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Journal of Structural Geology 29 (2007) 541–558

JOURNAL OF STRUCTURAL GEOLOGY

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Structural and stratigraphic controls on the origin and tectonic history of a subducted continental margin, Oman

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Received 14 December 2005; received in revised form 28 September 2006; accepted 16 October 2006
Available online 18 December 2006

Abstract

Eclogites and blueschists exposed in Saih Hatat, Oman, record the subduction and exhumation of continental crustal material beneath the Cretaceous Semail Ophiolite during ophiolite obduction. The eclogite-bearing lower plate, originally part of Oman's distal continental margin, is exposed in two tectonic windows through the less metamorphosed upper plate by a previously mapped low angle, high strain, décollement structure. A major tectonic break, currently poorly exposed, records the juxtaposition of the highest pressure eclogites and garnet blueschists against lower pressure epidote-blueschists. The subsequent exhumation of the entire lower plate to mid crustal levels is marked by a pervasive shearing event associated with a regional greenschist facies overprint. The décollement truncates structures and the metamorphic field gradient in the lower plate, but does not significantly truncate structures or stratigraphy in the upper plate. It is not responsible for the exhumation of the high pressure rocks to mid-crustal levels. Most of the displacement across this structure was accommodated during continuing convergence after the subduction system had ceased to be active, and post ophiolite emplacement onto the platform carbonate sequences. A revised tectonic model is presented which accounts for the structural, geochronological and metamorphic observations.

Keywords: Oman; Eclogite; Subduction; Exhumation; High pressure metamorphism

1. Introduction

The Late Cretaceous Semail ophiolite is exposed in northern Oman, where it forms the world's largest exposed tract of oceanic crust and upper mantle emplaced onto continental crust (e.g. Glennie et al., 1974) (Fig. 1). High pressure rocks, including carpholite-bearing meta-sediments, garnet-blueschists and eclogites of continental crustal origin are exposed in the Saih Hatat window, north-eastern Oman, structurally beneath the ophiolite (e.g. Lippard, 1983).

Despite almost 100% exposure, factors including variable and complex stratigraphy, multiple episodes of deformation and rough, often inaccessible terrane have complicated the geological interpretation of the region. This has led to numerous tectonic models and much debate about the evolution of the Arabian margin in general and the high pressure terrane in particular (e.g. Goffé et al., 1988; Montigny et al., 1988; El-Shazly and Lanphere, 1992; Searle et al., 1994, 2004; Gregory et al., 1998; Gray et al., 2000; El-Shazly et al., 2001; Breton et al., 2004).

The Semail Ophiolite and associated thrust sheets of former Tethyan ocean sediments were emplaced onto the Arabian continental margin rapidly after ophiolite crystallisation 95–94 million years ago (Tilton et al., 1981; Hacker, 1994; Hacker et al., 1996; Warren et al., 2005). Windows through the ophiolite and associated thrust sheets in the Jebel Akhdar and Saih Hatat regions (Figs. 1 and 2) expose Permian to Cretaceous

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doi:10.1016/j.jsg.2006.10.006

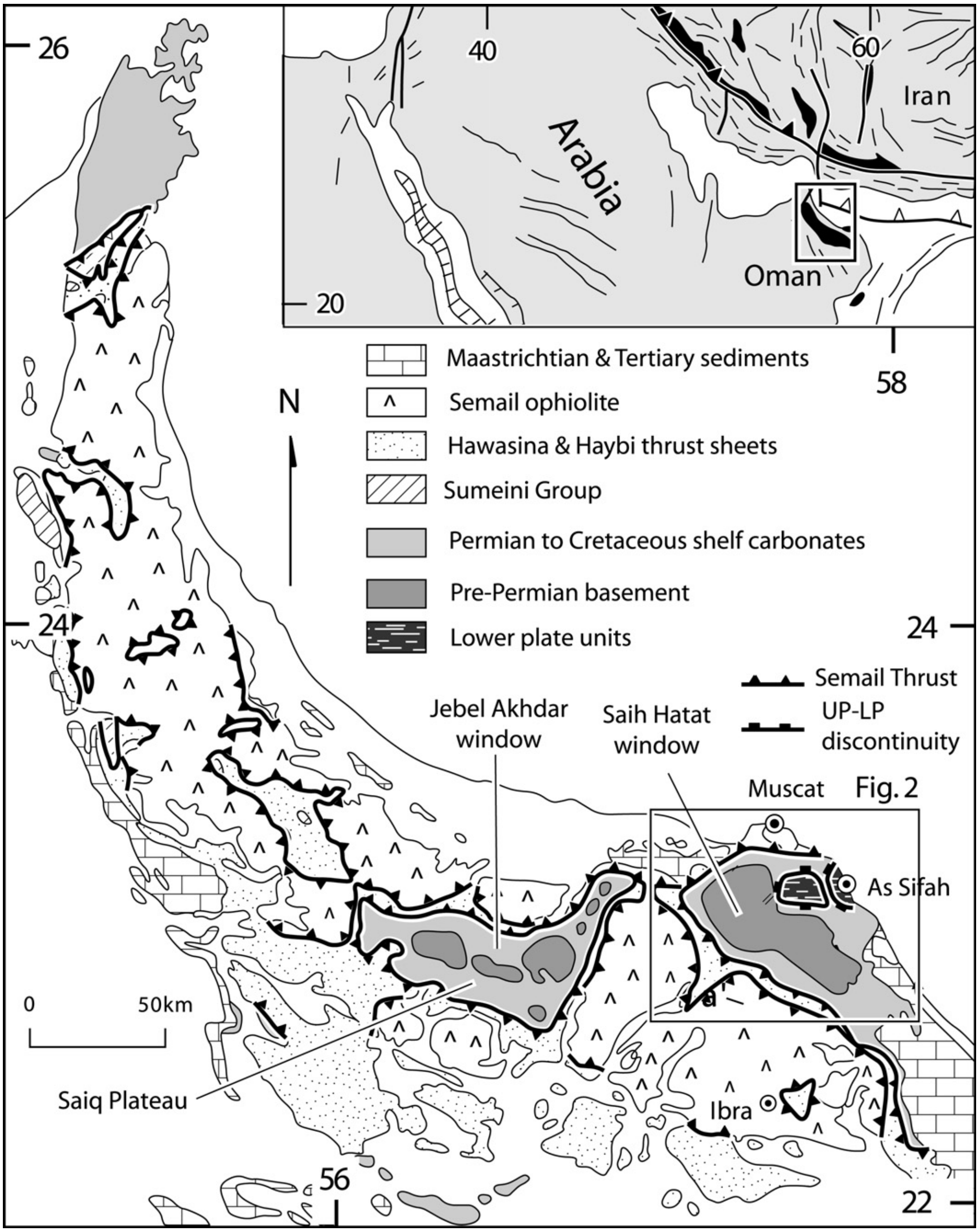


Fig. 1. Locality map showing location of Oman and the Semail Ophiolite in Arabia, and the major geological units. Box shows location of the larger scale map of Fig. 2.

continental margin successions and the unconformably underlying Permian to neo-Proterozoic marine sedimentary cover of the crystalline basement. Metamorphism and deformation of the Permian and pre-Permian successions in the Jebel Akhdar window are weak, whereas equivalent successions in the Saih Hatat window have been affected by high-pressure, low-temperature (HP-LT) metamorphism, ranging from greenschist grade in the southwest through to eclogite grade in the northeast.

Within the Saih Hatat window a major low-angle fault separates a lower metamorphic grade "upper plate" from a higher grade "lower plate" (the upper plate–lower plate (UP–LP) discontinuity of Gregory et al., 1998; Miller et al., 1998), and each plate preserves a distinctive stratigraphy, structural style and metamorphic history. The upper plate preserves relatively homogeneous HP-LT metamorphism, with the index mineral carpholite occurring in certain rock units. In contrast, the lower plate, exposed in two windows beneath the upper plate (Fig. 2), preserves a highly telescoped metamorphic field gradient, from epidote-blueschist-grade (P ~9 kbar) in the western Hulw window to garnet-blueschist and eclogite-grade (P ~18–22 kbar) in the eastern As Sifah window (Goffé et al., 1988; El-Shazly et al., 1990, 1997; El-Shazly and Liou, 1991; Searle et al., 1994; El-Shazly, 2001; Warren and Waters, 2006).

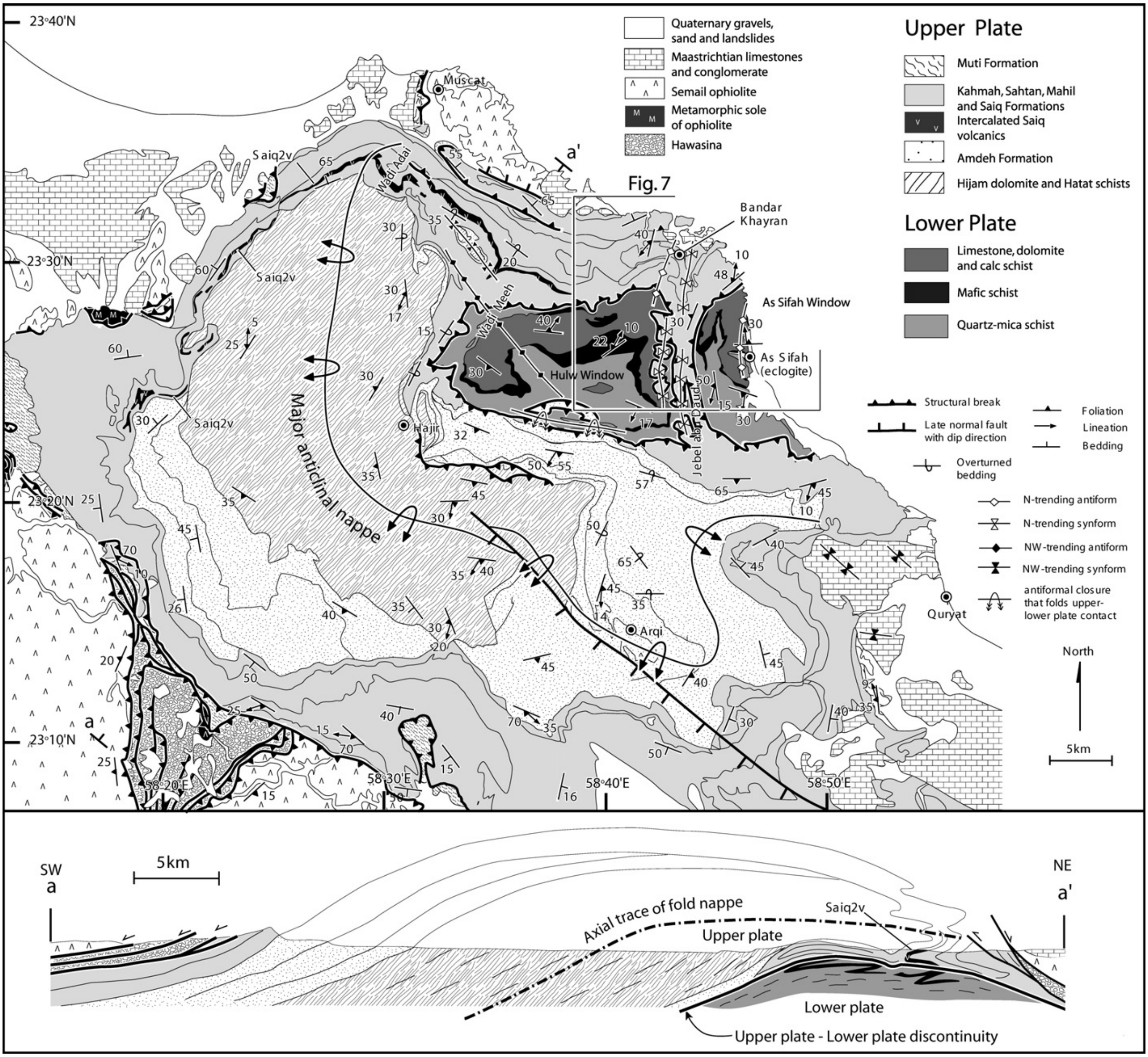


Fig. 2. (a) Geological map of Saih Hatat showing major lithological units, folds and faults. (b) Cross section through Saih Hatat from NE to SW along section line marked on map (a to a′).

The locations of major structural breaks, as indicated by jumps in peak metamorphic pressures, have been placed in various locations by different workers (Fig. 3). Early workers e.g. Le Métour et al. (1986) and Montigny et al. (1988) mapped a series of north- and south-dipping breaks (Fig. 3a and b). There was early recognition of the similarity between calc-schists exposed in the Wadi Meeh (Mayh) region (Fig. 2) and at As Sifah, and the maps of Montigny et al. (1988), and Michard et al. (1994) show these regions as tectonic windows exposing deeper structural levels (Fig. 3b and c). Searle et al. (1994) subdivided the highest pressure As Sifah region into separate eclogite, garnet-blueschist and blueschist zones (Fig. 3d).

Gregory et al. (1998) and Miller et al. (1998) mapped a major discontinuity which separated the region into ‘‘upper’’ and ‘‘lower’’ plates, with the lower plate exposed in two tectonic windows (Fig. 3e). Miller et al. (2002) suggested that a large structural break, defining a major omission in peak metamorphic conditions, existed in the lower plate in the western sector of the As Sifah window. The UP–LP discontinuity truncated this break, and also truncated the overall metamorphic field gradient in the lower plate (Fig. 4a). Miller et al. (2002) called this major break, not presently well exposed, the ‘‘disrupted zone’’. Searle et al. (2004) subsequently argued that the tectonostratigraphy of the Saih Hatat region should be represented by 4 stacked units, from the lowest As Sifah eclogite unit,

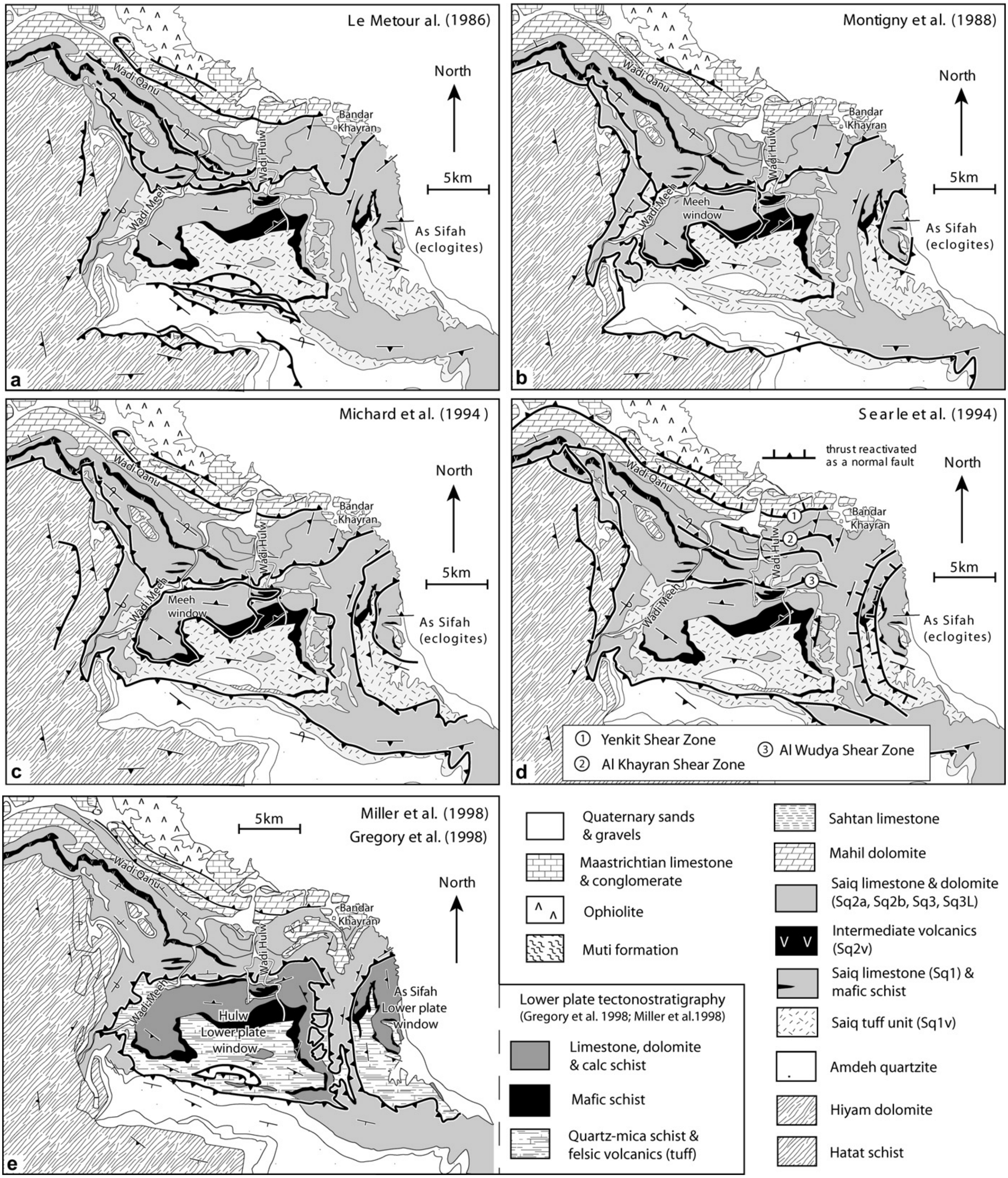


Fig. 3. Structural model comparison showing the different structural interpretations of (a) Le Métour et al. (1986), (b) Montigny et al. (1988), (c) Michard et al. (1994), (d) Searle et al. (1994), (e) Miller et al. (1998) and Gregory et al. (1998).

through the As Sifah garnet-blueschist unit, into the Hulw unit and the Upper Plate unit. The UP–LP discontinuity in their model separated the Hulw unit from the upper plate but did not truncate the underlying metamorphic field gradient.

The two geometries presented in Fig. 4 have led to substantially different interpretations of the structural evolution and exhumation history of the Saih Hatat region in general and the exhumation of the high pressure rocks in particular. This

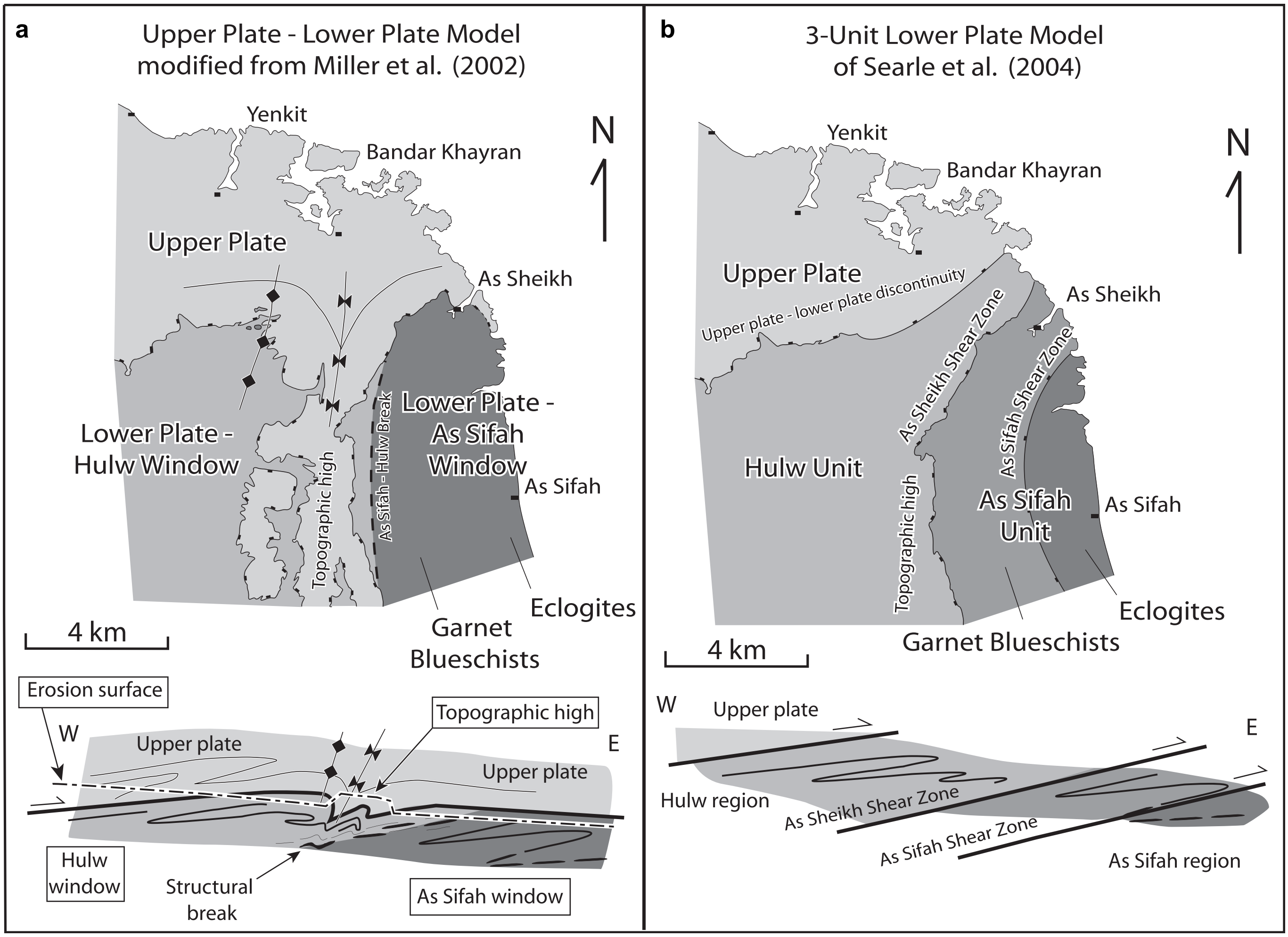


Fig. 4. Schematic figure showing the recent (Miller et al., 2002; Searle et al., 2004) differences in the interpretation of structural relationships within and between the upper and lower plates. (a) Upper Plate–Lower Plate model, adapted from Miller et al. (2002) and adopted during this study. (b) Three-unit model of Searle et al. (2004).

contribution combines new mapping, (bio) stratigraphic data and microstructural constraints with data and observations from research groups who have previously been involved in debate about the structural relationships, geochronology and tectonic setting of this area (e.g. Gray et al., 2005a; Searle et al., 2005, among others). We have attempted to resolve some of the major controversies, including:

- The original stratigraphic (age and space) relationships between the lower and upper plates: was the lower plate an "exotic" terrane or part of the distal Arabian margin?
- Which upper and lower plate stratigraphic units were cut by the discontinuity?
- The polarity of the subduction zone
- The exhumation history of the lower plate eclogites
- The present day tectonic relationships between the zones of different metamorphic grade
- The location, relative timing of motion, and relative importance of structural breaks in the Saih Hatat region.

2. The lower plate

2.1. Stratigraphy

The lower plate exposes a tri-part stratigraphy: carbonates overlie mafic rocks which in turn overlie quartz-rich rocks. This is similar to part of the upper plate stratigraphic section (Fig. 5) where the Ordovician Amdeh (quartzite) Formation is overlain by the Late-Permian Saiq (carbonate) Formation, which contains intrusive lenses and sills of mafic rocks. The correlation in age and depositional setting between the lower and upper plate rocks, however, has been the subject of much discussion.

Gray et al. (2005c) showed that a tuffaceous unit exposed beneath the eclogites in As Sifah yielded 298 ± 3 Ma U–Pb SHRIMP zircon ages, i.e. straddling the Carboniferous–Permian boundary. They also showed that the stratigraphically lowest carbonates and calc-schists in the lower plate have $\delta^{13}C$ signatures which are consistent with deposition during the Early Permian. The stratigraphically highest lower plate unit

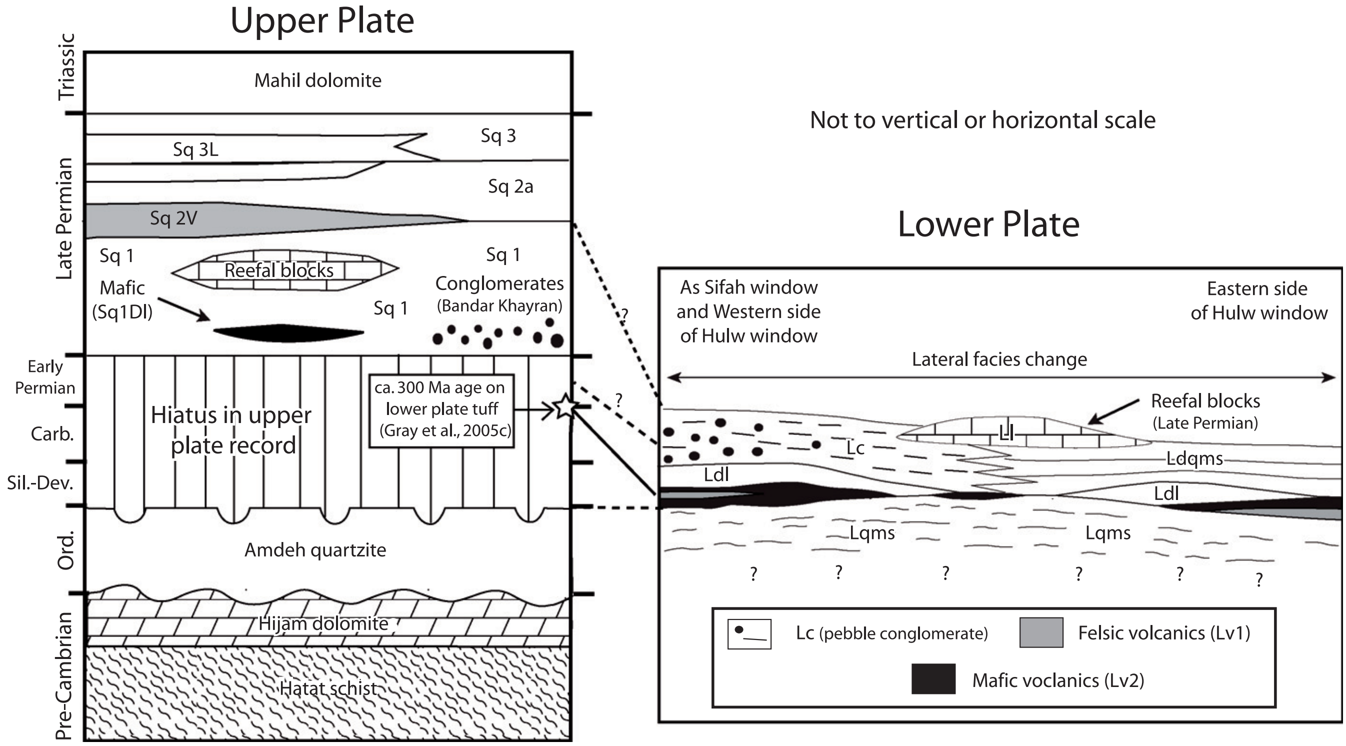


Fig. 5. Schematic figure showing the current understanding of the relationships between the stratigraphy of the upper and lower plates.

(Ll on Fig. 5) has a $\delta^{13}C$ signature which is more consistent with Late Permian deposition.

El-Shazly et al. (1994), on the basis of major, trace and rare earth element data, interpreted the blueschists, eclogites and greenschists of the lower plate as enriched tholeiitic MORB (mid-ocean ridge basalt), possibly erupting at an oceanic spreading centre. This interpretation contrasts with that of the mafic units intercalated within the upper plate Saiq Formation: these were interpreted as within-plate alkali basalts, and hence a more distal origin for the lower plate rocks was suggested.

Detailed mapping during this study revealed the presence of crinoid fossils in the high-pressure dolomites of the As Sifah region (Fig. 6; sample localities are marked on Figs. 7 and 8). Crinoids have previously only been reported from the lower pressure Hulw region and the upper plate (Le Métour et al., 1986). Their close association with the eclogite and garnet-blueschist grade mafic rocks implies that the fossils survived subduction to ~20 kbar as well as pervasive deformation during exhumation. At the highest grade, the crinoids have been preserved as low-iron dolomite $(Ca_{0.58}Mg_{0.41}Fe_{0.01})CO_3$ in a more iron-rich dolomite matrix $(Ca_{0.51}Mg_{0.44}Fe_{0.05})CO_3$ with matrix crystals yielding rims of low-Mg calcite $(Ca_{0.96}Mg_{0.04})CO_3$. The crinoids and dolomites in the garnet-blueschist and epidote-blueschist zones of the As Sifah and Hulw windows have similar compositions, and the fossils are very similar in appearance to those found in the upper plate.

Current data suggest that the lower plate quartz-mica schist (Lqms) correlates with the upper plate Amdeh Formation (as suggested by Miller et al., 2002; Searle et al., 2004). The mafic and felsic volcanic rocks of the As Sifah lower plate region are of latest Carboniferous/earliest Permian age and do not correlate with any upper plate rocks in Saih Hatat (Gray et al., 2005c), although early Permian rocks are documented from the subsurface of interior Oman and are locally exposed in the Haushi-Huqf area (Blendinger et al., 1990). On the basis of $\delta^{13}C$ analyses, the highest lower plate carbonate unit may be correlated with the upper plate Saiq Formation (Gray et al., 2005c). The presence of crinoids in the lower plate is consistent with a Carboniferous to Late Permian age range for the carbonates and rules out the rocks being Precambrian analogues of the upper plate Hijam dolomite.

2.2. Metamorphism

There is a major change in metamorphic grade across the lower plate, from epidote-blueschist in the Hulw region to garnet-blueschist and eclogite in the As Sifah region. The eclogites reached peak temperatures of 520–550 °C (El-Shazly et al., 1990; Searle et al., 1994; El-Shazly et al., 2001). Estimated peak pressures vary from 16 kbar (El-Shazly, 2001) to as much as 23 kbar (Searle et al., 1994), with the most recent estimates at around 20–22 kbar (Warren and Waters, 2006). Recent pseudosection modelling of the overlying garnet-blueschists suggests that they reached similar conditions of 500–520 °C and 18–20 kbar (Warren and Waters, 2006).

The peak conditions reached by the Hulw window epidote-blueschists were estimated at 450–500 °C and 7–9 kbar from phase relations in the metapelitic rocks (Goffé et al., 1988), and 400–460 °C, 6.5–8.5 kbar from phase relations in the metabasites (El-Shazly, 2001). Unlike the eclogites, the mafic rocks in the Hulw lower plate window contain albite-quartz in

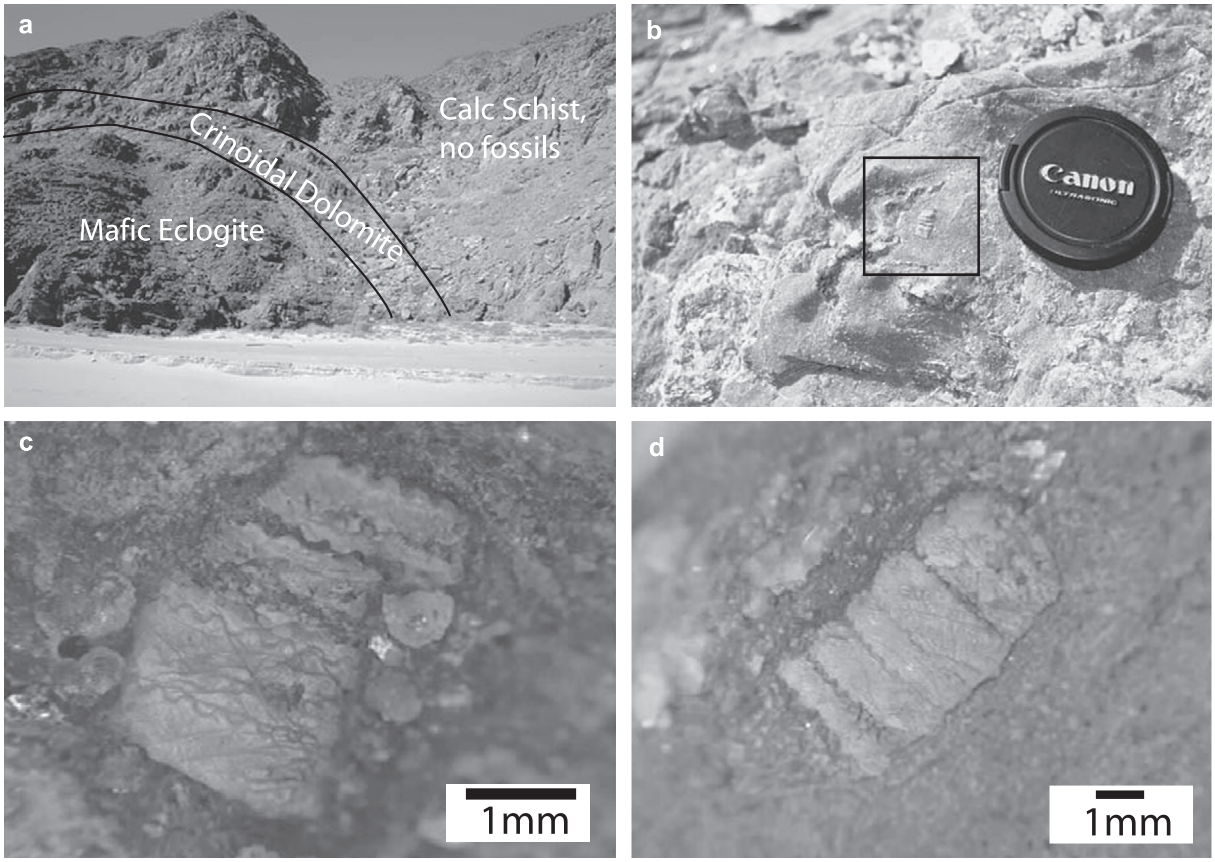


Fig. 6. Photographs and photomicrographs of the upper and lower plate crinoids—samples are marked on maps in Figs. 7 and 8 (*C1–5). (a) The dolomite layer overlying the eclogite boudin exposed on the first beach north of Saih Hatat village; (b) a crinoid stem fragment (specimen C5) exposed within that layer. Stem fragment is ∼1 cm long. (c) Photomicrograph of crinoid fragment (specimen C2) found in the dolomite unit overlying garnet blueschists exposed along the road ∼1 km inland of As Sifah village (note: as of early 2005 the road to As Sifah has been upgraded, so road-side exposures in this region will have changed). (d) Crinoid stem fragment (specimen C3) in a dolomite boudin within calc schists on the hill south of Wadi As Sifah.

equilibrium with sodic amphibole and thus experienced peak pressures below the albite = jadeite + quartz transition.

The entire lower plate is overprinted by the same greenschist facies assemblage: Na–Ca amphiboles (actinolite and winchite; Miller et al., 2002), epidote of higher pistacite content than the HP assemblage, chlorite and albite. This overprint is associated with major shearing and folding, and affects the entire lower plate, implying that the eclogites, garnet-blueschists and epidote-blueschists had all reached the same crustal level before or during the shearing/overprinting event. There are no quantitative PT determinations for this overprint.

2.3. Geochronology

The timing of peak metamorphism of the As Sifah eclogites has been the subject of much recent discussion, with K–Ar, ^{40}Ar/^{39}Ar, Sm–Nd, Rb–Sr and U–Pb techniques employed to tackle the problem. In contrast to the somewhat scattered ^{40}Ar/^{39}Ar and Sm–Nd datasets, the U–Pb zircon, U–Pb rutile and Rb–Sr phengite-whole rock isochron data appear to form a tight and self-consistent dataset which indicates that peak metamorphism of the eclogites occurred at 82–79 (El-Shazly et al., 2001; El-Shazly and Walker, 2003; Warren et al., 2003, 2005; Gray et al., 2004a). They were rapidly cooled below ∼500 °C as indicated by the Rb–Sr and U–Pb rutile data, and, if the ^{40}Ar/^{39}Ar data from the retrograde fabrics (Miller et al., 1999; Gray et al., 2004b) is reliable, may have equally rapidly cooled to below ∼ 350 °C within a few million years. The eclogite facies rocks cooled through 210 °C at ∼68 ± 2 Ma, and through the 100 °C isotherm at ∼54 ± 3 Ma, as indicated by fission track ages on zircon and apatite, respectively (Saddiqi et al., 1995; Poupeau et al., 1998).

2.4. Structure and microstructure

The lower plate has been deformed by intense, northeast-directed non-coaxial shear, producing L-S tectonite fabrics and sheath folds at all scales (Miller et al., 2002; Gray et al., 2004b). Unlike in the upper plate, where a clear strain increase is seen down towards the UP-LP discontinuity, this shearing is pervasive throughout the lower plate. The shearing event produced a series of regional, inclined to recumbent, sheath-like folds that are generally identified by the trace of the mafic volcanics in the lower plate (F1 generation, Figs. 8 and 9). These lower plate closures fold earlier higher-pressure assemblages and have the same retrograde axial planar mineral

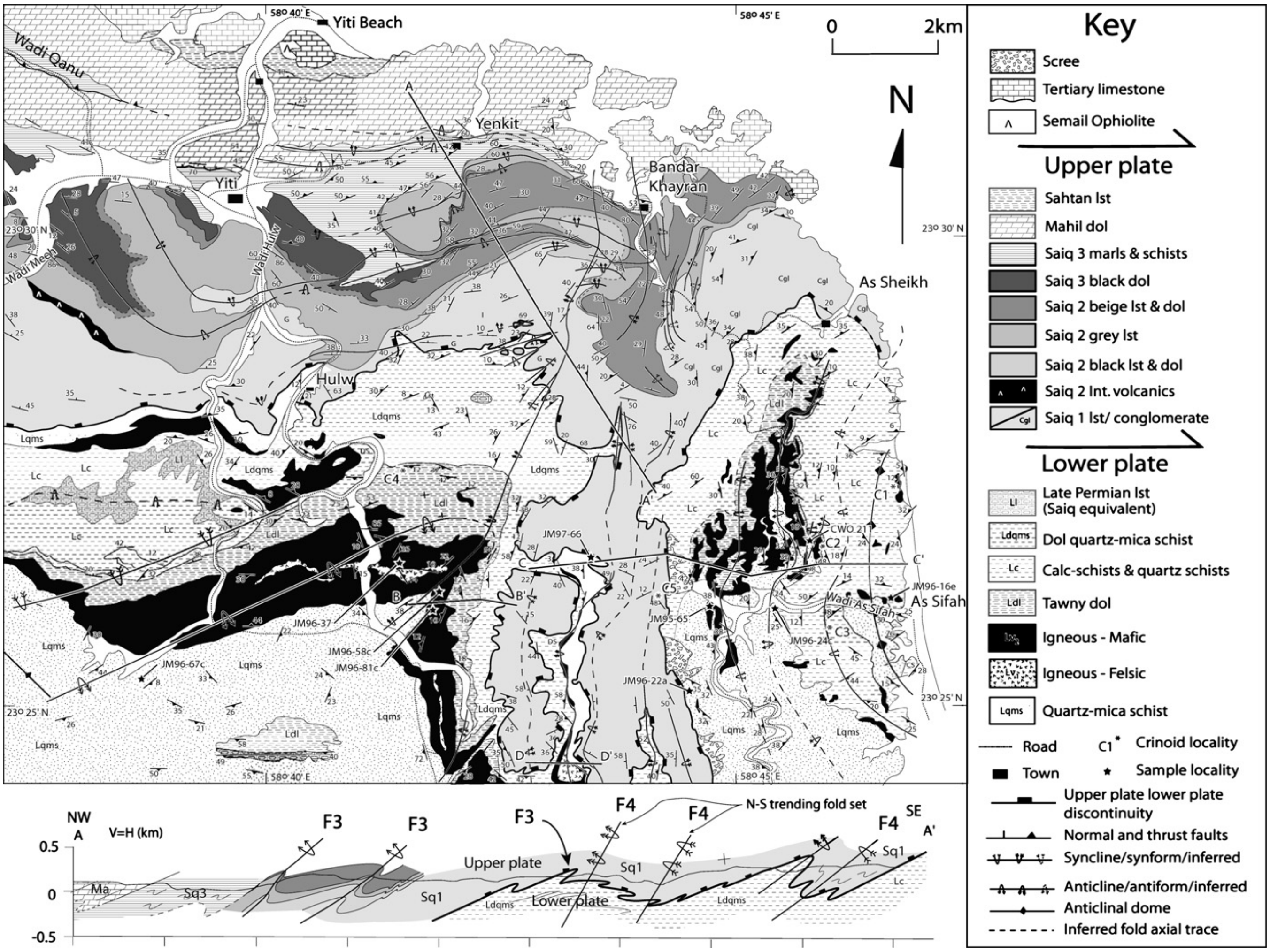


Fig. 7. Geological map of NE Saih Hatat showing the results of new mapping, which changes the stratigraphic and structural relationships around the Bandar Khayran region, based on the mapping of Le Métour et al. (1986), Miller et al. (2002) and Warren (2004). The localities of the crinoid samples are marked as *C1–5. The localities of thin section samples shown in Fig. 9, the locations of section line A–A′ (this figure), section line B–B′ (Fig. 9), section line C–C′ (Fig. 9), and section line D–D′ (Fig. 10) are marked.

assemblages in the As Sifah and Hulw lower plate windows. The key difference between the two lower plate windows lies in their different early metamorphic histories, as their later metamorphic and structural histories converge.

2.4.1. The As Sifah Window

Compared to the Hulw lower plate window, the As Sifah window is not as strongly affected by later fold interference. The map pattern is dominated by a series of regional anticlinal and synclinal F1 closures in the mafic units (Figs. 8 and 9). These structures are associated with the retrograde overprint seen throughout the lower plate, defined in mafic rocks by a retrograde assemblage of epidote, sodic-calcic amphibole, albite, haematite and chlorite (Miller et al., 2002).

The eclogite-facies rocks occur in a series of mafic lenses on the lower limb of a synclinal closure that is refolded by a later broad N-trending anticline (Figs. 7–9). A structural break has been inferred at the location where the eclogite boudins trend into the more coherent garnet-blueschist mafic unit—the ‘‘As Sifah Shear Zone’’ of Searle et al. (2004) and Gray et al. (2004b); Figs. 4b and 8. Mapping cannot delineate a break in stratigraphy at this point, with the mafic layers clearly tracing a synclinal fold that links with the overlying anticlinal structure (Fig. 9). Revised metamorphic PT estimates of the eclogites and garnet-blueschists (Warren and Waters, 2006) suggest that a major structural break is unnecessary here. The eclogite lenses have previously been termed tectonic boudins (Miller et al., 2002; Gray et al., 2004b), although their lens-like nature may also reflect the primary stratigraphic architecture. Discontinuous mafic lenses also occur throughout the Hulw lower plate window.

The earliest structural history of the As Sifah window is only preserved within the eclogite-bearing mafic lenses. Rare evidence for the subduction history is preserved as south-vergent isoclinal sheath-like cm-scale folds, and as inclusion trails within garnet (Gray et al., 2004b). This early fabric is folded by NE-vergent inclined folds (Searle et al., 1994; Miller et al., 1999, 2002; Gray et al., 2004b) associated with high pressure minerals such as crossite and sodic pyroxene in the hinge zones (Searle et al., 1994; Gray et al., 2004b).

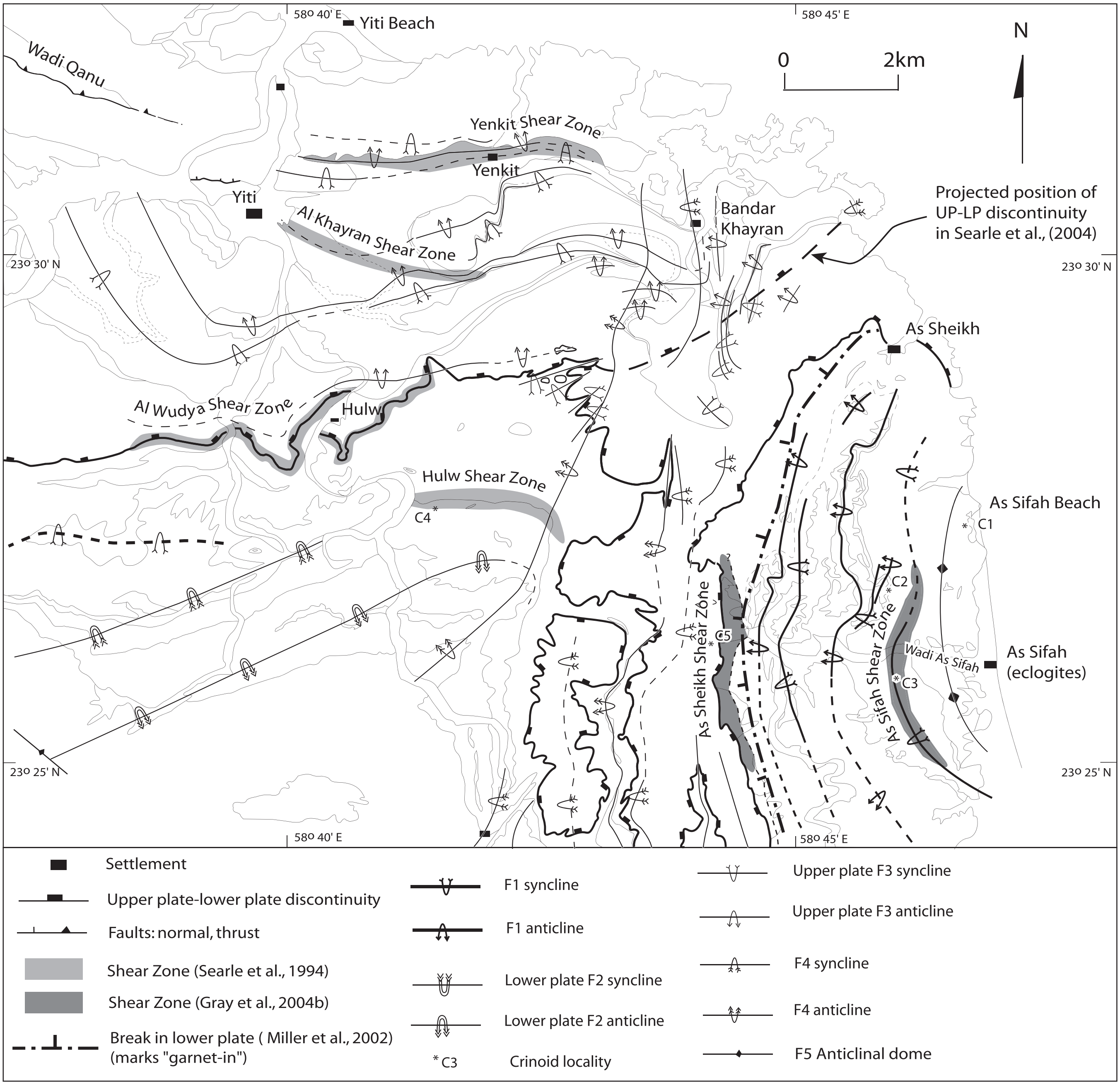


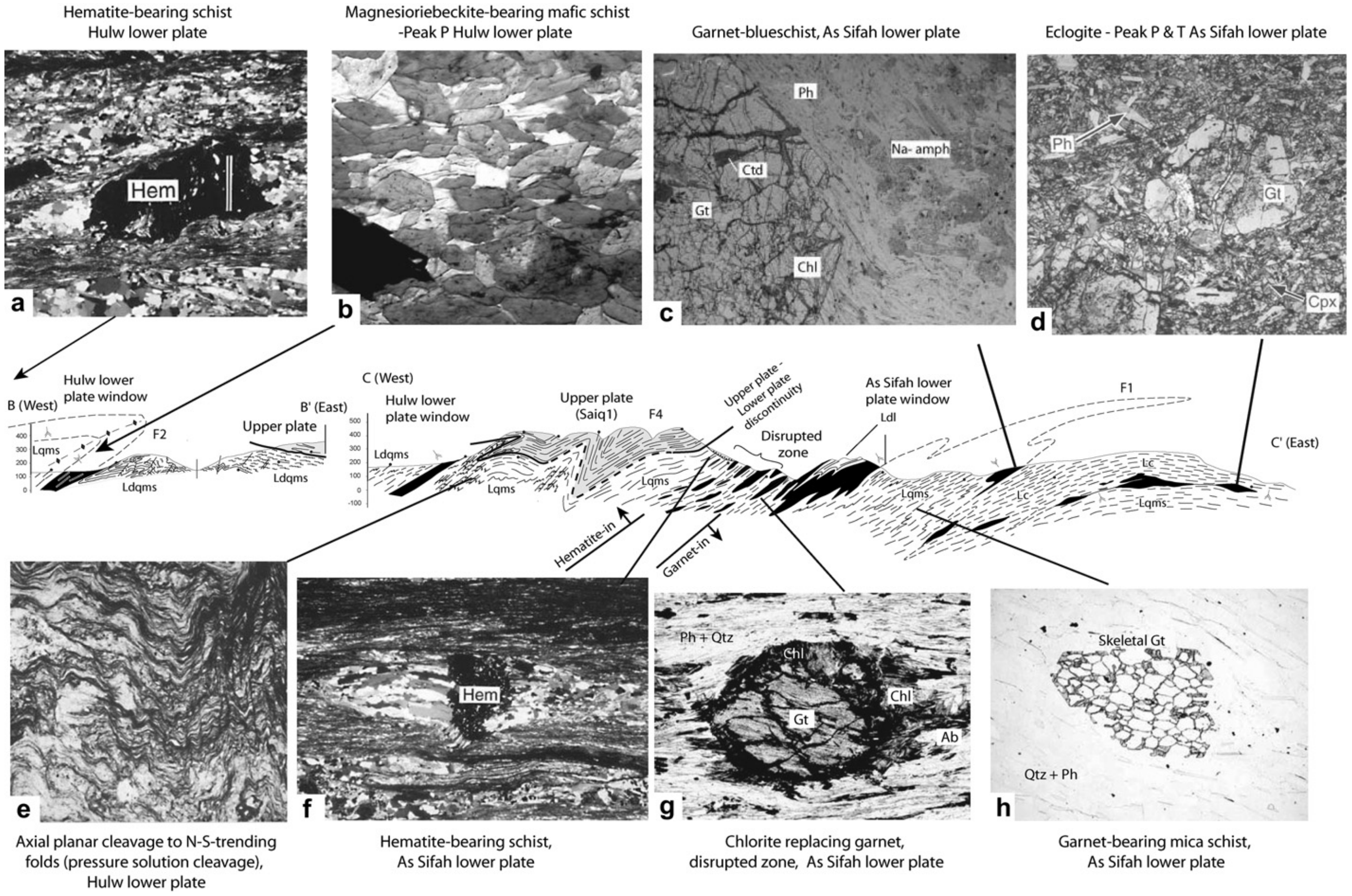
Fig. 8. Structural map of Saih Hatat, based on mapping by Gregory et al. (1998), Miller et al. (2002), Searle et al. (1994, 2004) and Warren (2004). Crinoid localities (*C1–5) are marked.

Greenschist facies minerals outside the boudins define a NNE-trending mineral lineation associated with a shearing event (Miller et al., 2002).

2.4.2. The lower plate break

Existing P–T estimates imply a general increase in peak pressure and temperature from west to east across the lower plate, with a marked jump between the Hulw and As Sifah regions. The Hulw window preserves epidote-blueschist grade metamorphism, with no evidence for garnet growth. Eclogites and garnet-blueschists, however, are preserved in the As Sifah window and the difference in peak pressures has been inferred to be 7–14 kbar (Searle et al., 1994; El-Shazly, 2001).

This jump has been accommodated differently by different researchers (Fig. 4). Searle et al. (1994, 2004) place the As Sifah unit as the lowest structural unit in a stack of fault-bound slices (Fig. 4b). The UP–LP discontinuity, however, truncates structures and the metamorphic gradient across both lower plate regions (Fig. 4a), and therefore the big jump in peak pressure must be accommodated by a break *within the lower plate* between the Hulw and As Sifah regions (Miller et al., 1999, 2002; Gray et al., 2004b).


Hematite-bearing schist Hulw lower plate

Magnesioriebeckite-bearing mafic schist -Peak P Hulw lower plate

Garnet-blueschist, As Sifah lower plate

Eclogite - Peak P & T As Sifah lower plate

Axial planar cleavage to N-S-trending folds (pressure solution cleavage), Hulw lower plate

Hematite-bearing schist, As Sifah lower plate

Chlorite replacing garnet, disrupted zone, As Sifah lower plate

Garnet-bearing mica schist, As Sifah lower plate

Fig. 9. Photomicrographs of key microstructures in lower plate rocks from west to east across a Hulw-As Sifah transect. Sample localities and section lines B–B′, and C–C′ are indicated on the map in Fig. 7. (a) Haematite-bearing schist from the Hulw window. Sample number JM96-67c, crossed polars, base of photomicrograph approx. 6 mm. (b) Magnesioriebeckite-bearing mafic schist from the Hulw window (with iron-oxide and white mica). Sample number JM-96-37, plane polarised light, base of photomicrograph approx. 2 mm. (c) Garnet-blueschist from the As Sifah window. Sample number CWO 211, plane polarised light, base of photomicrograph approx. 0.75 mm. (d) Granoblastic eclogite from the As Sifah window. Sample number JM-96-16e, plane polarised light, base of photomicrograph approx. 3 mm. (e) Axial planar cleavage to N–S trending folds in quartz mica schists beneath the UP–LP discontinuity on the eastern side of the Hulw window. Sample number JM-97-66, plane polarised light, base of photomicrograph approx. 4 mm. (f) Haematite-bearing schist from the top of the "disrupted zone" in the As Sifah lower plate window. Note the similarity to Fig. 10a. Sample number JM-96-22a, crossed polars, base of photomicrograph approx. 10 mm. (g) Chlorite–albite–Fe-oxide replacing garnet at the base of the "disrupted zone". Sample number CWO 125, plane polarised light, base of photomicrograph approx. 5 mm. (h) Garnet-mica schist from the garnet-blueschist zone of the As Sifah window. Sample number CWO 119, plane polarised light, base of photomicrograph approx. 5 mm.

This break is only poorly exposed at the present day, as a 200-m wide "disrupted zone" containing extensively retrogressed rocks in the western region of the As Sifah lower plate window, directly below the outcrop trace of the UP–LP discontinuity (Miller et al., 2002). The change in metamorphic grade is clearly shown by mineralogical differences across the disrupted zone. Firstly, there is a distinct change in amphibole chemistry between the two lower plate windows (Miller et al., 2002): peak sodic amphibole in the Hulw region is magnesio-riebeckite (Fig. 9b), whilst in the As Sifah region it is crossite or glaucophane (Fig. 9c and d). Secondly, there is a change from porphyroblastic haematite-bearing quartz-mica schists in the Hulw region (Fig. 9a and f) to porphyroblastic garnet-bearing quartz-mica schists in the As Sifah region (Fig. 9c,d,g,h). Significantly, the quartz-schists in the western-most exposure of the As Sifah window show the same mineralogy and microstructure as quartz-schists in the Hulw window (Fig. 9a and f).

2.4.3. Hulw window

In the Hulw lower plate window, the earliest regionally traceable fold is associated with the regional lower plate greenschist-facies overprint (Miller et al., 2002) and is therefore an F1 generation fold. The projection of this fold is marked as a dashed line on Figs. 7 and 8; Miller et al. (2002) presented detailed section lines. This and other early folds are refolded by at least three later phases of folding, all of which also affect the upper plate and the UP–LP discontinuity.

The F2 folds within the Hulw lower plate window are a series of N-vergent, E–W-trending asymmetric folds (Figs. 7 and 8). These folds are associated with strong crenulation cleavages and new mica growth.

S-vergent F3 folds affect the northern part of the Hulw window, the UP–LP discontinuity, and the upper plate (Fig. 8). Field mapping has not yet revealed where the change from dominant N-vergence (F2) to S-vergence (F3) occurs within the lower plate. In the upper plate the S-vergent folds are associated with a S-vergent fault which post-dates the F2 upper plate fold nappe.

The F4 fold generation comprises a series of E-vergent, N-trending folds which fold the UP–LP discontinuity and lower plate rocks in the eastern part of the Hulw window and the upper plate between the Hulw and As Sifah windows (Figs. 8 and 10). In the eastern side of the Hulw window these N-trending folds are the dominant feature in the map pattern. They have a strongly developed crenulation cleavage with marked axial planar pressure solution but no new mica growth (Fig. 9e).

The latest set of folds (F5) are a series of NE-trending folds which produce a broad dome in the western sector of the Hulw lower plate window (fold trace marked on Fig. 2). These folds are dealt with in more detail by Miller et al. (2002) and Searle et al. (2004).

In thin section, quartz grains from the Hulw rocks exhibit static recovery processes, with the size of the quartz crystals being controlled by interlayered muscovite (Miller et al., 2002). This is in marked contrast to the quartz deformation microstructures observed in upper plate rocks (Miller et al., 2002), and implies that a temperature gap may exist across the UP–LP discontinuity.

3. The upper plate–lower plate discontinuity

The UP–LP discontinuity (Gregory et al., 1998; Miller et al., 2002) is a high strain zone showing later brittle reactivation. This structure exerts a major control on the structural geometry of the upper plate, truncates the lower plate metamorphic field gradient and also truncates the F1 lower plate regional closures associated with the greenschist facies overprint (Gregory et al., 1998; Miller et al., 1998, 2002). In the western region of the As Sifah window, and throughout the Hulw window, haematite-bearing schists occur in the footwall of this discontinuity (Fig. 9) with no major pressure change across the structure (although quartz microstructures in upper plate and Hulw window lower plate quartzites indicate a temperature jump). Near the village of As Sheikh, north of As Sifah (Figs. 7 and 8), however, garnet blueschists are in the direct footwall, suggesting an 8–10 kbar pressure difference.

Strain markers associated with the UP–LP discontinuity (including pressure shadows on pyrite and sheath folds) are folded by the upper plate fold-nappe (Gray et al., 2005b) and the UP–LP discontinuity is also folded by F2 and later generation folds (Miller et al., 1999, 2002; this study). Fold asymmetry and C′-type shear bands were used to determine a top-to-the-north transport direction (Miller et al., 2002).

4. Geology of the upper plate

4.1. Stratigraphy

The rocks of the upper plate have been age-correlated with formations exposed elsewhere in the Oman mountains (Glennie et al., 1974; Mann and Hanna, 1990). The oldest rocks exposed in the upper plate belong to the Precambrian Hatat Schist Formation, and these are subsequently overlain by the Hijam (dolomite) Formation, the unconformable Ordovician Amdeh (quartzite) Formation and the Permian Saiq (carbonate) Formation (Fig. 5). The UP–LP discontinuity cuts through the unconformable Amdeh-Saiq contact, and the correct stratigraphical interpretation of the units along this contact is therefore crucial for determining the discontinuity's significance in the regional geological and structural history.

Detailed mapping was undertaken in key areas of NE Saih Hatat (Fig. 7) to clarify the field relationships, especially in the complexly deformed and relatively inaccessible Bandar Khayran region. Mapping at a smaller scale allowed stratigraphic relationships between over and underlying units to be more clearly delimited. This has led to a re-interpretation of the local stratigraphy and some of the structural elements. The most significant results are:

- A large tract of rocks mapped as Mahil dolomite by Miller et al. (1998; 2002) south of Bandar Khayran has been

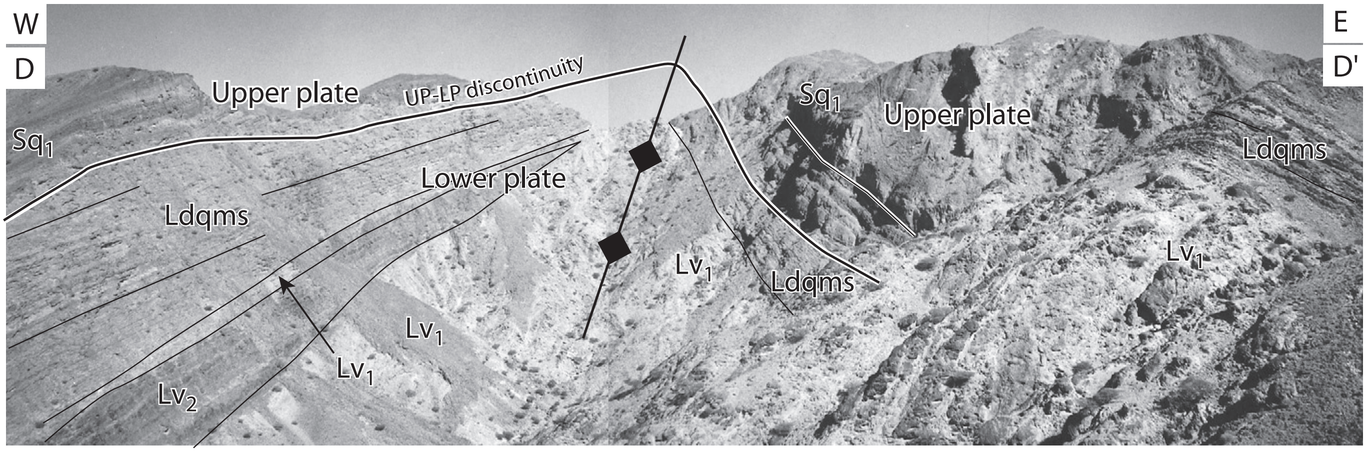


Fig. 10. Photocollage of major N-trending fold (F3) folding the UP–LP discontinuity. Location of section is marked on Fig. 7.

re-interpreted as Saiq 2, as originally mapped by Le Métour et al. (1986) (Compare Figs. 3e and 7). Although similar in appearance, there is a distinct fossil assemblage in the Saiq Formation which is absent from the Mahil Formation. The relationships between over and underlying rock packages confirm the reinterpretation. This is significant as many of the folds previously interpreted to invert stratigraphy, now no longer do so.

- Rocks exposed between Bandar Khayran and As Sheikh (Fig. 7), previously mapped as Saiq 3 by Miller et al. (1998, 2002), have been re-interpreted as Saiq 1 conglomerates (Fig. 7). Again, this revision allows this region to be the right way up rather than upside down with major implications for the interpretation of fold vergence.
- The location of the UP–LP discontinuity presented by Miller et al. (1998, 2002) and Gregory et al. (1998) has been confirmed. There is no evidence for any major structural discontinuity projecting from the Hulw region across to the coast line between Bandar Khayran and As Sheikh as depicted by Searle et al. (2004), Fig. 4b.
- The UP–LP discontinuity around the Hulw window is folded along its northern margin, as well as the southern and eastern margins as previously reported by Miller et al. (2002).
- The UP–LP discontinuity only cuts through the Amdeh–Saiq 1 contact, itself an unconformity. Previous mapping (e.g. Miller et al., 2002) showed the discontinuity cutting through Amdeh to Saiq 3. This revision indicates the fault may have had a much lower dip angle to the stratigraphy than previously thought.
- The axes of the F3 folds around Bandar Khayran are generally preferentially focussed into more thinly bedded units, where localised zones of high strain have been previously mapped (e.g. Searle et al., 1994, 2004). There is no loss or repetition of stratigraphic section across these zones, and the "Yenkit", "Al Wudya" and "Hulw" shear zones of Searle et al. (1994, 2004) are re-interpreted as relatively minor structures forming on the limbs of the F3 folds.

4.2. Metamorphism and geochronology

Unlike the lower plate, peak metamorphic grade in the upper plate is relatively homogeneous, with no large reported changes or breaks in metamorphic grade. Lawsonite-bearing assemblages in the uppermost units of the upper plate (the Ruwi schist underlying the Muscat peridotite) were metamorphosed at 3–6 kbar and 250–300 °C (El-Shazly, 1994). Carpholite-bearing assemblages were estimated at 280–315 °C and 3-6 kbar for the shallower Late Cretaceous Muti Formation near Quyrat in south-eastern Saih Hatat through to 325-440 °C and 6-9.5 kbar for the deeper Permian Saiq Formation and Precambrian Hatat Formation in Wadi Adai, north-western Saih Hatat (El-Shazly, 1995, Fig. 2). Crossite-bearing mafic dykes and sills in the Precambrian Hatat Formation and Permian Saiq Formations were metamorphosed at $P > 6.8$ kbar and $T > 310$ °C (El-Shazly, 1994).

In context, the metamorphic evolution of the lawsonite-bearing rocks in Ruwi may be explained by the presence of a ~20 km thick oceanic crust and upper mantle overburden. The presence of carpholite in the deeper units, however, can only be explained by subduction, as the temperatures are too cold and the pressures too great to be ascribed purely to lithostatic overburden.

Sodic amphibole (crossite) in the mafic rocks of the upper plate has been partially replaced by calcic amphibole (winchite) and chlorite (El-Shazly et al., 1994; Miller et al., 1999). As yet there are no absolute PT estimates for the retrograde overprint in the upper plate.

^{40}Ar/^{39}Ar systematics of mica from strongly foliated carbonates in the upper plate nappes just above the UP–LP discontinuity yields ages of 76–70 Ma (Miller et al., 1999). These have been interpreted as crystallisation ages (Miller et al., 1999), because these ages are close to, and in some cases, younger than, zircon fission track ages for the same region (Saddiqi et al., 1995). The ages are inferred to indicate the timing of fold nappe formation and also motion on the UP–LP discontinuity. Apatite fission track ages on upper plate rocks suggest that they cooled through the 100 °C isotherm between 57 and 40 Ma (Poupeau et al., 1998).

4.3. Structure and microstructure

The upper plate structure is dominated by a major anticlinal fold-nappe which developed via top-to-the-NE transport along the UP–LP discontinuity, and which is associated with a marked strain gradient downwards towards the discontinuity (Gregory et al., 1998; Miller et al., 2002; Gray et al., 2005b). It is also associated with a series of smaller N-vergent (F2 generation) parasitic isoclinal folds, which are best exposed in the upper plate to the south of the Hulw window, where they also fold the UP–LP discontinuity (Fig. 11 and Miller et al., 2002).

North of the Hulw window, the earliest folds are a set of E–W trending, S-vergent F3 folds, which fold the upper plate units, the UP–LP discontinuity and the northern Hulw window. These folds are associated with a prominent N-dipping thrust fault which runs along Wadi Qanu, west of Yiti, and which causes repetition of Saiq 3, Mahil and Sahtan units via south-directed fault transport (Le Métour et al., 1986; Miller et al., 2002; Fig. 7). The south-eastern segment of the structure trends into the strongly developed S-vergent F3 folds, where it is difficult to measure structural offset.

The F4 folds in the upper plate form a strong E-vergent, N-trending set most prominently developed between the two lower plate windows (Fig. 10). In the Bandar Khayran area complicated large-scale fold-interference patterns occur between the F3 and F4 folds (Figs. 7 and 8). Later compression resulted in both N–S and E–W aligned folds (F5) which fold the entire region including the unconformable Tertiary sediments (Miller et al., 2002; Searle et al., 2004; Gray et al., 2005b).

The current contact between the ophiolite and underlying Permian shelf carbonates in northern Saih Hatat (Muscat area) is a late-stage normal fault (Fig. 2). This fault also offsets

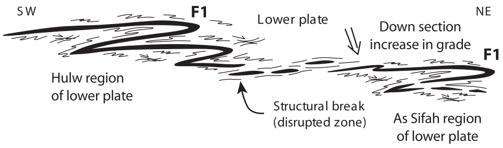
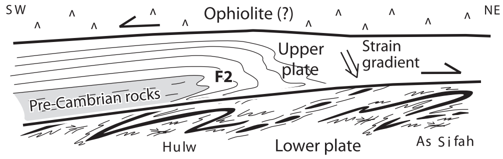
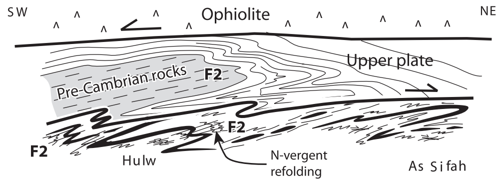
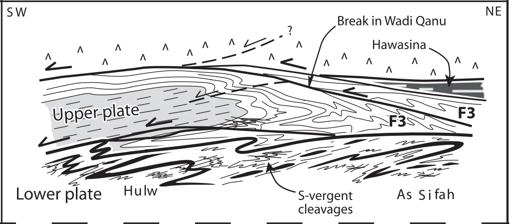
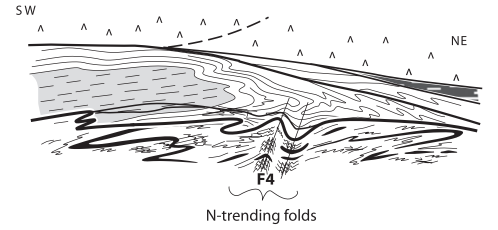
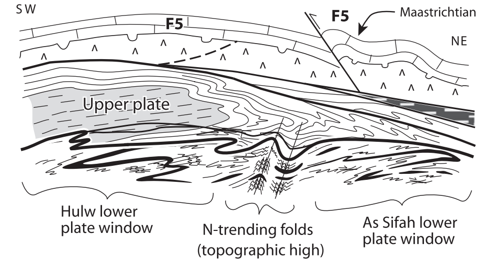
Age	Upper Plate	Lower Plate	Regionally mappable deformation - Saih Hatat
82-79 Ma[1]		Planar fabric formed in eclogite bodies. ENE stretching lineations, top-to-south transport (E lineations in As Sifah boudins) Fabric folded into isclinal folds Boudinage (Na-pyroxene in boudin necks inside mafic eclogite bodies)	Only preserved inside mafic maga boudins within the As Sifah lower plate window (see Gray et al., 2004)
	HP-LT metamorphism of Upper plate rocks and Hawasina units (carpholite association - age not well constrained)	Regional isoclinal sheath folds form during As Sifah - Hulw amalgamation (greenschist facies overprint of both lower plate windows, shearing intiated at High-P). Regional NNE stretching lineations and top-to-NNE transport. **F1 fold generation**	Exhumation of lower plate eclogites to shallower crustal levels - formation of lower plate metamorphic field gradient 
70-76 Ma[2]	Development of UP-LP discontinuity and formation of strain gradient in upper plate prior to fold-nappe development. Deformation linked to fold nappe development inferred to occur beneath obducted ophiolite (Gray et al., 2005b).	Truncation of early isoclinal folds during emplacement beneath upper plate along the UP-LP Discontinuity	
	Regional fold-nappes form during amalgamation of lower and upper plates (**F2 generation folds**), affecting the discontinuity as well. NNE stretching lineations and retrograde overprint.	Refolding of the lower plate folds by tight N-vergent **F2** folds in the southern Hulw lower plate window. The UP-LP Discontinuity is also folded by these fold generations.	
70-66 Ma	S-directed faulting with development of crenulation cleavages adjacent to major faults with major S-vergent folds forming in upper plate rocks in Bandar Khayran area (**F3 generation**). Final juxtaposition of ophiolite, Hawasina and upper plate rocks (possible thinning of ophiolite).		
	East-West compression producing overturned, east-vergent folds with N-trending axes - especially apparent around Bandar Khayran and the eastern Hulw lower plate window (**F4 generation**). These N-trending folds now define a topographic high between the two lower plate windows.		
~68 Ma[3]	Erosion and deposition of Late Maastrichtian units		
<66 Ma	NE-SW compression, faulting and tight to open folding (NE-trending fold axes; **F5 generation**), producing dome and basin fold interference with earlier fold structures. Late normal faulting.		

Fig. 11. Table and figures showing the sequence of deformation in the upper and lower plates. Early deformation in the lower plate has been truncated by the UP–LP discontinuity, which has then itself been folded. Ages: 1: U–Pb zircon and rutile (Warren et al., 2003; Gray et al., 2004a; Warren et al., 2005); 2: ^{40}Ar/^{39}Ar muscovite (Miller et al., 1999); 3: Maastrichtian/early Tertiary sediment depositional age (Nolan et al., 1990).

the unconformably overlying Maastrichtian/Tertiary limestones, placing an upper age constraint on late-stage movement.

Upper plate rocks still retain detrital quartz grains with evidence for quartz pressure solution but no major grain-boundary recovery of deformation-induced sub grains (Miller et al., 2002). The axial-planar fabric of F2 and F3 folds is associated with new mica growth and pressure solution within both carbonates and quartz-rich lithologies. In mafic units this cleavage is associated with a retrograde calcic amphibole-albite-chlorite-sphene overprint, indicating that the folding post-dated the peak high-P metamorphism in the upper plate (Miller et al., 2002).

5. Discussion

5.1. Sequence of deformation

The inferred structural evolution is presented in Fig. 11 with current age estimates in the left hand column. Key elements of this history are:

- Early top-to-the-S shearing, E-trending mineral lineations, isoclinal folding and boudinage (Gray et al., 2004b).
- Regional lower plate F1 folds linked to northeast-directed non-coaxial shear. This shearing initiated while high-pressure metamorphism was still occurring and is part of an extensional shear zone that still preserves a down-section increase in grade. Both the lower plate units (Hulw and As Sifah) attained a similar crustal level during this shearing event, with a major change in metamorphic grade occurring across a structural break within the lower plate (“Disrupted Zone” on Fig. 11).
- Truncation of the lower plate metamorphic field gradient and regional fold closures by the UP–LP discontinuity, which is itself associated with a major strain gradient and F2 upper plate fold-nappes.
- S-vergent faulting, affecting the entire sequence, occurring during the latest stages of movement along the discontinuity, or after motion had ceased. This was coeval with the development of the F3 folds (Fig. 7).
- E–W compression occurred more than once throughout the region’s history: the first time producing the E-vergent F4 folds which only affect the north-eastern corner of Saih Hatat, and the second producing the gentle dome and basin F5 folds.

5.2. Tectonic model

The main issues that have complicated efforts to produce a coherent tectonic model are the polarity of the subduction zone which produced the eclogites, the original location of the lower plate rocks along the passive margin, the true age of the eclogite facies metamorphism and the interpretation of the UP–LP discontinuity (Fig. 12). The tectonic model presented below incorporates the following interpretations:

1. Saih Hatat is subdivided into two major regions with different stratigraphic, metamorphic and deformational histories by means of the major, low-angle décollement, the UP–LP discontinuity (Gregory et al., 1998). This structure is a high-strain shear zone, which juxtaposes different parts of the orogenic wedge late in the deformation history. It truncates structures and the metamorphic field gradient in the lower plate. Whilst there may have been some exhumational motion along the fault, this was minor compared to the exhumation along the lower plate shear zone. The entire lower plate was already exhumed to high crustal levels and had experienced a major greenschist facies overprint before motion along the UP–LP discontinuity.
2. The exhumation of the eclogites is linked to a shear zone within the lower plate which preserves a top-to-the-NNE transport direction and a down-section increase in grade consistent with an extensional shear zone (Miller et al., 2002). There is no preserved information regarding the angle of dip of the shear zone at the time it was active. However, to have exhumed the eclogites and produced the observed relationships this shear zone must have dipped *away* from the current margin.
3. Both upper and lower plates preserve an upward-facing sequence, which can be tentatively correlated: the lowest lower plate unit, Lqms, is equivalent to the upper plate Amdeh Formation and the highest upper plate unit, Ll, is equivalent to the Late Permian Saiq Formation (Fig. 5). The lower plate rocks formed a distal part of the Oman continental margin (e.g. Searle et al., 1994, 2003, 2004; Fig. 13a) rather than a completely outboard fragment (e.g. El-Shazly and Lanphere, 1992; Gray et al., 2005c), or in the middle of the continental margin (El-Shazly et al., 2001). The lateral facies variations and pebble conglomerates in the upper plate carbonates suggest that these rocks were closer to the shelf edge than the Permian rocks preserved elsewhere in the Oman Mountains (e.g. Jebel Akhdar). Subduction therefore did not initiate within the stable part of the carbonate platform.
4. The ophiolite crystallised at ca. 95 Ma, with rapid obduction starting at ca. 94 Ma (Tilton et al., 1981; Hacker, 1994; Hacker et al., 1996; Warren et al., 2005). High pressure eclogite facies metamorphism occurred ca. 15 Myr later, at 82–79 Ma (El-Shazly and Walker, 2003; Warren et al., 2003, 2005; Gray et al., 2004a).

Rifting in the Late Permian and onwards produced the Hawasina ocean basin with outboard Permian-Triassic exotics being deposited on paleo-highs (Fig. 13b). Lateral facies variations in the upper plate Saiq Formation near Bandar Khayran indicate deposition on a rugged submarine topography; this is in marked contrast to the evidence for an open shelf environment preserved in the Saiq Formation elsewhere in the Oman Mountains. The lower plate rocks are inferred to be attached to the rest of the continental margin at this time.

The initial stage of intra-oceanic thrusting associated with the emplacement of the Semail ophiolite occurred between 94-93 Ma (Hacker, 1994; Hacker et al., 1996; Warren

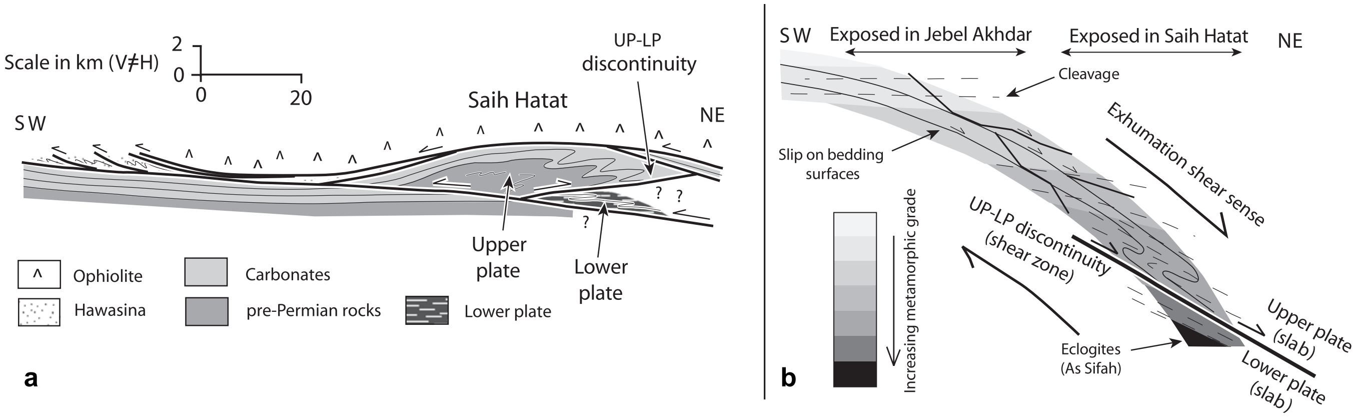


Fig. 12. Diagram highlighting some different possible interpretations for the formation of the UP–LP discontinuity. (a) Discontinuity forming as a backthrust or zone of retrocharriage above a northeast-dipping décollement (Searle et al., 2004; Gray et al., 2005b). (b) Model of Breton et al. (2004) of a northeast-dipping subduction zone with the UP–LP discontinuity, and associated folds, developing as an extensional structure associated with the exhumation of the lower plate rocks (termed the lower slab by these authors).

et al., 2005; Fig. 13c). There is also clear evidence that passive continental margin sedimentation underwent significant disruption not long afterwards (90–88.5 Ma), when the Semail ophiolite and associated thrust sheets started to load the continental margin. This resulted in the cessation of regional deposition on the Arabian margin (Glennie et al., 1974; Robertson, 1987).

The platform carbonates of the (distal) continental margin (upper and lower plates) were continuously subducted and subjected to high-pressure metamorphism (Fig. 13d). Meanwhile, the more outboard Late Permian–Triassic carbonate platforms were scraped up within the Haybi thrust sheet and were not subjected to high-pressure metamorphism. Continued convergence triggered the emplacement of the ophiolite over the platform carbonates (Fig. 13f), and the eventual blocking of the subduction zone.

The lower plate was metamorphosed to garnet-blueschist and eclogite grade between 82 and 79 Ma and was then very rapidly exhumed, via extension, with the rocks cooling below 350 °C within a few million years of peak metamorphism (Fig. 13e). Once the entire lower plate had exhumed to mid-crustal levels, the lower plate was further exhumed as a relatively coherent slab. The exact trigger (blocking of the subduction zone, buoyancy forces, etc.) and the mechanism that exhumed the eclogite-facies rocks are major unresolved scientific questions. The lower plate is mainly composed of very buoyant quartzites and carbonates, with the mafic (eclogites) being volumetrically very insignificant (similar to (U)HP regions of Norway, the Alps and the Himalayas). The initial exhumation of the deeper portion of the lower plate probably occurred due to buoyancy contrasts between the detached continental margin slab and the much denser lower crust and mantle (e.g., Gregory et al., 1998); and may have assisted with the choking of the subduction zone.

Meanwhile, the upper plate was also undergoing high-pressure, low-temperature metamorphism. Peak metamorphism in the upper plate occurred at 80 ± 1 Ma (El-Shazly and Lanphere, 1992), simultaneously with peak metamorphism in the lower plate. This metamorphism also affects syn-tectonic Muti/Hawasina melange sequences (El-Shazly et al., 1990; Michard et al., 1994), indicating that at least the Hawasina thrust sheets, if not also the Semail ophiolite, formed the roof to the subduction/exhumation system at this time.

The final major stage of deformation was the development of the upper plate fold-nappes and the formation of the UP–LP discontinuity (Fig. 13f) between 76 and 70 Ma (Miller et al., 1999). The upper plate transport direction reflects deformation associated with continuing convergence. The fold nappe and associated high strain gradient are inferred to have developed beneath the ophiolite and associated thrust sheets (Gray et al., 2005b). The UP–LP discontinuity juxtaposed rocks from two different locations within the wedge that have different stratigraphy and P–T histories. Breton et al. (2004) argued that the development of the UP–LP discontinuity and associated folds occurred in response to extensional exhumation of the lower plate rocks within a subduction channel (Fig. 11b). The discontinuity may have initiated via such a process, but it cannot have accommodated a major component of the exhumation of the lower plate eclogites because there is no major pressure change across the structure during its development.

The resultant thickening of deeper levels of the orogenic wedge facilitated (and/or drove) rapid higher level erosion of the now overlying ophiolite. This is marked by the ultra-mafic detritus of the Juweiza Formation, deposited in sedimentary basins at the end of the Campanian when the ophiolite was subjected to deep, sub-aerial lateritic weathering (Glennie et al., 1974; Warburton et al., 1990; Miller et al., 1999). This time period also marks the cooling of the eclogite facies rocks through 210 °C at c. 68 ± 2 Ma as indicated by fission track ages on zircon (Saddiqi et al., 1995; Poupeau et al., 1998). By 60 Ma the continuing convergence between Arabia and Asia was being accommodated by the formation of the Makran accretionary prism.

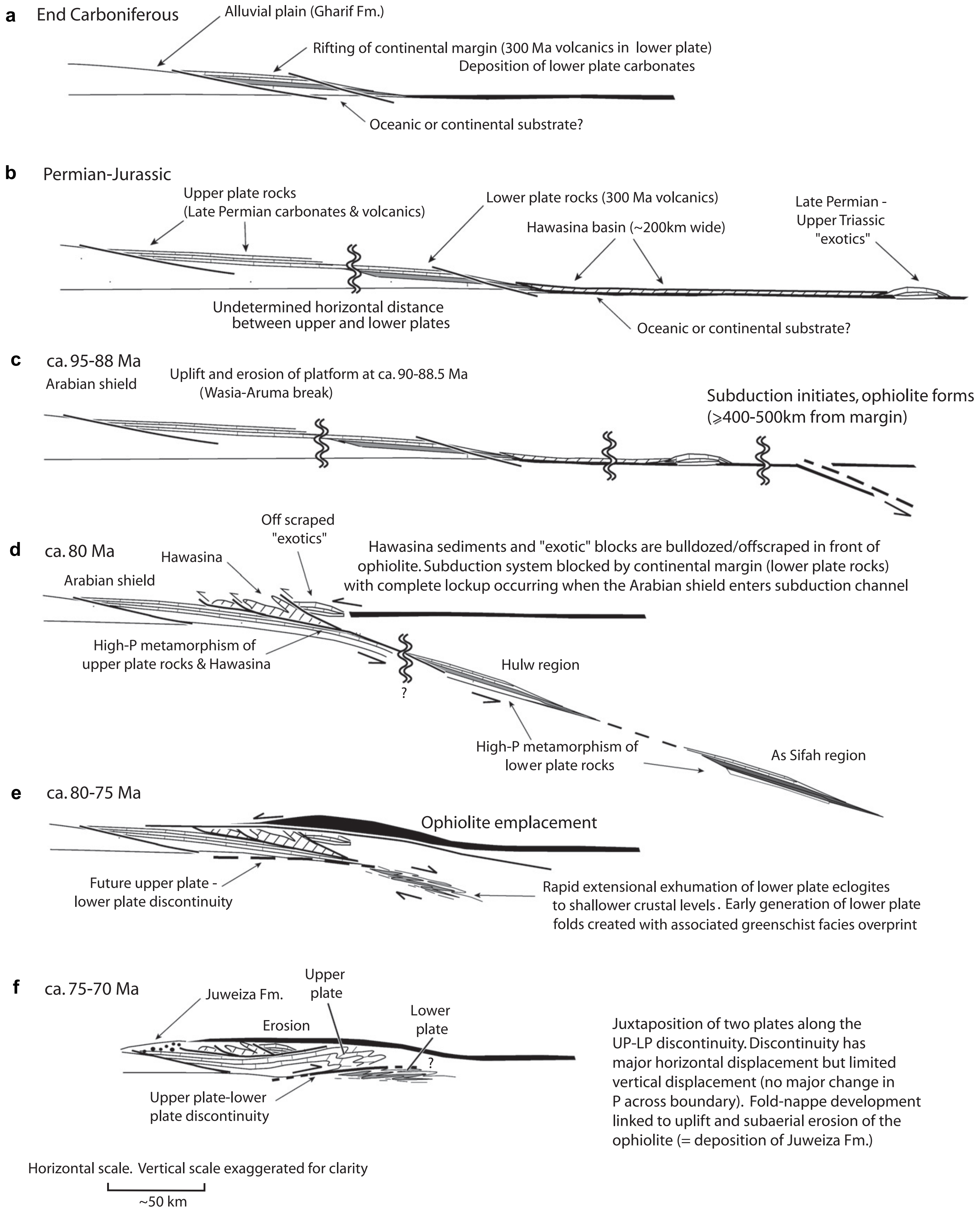


Fig. 13. Tectonic model for the development of the Oman margin.

Acknowledgements

C.J.W. acknowledges support from the Natural Environment Research Council (NERC), UK, for studentship award NER/S/A/2001/06065 and the Killam Foundation for present postdoctoral funding at Dalhousie University, Halifax, Canada. J.M.M. was supported by a Monash University Graduate Scholarship and funding from Australian Research Council Grants ARCSM95 and A39601548 (both to David Gray). Both authors would like to extend thanks to Mike Searle, Randy Parrish, Dave Waters, David Gray and Robert Gregory for PhD supervision and animated tectonic discussions, both in the field and back in the office. Further thanks are extended to M. Kassim, Dr Hilal Al Azri, Jean-Paul Breton, Gavin Graham, Samir Hanna, David and Judy Willis, Tom Jordan and Simon Gough, for logistical support during numerous field seasons. John Platt, John Wheeler and an anonymous reviewer supplied detailed and thorough reviews which substantially improved the original version of the manuscript. Editorial assistance was provided by J. Hippertt.

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