey as part of the geophysical investigation of the Carnmenellis Granite. *Proceedings of the Ussher Society,* **7**, 418-420.
KETTANEH, Y.A. and BADHAM, J.P.N. 1978. Mineralization and paragenesis at the Mount Wellington Mine, Cornwall. *Economic Geology,* **73**, 486-495.
LEAT, P.T., THOMPSON, R.N., MORRISON, M.A., HENDRY, G.L. and TRAYHORN, S.C. 1987. Geodynamic significance of post Variscan intrusive and extrusive potassic 'Dogmatism in SW England. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* **77**, 349-360.
LEVERIDGE, B.E., HOLDER, M.T. and DAY, G.A. 1984. Thrust nappe tectonics in the Devonian of south Cornwall and the western English Channel. In: *Variscan Tectonics of the North Atlantic Region.* Eds: D.H.W. Hutton and DJ. Sanderson. Special Publication of the Geological Society, London, **14**, 103-112.
LEVERIDGE, B.E. and HOLDER, M.T. 1985. Olistostromic breccias at the Mylor/Gramscatho boundary, south Cornwall. Proceedings *of the Ussher Society,* **6**, 147- 154.
LEVERIDGE, B.E., HOLDER, M.T. and GOODE, A.J.J. 1990. *Geology of the country around Falmouth.* Memoir of the British Geological Survey, Sheet 352 (England and Wales).
MENARD, G. & MOLNAR, P. 1988. Collapse of a Hercynian Tibetan Plateau into a late Palaeozoic European Basin and Range province. *Nature,* **334**, 235-237.
MOORE, J.M. 1975. A mechanical interpretation of the vein and dyke systems of the S.W. England orefield. *Mineralium Deposita,* **10**, 374-388.
PATERSON, S.R., VERNON, R.H. and FOWLER, T.K. 1991. Aureole tectonics. In: *Contact metamorphism.* Ed: D.M. Kerrick, Mineralogical Society of America Reviews in Mineralogy, **26**, 673-722.
PETFORD, N., KERB, R.C. and LISTER, J.R. 1993. Dike transport of granitoid magmas. *Geology,* **21**, 845-848.
PINET, B., MONTADERT, L., MASCLE, A., CAZES, M. and BOIS, C.1987. New insights on the structure and the formation of sedimentary basins from deep seismic profiling in Western Europe. In: *Petroleum Geology of North West Europe. Eds:* J. BROOKS and K. GLENNIE, Graham and Trotman, London, 11-31.
PLATT, J.P. 1993. Exhumation of high-pressure rocks: a review of concepts and processes. *Terra Nova.* **5**, 119-133.
PLATT, J.P. and ENGLAND, P.C. 1993. Convective removal of lithosphere beneath mountain belts: thermal and mechanical consequences. *American Journal of Science,* **293**, 307-336.
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.
RAYMENT, B.D., DAVIS, G.R. and WILLSON, J.D. 1971. Controls to mineralization at Wheal Jane, Cornwall. *Transactions of the Institution of Mining and Metallurgy,* **80**, B224-237.
SCRIVENER, R.C., SHEPHERD, T.J. and GARRIOCH, N. 1986. Ore genesis at Wheal Pendarves and South Crofty Mine, Cornwall - a preliminary fluid inclusion study. *Proceedings of the Ussher Society,* **6**, 412-416.
SEAGER, A.F., FITCH, F.J. and MILLER, J.A. 1978. Dating of adularia and the relationship of hydrothermal events in the Lizard Complex, Cornwall. *Geological Magazine,* **115**, 211-214.
SHACKLETON, R.M., RIES, A.C. and COWARD, M.P. 1982. An interpretation of the Variscan structures in SW England. *Journal of the Geological Society, London,* **139**, 533-541.
SHEPHERD, T.J., MILLER, M.F., SCRIVENER, R.C. and DARBYSHIRE, D.P.F. 1985. Hydrothermal fluid evolution in relation to mineralization in S.W. England with special reference to the Dartmoor-Bodmin area. In: *High heat production (HHP) granites, hydrothermal circulation and ore genesis.* Institution of Mining and Metallurgy, London, pp 345-364.
SHEPHERD, T.J. & SCRIVENER, R.C. 1987. The role of basinal brines in the genesis of polymetallic vein deposits. Kit Hill-Gunnislake district, S.W. England. *Proceedings of the Ussher Society,* **6**, 491-497.
TAYLOR, E.G. 1966. Distribution and deposition of cassiterite at South Crofty

mine, Cornwall. *Transactions of the Institution of Mining and Metallurgy,* **75**, B35-B49.
TURNER, R.G. 1968. *The influence of granite emplacement on structures in South-West England.* Unpublished Ph.D. Thesis, University of Newcastle-upon-Tyne.
WARR, L.N. 1988. The deformational history of the area north-west of the Bodmin Moor granite, north Cornwall. *Proceedings of the Ussher Society,* **7**, 67-72.
WARR, L.N. 1989. The structural evolution of the Davidstow Anticline, and its relationship to the southern Cuba Overfold, north Cornwall. *Proceedings of the Ussher Society*, **7**, 136-140.
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.
WHEELER, J. and BUTLER, R.W.H. 1993. Evidence for extension in the western Alpine orogen: the contact between the oceanic Piemonte and the overlying continetla Sesia units. *Earth and Planetary Science Letters,* **117**, 457-474
WILKINSON, J.J. 1990a. The origin and evolution of Hercynian crustal fluids, south Cornwall, England. *PhD. Thesis, University of Southampton.*
WILKINSON, J.J. 1990b. The role of metamorphic fluids in the evolution of the Cornubian orefield: Fluid inclusion evidence from south Cornwall. *Mineralogical Magazine,* **54**, 219-230.
WILKINSON, J.J. 1991. Volatile production during contact metamorphism: the role of organic matter in pelites. *Journal of the Geological Society*, London. **148**, 731736.
WILKINSON, J.J. and KNIGHT, R.R.W. 1989. Palynological evidence from the Porthleven area, south Cornwall: implications for Devonian stratigraphy and Hercynian structural evolution. *Journal of the Geological Society,* London. **146**, 739-742.
WILLIS-RICHARDS, J. and JACKSON, N.J. 1989. Evolution of the Cornubian Ore Field, Southwest England: Part 1. Batholith Modeling and Ore Distribution. *Economic Geology,* **84**, 1078-1100.