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The emplacement of peridotites and associated oceanic rocks from the Lizard Complex, southwest England

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Abstract – Upper mantle peridotites and associated oceanic rocks from the Lizard Complex, southwest England, preserve evidence for a multistage geological history. Steeply dipping pre-emplacement fabrics record high-temperature (900–1100 °C) shearing and exhumation of the mantle peridotites apparently formed during localized NE–SW rifting in a pull-apart basin setting (*c.* 400–390 Ma). Associated oceanic rocks (Landewednack amphibolites) preserve a pre-emplacement prograde brown amphibole-bearing metamorphic assemblage and steeply dipping fabric thought to have formed as the newly formed oceanic crust was juxtaposed with newly exhumed hot mantle peridotite during NE–SW rifting. In both the peridotites and Landewednack amphibolites, steep pre-emplacement structures are cross-cut by low-angle mylonitic fabrics thought to have formed during the initial phases of emplacement of mantle over crustal rocks in a partially intra-oceanic setting (*c.* 390–375 Ma). The fabrics in peridotites and amphibolites exhibit retrograde mineral assemblages (*c.* 500–800 °C), with the amphibolites preserving two superimposed assemblages, green amphibole + titanite and colourless magnesio-hornblende, respectively, that are thought to record progressive down-temperature deformation during thrusting. Emplacement-related structures in both the basal peridotites and amphibolites consistently dip at low to moderate angles NW, with down-dip lineations and kinematic indicators showing consistent top-to-the-NW senses of shear. Syn-emplacement magmatism is recorded by intrusions of foliated Kennack Gneiss. Anastomosing serpentine-filled faults mark many existing low-angle contacts between the peridotites and Landewednack amphibolites and appear to represent the final, lowest-temperature (< 250 °C) stages of emplacement (*c.* 370 Ma). This study shows that 'dynamothermal aureoles' in ophiolites may preserve evidence for tectonothermal events that pre-date thrust emplacement.

1. Introduction

Metamorphic soles have been described beneath ultramafic rocks in orogenic peridotite massifs and ophiolite suites in many parts of the world (e.g. Williams & Smyth, 1973; Jamieson, 1980, 1986; Searle & Malpas, 1980; Lippard, Shelton & Gass, 1986; Boudier, Ceuleneer & Nicolas, 1988; Boudier *et al*. 1988). Such metamorphic soles are usually defined as thin zones of metamorphic rocks which show mylonitic fabrics, polyphase deformation and an inverted sequence of metamorphic assemblages that decrease in grade from granulite–amphibolite facies immediately in contact with overlying basal peridotites to greenschist facies at lower structural levels (Jamieson, 1980). In early investigations, the development of a metamorphic sole was interpreted to result from the thermal effect of associated ultramafic rocks, which were regarded as hot intrusions or diapirs (Green, 1964*a*; MacKenzie, 1960). Since the early 1970s, however, it has been shown that most metamorphic soles are related to metamorphism and deformation during overthrusting of hot lithospheric fragments either in an intra-oceanic setting (Church & Stevens, 1971; Williams & Smyth, 1973; Searle & Malpas, 1980; Boudier, Ceuleneer & Nicolas, 1988; Cawood & Suhr, 1992; Fergusson & Cawood, 1995), or within orogenic belts (e.g. Tubia, Cuevas & Gil Ibarguchi, 1997). The relatively hot overriding ultramafic sheet is inferred to provide most of the heat necessary for the observed metamorphism in the cooler footwall rocks (Jamieson, 1980). In the better-preserved examples (e.g. Bay of Islands Complex and Oman), mylonitic fabrics in the metamorphic sole parallel those in the basal peridotite mylonites, and kinematic indicators show the same sense of shear (Boudier, Nicolas & Bouchez, 1982; Girardeau, 1982; Boudier *et al*. 1985; Boudier, Ceuleneer & Nicolas, 1988; Cawood & Suhr, 1992; Fergusson & Cawood, 1995).

The Lizard Complex has long been described as an ophiolite based on the intimate association of peridotites, gabbros and a mafic dyke complex (e.g. Thayer, 1969; Bromley, 1973). Geochemical studies have shown that many of the mafic crustal rocks have compositions typical of mid-ocean ridge basalts (MORB; e.g. Floyd, Lees & Parker, 1976; Kirby, 1979). Previous studies

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have proposed that the metamorphosed oceanic rocks (known as the Landewednack amphibolites) underlying the Lizard Complex peridotites represent part of a metamorphic sole formed due to peridotite emplacement, either as a diapir (Green, 1964*a*,*b*) or as a hot mantle thrust sheet during Variscan tectonics (Bromley, 1979; Styles & Kirby, 1980; Jones, 1997). This event was then followed by 'cold' emplacement of the Lizard Complex as a thrust sheet over the Devonian continental margin rocks to the north, probably during earliest Carboniferous times (Barnes & Andrews, 1984). In this paper, the contacts between the Lizard peridotites and Landewednack amphibolites are re-examined in detail, together with shear zone fabrics and faults in the overlying peridotites and underlying Landewednack amphibolites. Several phases of shearing are observed, each with distinct associated metamorphic mineral assemblages, suggesting that the emplacement of the Lizard Complex involved a progressive sequence of events (cf. Jones, 1997; Vearncombe, 1980).

2. Geological setting of the Lizard Complex

The various components of the Devonian Lizard Complex collectively form the structurally highest, fault-bounded unit exposed in the late Palaeozoic Variscan fold and thrust belt of mainland southwest England (Holder & Leveridge, 1986). To the south, the Lizard Complex structurally overlies Cambro-Ordovician metamorphic basement rocks (*c.* 500 Ma) whilst to the north, it overlies mid-Devonian, very low-grade metasedimentary units of the Gramscatho Group (Fig. 1). All units have been tectonically disrupted by top-to-the-NNW thrusts formed during the main phase of Variscan orogenesis, and these structures are in turn cross-cut by late- to post-Variscan normal faults (Power *et al.* 1996; Shail & Alexander, 1997).

The metamorphic basement comprises two units: a structurally higher Old Lizard Head Series and lower Man of War Gneiss (Fig. 1). The Man of War Gneiss comprises a foliated sequence of dioritic, tonalitic and quartzo-feldspathic gneisses with relict igneous textures that are exposed on reefs south of Lizard Point (Fig. 1). Sandeman *et al.* (1997) obtained a Cambro-Ordovician age (499^{+8}_{-3} Ma; U–Pb zircon concordia intercept age) from the Man of War Gneiss at this locality which they interpreted as dating a magmatic protolith. The thrust contact between the Man of War Gneiss and the structurally overlying Old Lizard Head Series is also preserved at Lizard Point (Jones, 1997). The Old Lizard Head Series comprises mica schists, garnet mica schists and hornblende mica schists. Using SHRIMP U–Pb zircon dating, Nutman *et al.* (2001) obtained ages of 499 ± 7 Ma and 488 ± 8 Ma from granodiorite sheets that cross-cut early fabrics in the schists at Lizard Head (parts of the 'Lizard Head Sill': Flett, 1946; Green, 1964*c*; Sandeman *et al.* 1997; C. A. Cook, unpub. Ph.D. thesis, Univ. Durham, 1999). This suggests that the volcano-sedimentary rocks of the Old Lizard Head Series formed prior to *c.* 499 Ma and that they may be broadly equivalent in age to the Man of War Gneiss. Whole-rock geochemical data (Sandeman *et al.* 1997; Nutman *et al.* 2001) suggest that these metamorphic basement rocks formed during a regional episode of late Cambrian to early Ordovician mafic and felsic magmatism within an intracontinental or continental margin setting. The contact between the Old Lizard Head Series and the overlying Landewednack amphibolites is exposed at Polbream Cove (Fig. 1) and has been interpreted to be a thrust (Jones, 1997).

The Devonian Gramscatho Group, which is exposed to the north of the Lizard Complex (Fig. 1), is interpreted to be a flysch sequence (Holder & Leveridge, 1986) comprising cleaved units of mudstone with subordinate turbidite sandstones and siltstones. A unit of matrix-supported mélange up to 1500 m thick, the Meneage mélange, is assigned to the southernmost part of the Gramscatho Group and carries clasts of mudstone, siltstone, sandstone, quartzite, schist and igneous rocks. Some of these clasts are thought to be derived from erosion of the Lizard Complex and associated Cambro-Ordovician metamorphic basement rocks as they were exposed in emergent thrust sheets prior to final emplacement (Holder & Leveridge, 1986).

The Lizard Complex comprises three distinct groups of igneous rocks (Fig. 1; Flett & Hill, 1912; Green, 1964*c*; Floyd, Exley & Styles, 1993): the mantle units (Lizard peridotites: Cook, Holdsworth & Styles, 1998; Cook *et al.* 2000), the crustal units (Traboe Cumulate Complex, Crousa Gabbro, MORB-type dykes, Porthoustock amphibolites and Landewednack amphibolites: Leake & Styles, 1984; Roberts *et al.* 1993; Floyd, Exley & Styles, 1993) and later, thrust emplacement-related intrusions locally focused along the tectonic contact between the Lizard peridotites and underlying metamorphic basement (Kennack Gneiss: Green, 1964*c*; Sandeman *et al.* 1995; Jones, 1997). Recently published U/Pb zircon isotopic ages of intrusion and metamorphic events (e.g. Table 1; Clark *et al.* 1998; Nutman *et al.* 2001) suggest that most components in the Lizard Complex were formed and juxtaposed between 400 and 375 Ma. Nutman *et al.* (2001) also recently obtained *c.* 500 Ma zircon ages from a pelite horizon in the Landewednack amphibolites, which could indicate that the volcanosedimentary protoliths of these rocks are part of the Cambro-Ordovician basement. However, the almost identical geochemical compositions of the Landewednack amphibolites, Crousa Gabbro and dolerite dykes of the Lizard Complex (Kirby, 1979; Floyd, 1984; C. A. Cook, unpub. Ph.D. thesis, Univ. Durham, 1999) seems to militate against this possibility and may

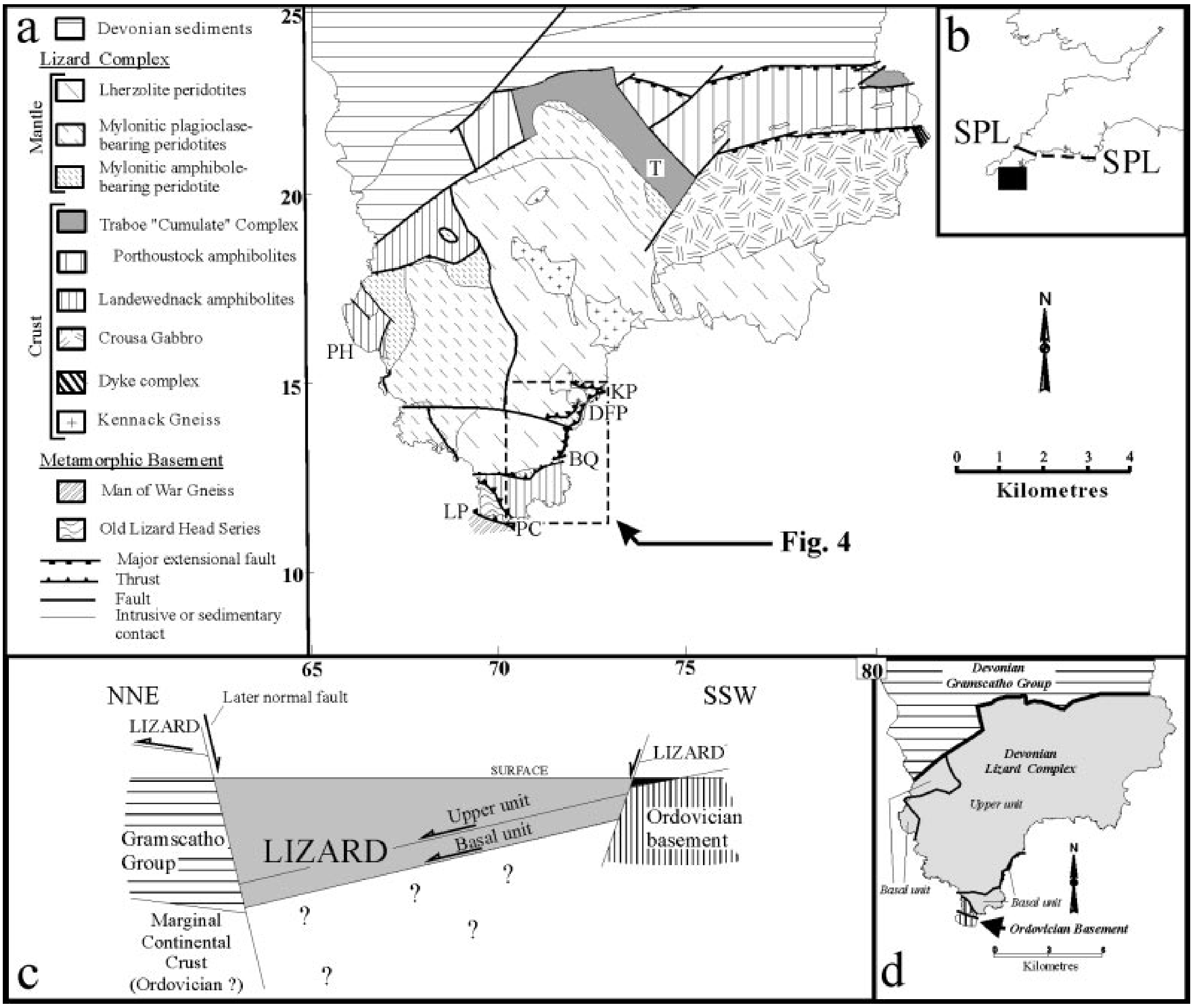

Figure 1. (a) The geological units of the Lizard Peninsula; modified after Flett & Hill (1912), Green (1964*a*), Floyd, Exley & Styles (1993) and Power *et al.* (1996). Abbreviations for localities: LP – Lizard Point, PC – Polbream Cove, BQ – Balk Quarry, DFP – Devils Frying-Pan, KP – Kildown Point, PH – Predannack Head, T – Traboe. Dashed box shows location of Figure 4. (b) Location of the study area (black box) and Start–Perranporth Line (SPL). (c) Cartoon NNE–SSW-orientated cross-section across the Lizard Peninsula. The Upper Unit comprises the peridotites, the Traboe Cumulate Complex, the Porthousstock amphibolites, the Crousa Gabbro and the MORB-type dykes; the Basal Unit comprises the Landewednack amphibolites. (d) Simplified geological map of the Lizard Complex showing the major structural units. (a),(c) and (d) modified from Cook *et al.* (2000).

suggest that the zircon cores are inherited components within Devonian-age rocks.

In the mantle rocks, variably deformed and serpentinized coarse-grained spinel lherzolites are the dominant peridotite type and pass transitionally, with increasing dynamic recrystallization and grain-size reduction into kilometre-scale domains of mylonitic plagioclase- and amphibole-bearing peridotites (Fig. 1; Cook *et al*. 2000). Crustal rocks of the Traboe Cumulate Complex locally display an equivalent mylonitic fabric and are interlayered with the mylonitic peridotites on the north and western margins of the peridotite body (C. A. Cook, unpub. Ph.D. thesis, Univ. Durham, 1999). A wide variety of rock types ranging from ultramafics such as dunites and clinopyroxenites through gabbros and norites to anorthosites (Leake & Styles, 1984) are observed in the Traboe Cumulate Complex. In the northeast of the Lizard Complex, the Crousa Gabbro intrudes and overlies the Lizard peridotites and is locally intensely mylonitized (Gibbons & Thompson, 1991; Roberts *et al*. 1993). Floyd, Exley & Styles (1993) demonstrated that the protoliths of the Landewednack amphibolites included mafic volcanics, tuffs, minor gabbros and locally discordant massive amphibolite derived from doleritic dykes. Similarly, the Porthoustock amphibolites are interpreted to be derived from highly deformed and metamorphosed

Table 1. Structural and metamorphic history of the basal peridotites and associated mafic units of the Lizard Complex prior to and during emplacement

Lithology (age)	Fabrics and shear sense	Mineral assemblage	*P–T* conditions# and other comments
Pre-emplacement (*c.* 393–386 Ma*)			
Peridotites	Sn: steeply dipping to sub-vertical Ln: plunge down-dip NE–SW extension in pull-apart setting ??	*Spinel lherzolite* – Ol + Opx + Cpx + spinel‡ *Mylonitic amphibole-bearing peridotite* – Ol + Pargasitic Hb + Opx ± Cpx ± Plag ± spinel‡	*Spinel lherzolite* – 1120 °C, 16 kbar *Mylonitic amphibole-bearing peridotite* – 990 °C, 7.5 kbar Presumed to be in shear zone footwall
Amphibolites	Sn: steeply dipping to sub-vertical Ln: plunge down-dip NE–SW extension in pull-apart setting ??	Brown amphibole+ Plag+Cpx	Preserved within shear augen; 550–700 °C, 2–6 kbar Presumed to be in shear zone hanging wall
Thrust emplacement (*c.* 396–376 Ma)**			
Peridotites			
Basal peridotite Mylonitic shear zones	Sn: low to moderate NW dip Ln: plunge down-dip Top-to-NW thrusting	Colourless Hb + chl + serpentine	Anastomosing shear zones in basal regions of hanging wall peridotites. Cross-cut early steep fabrics; 500–800 °C
Amphibolites			
(1) Mylonitic shear zones	Sn: low to moderate NW dip Ln: plunge down-dip Top-to-NW thrusting	Green amphib + Plag + Cpx + titanite	Dominant assemblage in footwall amphibolites; green amphiboles often preserve brown cores; 500–650 °C, 3–5.5 kbar
(2) Mylonitic shear zones	Sn: low to moderate NW dip Ln: plunge down-dip Top-to-NW thrusting	Colourless Hb + saussurite	Found in shear zones nearest to contacts with overlying peridotites
Magmatism			
Kennack Gneiss: mixed felsic and mafic magmas	Sn: low to moderate NW dip Ln: plunge down-dip Top-to-NW thrusting		Always cross-cuts pre-emplacement fabrics, locally cross-cuts emplacement-related fabrics: syntectonic
Late- to post-emplacement (*c.* 370 Ma)			
Serpentine-filled faults	Dip NW Top-to-NW thrusting and low-angle extn?	Lizardite–chrysotile	More than one movement/generation present; 20–250 °C

Sn = foliation; Ln = mineral lineation; Ol = olivine; Opx = orthopyroxene; Cpx = clinopyroxene; Hb = hornblende; Plag = plagioclase; chl = chlorite; amphib = amphibole.
* Based on U–Pb zircon ages thought to date metamorphism of Landewednack amphibolites (Nutman *et al.* 2001).
** Based on U–Pb ages thought to date intrusion of Kennack Gneiss (Sandeman *et al.* 2000; Nutman *et al.* 2001).
‡ End-members of a transitional series (see Cook *et al.* 2000 for further details).
# *P–T* estimates taken from C. A. Cook, unpub. Ph.D. thesis, Univ. Durham, 1999.

gabbros and dykes of upper oceanic crust origin (Bromley, 1979), which are geochemically distinct from the Landewednack amphibolites (C. A. Cook, unpub. Ph.D. thesis, Univ. Durham, 1999). MORB-type dykes cross-cut all of the aforementioned groups in the Lizard Complex, and deformed dykes of similar composition cross-cut the Old Lizard Head Series (Flett & Hill, 1912; C. A. Cook, unpub. Ph.D. thesis, Univ. Durham, 1999).

The Kennack Gneiss consists of a series of composite mafic–felsic intrusions that form locally deformed shallowly dipping sheets intruding all other units of the Lizard Complex (Sandeman *et al*. 1995). These intrusions are locally focused along the major contact between the Lizard peridotite and underlying metamorphic basement on the east coast of the Lizard Peninsula (Sandeman *et al*. 1995; Jones, 1997).

Based on the association of ultramafic rocks with metagabbro and metabasalt, which show many geochemical and stratigraphic similarities to ophiolitic sequences, the Lizard Complex has previously been thought to represent an ophiolite complex formed exclusively at a mid-ocean ridge (Bromley, 1979; Kirby, 1979; Styles & Kirby, 1980). Using new structural and geochemical data, Cook *et al.* (2000) refined this model and proposed alternatively that the Lizard Complex peridotites were exhumed by rifting in a continental margin setting, *prior to* opening of a short-lived incipient ocean basin that was then inverted and overridden during Variscan thrusting. The findings of Cook *et al*. (2000) support the results of an earlier geochemical study by Davies (1984) which suggested that the Lizard oceanic crust was formed in a narrow oceanic basin.

3. Lizard peridotites and sub-adjacent rocks: structure and contact relationships

3.a. Definition of terms

A number of equivalent deformational and metamorphic features are recognized throughout the mantle, crustal and metamorphic basement rocks of the Lizard Complex. In the present account we use the term 'emplacement' to refer to the thrusting of mantle peridotites over underlying oceanic crustal rocks and spatially associated Cambro-Ordovician metamorphic basement. Features that pre-date this event are referred to as 'pre-emplacement structures'.

3.b. Pre-emplacement structures

A range of peridotite units form the major part of the Lizard complex, almost all of which carry sub-vertical early fabrics that formed prior to the emplacement-related deformation described below (e.g. Figs 2a, 3). Similar and probably equivalent steep fabrics are also recognized in adjacent parts of the Traboe cumulate complex and Landewednack amphibolites (e.g. Figs 2b, 3) (Cook *et al.* 2000). The least-deformed mantle rocks are coarse-grained spinel- and plagioclase-bearing lherzolites in which the steep fabric is defined by stretched orthopyroxene porphyroclasts and aligned spinel, olivine and recrystallized clinopyroxene. These pass gradationally into kilometre-scale domains of finer-grained plagioclase- or amphibole-bearing mylonitic peridotite (Fig. 1a). Steeply dipping foliations strike mainly NNW and associated mineral lineations plunge down-dip (Fig. 3). These fabrics lie orthogonal to the regional Variscan cleavage in southwest England (e.g. Sanderson, 1984) and clearly pre-date thrust-related structures and fabrics (see Section 3.c). Using the *P–T* and textural history of the peridotites, Cook *et al*. (2000) recently proposed that all the steeply dipping fabrics were developed during high-temperature (> 990 °C) shearing and exhumation of the peridotites along lithosphere-scale, low-angle to moderately dipping extensional shear zones during continental break-up and rifting. An extensional origin for these fabrics correlates well with the observed NW–SE orientation of the later MORB-type dykes seen throughout the Lizard Complex and with the NE-dipping extensional shear zones in the Crousa Gabbro (Roberts *et al.* 1993). Cook *et al.* (2000) proposed that the presently observed steeply dipping orientation of the pre-emplacement fabrics resulted from rotations of regional fault blocks about horizontal axes during lithospheric extension prior to, or synchronous with, emplacement of the Crousa Gabbro (see also Roberts *et al.* 1993).

3.c. Emplacement-related structures

Three groups of emplacement-related phenomena are recognized throughout the Lizard Complex:

(1) Low-angle mylonitic shear zones (millimetre- to tens of metres-scale) are mainly preserved in the basal part of the peridotites and in up to 50 % of the underlying Landewednack amphibolites. In both rock types, the shear zone fabrics clearly cross-cut and rework steep, often mylonitic fabrics that are thought to be related to earlier exhumation (Fig. 2b).

(2) A syntectonic intrusive suite, the Kennack Gneiss, which comprises mixed felsic and mafic components, is ubiquitous in both hanging wall and footwall rocks adjacent to major shear zones that appear to represent the basal contacts of peridotite sheets. The intrusions locally cross-cut the low-angle shear zones in the wall rocks, but carry a strong, low-angle solid-state foliation sub-parallel to the peridotite contacts and associated mylonitic fabrics.

(3) Gently to moderately dipping serpentine-filled faults (e.g. Fig. 2c) and brittle faults cross-cut all earlier structures.

Emplacement-related contacts separating basal peridotites from the underlying Landewednack amphibolites are best preserved at three localities along the east coast of the Lizard Peninsula (Fig. 4) (from north to south): Kildown Point (Fig. 5), Devils Frying-pan (Fig. 6) and the Balk Quarry (Fig. 7).

At Kildown Point (Figs 4, 5; [SW 726 147]), the upper part of the Landewednack amphibolites is exposed beneath coarse-grained lherzolites and mylonitic peridotites in a 20 m cliff section. The contact between the amphibolites and the overlying peridotite thrust sheet is a late, serpentine-filled fault that dips gently to moderately (10° to 50°) NW, and S–C fabrics within this foliated fault rock indicate a top-to-the-N displacement (Figs 2c, 5b). A narrow (30 cm) shear zone composed of hornblende, chlorite, anthophyllite and secondary serpentine ± talc immediately overlies the serpentine-filled fault. The fabric in this basal peridotite shear zone dips NW at moderate angles and mineral stretching lineations plunge down-dip (Fig. 5c). The sense of rotation of the earlier, pre-emplacement, sub-vertical fabric in the overlying mylonitic peridotite into this contact shear zone is consistent with a top-to-the-NW displacement.

Below the serpentine-filled fault occur dark green mylonitized Landewednack amphibolites (Fig. 2c) which are generally massive, although some composi-

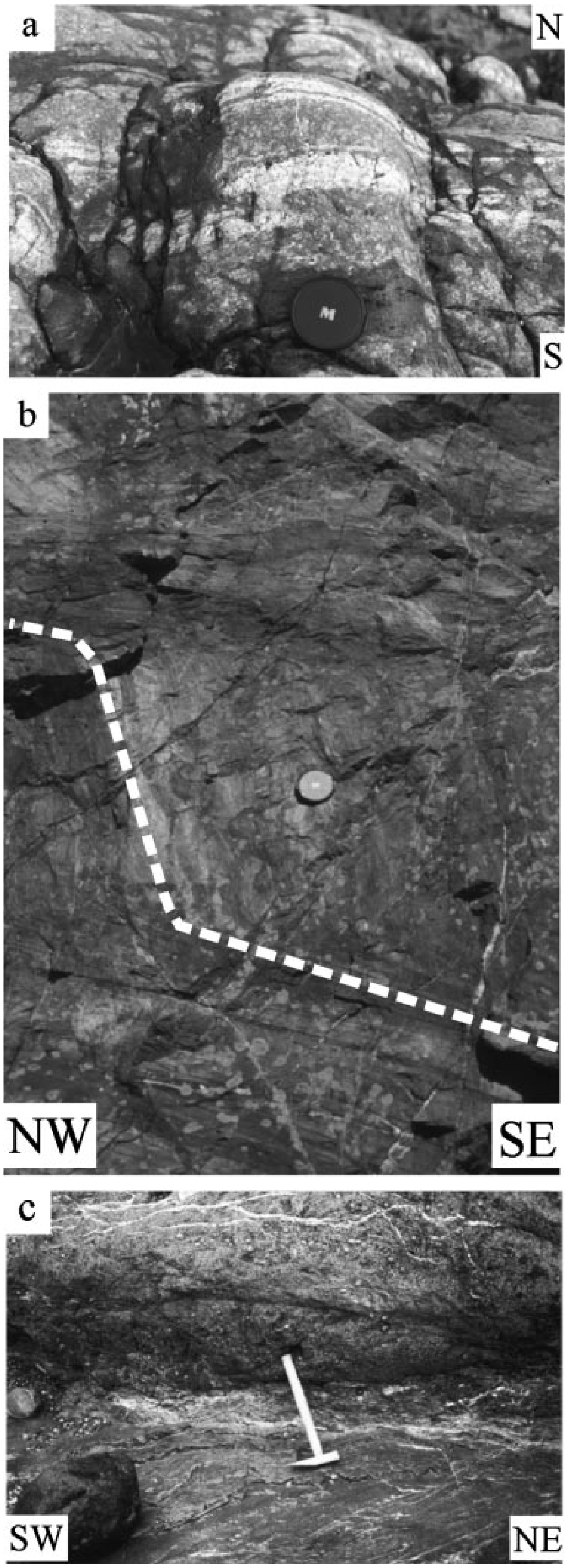

Figure 2. (a) Plan view looking down on a low-angle mylonitic shear zone (composed of hornblende, chlorite and secondary serpentine) cross-cutting coarse-grained lherzolite and pyroxene-rich layers (pale) at Pentreath Beach. The rotation of the pyroxene-rich layer into the shear zone indicates a top-to-the-NW displacement (top left of view). Lens cap is 50 mm across. (b) Landewednack amphibolites near Cadgwith. Low-angle shear zone fabrics (top and bottom of view) cross-cut an earlier steeper fabric (centre of view) and indicate top-to-the-NW sense of shear; fabric trace indicated by white dashed line. (c) Serpentine-filled fault forming a basal detachment at the contact between overlying mylonitic peridotite and underlying Landewednack amphibolite at Kildown Point. Hammer handle is 0.5 m long.

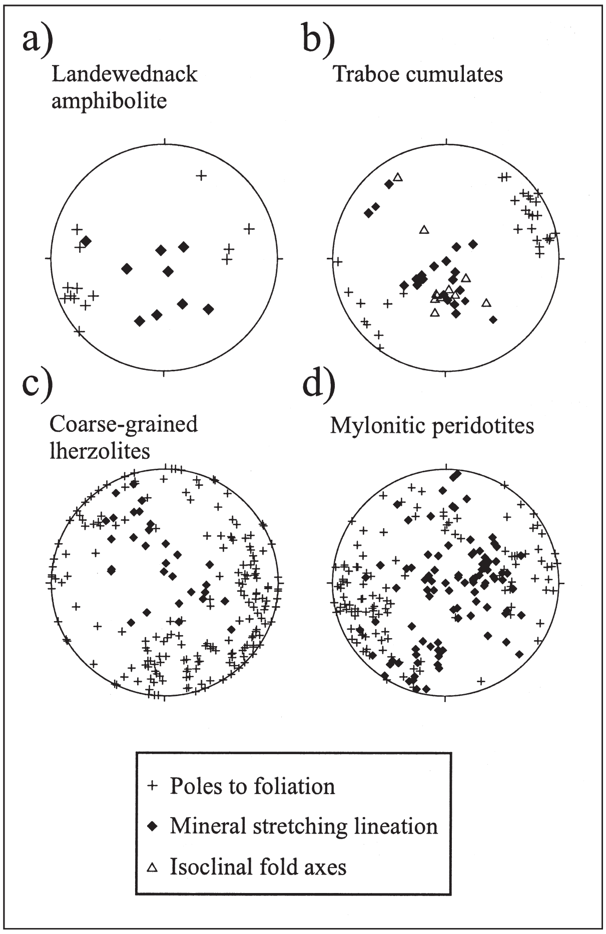

Figure 3. Lower-hemisphere equal-area stereographic plots of pre-emplacement, steep fabrics in (a) Landewednack amphibolites (Predannack Head), (b) Traboe cumulate complex (Traboe), (c) coarse-grained lherzolites, and (d) mylonitic peridotites. (b), (c) and (d) are taken from figure 4a of Cook *et al.* (2000). Note the prevalence of steeply dipping, NNW–SSE foliations and down-dip lineations in (a), (b) and (d); see text for details.

tional layering is observed, and grain-size varies between coarse- and fine-grained. The amphibolite comprises variable proportions of green hornblende and plagioclase, with pale green epidote-rich layers locally present. Foliations in the amphibolites dip at low to moderate angles (10°–50°), predominantly to the NW. Mineral lineations defined by amphibole crystals plunge down-dip, predominantly towards the NW. Kinematic indicators (shear-bands) suggest a top-to-the-NW sense of shear (Fig. 5b). Thus, the sub-parallel, NW-dipping fabrics in the amphibolite and

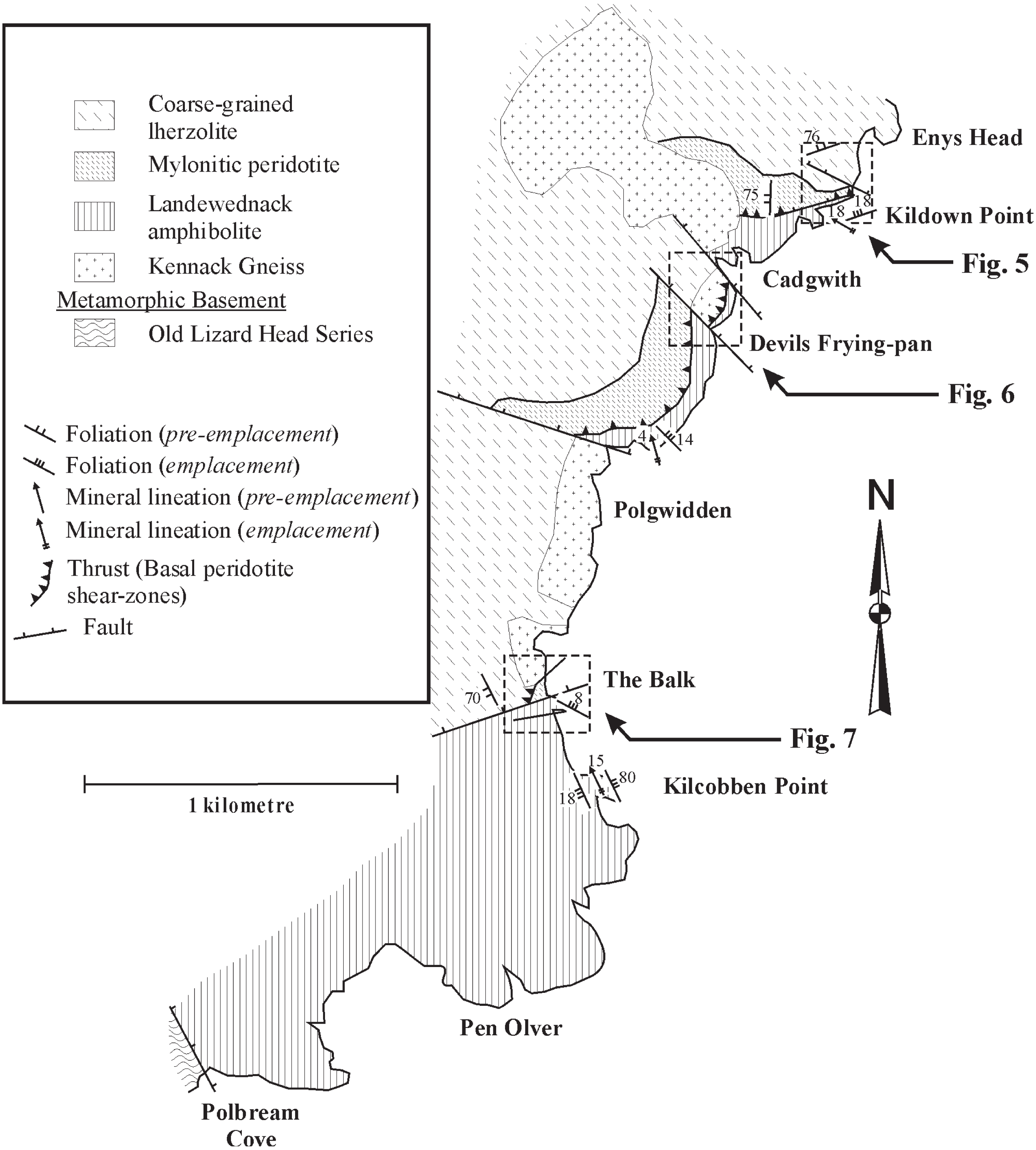

Figure 4. Geological map showing the southeast coast of the Lizard Complex and localities mentioned in the text. See Figure 1 for location. Dashed boxes indicate the location of the maps shown in Figures 5, 6 and 7.

basal peridotite shear zone (Fig. 5b) both preserve apparently top-to-the-NW shear-sense indicators that are consistent with these fabrics being related to the same kinematic event.

Kennack Gneiss intrusions are present near to the contact between peridotite and amphibolite, and also higher up in the hanging wall section (Fig. 5b). These intrusions cross-cut fabrics in the coarse-grained lherzolite, mylonitic amphibole-bearing peridotite, amphibolite and basal peridotite shear zone. The Kennack Gneiss is foliated and lineated parallel to the NW-dipping fabrics in the amphibolite. The intrusions therefore locally cross-cut and are deformed by emplacement-related fabrics, a relationship that is consistent with syntectonic emplacement. Low-angle serpentine-filled faults cross-cut the Kennack Gneiss intrusions.

At Devils Frying-pan (Figs 4, 6; [SW 721 142]) and on the seaward cliff to the east, a zone of gently dipping, anastomosing faults, 0.5–3 m wide, forms the contact zone between the overlying peridotite sheet

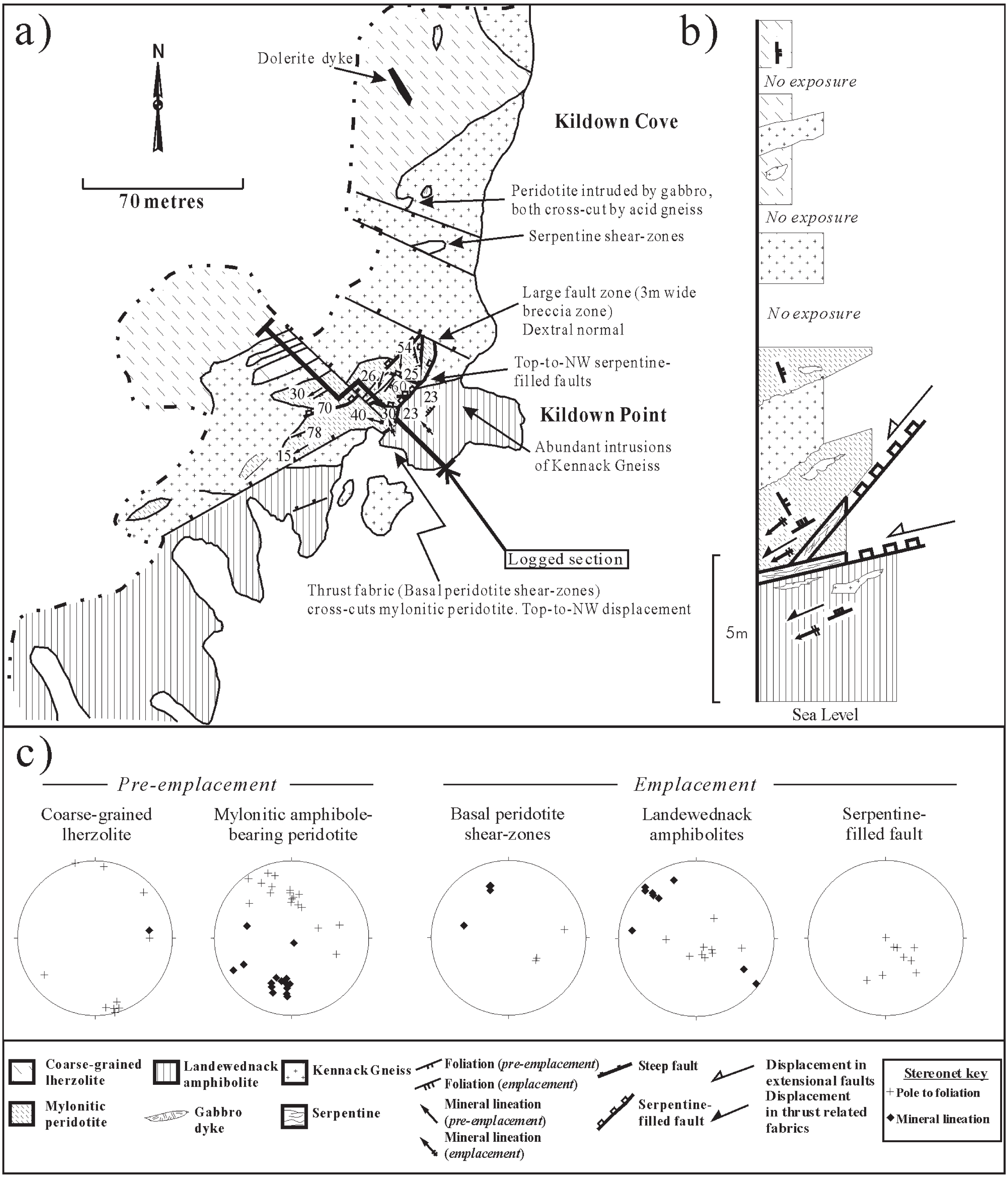

Figure 5. (a) Simplified geological map of Kildown Point, showing location of logged section in (b). (b) Simplified structural log across the thrust contact and adjacent rocks at Kildown Point. The logged section is oriented close to the inferred direction of emplacement and is drawn with NW to the left. (c) Stereographic plots of pre-emplacement and emplacement-related foliations and mineral lineations at Kildown Point.

and underlying Landewednack amphibolites. Fibrous serpentine, tremolite/anthophylite ± talc fills these fault zones, which enclose centimetre- to metre-scale phacoids of mylonitic peridotite, Landewednack amphibolite and Kennack Gneiss. The faults dip NW at low angles and long axes of the enclosed phacoids plunge towards the NW. S–C fabrics and asymmetric wrapping of the phacoids by foliation in the serpentine-filled fault zones indicate top-to-the-NW displacement (Fig. 6b). Evidence for earlier emplacement-related shear zones within the basal part of the peridotite sheet is almost completely obliterated by these serpentine-

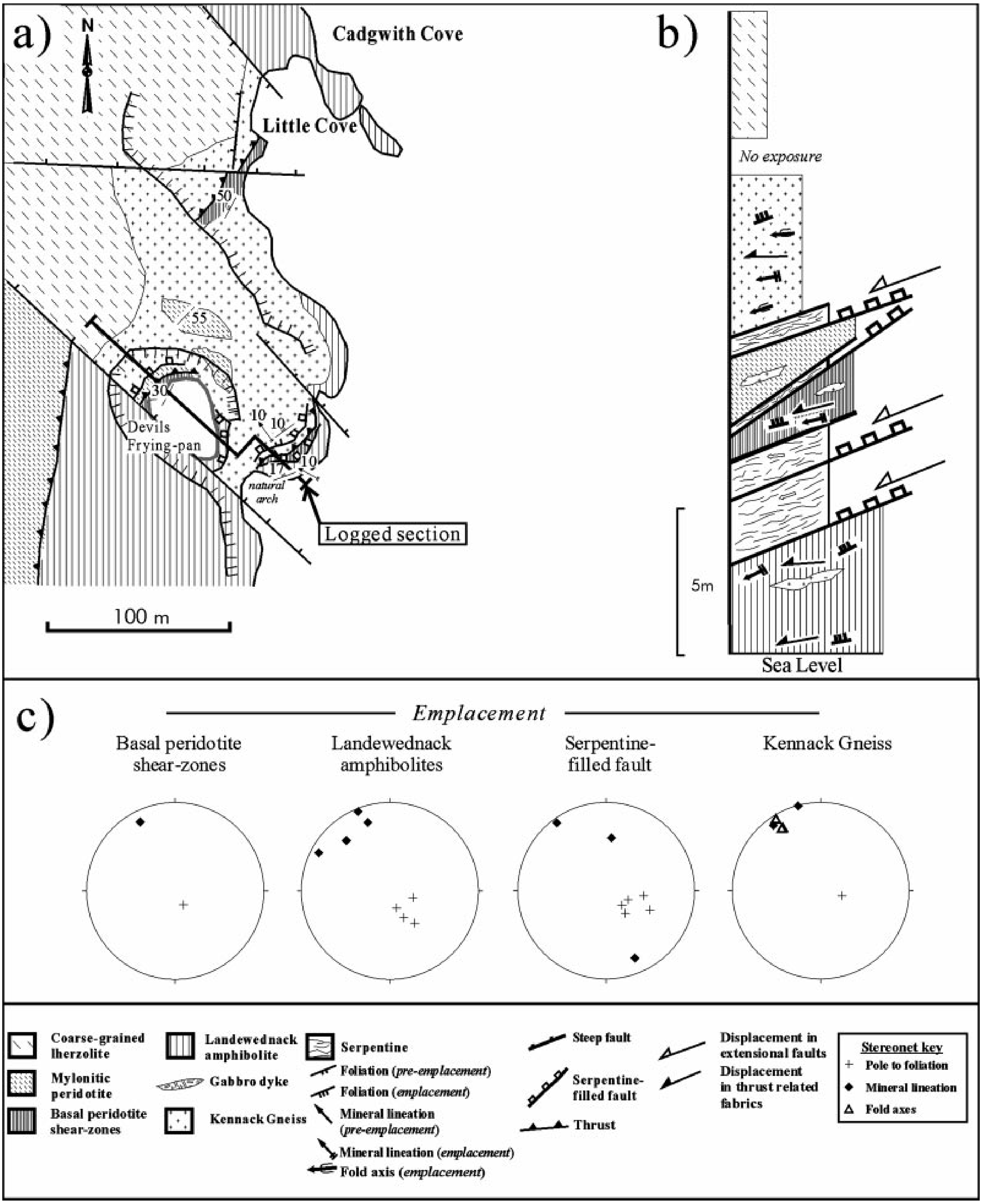

Figure 6. (a) Simplified geological map of Devils Frying-pan, showing location of logged section in (b). (b) Simplified structural log across the thrust contact and adjacent rocks at Devils Frying-pan. The logged section is oriented close to the inferred direction of emplacement and is drawn with NW to the left. (c) Stereographic plots of pre-emplacement and emplacement-related foliations, mineral lineations and fold axes at Devils Frying-pan.

filled faults. However, within several of the larger phacoids of mylonitic amphibole-bearing peridotite, pre-emplacement sub-vertical fabrics are reworked by centimetre-scale low-angle shear zones composed of hornblende, chlorite and serpentine. The shear zones are schistose and foliations dip NW at low angles (15°–30°); associated mineral lineations plunge down-dip (Fig. 6c).

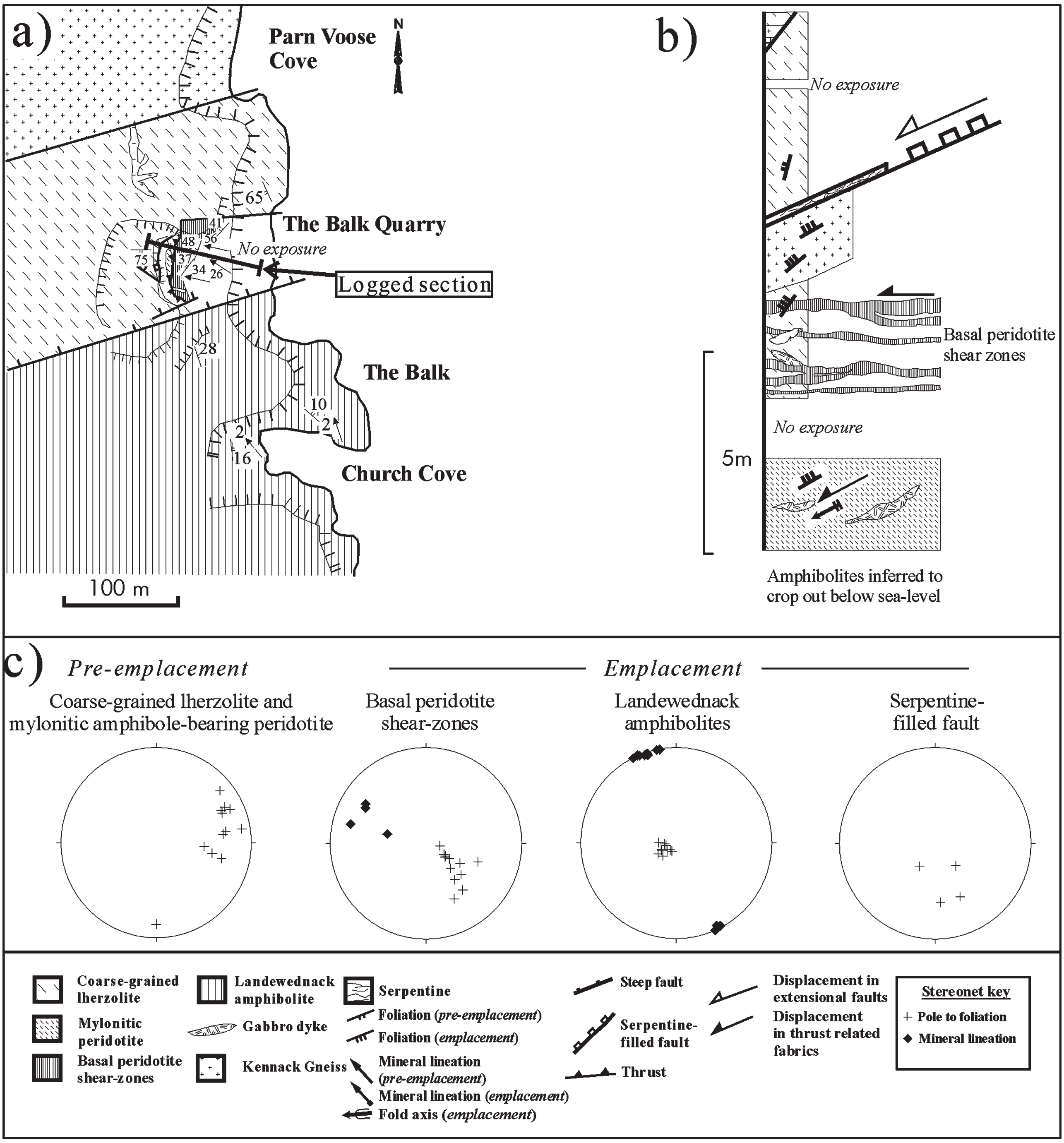

Figure 7. (a) Simplified geological map of Balk Quarry, showing location of logged section in (b). (b) Simplified structural log across the thrust contact and adjacent rocks at Balk Quarry. The logged section is oriented at low angles to the inferred direction of emplacement and is drawn with WNW to the left. (c) Stereographic plots of pre-emplacement and emplacement-related foliations and mineral lineations at Balk Quarry.

The underlying amphibolites are identical to those at Kildown Point. The fabric is sub-parallel to the basal peridotite shear zones, with foliations dipping NW at low angles, and mineral stretching lineations plunging down-dip (Fig. 6c). Shear bands and asymmetrically wrapped plagioclase porphyroclasts in the amphibolite are consistent with a top-to-the-NW sense of shear. Banded felsic and mafic Kennack Gneiss intrusions cross-cut the sub-vertical and low-angle fabrics in the peridotites and amphibolites, but carry fabrics sub-parallel to those in the amphibolite and contact shear zone in the basal peridotite. Foliations dip at a low angle (0°–20°) towards the NW and mineral lineations plunge down-dip. The banded gneiss is folded, and tight folds have axes that plunge mainly NW at low angles to mineral lineations (Fig. 6c).

At the Balk, the rocks are exposed in the old workings of a quarry, at two levels approximately 25 and 30 m above sea-level (Figs 4, 7; [SW 714 129]). Although the basal contact is not actually exposed, Landewednack amphibolites occur in an up-faulted block to the south of the quarry. The foliation of the amphibolites dips NE at low angles and mineral stretching lineations plunge at low angles (0°–5°), predominantly towards the NNW (Fig. 7c). Asymmetric plagioclase porphyroclasts in the coarse-grained layers suggest a top-to-the-NNW sense of shear.

Foliations in the coarse-grained lherzolite exposed in the upper level of the quarry dip steeply WSW (Fig. 7c). A similarly oriented fabric occurs in the pre-emplacement-related mylonitic amphibole-bearing peridotite exposed lower down in the hanging wall section (Fig. 7b). Gabbro and Kennack Gneiss also intrude these mylonitic peridotites. The contact between the coarse-grained lherzolite and the early mylonitic peridotite is a gently NE-dipping serpentine-filled fault (Fig. 7a,b). In the cliff between the upper and lower levels of the quarry, an anastomosing network of gently to moderately dipping, emplacement-related shear zones is exposed. These shear zones cross-cut the steep fabric in the coarse-grained lherzolite, mylonitic peridotite and gabbro, and are, in turn, cross-cut by intrusions of banded felsic and mafic Kennack Gneiss. The shear zones have a mylonitic fabric composed of mainly hornblende and chlorite, which wraps around phacoids of peridotite and gabbro. The foliation dips gently to moderately NW; mineral lineations, defined by elongate hornblende crystals and relict augen of orthopyroxene plunge down-dip (Fig. 7c). A top-to-the-NW displacement is indicated by asymmetric orthopyroxene porphyroclasts within the shear zones and the deflection of pre-emplacement fabrics within the peridotites into the shear zone (Fig. 7b). Moderately NW-dipping late serpentine-filled faults disrupt the shear zones in the basal part of the peridotite sheet. Shear-sense criteria associated with the faults, including asymmetric shape fabrics, indicate top-to-the-NW displacements (Fig. 7b).

Apart from the three localities described here, emplacement-related shear zones with associated top-to-the-NW shear sense criteria are also preserved within the peridotites at several localities exposed along the coastline, notably between Pentreath Beach [SW 6923 1285] and Vellan Head [SW 6680 1490].

In summary, emplacement-related shear zone fabrics in the peridotites and Landewednack amphibolites consistently dip at low to moderate angles NW, with lineations plunging NW and kinematic indicators showing a top-to-the-NW sense of shear. Felsic and mafic intrusions of the Kennack Gneiss consistently cross-cut local emplacement-related structures, although they carry fabrics sub-parallel to those developed in the basal peridotite shear zones and underlying Landewednack amphibolites. Detailed studies of field relationships described by Sandeman *et al.* (1995) and Jones (1997) demonstrate that the Kennack Gneisses are syn-emplacement intrusions.

The contact between the peridotite sheet and underlying Landewednack amphibolites is typically marked by anastomosing serpentine-filled faults. These faults contain a matrix of serpentine, which shows a ductile flow fabric and encloses sheared phacoids of peridotite, Landewednack amphibolite and Kennack Gneiss. Similar serpentine, hornblende, chlorite, anthophyllite ± talc-filled faults also cross-cut the peridotites above and amphibolites below the contact. The faults at the contact zone are oriented parallel to the basal peridotite shear zones and the fabric in the amphibolite. They dip gently to moderately NW, and slickenfibres and sheared phacoids are orientated NW–SE (Figs 2c, 5–7). S–C fabrics and the asymmetric shape of phacoids demonstrate a top-to-the-NW displacement. Thus, the serpentine-filled faults are kinematically similar to the earlier shear zones in the basal peridotites and Landewednack amphibolites. Serpentine-filled faults cross-cutting the peridotite above the contact zone also dip NW and show top-to-the-NW senses of displacement. However, they typically dip more steeply than the faults at the base of the peridotites (e.g. Fig. 5b).

4. Microstructure and metamorphism of the Lizard peridotites

4.a. Pre-emplacement fabrics

The microstructure and metamorphic mineral assemblages associated with the NNW–SSE-striking, steeply dipping, extension-related fabrics of the Lizard peridotites are discussed in detail by Cook *et al.* (2000) (see also Table 1). In summary, variably deformed and serpentinized coarse-grained spinel lherzolites are the dominant peridotite type and pass with increasing dynamic recrystallization and grain-size reduction into plagioclase lherzolites, transitional assemblage peridotites, mylonitic plagioclase- and amphibole-bearing peridotites. Mineral assemblages range between olivine + orthopyroxene + clinopyroxene + spinel, in the spinel lherzolite, to olivine + orthopyroxene + spinel ± clinopyroxene ± amphibole ± plagioclase in the mylonitic peridotites.

4.b. Emplacement-related fabrics

In the peridotites, the fabrics in the emplacement-related shear zones are defined by aligned grains of fine-grained colourless magnesio-hornblende and chlorite forming narrow (~0.5 mm wide) anastomosing shear band networks (Table 1). The hornblende and chlorite grains usually possess well-defined crystallographic- and shape-preferred orientations parallel to the margins of the shear bands. The shear bands asymmetrically wrap around relict orthopyroxene and

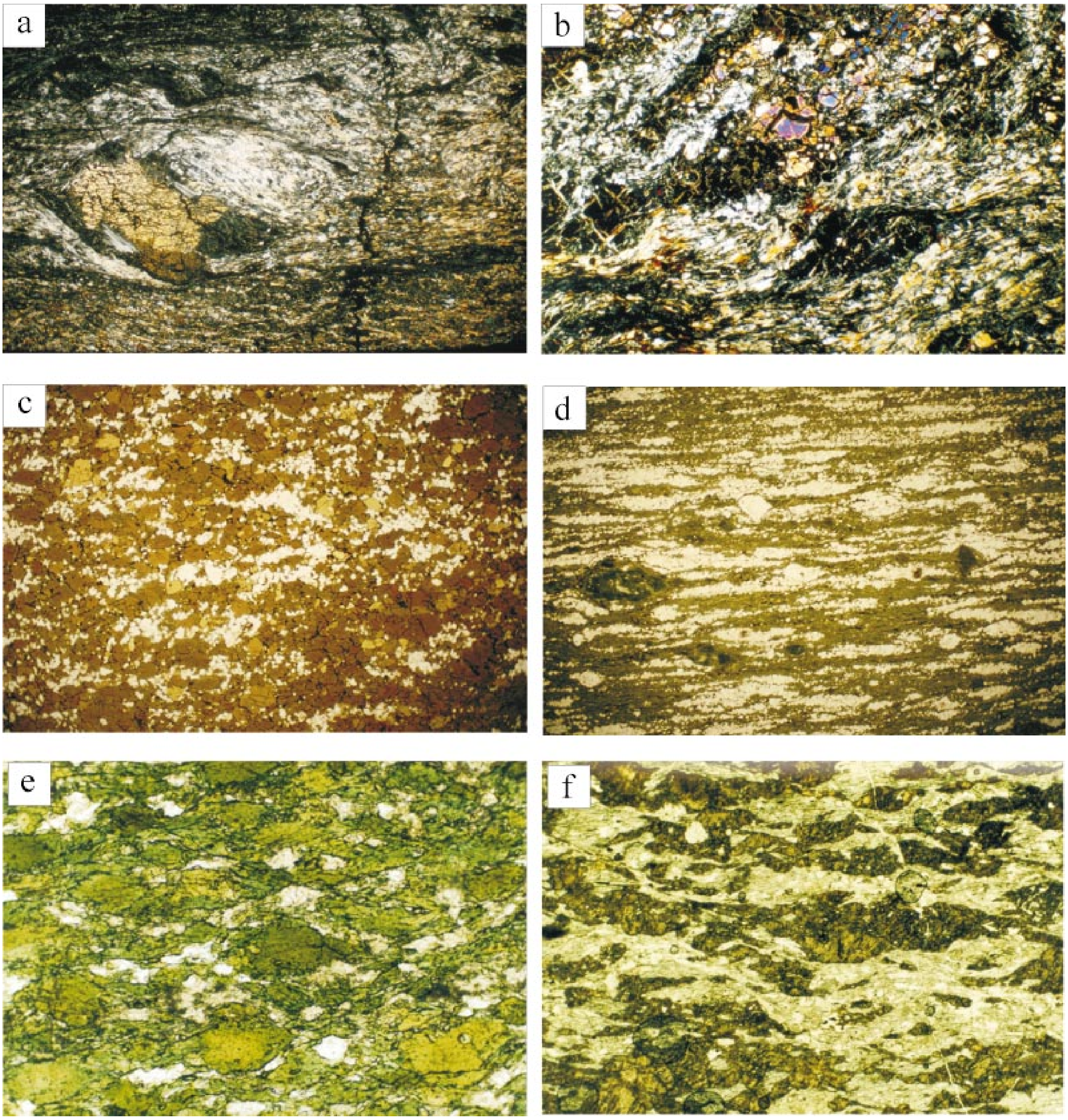

Figure 8. Photomicrographs of deformation fabrics and mineral assemblages associated with pre-emplacement and emplacement-related structures in the Lizard Complex. (a) Crossed-polars view of emplacement-related hornblende and chlorite-bearing mylonitic shear zone fabric in basal peridotite unit wrapping around relict asymmetric olivine porphyroclast; width of micrograph 6 mm. (b) Crossed-polars view of emplacement-related, anastomosing mylonitic shear zone fabric in basal peridotite unit. View shows both aligned and randomly orientated chlorite grains and aligned hornblende grains wrapping around asymmetric lenticular domains of olivine; width of micrograph 1.5 mm. (c) Plane-polarized light view of typical brown amphibole-bearing assemblage of the Landewednack amphibolites, interpreted to be of pre-emplacement origin. Note aligned clusters of recrystallized plagioclase and brown amphibole; width of micrograph 12 mm. (d) Plane-polarized light view of emplacement-related green amphibole-bearing assemblage of the Landewednack amphibolite. Note layers composed of clinopyroxene and green amphibole after clinopyroxene and brown amphibole. Plagioclase is altered to saussurite; width of micrograph 6 mm. (e) Plane-polarized light view of relict brown amphiboles (pre-emplacement) rimmed by emplacement-related green amphibole-bearing assemblage of the Landewednack amphibolite. Plagioclase is also present; width of micrograph 1.5 mm. (f) Plane-polarized light view of sheared green amphibole-bearing assemblage of the Landewednack amphibolite. Note that colourless hornblende wraps around relict green amphibole and also hosts narrow anastomosing shear zones. Plagioclase is completely replaced by saussurite; width of micrograph 3 mm.

olivine porphyroclasts, together with asymmetric lenticular domains of olivine (Fig. 8a). Pull-apart fractures and clinopyroxene exsolution lamellae within relict orthopyroxene porphyroclasts are filled with hornblende. Brittle fractured clasts at margins of porphyroclasts are also enveloped in growths of fibrous colourless hornblende. The development of amphibole is therefore inferred to be synkinematic and suggests the infiltration of a hydrous fluid and its interaction with the pre-existing peridotite mineral assemblage (e.g. see examples discussed by Drury, Hoogerduijn Strating & Vissers, 1990; Bailey, Holdsworth & Swarbrick, 2000). Fine-grained chlorite usually occupies the central portion of these shear bands and develops a fabric that overprints the amphibole fabric, asymmetrically wrapping amphibole porphyroclasts (Fig. 8b). The amphiboles are tremolite and tremolitic hornblende to magnesio-hornblende (C. A. Cook, unpub. Ph.D. thesis, Univ. Durham, 1999; amphibole names according to the IMA classification of Leake *et al.* 1997) The stability of olivine, chlorite and tremolite to magnesio-hornblende in the shear zones and the breakdown of wall-rock spinel to magnetite + chlorite suggest temperatures between 500 and 800 °C (Evans *et al*. 1976; Oba, 1980).

5. Microstructure and metamorphism of the Landewednack amphibolites

5.a. Pre-emplacement fabrics

The Landewednack amphibolites do not preserve original primary igneous mineral assemblages, although a weak compositional banding defined by the metamorphic minerals (Fig. 8c) may represent a relict primary igneous layering. The earliest metamorphic mineral assemblage in the Landewednack amphibolites defines NNW–SSE-striking, steeply dipping fabrics (Fig. 3a) that are interpreted to have developed prior to the thrust emplacement of the Lizard Complex and synchronously with the extension-related fabrics of the peridotites. It is distinguished by the presence of brown amphibole in association with relict clinopyroxene and plagioclase (Fig. 8c–e). Relict clinopyroxene occurs as 'corroded' anhedral porphyroclasts, and minor brown amphiboles are common as a secondary replacement mineral assemblage along cleavage planes. Further evidence for the breakdown of clinopyroxene to brown amphibole includes the presence of diffuse brown amphibole rims around clinopyroxene.

5.b. Emplacement-related fabrics

The first metamorphic mineral assemblage thought to be related to thrust emplacement is distinguished by the appearance of green amphibole and titanite (Fig. 8d,e). This is the dominant metamorphic assemblage and is typical of the amphibolites with gently to moderately dipping fabrics. The green amphibole + titanite-bearing assemblage may partially or wholly replace the brown amphibole-bearing assemblage. Evidence for retrogression of the brown amphibole-bearing assemblage is seen where fine-grained green amphibole grains surround porphyroclasts of brown amphibole or where brown amphiboles have green rims. In many samples, the only evidence for an earlier assemblage is the presence of green amphiboles with relict brown cores (e.g. Fig. 8e). Relict clinopyroxene porphyroclasts are common and are always rimmed by green amphibole, which may define asymmetric porphyroclast shapes (e.g. Fig. 8d). Minor minerals that occur in this metamorphic assemblage include rare biotite and opaque minerals.

Close to the contact with the overlying peridotite sheet, a later metamorphic mineral assemblage is found within cross-cutting shear zones in the Landewednack amphibolite. This metamorphic assemblage is characterized by the presence of colourless hornblende (Fig. 8f). It occurs as weakly aligned fibrous laths that rim earlier clinopyroxenes, brown amphiboles or green amphiboles. The hornblende also hosts narrow cross-cutting shear zones that may wrap around relict porphyroclasts of the pre-existing mineral assemblages (Fig. 8f). Epidote veinlets cross-cut all mineral assemblages and other later, retrogressive, assemblages include chlorite and prehnite.

6. Discussion

6.a. Pre-emplacement events and their regional context

Given the presence of similar pre-emplacement fabrics in the peridotites and Landewednack amphibolites, it seems reasonable to suggest that the metamorphism of these units was closely related. Cook *et al.* (2000) recently demonstrated that initial upper mantle equilibration of spinel lherzolite took place at high pressure (*c.* 16 kbar) and high temperature (*c.* 1120 °C). This was followed by progressive re-equilibration during formation of the following rock types: plagioclase lherzolite (*c.* 11 kbar, 1070 °C), transitional assemblage peridotite (*c.* 7.5 kbar, 1020 °C), mylonitic plagioclase-bearing peridotite (*c.* 7.5 kbar, 1010 °C) and mylonitic amphibole-bearing peridotite (*c.* 7.5 kbar, 990 °C). Cook (unpub. Ph.D. thesis, Univ. Durham, 1999) showed that metamorphism of the brown amphibole + plagioclase metamorphic mineral assemblage in the Landewednack amphibolites took place at 550–700 °C and 2–6 kbar. Nutman *et al.* (2001) recently presented SHRIMP™ U–Pb isotopic ages of *c.* 393 Ma and 386 Ma for metamorphic zircons in Landewednack amphibolites that display steep fabrics and a brown amphibole + plagioclase metamorphic mineral assemblage (Table 1). These ages are interpreted to record metamorphism and recrystallization of the amphibolites that occurred *c.* 390 Ma as they came into contact with the adjacent relatively hot peri-

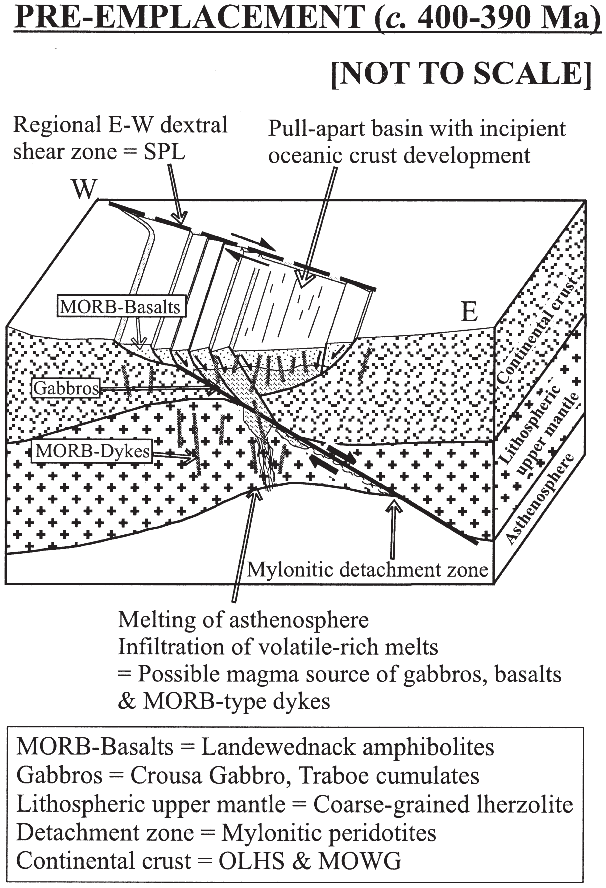

Figure 9. Schematic 3-D model for the Emsian–Eifelian Lizard Complex–Gramscatho pull-apart basin prior to ophiolite emplacement. The basin is shown lying to the south of an E–W-trending dextral regional shear zone thought to correspond to the present-day position of the Start–Perranporth Line (see Fig. 1b for location). Rifting is associated with the development of a lithosphere-scale, ENE-dipping extensional shear zone thought to be responsible for the rapid exhumation of the mantle peridotites, the development of a localized oceanic basin and the juxtaposition of the peridotites with oceanic crust (Landewednack amphibolites) to produce the early brown amphibole-bearing mineral assemblage. The basin is shown in its most mature state immediately prior to basin closure, inversion and ophiolite obduction during top-to-the-NW Variscan thrusting (see Fig. 10a,b). MOWG – Man of War Gneiss; OLHS – Old Lizard Head Series; SPL – Start–Perranporth Line.

dotites during exhumation and displacement along a low-angle to moderately dipping extensional shear zone during rifting in a continental margin setting. This model would require that the Landewednack amphibolites lay in the hanging wall of the extensional shear zone, whilst the peridotites were part of the exhumed footwall. The *P–T* data discussed above also imply that prograde metamorphism of the Landewednack amphibolites occurred relatively late in the exhumation history of peridotites prior to thrust emplacement. This interpretation is similar to some aspects of the models developed for Zabargad Island, Red Sea (Nicolas, Boudier & Montigny, 1987; Boudier *et al.* 1988) and Sierra Alpujata, southern Spain (Tubia & Cuevas, 1987).

On the basis of field and textural data, *P–T* estimates and geochemistry, Cook *et al.* (2000) proposed that the NE/ENE–SW/WSW-stretching of the lithospheric mantle occurred near to a small *incipient* oceanic basin in either an extensional or transtensional setting, rather than at a mid-ocean ridge. Previous studies (e.g. Gibbons & Thompson, 1991; Roberts *et al.* 1993) had suggested that deformation in the Crousa Gabbro occurred during amagmatic extension around a spreading centre. Cook *et al.* (2000) supported an extensional setting, but proposed that the geological history of the Lizard preserves a more gradual evolution between earlier lithospheric extension in the sub-continental mantle through to the later development of oceanic crust. In common with several other authors (e.g. Badham, 1982; Barnes & Andrews, 1986; Holdsworth, 1989; Cook *et al.* 2000) we prefer to believe that the rocks of the Lizard Complex were formed in a local pull-apart basin (Fig. 9). The pre-emplacement NNW–SSE-striking foliations and down-dip stretching lineations in the mylonitic peridotites, Landewednack amphibolites and deformed Traboe cumulates suggest ENE–WSW extension and correspond well with the NW–SE orientation of mafic dykes throughout the Lizard Complex and NE-dipping extensional shear zones in the Crousa Gabbro (Roberts *et al.* 1993; Cook *et al.* 2000). All these features seem to be most consistent with a local pull-apart basin developed along an E–W-oriented zone of right-lateral shear (Fig. 9), an increasingly recognized tectonic component of the pre-Variscan and Variscan evolution of southwest England and Europe (e.g. Barnes & Andrews, 1984). Oceanic, MORB-type rocks are also recognized in the Start Complex of Devon (Holdsworth, 1989; Floyd, Holdsworth & Steele, 1993) south of the E–W-trending Start–Perranporth line (Fig. 1b), a structure that coincides with the northern margin of the Gramscatho Basin across Cornwall. The Start–Perranporth line is defined by an anomalous, narrow zone of Variscan dextral transpression that Holdsworth (1989) proposed formed due to oblique collision against a pre-existing, E–W-trending dextral fault zone which formed the northern margin of a domain of pull-apart basins, locally floored by oceanic crust, in the region separating eastern Avalonia (e.g. southwest England north of the Start–Perranporth line) and Armorica (e.g. the Normannian Nappe).

The proposal that the *c.* 500 Ma zircons in the metapelite horizon in the Landewednack amphibolites (Nutman *et al.* 2001) are inherited is extremely significant as it suggests a close spatial association between the oceanic crust formed in the pull-apart basin and the Cambro-Ordovician continental basement unit (Old Lizard Head Series and Man of War Gneiss). It is

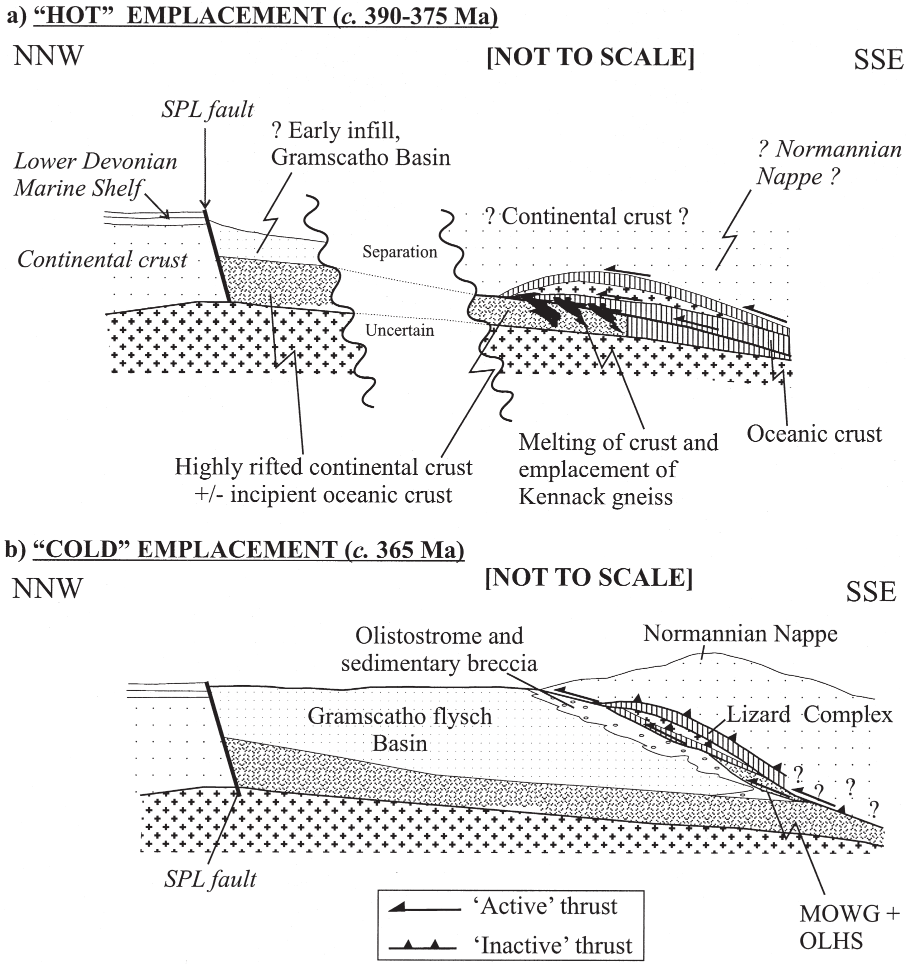

Figure 10. Schematic NNW–SSE cross-sections showing: (a) early 'hot' emplacement (Eifelian–Famennian) during stacking of mantle units, oceanic crust and the highly rifted continental basement forming the floor of the pull-apart basin shown in Figure 9; (b) later 'cold' emplacement (approximately earliest Carboniferous) of the Lizard Complex over the Gramscatho Basin sedimentary fill and Meneage mélange. (b) adapted from figure 4b of Holder & Leveridge (1986). For a cross-section showing the present-day configuration of units, see Figure 1c. Note that the Ordovician basement currently exposed below and to the south of the Lizard Complex is interpreted to be a detached thrust sheet derived from the rifted margin floor of the pull-apart basin shown in Figure 9.

certainly consistent with the existence of a small, short-lived ocean basin.

6.b. Emplacement-related events

The subsequent NNW-directed closure of the pull-apart basin, tectonic inversion and emplacement of the Lizard Complex are recorded by the dismemberment of the various units by shallow-dipping detachment faults and shear zones (Fig. 10a,b). Sandeman *et al.* (1995) demonstrated by thermobarometry of plagioclase–amphibole pairs that metamorphism of the predominant, 'hot' emplacement-related green amphibole + plagioclase assemblage of the Landewednack amphibolite took place at *c.* 600 °C, ~3–4 kbar and obtained $^{40}Ar/^{39}Ar$ incremental heating dates of 360–370 Ma for amphibole. More recently, Cook (unpub. Ph.D. thesis, Univ. Durham, 1999) provided geothermometry estimates of 500–650 °C and 3–5.5 kbar for the metamorphism of the Landewednack amphibolites adjacent to the basal peridotites. Interpretations of SHRIMP™ U–Pb isotopic dates by Nutman *et al.* (2001) for zircons and monazites and a U–Pb single-zircon date by Sandeman *et al.* (2000) from the Kennack Gneiss suggest that syntectonic granite emplacement took place from 396 to 376 Ma (Table 1). Nutman *et al.* (2001) suggest that both the *c.* 369 Ma Rb–Sr isochron date for a felsic vein of the Kennack Gneiss (Styles & Rundle, 1984) and the *c.* 370 Ma $^{40}Ar/^{39}Ar$ incremental heating dates for hornblendes in the mafic components of the Kennack Gneiss (Sandeman *et al.* 1995) may record the ongoing metamorphism associated with the thrust-related emplacement of the Lizard Complex (Fig. 10a).

The origin of the Kennack Gneiss is controversial (see Sandeman *et al.* 2000). Sanders (1955), Styles & Kirby (1980) and Malpas & Langdon (1987) proposed derivation following melting of the Old Lizard Head

Series schists and the Landewednack amphibolites beneath a hot overriding peridotite sheet. In contrast, Teall (1887), Flett & Hill (1912), Green (1964*c*), Bromley (1979) and Sandeman *et al*. (1995, 2000) suggested that the Kennack Gneiss was derived from mixed mafic and felsic magmas intruded syntectonically in proximity to the base of the Lizard Complex. The latter intrusion model seems more likely, because the *P–T* estimates recorded in the Landewednack amphibolites (Sandeman *et al*. 1995; C. A. Cook, unpub. Ph.D. thesis, Univ. Durham, 1999) suggest that syn-emplacement temperatures were unlikely to be high enough to have led to melting. In addition, Sandeman *et al*. (2000) and Nutman *et al*. (2001) observed that the protolith for the felsic component of the Kennack Gneiss includes much older zircons (490 Ma to 1712 Ma), consistent with deeper melting of a unit of older continental crustal material structurally underlying the Lizard Complex (Fig. 9b). Sandeman *et al*. (2000) also demonstrated that the mafic component of the Kennack Gneiss is comparable to EMORB and probably generated through partial melting of a weakly enriched mantle source, and not anatexis of the Landewednack amphibolites as suggested by earlier studies.

Although the basal peridotite shear zones and Landewednack amphibolites of the Lizard Complex display some features in common with the metamorphic soles of ophiolite complexes, there are also several major differences. One of these is the lack of an inverted metamorphic field gradient, from granulite facies down to greenschist facies, within the Landewednack amphibolites underlying the peridotites. If it ever existed, this gradient must have been omitted due to the effects of thrust-related imbrication or late Variscan extensional faulting in the thrust sheets. However, it seems more likely that the apparent absence of an inverted metamorphic gradient may reflect the polyphase metamorphic history of the Landewednack amphibolites in the footwall. Our observations suggest that the early, relatively high-temperature, NNW–SSE-striking, steeply dipping fabrics in the amphibolites can be broadly correlated with similar structures in the peridotites where they are interpreted as having formed prior to emplacement during rifting and exhumation of the mantle (Fig. 9; Table 1; Cook *et al.* 2000). The subsequent development of the predominant green amphibole + plagioclase and later, lower-temperature mineral assemblages in the Landewednack amphibolites during subsequent 'hot' and later 'cold' thrust emplacement of the Lizard peridotites (Fig. 10a,b; Table 1) therefore both represent *retrograde* metamorphic assemblages. These appear to contrast with the predominantly prograde assemblages found within the metamorphic soles of most ophiolites (however, see Jamieson, 1986).

The basal shear zones in the Lizard peridotites related to top-to-the-NW thrust emplacement are characterized by a relatively low-temperature (500–800 °C) mineral assemblage composed of tremolite to magnesio-hornblende and chlorite. This contrasts with the higher-temperature (900–1000 °C) orthopyroxene, clinopyroxene and olivine ± Ti-pargasite assemblages observed in the basal peridotite mylonites of many ophiolites (Malpas, 1979; Girardeau, 1982; Suhr & Cawood, 1993). We propose that the reduced temperatures reflect cooling of the mantle rocks, following extension and prior to their subsequent 'hot' emplacement.

The serpentine associated with later emplacement-related faults consists of a pale to dark green, pseudo-fibrous mixture of lizardite and chrysotile, and suggests relatively low temperatures between 20–250 °C (Power *et al*. 1997). These faults probably formed during the final stages of 'hot' emplacement or may have been active right up to the final 'cold' emplacement of the Lizard Complex over the Gramscatho Group to the north. However, Power *et al*. (1997) suggest that vein serpentine infills of later high-angle faults post-date emplacement.

6.c. Post-emplacement events

The present-day geometry of the emplacement-related contacts is NW-dipping (e.g. Fig. 1c). If top-to-the-NW thrusting were responsible for the emplacement of the peridotite sheet, a SE-dipping contact zone would be expected, as demonstrated, for example, by emplacement-related fabrics in the metamorphic basement rocks of the Old Lizard Head Series at Lizard Point (Jones, 1997). This suggests that the contact zone, together with the overlying peridotite sheet and underlying Landewednack amphibolites, have been rotated from a SE-dipping orientation to the present day NW-dipping attitude. It is suggested that this reorientation occurred due to *post-emplacement* fault-block rotation facilitated by displacement along later, mainly NE–SW-striking, steeply dipping normal faults (e.g. Power *et al*. 1996). This later rotation would not significantly reorient the steeply dipping, pre-emplacement foliation in the Lizard Complex as the inferred subhorizontal NE–SW rotation axes lie at high angles to the NNW–SSE strike of these planar fabrics (e.g. Fig. 3). It is also possible that some low-angle movements along the serpentinized fault zones may have occurred during late Variscan reactivation of pre-existing thrust faults and fabrics during extensional collapse of the thrust nappe (e.g. Jones, 1997; Shail & Alexander, 1997). Extensional collapse of a thrust wedge also accounts for the development of late extensional fault systems in the Bay of Islands Complex (Fergusson & Cawood, 1995).

7. Conclusions

The peridotites and Landewednack amphibolites of the Lizard Complex experienced at least four phases of deformation and associated metamorphism together with an episode of syntectonic magmatism. Steep fabrics in the peridotites and amphibolites were developed during NE/ENE–SW/WSW extension associated with the earlier exhumation of the Lizard peridotites in an extensional or transtensional continental margin setting (Fig. 9). Juxtaposition of newly formed oceanic crust with the hot peridotites at this time, possibly across an extensional shear zone, produced an early, prograde, brown amphibole-bearing metamorphic assemblage in the Landewednack amphibolites.

Later, thrust emplacement-related shear zones and associated mylonitic fabrics in the Lizard peridotite unit and underlying Landewednack amphibolites cross-cut the earlier steep fabrics. These structures presently dip at low to moderate angles NW, with down-dip lineations and kinematic indicators showing top-to-the-NW senses of shear that formed during thrusting of the peridotite sheet over the Landewednack amphibolites in a partially intra-oceanic setting (Fig. 10a). Two retrograde metamorphic mineral assemblages recognized in the Landewednack amphibolites are interpreted to record down-temperature phases of deformation and metamorphism during overthrusting of the Lizard Complex. These are defined by the presence of green amphibole + titanite, and colourless hornblende, respectively. At least one of these retrogressive phases is also recognized in narrow shear zones developed in the overlying peridotites. Syntectonic magmatism is recorded by the cross-cutting intrusions of the foliated Kennack Gneiss (Fig. 10a). Anastomosing serpentine-filled faults mark the existing low-angle contacts between the peridotites and Landewednack amphibolites. The serpentine-filled faults are kinematically compatible with the earlier shear zones in the basal peridotites and Landewednack amphibolites and may have formed during the transition from 'hot' to 'cold' emplacement in which the Lizard Complex was finally thrust northwards over the Gramscatho Group (Fig. 10b; Barnes & Andrews, 1984). The original thrust contact between the Lizard Complex and the Gramscatho Group is nowhere preserved due to the effects of later extensional faulting.

The present study shows that metamorphic soles may record early juxtaposition of hotter mantle and cooler crustal rocks during extension-related phases of deformation that pre-date ophiolite emplacement during collisional overthrusting. Similar deformational and metamorphic histories may be preserved in metamorphic soles associated with other orogenic peridotite massifs and ophiolites elsewhere in the world (e.g. Searle & Malpas, 1980; Boudier, Ceuleneer & Nicolas, 1988; Fergusson & Cawood, 1995).

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