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THE MOST SOUTHERLY POINT THRUST - AN EXAMPLE OF DUCTILE THRUSTING IN THE LIZARD COMPLEX, SOUTH-WEST CORNWALL

K. A. Jones

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The Lizard Complex has been interpreted as a dismembered ophiolite obducted during the upper Palaeozoic Variscan Orogeny. The Complex is constructed of three tectonic units each separated by low-angle faults; the Crousa Downs Unit, Goonhilly Downs Unit and Basal Unit. A series of four recently mapped low-angle shear zones occur within the Basal Unit, one of which, the Most Southerly Point Thrust (MSPT), is described here. The MSPT consists of a thick sequence of mylonitic rocks which dip at shallow angles, up to 30°, to the south-east. The footwall and hangingwall successions of the MSPT consist of Old Lizard Head Series pelitic and semi-pelitic schists and interleaved hornblende schists. In the footwall and in low-strain zones within the hangingwall a series of upright isoclinal folds define an early pre-thrust history. The base of the MSPT is marked by a 1 mm-thick zone of mylonites. Above the basal zone a 10 to 15 m-thick zone is characterised by a series of narrow anastomosing mylonites separating areas of low strain. This latter zone passes upwards into a thick continuous sequence of mylonites, of which the top is not exposed. In low strain zones the early upright structures are deformed by a series of chevron-like folds. In high strain zones three fold types are observed; flat lying isoclinal folds, sheath-like folds and asymmetric folds, all structures which are interpreted as resulting from progressive deformation. Shear sense indicators determine a top to the north-west-directed thrusting on the MSPT. In the footwall sequence a near-vertical shear zone with sinistral sense of displacement is interpreted as a lateral ramp to the MSPT. These data indicate that a significant phase of crustal shortening has been accommodated on a series of ductile thrusts during the accretion history of the Lizard Complex.

K.A. Jones. School of Construction & Earth Sciences, Oxford Brookes University, Gipsy Lane Campus, Headington, Oxford, OX3 OBP.

INTRODUCTION

There is a general consensus of opinion regarding the structural features observed in metamorphic sheets underlying ophiolite complexes (Williams and Smyth, 1973; Jamieson, 1980, 1986; Searle and Malpas, 1980, 1982; Searle and Stevens, 1984; Spray, 1984). Metamorphic sheets below ophiolites preserve a record of the earliest stages of accretion of the ophiolite complex. Most rocks below ophiolite sheets are schistose and mylonitic, and show intense deformation and a polyphase evolution. Juxtaposition of sheets from different crustal levels may occur along discrete ductile thrust zones. Such zones are interpreted as having resulted from progressive and continuous overthrusting of the ophiolite.

This paper presents data which illustrate the presence of a series of low-angle ductile thrusts within the Basal Unit of the Lizard ophiolite. Detailed description concentrates on one of these thrusts, the Most Southerly Point Thrust. These data indicate that the Basal Unit of the Lizard Complex contains structures comparable with other ophiolite complexes.

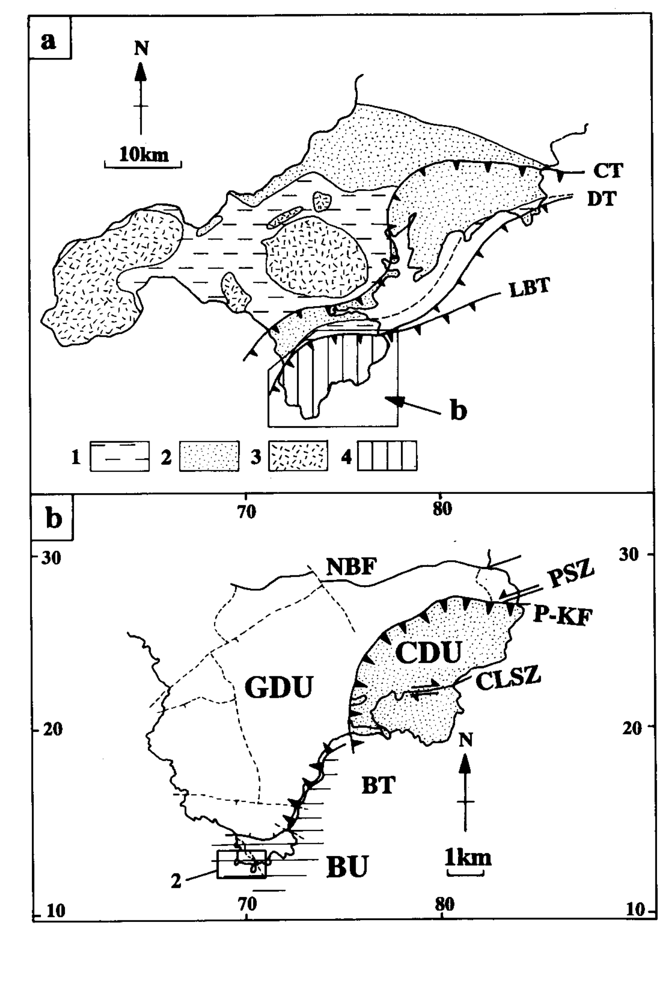


Figure 1. a) Geology of south-west England. CT - Carrick Thrust. DT - Dodman Thrust. LBT- Lizard Boundary Thrust. 1. Mylor Slates Group, Meneague and Roseland Breccias. 2. Gramscatbo Group. 3. Granite. 4. Lizard Complex. b) Structural subdivisions of the Lizard Complex (for location see figure 1a). GDU - Goonhilly Downs Unit. CDU - Crousa Downs Unit. BU - Basal Unit. P-K F - Porthoustock - Kennack Fault. BT -Basal Thrust. CLSZ -Carrick Luz Shear Zone. PSZ - Portboustock Shear Zone. NBF - Northern Boundary Fault.

GEOLOGICAL SETTING

The Lizard Complex

The Lizard ultrabasic-basic Complex (for location see Figure la) is an ophiolite (Thayer, 1967, 1969; Bromley, 1976, 1979; Badham and Kirby, 1976; Strong *et al.*, 1975; Kirby, 1979; Styles and Kirby, 1980) of late Devonian age (Davies, 1984; Styles and Rundle, 1984) which was obducted during the Upper Palaeozoic Variscan Orogeny. The ophiolite formed the floor to the late—early Devonian Gramscatho basin (Rattey and Sanderson, 1984; Barnes and Andrews, 1986; Holder and Leveridge, 1986) and subsequently underwent a complex accretion and obduction history during closure of the short lived 'Lizard ocean' (Lefort and Max, 1992). Early deformation and metamorphism are indicated by the presence of two high-temperature

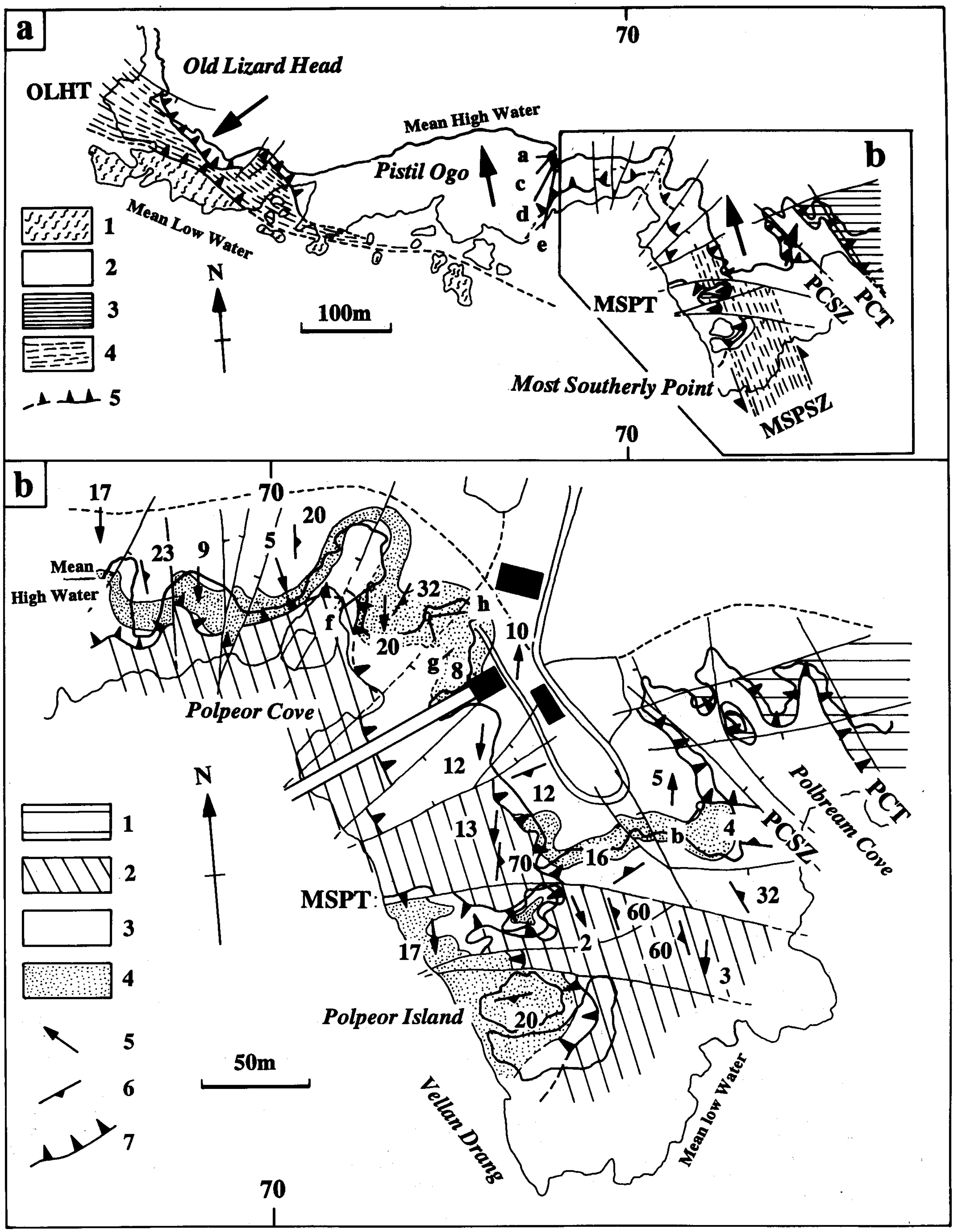


Figure 2. a) Geology between Old Lizard Head and Polbream Cove (for location see Figure 1b). 1. Man O'War Gneiss. 2. Old Lizard Head Series. 3. Hornblende schists. 4. Shear zones. 5. Thrusts. OLHT - Old Lizard Head Thrust. PCT- Polbream Cove Thrust. PCSZ - Polbream Cove Shear Zone. MSPT -Most Southerly Point Thrust. MSPSZ -Most Southerly Point Shear Zone. Arrows indicate sense of movement determined on ductile thrust zones. b) Geology of the Most Southerly Point area (for location see Figure 2a). 1. Hornblende schists. 2. OLHS in footwall to MSPT. 3. *OLHS in hangingwall to MSPT. 4. Low strain zone. Location of photographs a - h of figure 5 are indicated on figures 2a and b.*

mylonite zones, the Carrick & Luz and Porthoustock shear zones (Figure b), which are interpreted as the result of ductile extension at an oceanic spreading centre (Gibbons and Thompson, 1991). The initial stages of accretion of the Lizard ophiolite involved the amalgamation of hot slices in the sub-oceanic domain (Vearncombe, 1980) and was followed by cold obduction (Barnes and Andrews, 1984) on the top of a series of northward-directed nappes (Holder and Leveridge, 1986) (see Figure la).

The Internal Structure

The lizard complex is bounded to the north by the Meneague Breccia and the Lizard Boundary Thrust (Figure la) or according to Bromley (1979) the Northern Boundary Fault (Figure 1b). The internal structure of the Lizard is thought to consist of three tectonic units

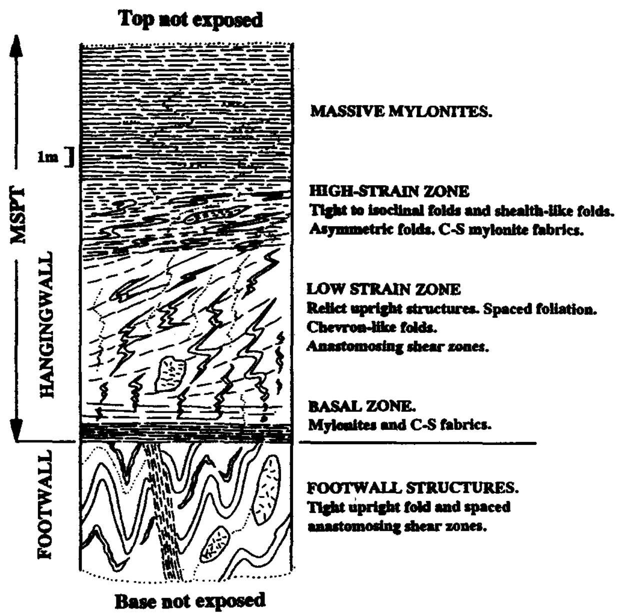


Figure 3. Schematic structural log through the MSPT

each separated by sub-horizontal thrusts (Bromley, 1979); the Crousa Downs Unit, the Goonhilly Downs Unit and the Basal Unit (Figure 1b). The Crousa Downs Unit is the highest structural unit and consists of an ophiolitic sequence, peridotite - gabbro - sheeted dyke complex and the Treleague Quartzite. The Goonhilly Downs Unit is interpreted as a deformed and dismembered ophiolite sequence. The unit consists of peridotite (serpentinite), gabbro and hornblende schists. The Basal Unit is composed of pelitic and semi-pelitic schists (the Old Lizard Head Series), hornblende schists, the Kennack Gneiss and the Man O'War Gneiss.

According to Bromley (1979), the Crousa Downs Unit and Goonhilly Downs Unit are separated by the Porthoustock -Kennack fault, although the significance of this structure has been questioned (Leake and Styles, 1984; Leake *et al*., 1990). The top of the Basal Unit is marked by the Basal Thrust (Sanders, 1955) (see Figure 1b). For a comprehensive review of the geology of the lizard the reader is referred to Floyd *et al.* 1993.

Geology of the Basal Unit

The Basal Unit of the Lizard Complex is composed of the Old Lizard Head Series (OLHS), hornblende schists, the Man O' War Gneiss and the Kennack Gneiss. The OLHS is a series of pelitic, semi-pelitic and psammitic schists with interleaved hornblende schists. The occurrence of locally preserved migmatites in pelitic assemblages attests to high-grade amphibolite facies metamorphism.

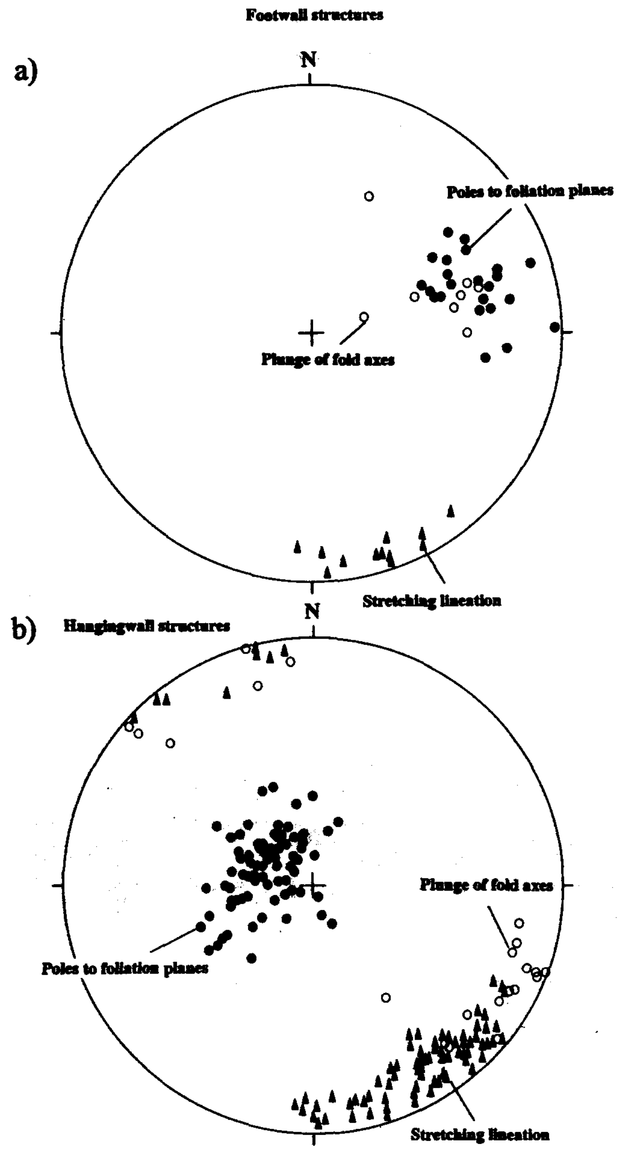
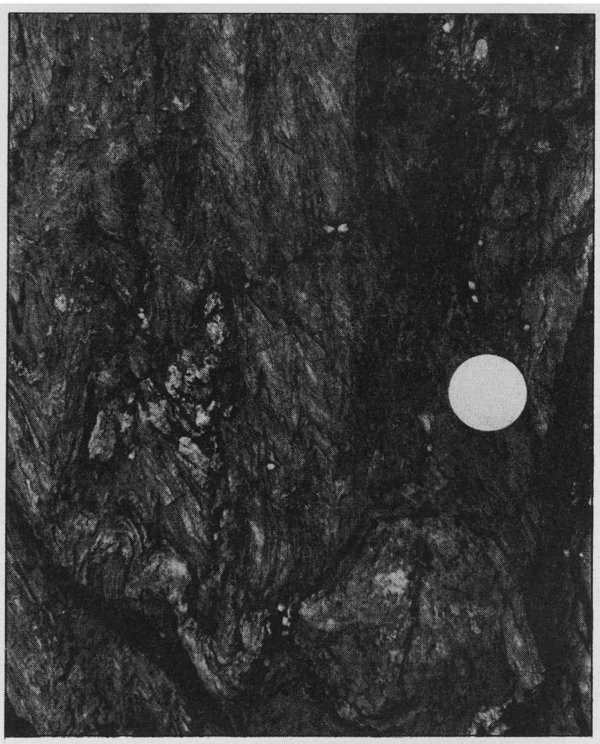


Figure 4. Equal area stereoplots showing structural data.

The OLHS has been interpreted as a sequence of sediments and tuffs, basic lavas and intrusives (Flett, 1946) typical of the upper parts of an ophiolite suite. The hornblende schists (Lower Landewednack type of Bromley, 1979) have been interpreted as a series of deformed and metamorphosed basalts, gabbros and dykes which constitute the upper part of the ocean crust. The Man O' War Gneiss consists of a series of dioritic and granitic gneisses (Fox, 1888; Flett, 1946). Coarse and fine facies have been identified. The coarse facies is restricted to the islands and skerries off Lizard Head, and the fine facies is exposed near shore (see Figure 2a). The Kennack Gneiss has been interpreted as the product of mixing between granitic and gabbroic magmas. The reader is referred to Floyd *et al* (1993) for a further discussion on the origins of the Kennack Gneiss.

Limited data exist on the structural history and nature of the relationships within the Basal Unit. Previous studies indicate that steep faulted contacts occur between the OLHS and the rest of the ophiolite complex (Flett, 1946; Sanders, 1955; Bromley, 1979; Styles and Kirby, 1980). Vearncombe (1980) has inferred that although faulted, the OLHS passes conformably upwards into the hornblende schists. Styles and Kirby (1980) have indicated that this relationship is not dear. The intimate relationship between the OLHS and the



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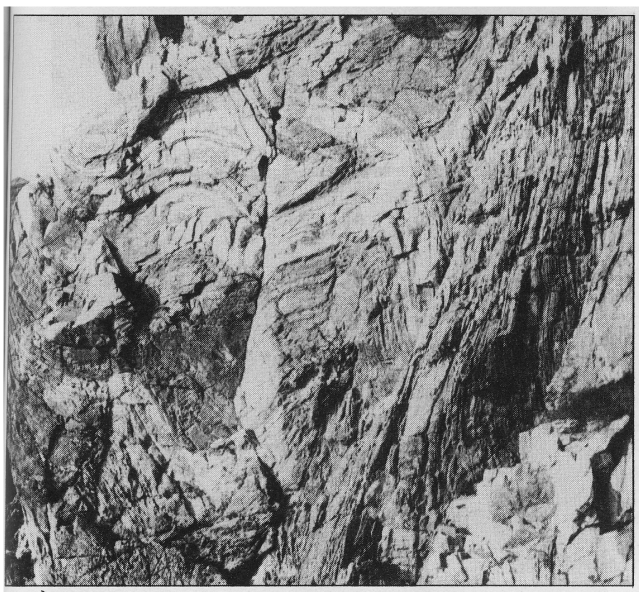
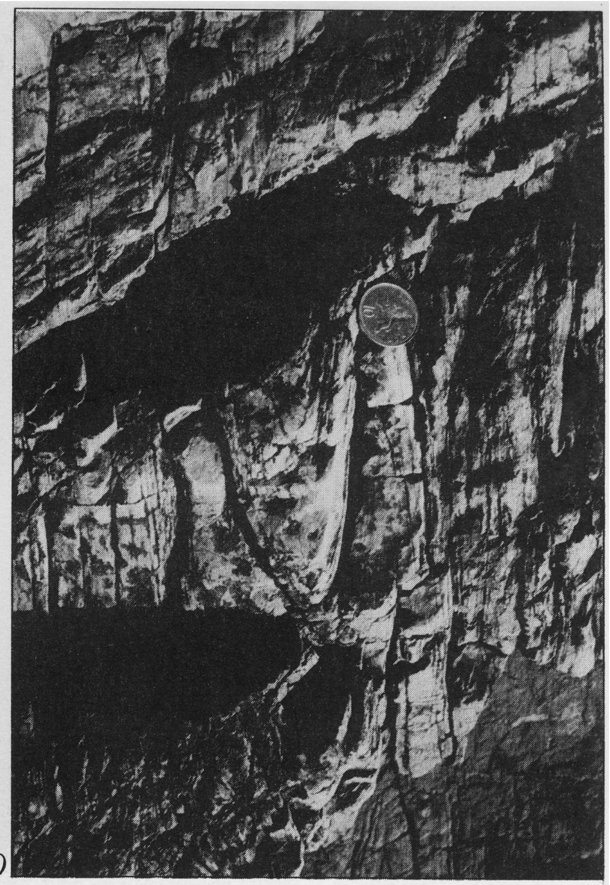


a)

Figure 5. Field photographs of the structures in the MSPT (location of photographs are indicated on Figures 2a and b. a) Relict upright F3 fold preserved in low strain area. The F3 folds S2. Note the development of F4 chevron-like folds refolding F3 structures. The low strain area is bounded at its base by a local high-strain mylonite zone [SW 6993 1154] b) Tight crenulation fabric S4 and minor chevron like-folds F4 in low-strain zone [SW 70151146]. c) F4 isoclinal fold with S4 axial planar fabric refolded by F4' asymmetric folds with S4' axial planar fabric [SW 6993 1154] d) F4 isoclinal fold. Note the folding of S4 mylonite schistosity [SW 6993 1154]. e) F4' isoclinal fold (top left centre) refolded by F4' asymmetric fold (bottom right centre) [SW6993 1154]f) Complex 'eye structures' in sheath-like fold F4'. Note the fold nose closing to left of photograph (NW) (SW 7003 1155]. g) Curvilinear fold hinge in sheath-like fold F3' [SW 7003 1155]. h) F4' asymmetric fold with weakly developed axial planar fabric S4' [SW 7006 1153]



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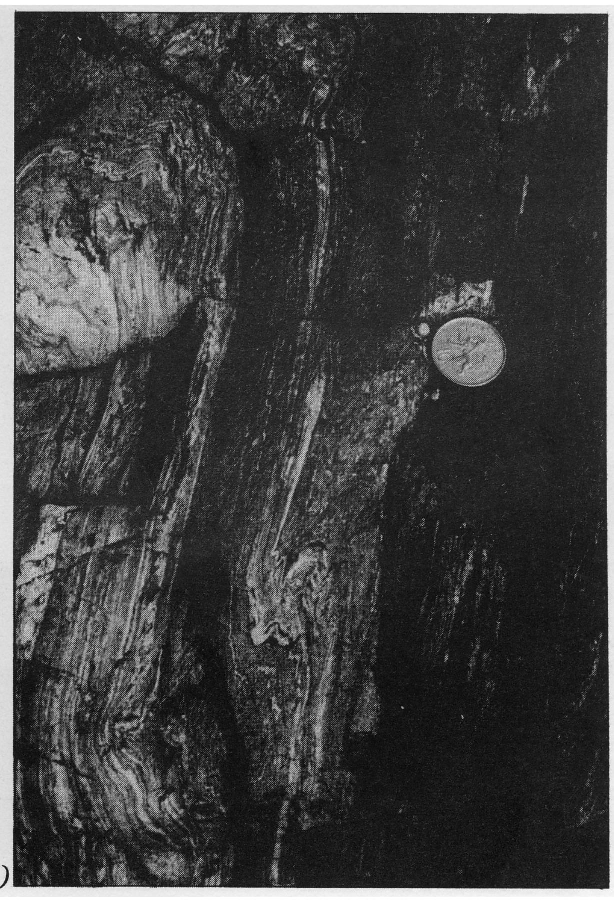

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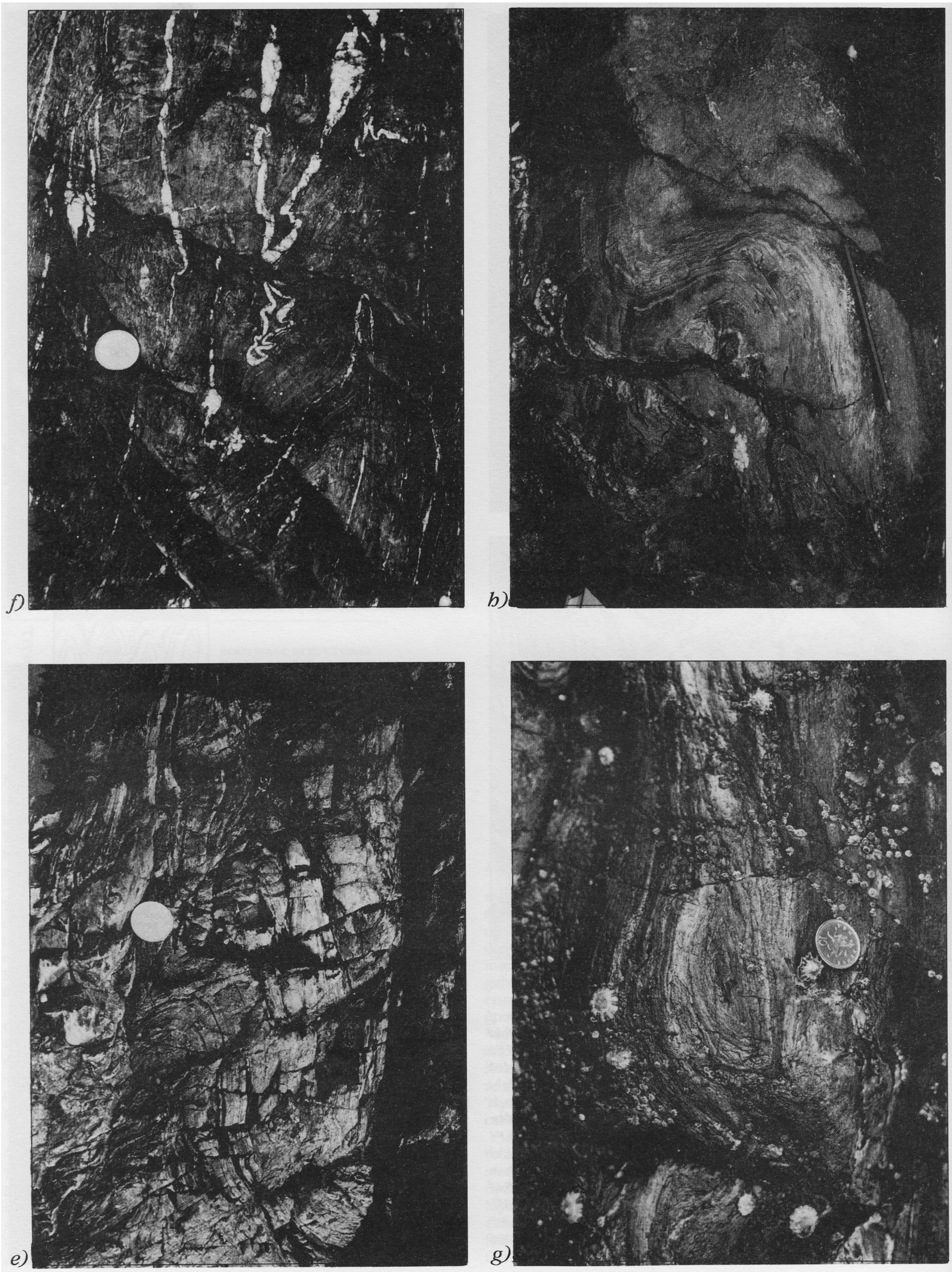
f)
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e)
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hornblende schists is inferred from occurrences of infolded pelitic schists throughout the Basal Unit (Fox, 1891; Flett, 1946; Bromley, 1979). It is clear the OLHS and hornblende schists have been subjected to intense deformation and metamorphism. Vearncombe (1980) points to a complex deformation history and polyphase folding in the hornblende schists. Few data at present, point to the nature and geometry of a series of early north-south-oriented structures (Vearncombe, 1980). The characteristic feature of the hornblende schists is the consistently flat lying foliation, associated recumbent and asymmetric folding and strong lineation. These structures record a north-westerly transport direction for the main deformation event. The Man O' War Gneisses are intrusive into the OLHS and show a similar deformation history (Flett, 1946). The main deformation to have affected the Basal Unit is interpreted as resulting from amphibolite facies stacking of thrust slices in an oceanic environment (Bromley, 1979; Vearncombe, 1980). The high-grade metamorphism observed in the OLHS is thought to have resulted from ophiolite obduction (Styles and Kirby, 1980).

FIELD OBSERVATIONS

Ductile thrusting in the Basal Unit

Detailed mapping along a coastal section from Old Lizard Head [SW 6950 1158] to Polbream Cove [SW 7020/1152] (Figure 2a) has revealed the presence of at least four major low-angle ductile thrusts. The Old Lizard Head Thrust (OLHT) consists of a 30 to 50 m-wide zone of ductile to brittle deformation in which shear sense indicators suggest top to the south-westerly movement direction (Figure lb). The OLHT results in the emplacement of the OLHS structurally above the Man O'War Gneiss. The boundary between the OLHS and the hornblende schists is marked by the Polbream Cove Thrust (PCT) (Figures 2a and b). Preliminary observations indicate that the PCT is responsible for the emplacement of the hornblende schists structurally above the OLHS. A second ductile thrust, the Polbream Cove Shear Zone (PCSZ), occurs directly below the hornblende schists and the PCT (Figures 2a and b). Shear sense indicators determine a top-down to the north-west directed movement on the PCSZ, resulting in the juxtaposing of the OLHS and hornblende schists. In the vicinity of Most Southerly Point [SW 7010 1145] and Polpeor Cove [SW 7005 1155], within the OLHS, a major ductile thrust, the Most Southerly Point Thrust (MSPT) crops out (see below) (Figures 2a and b). The ductile thrust zones have all been affected by late brittle faulting.

The Most Southerly Point Thrust (MSPT)

The MSPT crops out on the rock platforms below Most Southerly Point, in Polpeor Cove [SW 7005 1155] and on Polpeor Island [SW 7010 1138] (Figure 2a and b). The base of the MSPT is marked by a 1 m-thick zone of mylonites, the basal zone (Figure 3). The mylonite schistosity dips at 15 to 25° to the south-east. Shear sense indicators, C-S fabrics and asymmetric porphyroclast tails, determine a top to the north-westerly directed overthrusting on the MSPT.

Evidence for the early history of the OLHS is preserved beneath the basal mylonite zone in the footwall succession. A compositional layering S0? which may constitute bedding is preserved in the cores of subsequent (F3) fold hinges (see below). The earliest fabric S1 is only preserved in andalusite porphyroblasts. A metamorphic foliation/segregation S2 is developed layer parallel to the S0 surface. No F2 folds associated with this foliation event have been observed. The S2 foliation is deformed by a phase of tight to isoclinal F3 folds with near-vertical axial planes (see Figure 5a and below). In micaceous and hornblendic rocks a weak axial planar schistosity S3 is developed. Fold axes and the S2 surface trend north-north-west - south-south-east (Figure 4a). In the footwall succession a near-horizontal spaced schistosity, a weak development of S4 (see below), cuts across these early structures. The above fold types and structures are reoriented within a steeply-dipping shear zone, the Most Southerly Point Shear Zone (MSPSZ) (Figure 2a).

The MSPSZ consists of a series of near-vertical anastomosing and bifurcating mylonite zones, each up to 1 m thick. The mylonite schistosity dips at 50 to 90° to the south-west and stretching

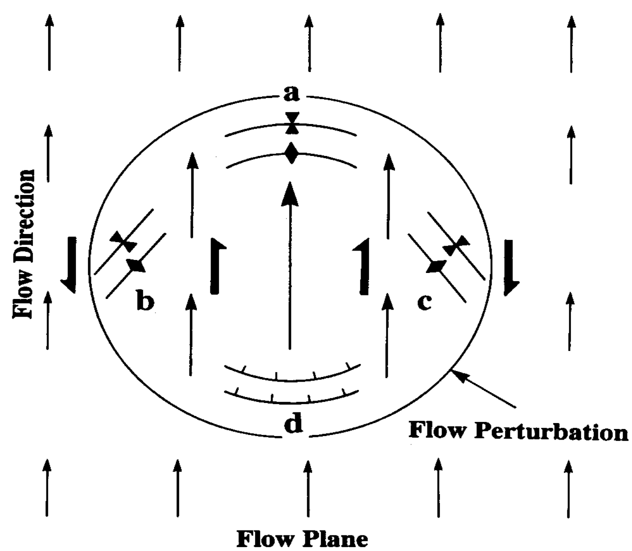

Figure 6. A plan view of the flow perturbation model after Ridley (1986) and Alsop and Holdsworth (1993). A local increase in flow velocity is illustrated by the size of the arrows. Minor structures are illustrated diagrammatically. (a) Asymmetric folds with axes orthogonal to flow direction, these include sheath folds. Asymmetric folds generated during sinistral (b) and dextral (c) differential shear. (d) Shear bands and mylonitic banding dipping in the flow direction.

lineations record a shallow, up to 20°, plunge to the south-southeast (Figure 4a). Shear sense indicators suggest a sinistral sense of movement on the MSPSZ.

Above the basal zone, in the hangingwall, a 10 to 15 m— thick zone is characterised by a series of narrow anastomosing shear zones separating areas of low strain (Figure 3). This zone passes transitionally upwards into a thick continuous series of platy mylonites of which the top is not preserved (Figure 3). The mylonite schistosity dips at 15-25° to the south-west and a strong stretching lineation L4 plunges at shallow angles down-dip (Figure 2b and 4b). Stretching and mineral lineations are strongest in the mylonite zones.

Above the basal zone in areas of low strain a gentle schistosity S4, in micaceous and hornblendic rocks, intensifies in broad zones to a tight crenulation fabric (Figure 5b) and in localised high strain zones (see Figure 5a) into mylonites. S4 forms an axial planar fabric to open to tight chevron-like and isoclinal folds F4 (Figure 5c). Relict upright structures, typical of the footwall, are preserved in low strain areas (Figure 5a).

High strain zones are characterised by the development of platy mylonites, C-S fabrics and a progression of fold types F4' (see Figures 5c - h). Isoclinal (Figure 5d and e), sheath-like and asymmetric buckle folds F4' (Figure 5c and h) deform S4/L4 and refold F4 structures (Figure 5c). Sheath-like folds (Figure 5f) are characterised by curvilinear fold hinges (Cobbold and Quinquis, 1980; Holdsworth, 1988) and eye structures (Cobbold and Quinquis, 1980) (Figure 5f and g). Fold axes are sub-parallel to the main stretching lineation L4 (Figure 4b). Fold axes of asymmetric folds are variable in orientation from sub-parallel with and orthogonal to the main stretching lineation

L4. A new S4' axial planar schistosity is developed in the cores of F4' asymmetric folds (see Figure 5c and h).

DISCUSSION

Origin of fold types

Structures in the hangingwall of the MSPT are consistent with those observed in orogenic belts displaying polyphase fold sequences (e.g. Coward and Potts, 1983; Bell and Hammond, 1984). The development of isoclinal and chevron-like folds (F4) in low strain areas and the progressive development and refolding of earlier structures by isoclinal, sheath-like and asymmetric folds (F4') in high strain zones is typical of deformation associated with progressive shear in mylonite zones (Carreras *et al.,* 1977; Cobbold and Quinquis, 1980; Evans and White, 1984; Holdsworth, 1990; Alsop and Holdsworth, 1993). The progressive development of 'secondary' or 'flow' fold (Holdsworth, 1990) types during protracted deformation in ductile shear zones has been related to local flow perturbations and shear strain gradients (Coward and Potts, 1983; Ridley, 1986). In the flow perturbation model (Figure 6) shear strain gradients are greatest in directions parallel to flow, and local zones of flow normal to compression result in buckle and sheath type folds developing orthogonal to the flow direction. Changes in rates of shear strain result in local differential wrench shear and the generation of asymmetric or buckle folds with axes sub-parallel with the flow direction (Coward and Potts, 1983). It is therefore proposed that the fold types observed in the hangingwall of the MSPT are consistent with those predicted by the flow perturbation model.

Comparison with other ophiolites

The structures described above show clear similarities with other ophiolite sequences, e.g. the Bay of Islands and Oman ophiolites. The metamorphic sole or dynamothermal aureole of these complexes is characterised by a series of polydeformed schists, mylonites and ductile thrust zones (e.g. Williams and Smyth, 1973; Malpas, 1979; Girardeau, 1982; Searle and Malpas, 1980, 1982; Spray, 1984). The metamorphic rocks show clear evidence of strong and composite foliations with extreme stretching lineations which parallel the base of the ophiolite (Williams and Smyth, 1973). The occurrence of isoclinal and recumbent folds with axes sub-parallel to the main foliation is characteristic and in most cases these are secondary folds which deform earlier structures. Giradeau (1982) has described large-scale asymmetric folds and tight to isoclinal folds oriented parallel with flow in mylonite zones, and the presence of local shear zones with shear folds. These structures are interpreted as having resulted from the progressive and continuous overthrusting or obduction of the ophiolite. In these instances thrust movement has been concentrated along ductile thrust zones within the metamorphic sole (Malpas, 1979).

CONCLUSIONS

The MSPT is one of four major low-angle ductile thrust zones which record a complex deformation history for the Basal Unit of the Lizard ophiolite. Structures in the footwall to the MSPT preserve evidence of the early deformation history in the OLHS. A phase of upright near-vertical F3 folds deforms a pre-existing metamorphic foliation. Similar near-vertical north-south-oriented structures are preserved throughout the Lizard complex (Flett, 1946; Vearncombe, 1980). These structures may attest to a phase of east-west compression subsequent to the early metamorphic episode or, alternatively, may be the result of flow perturbation during an earlier phase of ductile thrusting. Structures in the hangingwall are consistent with progressive north-west-directed overthrusting in a ductile thrust zone. Polyphase folding and the progressive development of fold types in low and high strain zones are typical of 'syn-mylonitisation' structures developed during progressive shear. Structures are interpreted to have resulted from protracted ductile deformation during progressive D4 overthrusting. The MSPSZ is a near-vertical structure which displays a sinistral sense of shear and is interpreted as an overridden lateral ramp structure. These structures preserve evidence for a phase of north-west-directed ductile thrusting which has accommodated significant crustal shortening during the accretion history of the Lizard complex. The structural features observed in the MSPT show dear similarities with those recorded from other ophiolite complexes.

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