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Structural evolution, metamorphism and restoration of the Arabian continental margin, Saih Hatat region, Oman Mountains

M.P. Searle[a,*], C.J. Warren[a], D.J. Waters[a], R.R. Parrish[b,c]

[a]*Department of Earth Sciences, Oxford University, Parks Road, Oxford OX1 3PR, UK*
[b]*Department of Geology, University of Leicester, Leicester LE1 7RH, UK*
[c]*NERC Isotope Geosciences Laboratory, Keyworth, Nottingham NG12 5GG, UK*

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Abstract

170 m.y. of relatively stable passive margin sedimentation along the northern continental margin of Arabia was abruptly terminated during the Cenomanian–Turonian (~95 Ma) when the Oman continental margin collapsed and subsided rapidly (Aruma basin) to accommodate obduction of the Semail ophiolite complex and underlying thrust sheets (Haybi and Hawasina complexes) in the Oman mountains. The ophiolite was emplaced at least 200 km over the passive margin, probably over 450 km in total, from NE to SW. During the later stages of obduction the leading edge of the continental margin was subducted to depths where carpholite-bearing rocks (6–8 kbar), blueschist (12–15 kbar) and eclogite (ca. 20 kbar) facies metamorphism formed in a ductile deforming NE-dipping subduction zone. Along the northeastern margin of the Saih Hatat culmination in NE Oman the Mesozoic shelf carbonates are deformed by recumbent folding on all scales. The present-day structure is dominated by four SW-vergent thrust slices in carpholite grade rocks at higher structural levels, overlying lower units of crossite-bearing blueschist (Hulw unit), garnet + glaucophane ± chloritoid blueschists and garnet + clinopyroxene + phengite + glaucophane eclogites (15–20 kbar). The largest shear zone separates 7–8 kbar Hulw unit blueschists above from ~12–15 kbar retrogressed eclogites and ca. 20 kbar eclogites of the As Sifah unit below. Further inboard (SW) a major shear zone separates the lower plate Hulw blueschist facies rocks from the upper plate sedimentary rocks (Upper plate–Lower plate discontinuity), which also show carpholite grade HP metamorphism towards the NE.

Restoration of the entire Saih Hatat continental margin shows that the Upper plate–Lower plate discontinuity cuts down-section to the SW as far as the Proterozoic Hatat schists. NE-directed extensional crenulation schistosity and NNE oriented stretching lineations in the eclogite and blueschist facies rocks are consistent with SW-directed exhumation of footwall HP rocks. NE facing folds and spectacular sheath folds with greatly attenuated limbs in the upper plate sediments are interpreted as antithetic backfolds, with shortening in the upper plate balanced by the subduction of the lower plate, consistent with a NE-directed subduction of the continental margin rocks beneath the SW-obducting ophiolite, Haybi and Hawasina thrust sheets. Recent suggestions of a nascent SW-directed subduction beneath the Oman margin are not consistent with the sedimentary evolution of the shelf and slope carbonates or the geological structure of Saih Hatat. Two main phases of tectonic uplift of Saih Hatat and Jebel Akhdar are firstly, the latest Cretaceous ramp culmination associated with foreland propagating thrusts in the SW and backfolds in the NE, and secondly, post-late Eocene–Oligocene uplift by ca. 2000 m.

Keywords: Ophiolite; Obduction; Subduction; Eclogite; Oman; Restored cross-section

1. Introduction

The Oman ophiolite is the largest, best exposed and most studied ophiolite complex in the world (e.g. Glennie et al., 1973, 1974; Coleman and Hopson, 1981; Lippard et al., 1986; Fig. 1). Most structural and tectonic models proposed for the emplacement of the ophiolite and underlying thrust sheets have involved the NE-directed subduction away from the passive continental margin of the Arabian plate (e.g. Searle and Malpas, 1980, 1982; Pearce et al., 1981; Searle, 1985; Lippard et al., 1986; Goffé et al., 1988; Le Métour et al., 1990; Hanna, 1990; Searle et al., 1994). The initial subduction event is recorded by amphibolite facies

* Corresponding author. Tel.: +44-1865-272022; fax: +44-1865-272072.

E-mail addresses: mike.searle@earth.ox.ac.uk (M.P. Searle), clare.warren@earth.ox.ac.uk (C.J. Warren).

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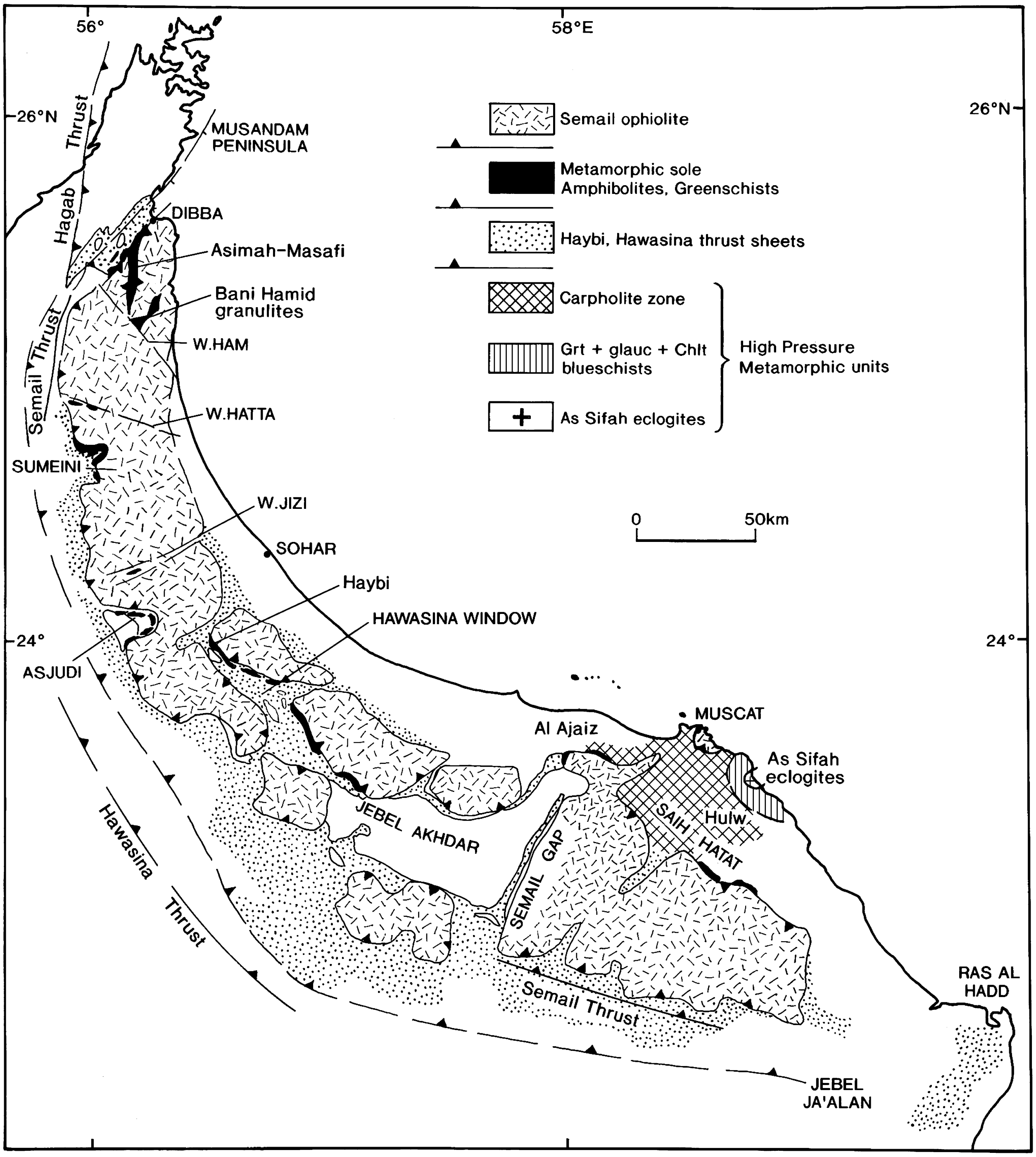


Fig. 1. Geological sketch map of the Oman Mountains showing the distribution of metamorphic sole rocks (black) and the high-pressure terrane in the southeastern part of the Oman mountains, after Glennie et al. (1974) and Searle and Cox (2002).

metamorphism at 13.9–11.8 kbar (54–46 km depth) along the base of the peridotite mantle sequence (Searle and Cox, 1999, 2002). Cooling through ~500 °C is recorded by $^{40}Ar/^{39}Ar$ age of hornblendes spanning 94.9 ± 0.5–92.6 ± 0.6 Ma from the metamorphic sole (Gnos and Peters, 1993; Hacker, 1994; Hacker et al., 1996), very similar timing to the U–Pb zircon ages from plagiogranites in the ophiolite crustal sequence (Tilton et al., 1981). Exhumation of amphibolites from the NE-dipping subduction zone beneath the ophiolite progressed to thin-skinned thrusting with the metamorphic sole and ophiolite emplaced from NE to SW onto the distal trench Haybi complex (Searle, 1985). Thrusting propagated from NE to SW with time, with more distal units thrust over more proximal units, and finally the entire allochthon was emplaced onto the northern margin of the Arabian continent.

In the southeastern part of the Oman mountains, a regional high-pressure belt in the shelf carbonate units and the pre-Permian basement rocks covers most of the northern part of the Saih Hatat culmination (Figs. 2 and 3; e.g. Goffé et al., 1988; El-Shazly et al., 1990; Searle et al., 1994; Miller et al., 1998, 2002). Structural mapping, combined with thermobarometry, suggests the attempted subduction of the leading edge of the thinned continental crust beneath the ophiolite during the later stages of obduction. Garnet + glaucophane + clinopyroxene + phengite + epidote eclogites at the deepest structural levels exposed were formed at pressures around 15–20 kbar suggesting subduction of continental crustal rocks to ~60–80 km depth beneath the ophiolite–oceanic crust and mantle (Searle et al., 1994). Five concordant U–Pb zircon ages from an eclogite sample collected from As Sifah gave an age of 79.1 ± 0.3 Ma (Warren et al., 2003), indicating that peak HP metamorphism occurred some 15 million years after initial ophiolite formation and detachment forming the HT metamorphic sole.

Recent re-mapping of the northern Saih Hatat region of the eastern Oman mountains has resulted in a fundamentally different interpretation of the structures, involving early SW-directed 'nascent' subduction beneath the continental margin of Oman, along which the eclogites formed at 130–95 Ma, before ophiolite formation (Gregory et al., 1998; Miller et al., 1998, 1999; Gray et al., 2000). This model is based largely on early $^{40}Ar/^{39}Ar$ ages from white micas from the lower structural units, and on the widespread presence of NE-directed shear zones and NE-facing folds across the northern Saih Hatat region. El-Shazly and Lanphere (1992) proposed two HP metamorphic events based on older $^{40}Ar/^{39}Ar$ ages, whereas Goffé et al. (1988) and Searle et al. (1994) argued that all the phengite micas from the eclogites and blueschists had uninterpretable spectra which reflected incorporation of excess Ar, and therefore were meaningless. A combination of detailed

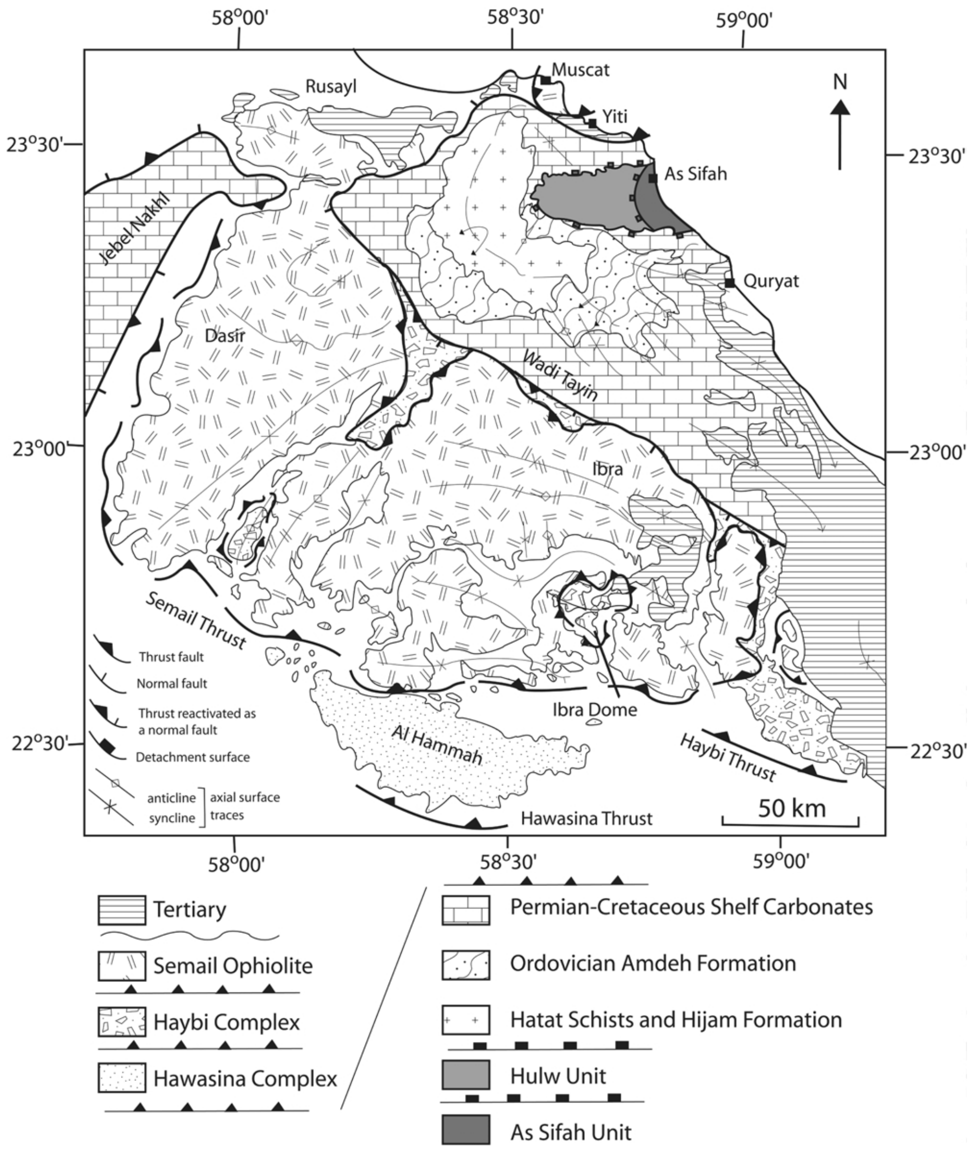


Fig. 2. Geological map of the Muscat–Quriat and Saih Hatat regions in the southeastern section of the Oman mountains, after Bailey (1981), Le Métour et al. (1986) and Miller et al. (2002).

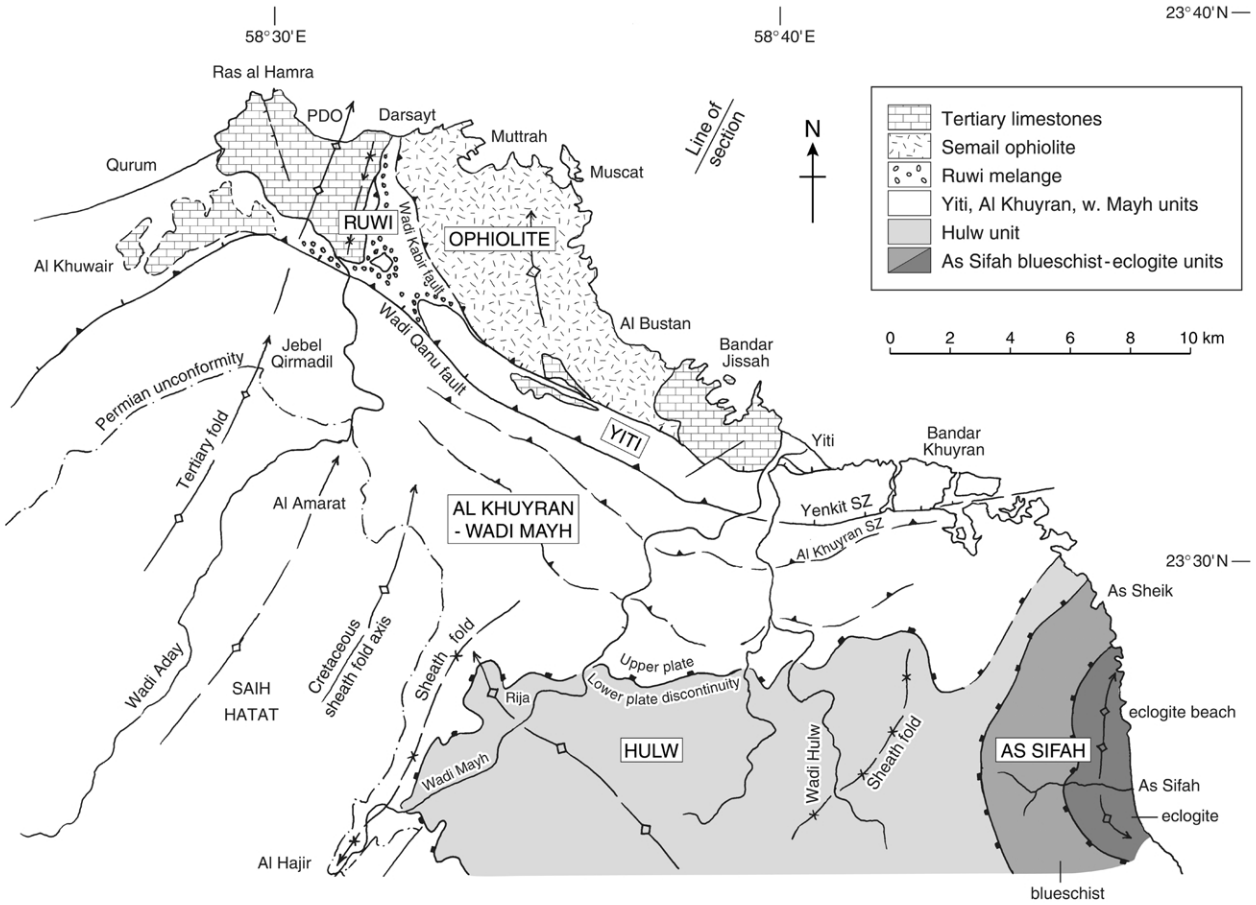


Fig. 3. Geological sketch map of the northern part of Saih Hatat showing the major thrust sheets, shear zones, faults and sheath fold axes, adapted from Searle et al. (1994). Major structural and metamorphic units are named in boxes. The line of section of Fig. 4 is also shown.

$^{40}Ar/^{39}Ar$ and Rb/Sr dating by El-Shazly et al. (2001), using clinopyroxene–phengite and epidote–phengite mineral pairs, of seven eclogite-facies samples showed identical Rb/Sr ages of 78 ± 2 Ma and all samples with phengite had excess Ar. This shows that all $^{40}Ar/^{39}Ar$ ages from the high-pressure Saih Hatat area should be viewed with caution unless corroborated by other geochronological methods.

The model involving an early SW-dipping nascent subduction zone beneath the Arabian continental margin (Gregory et al., 1998; Gray et al., 2000; Gray and Gregory, 2000) relies strongly on the regional scale NE-facing fold nappes in northern Saih Hatat. In this paper we present a composite, semi-balanced cross-section across northern Saih Hatat, based on down-plunge and along strike projection (Fig. 4), together with a restoration of this section at ca. 90 Ma, when the ophiolite and underlying Haybi and Hawasina thrust sheets were being emplaced onto the continental margin (Fig. 5). Stratigraphic abbreviations throughout follow those of the BRGM map sheets (Le Métour et al., 1986). We use structural geometry, crude area balancing techniques and depth constraints from thermobarometry to deduce the pre-deformation positions of each unit relative to the adjacent units. This exercise shows that the major Upper–Lower plate discontinuity of Gregory et al. (1998), Gray et al. (2000) and Miller et al. (2002) cuts down-section to the SW only as far as the top of the Proterozoic, and does not require SW-dipping subduction at all. This Upper plate–Lower plate discontinuity has similar metamorphic grade rocks above and below around the Hulw window, and is in fact just one structural discontinuity, albeit a major one, in at least five such shear zones. Our structural restoration shows that early top to SW-directed shear zones were reactivated as late top to NE-directed normal sense faults placing younger, lower-pressure rocks on top of older higher-pressure rocks.

We show that all the structures are compatible with SW-directed exhumation and NE-directed subduction throughout the late Cretaceous ophiolite emplacement history. All the high-pressure units along the northeast margin of the Oman mountains in Saih Hatat were formed during the late Cretaceous attempted subduction of the thinned leading edge of the continental crust along a NE-dipping subduction zone.

2. Mapping and stratigraphy of the shelf and margin in Saih Hatat

The original mapping of the Oman mountains was carried out by the Shell team of Glennie et al. (1974), who originally defined the stratigraphy of the entire mountain belt, most of which is still valid and used today. A USGS team mapped a strip from Muscat south across the mountain belt (Bailey, 1981; Hopson et al., 1981). They concentrated on the ophiolite, although Bailey (1981) did map some of the large-scale NE-vergent folds in the shelf carbonate units across northern Saih Hatat. The first detailed mapping at 1:100,000 scale was carried out by the BRGM who also recognised the large nappe structures and the high-pressure metamorphism (Le Métour et al., 1986; BRGM map sheets Masqat, Quriat, Fanjah). Several groups carried out mapping in selected areas combined with metamorphic and thermobarometric studies (Michard et al., 1984; Goffé et al., 1988; El-Shazly and Coleman, 1990; El-Shazly et al., 1990; Searle et al., 1994). Fig. 2 shows a simplified geological map of the Saih Hatat region.

The whole northeastern Saih Hatat area was re-mapped by Gregory et al. (1998) and Miller et al. (1998, 2002). Their map is similar to the BRGM map (Le Métour et al., 1986), except that they stressed the importance of a large-scale shear zone, which they termed the Upper plate–Lower plate discontinuity. This shear zone separates two lower plate windows, the Hulw window and As Sifah window, which expose high-pressure rocks, from upper plate rocks with large sheath-type folds and nappes.

Fig. 3 shows a summary structural map of the northern part of Saih Hatat showing the major structural units and the main fold axes. The flat-lying or gently dipping axial traces of the sheath folds have not been mapped here for simplicity, although the two major sheath fold axes in northern Saih Hatat and Wadi Mayh are shown. Many of the higher structural contacts are thrusts related to the obduction event, which have been reactivated during the latest Cretaceous exhumation of the HP rocks as normal faults. The large-scale shear zones bounding the top of the As Sifah eclogites are shown as detachment surfaces which have a multi-stage microstructural history involving early top-to-SW directed shearing followed by later top-to-NE directed relative 'extensional' fabrics related to exhumation of footwall HP rocks.

2.1. Pre-Permian stratigraphy and structure

A major, regional unconformity is exposed all around Saih Hatat separating the late Permian and Mesozoic shelf carbonates above from pre-Permian 'basement' rocks beneath. The oldest stratigraphic unit exposed in Saih Hatat is a succession, at least 2500 m thick, of late Proterozoic to early Cambrian greenschist facies greywackes, shales and cherts termed the Hatat Formation schists, with a thin, but prominent horizon (Ha2v) of transitional alkaline to tholeiitic basalts (Jahlut member; Le Métour et al., 1986). The Hatat schists are overlain by 500 m of grey and yellow dolomite (Hijam Formation) which are in turn overlain disconformably by a massive unit of quartzites (Amdeh Formation), up to 2300 m thick, with minor beds of shaley siltstones containing trilobites of Arenig to Caradocian (Ordovician) age (Lovelock et al., 1981). These Proterozoic to Ordovician sediments have been subjected to pre-Permian greenschist facies metamorphism and cleavage development associated with a regional phase of NE-verging folding. Lithologies, cleavage and fold axes are all truncated at the unconformity below the Late Permian Saiq Formation.

2.2. Permian–Mesozoic stratigraphy

Initial rifting, block faulting and subsidence may have begun as early as the late Carboniferous–early Permian (Blendiger et al., 1990). The main rifting and subsidence took place in the middle Permian following the major Gondwana glaciation, and accompanied by a major eustatic rise in sea level, between 270 and 260 Ma. By the late Permian a vast stable shelf carbonate platform was established along the whole northeast Arabian plate margin extending along the entire Zagros and Oman mountain region (Glennie et al., 1973). This stable carbonate platform lasted for over 160 million years throughout the Triassic (Mahil Formation), Jurassic (Sahtan Group), Early Cretaceous (Kahmah Group) and Aptian–Cenomanian (Wasia Group). Outboard of the shelf carbonates, slope facies (Sumeini Group) and proximal basin facies (Hamrat Duru Group; Hawasina complex) rocks in the lower allochthon are lateral, age-equivalent units.

Two volcanic horizons (Sq1v and Sq2v), comprising mildly alkaline volcanic flows and rhyolitic tuffs, lies within the Middle–Late Permian Saiq Formation (Le Métour et al., 1986). These volcanic flows probably formed the protolith for the meta-basaltic blueschists within the Hulw unit and in Permian limestones of carpholite grade along Wadi Mayh (Fig. 5). Triassic alkali volcanic rocks also occur within the Hamrat Duru proximal Hawasina basin and in the distal parts of Tethys, where alkali basalt oceanic islands (Haybi volcanics; 233–200 Ma; Searle et al., 1980) formed the basement of the isolated late Triassic Oman exotic limestones (Searle and Graham, 1982).

Stable sedimentation along the north Arabian platform ended abruptly at the end of the Cenomanian, 90 Ma ago, when the passive margin was flexed down to form the Aruma foreland basin filled with Fiqa Formation shales (Glennie et al., 1973, 1974; Warburton et al., 1990). Between 88 and 70 Ma (Coniacian–Campanian) the Hawasina, Haybi and Semail ophiolite thrust sheets were emplaced into the basin and on top of the shelf carbonates. A major regional unconformity with rudist-bearing limestones of Upper Maastrichtian age (68–65 Ma) overlies all allochthonous units throughout north Oman. The Oman

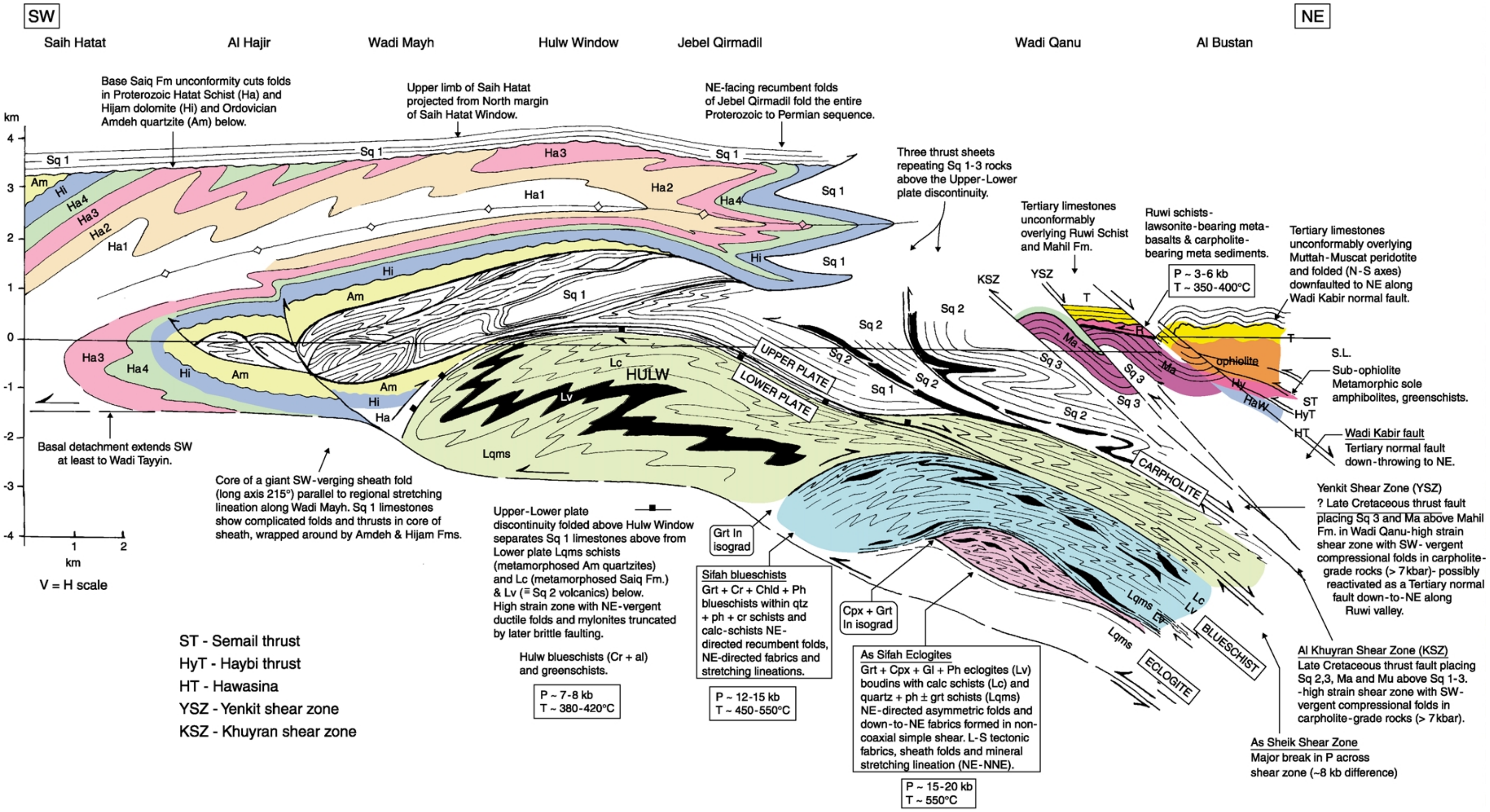


Fig. 4. Composite geological section across northern Saih Hatat; line of section is shown in Fig. 3. Stratigraphic abbreviations used follow those of Le Métour et al. (1986) and Miller et al. (2002).

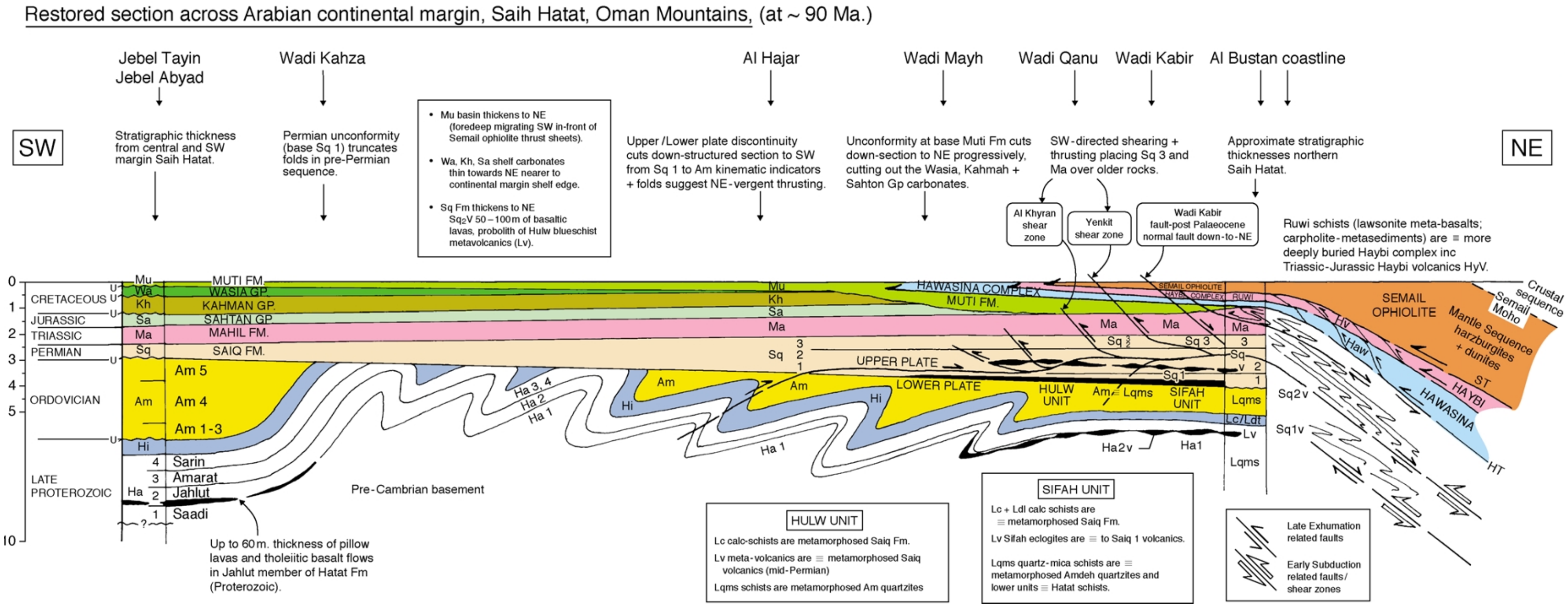
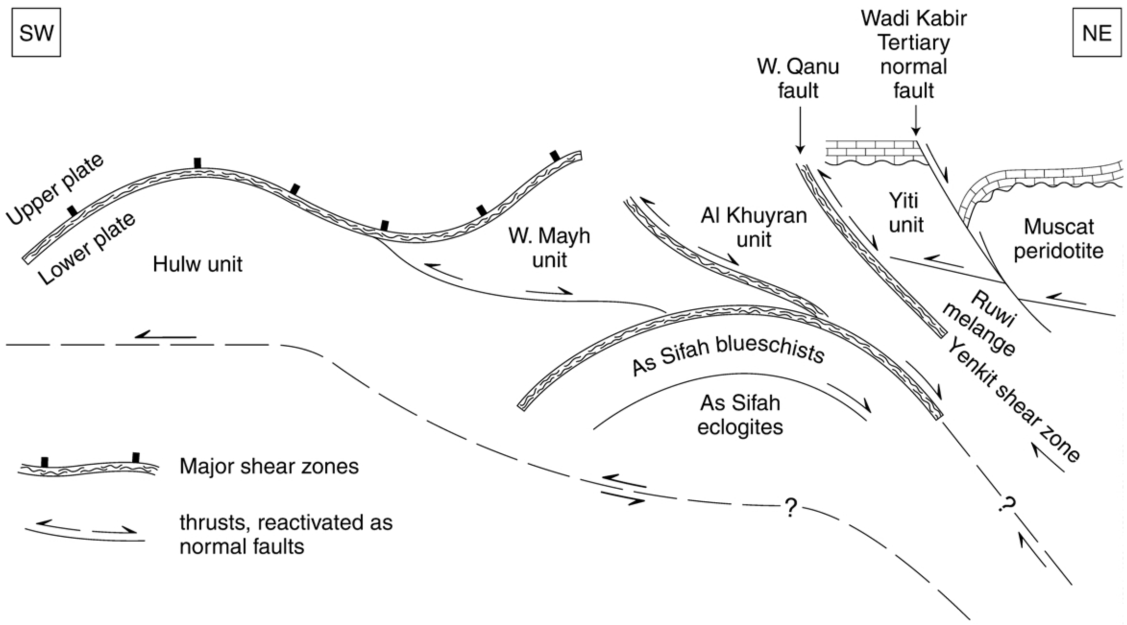


Fig. 5. Restored section (to ca. 90 Ma) of the cross-section in Fig. 4. The restoration is unbalanced due to the extreme ductile nature of the deformation, but shows the restored positions of each major structural unit; see text for discussion. The stratigraphic columns on the left and right are constrained by the logging of Glennie et al. (1974) and Le Métour et al. (1986). Note that much of the shelf slope facies (Sumeini Group) is missing between the shelf and the overlying allochthonous sheets.



	Meta-pelites	Meta-basites	P-T
Muscat peridotite			
Ruwi melange	Fe-Carpholite	Lawsonite	3-6 kb <280-315°C
Yiti unit	Fe-Mg Carpholite + pyrophyllite + sudoite		>7 kb 280-320°C
Al Khuyran unit W. Mayh unit	Carpholite + kaolinite	Crossite + epidote	8-10 kb 320-440°C
Hulw unit	Chloritoid + chlorite	Crossite + epidote	7-8 kb 380-420°C
	Grt in		
As Sifah blueschists	Garnet + chloritoid	garnet + glaucophane	12-15 kb 450-540°C
	Cpx in		
As Sifah eclogites	Garnet + chloritoid + phengite + cpx	garnet + clinopyroxene + glaucophane + phengite + epidote	15-20 kb 540°C

Fig. 6. Sketch showing the tectono-stratigraphy of the northern Saih Hatat region with major structural units and their bounding shear zones and faults. Index minerals in meta-pelites and meta-basites together with the P–T conditions of each unit (after Goffé et al., 1988; El-Shazly, 1994; Searle et al., 1994) are also shown.

mountains were emergent during the Maastrichtian following late Cretaceous thrusting and uplift along the Jebel Akhdar and Saih Hatat culminations. To the SW of the mountains, onlapping transgressive shallow marine clastics (Qahlah Formation) and carbonates (Simsima formation) unconformably overlie allochthonous units. To the NE of the proto-mountains, more rapid subsidence produced debris flows and turbidites of the Al Khawd and Thaqab Formations (Nolan et al., 1990). The entire ophiolite obduction-emplacement process therefore lasted about 27 million years from 95 to 68 Ma, and the whole process was over before the globally catastrophic meteorite impact and Deccan volcanic events at the Cretaceous–Tertiary boundary (65 Ma).

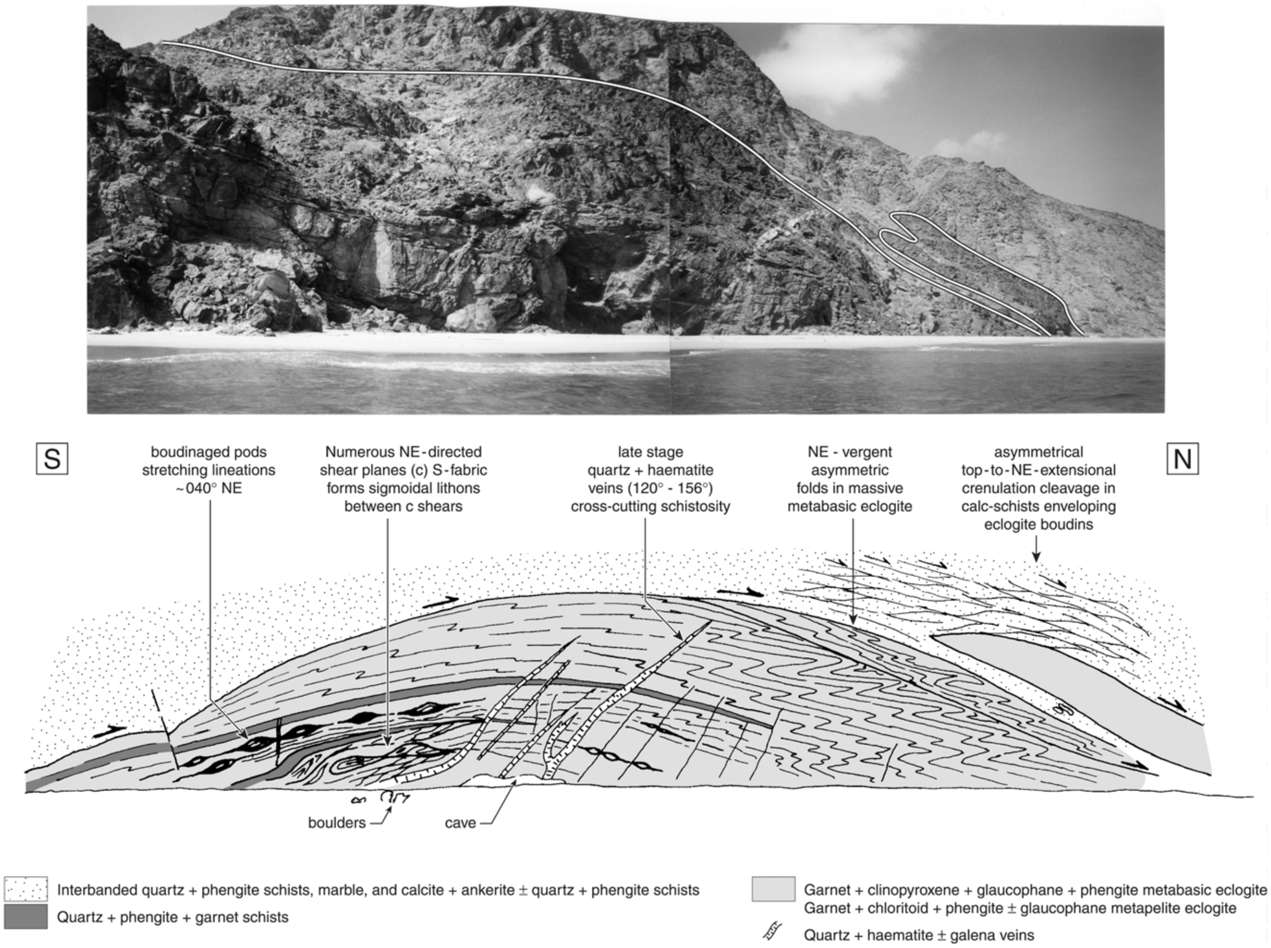


Fig. 7. Photograph and sketch section across the eclogite boudin on the beach north of As Sifah, viewed from the sea, showing the internal structure.

2.3. Tertiary stratigraphy and structure

A regional unconformity above the late Maastrichtian limestones indicates a short period of emergence and possible minor compression at the Cretaceous–Tertiary boundary. Shallow marine, fossiliferous carbonate sedimentation resumed along the NE and SW flanks of the mountains during the late Palaeocene to Middle–late Eocene (Jafnayn and Seeb Formations; ~58–42 Ma). These rocks crop out all around the Jebel Akhdar and Saih Hatat culminations but are not exposed directly over these structures. On the basis of regional stratigraphic relationships, the north Oman mountains, including Saih Hatat remained structurally high throughout the Late Cretaceous and early Tertiary (Mann et al., 1990; Nolan et al., 1990). Palaeocene and Eocene carbonates thin and become a more littoral facies towards Saih Hatat, indicting that it was a structurally high culmination by that time. However, to the SE of Saih Hatat the large Jebel Abiad massif shows late Palaeocene to middle Eocene limestones (Glennie et al., 1974; see also BRGM Sur map sheet, 1992). This jebel shows one very large-scale anticlinal fold, at least 25 km wavelength, and cascade type box folding along each flank. The style of folding, and uncommon high angle reverse faults, indicate only very minor amounts of shortening. Middle Eocene limestones were uplifted to 2200 m some time after the late Eocene–early Oligocene (<33 Ma) during a contractional phase which must also have elevated the Jebel Akhdar and Saih Hatat ranges by similar amounts. Mann et al. (1990) proposed that significant sub-aerial erosion of the Oman mountains did not start until Miocene times.

Late Palaeocene to early Eocene limestones around Ras al Hamra, and from Bandar Jissah to Bandar Khuyran (Fig. 3), show gentle folding around N–S aligned fold axes. These axes are aligned parallel to the major sheath fold axis in the shelf carbonates and pre-Permian basement rocks at Jebel Qirmadil. The fold structures along the north coast region show a complex interference pattern between late Cretaceous, flat-lying, NE-facing recumbent and isoclinal folds and N–S aligned axes along the sheath fold direction. The Tertiary folding around Ras al Hamra and Bandar Jissah appears to be parallel to the late stage sheath folds.

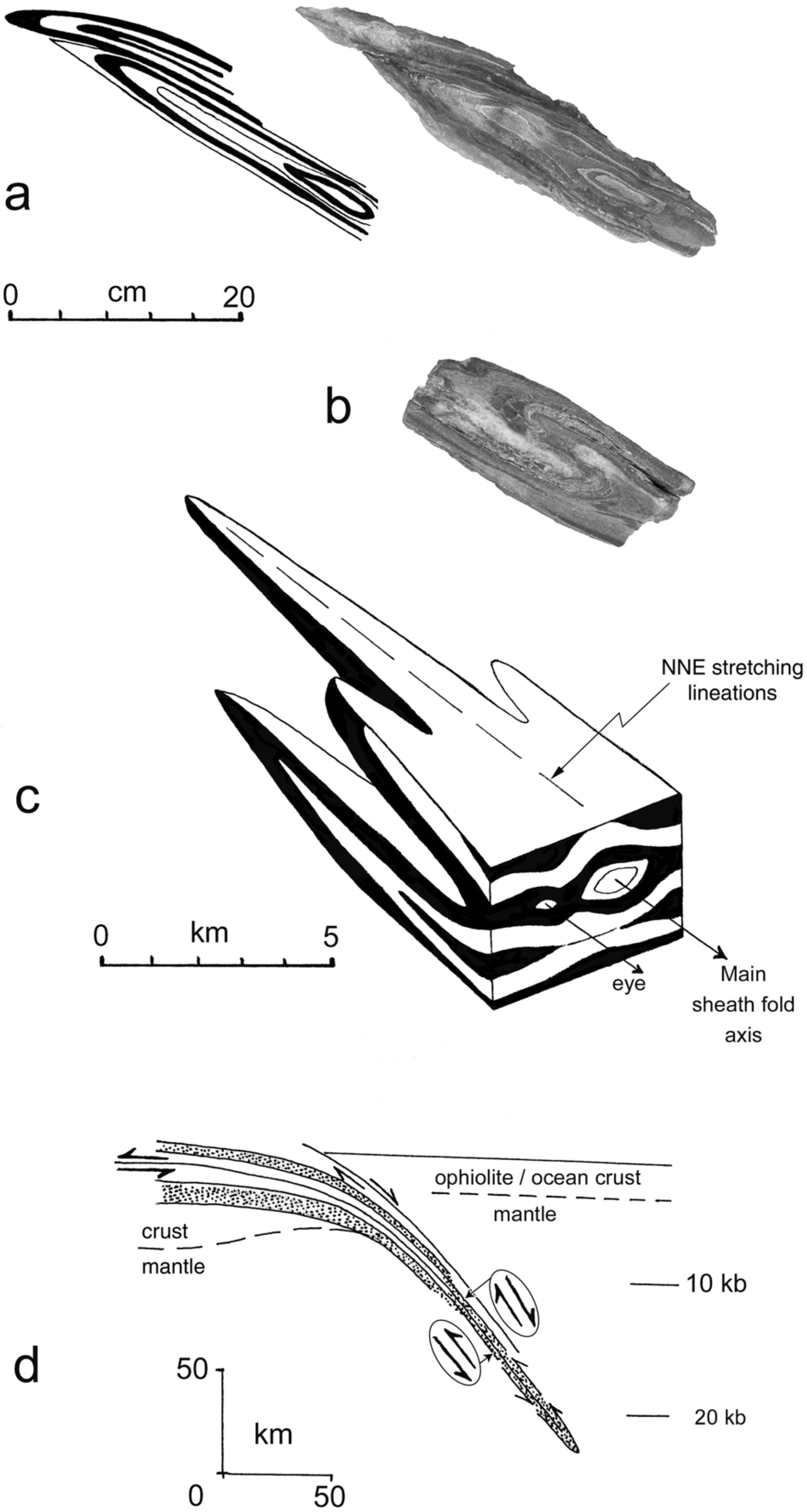


Fig. 8. (a) and (b). Photograph and sketch of isoclinal folds in the As Sifah eclogites showing the style of deformation, together with (c), an interpretation of the larger scale sheath fold structure.

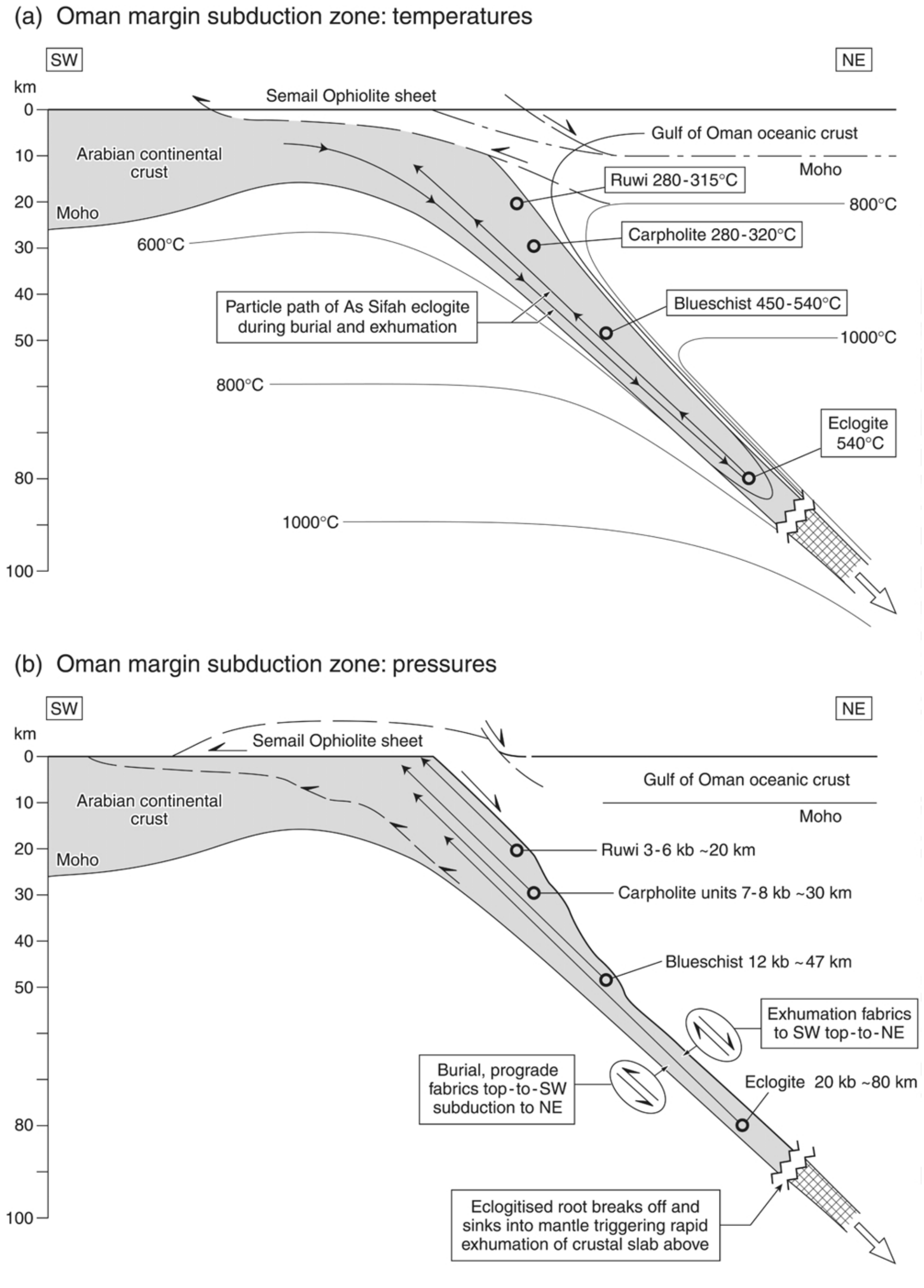


Fig. 9. Model for the Oman margin continental subduction zone (shaded area) showing (a) temperatures and (b) depths of each unit as derived from peak pressures. Also shown are the particle paths of As Sifah eclogite rocks and the micro-fabrics formed during NE-directed subduction and prograde burial, and later SW-directed exhumation of footwall HP rocks (with top-to-NE 'extensional' fabrics) during subsequent exhumation. The trigger for exhumation was likely to be break-off of the eclogitised root that originally dragged this narrow, cold continental crustal slab deep into the hot mantle.

3. Northern Saih Hatat integrated cross-section

3.1. Metamorphism and major structural units

Fig. 6 shows a sketch summary of the major structural units and shear zones across northern Saih Hatat together with the index minerals present in each unit and estimates of the pressure–temperature conditions of formation. The major shear zones are all thought to be late Cretaceous structures except for the structurally highest fault, the Wadi Kabir normal fault which offsets and downthrows late Palaeocene–early Eocene fossiliferous limestones. P–T conditions quoted are mainly from the work of Goffé et al. (1988) for the carpholite bearing units and Searle et al. (1994) for the eclogites. More detailed descriptions of the structures, together with the metamorphic constraints in each unit are given in the following sections.

Our composite section across northern Saih Hatat (Fig. 4) utilizes integrated field structural data from all across Saih Hatat, and the geology has been projected onto the line of section along strike. We have used down-plunge and along strike projections to construct the section, and standard area and line balancing techniques to restore it to its pre-deformation state (Fig. 5). Obviously the high degree of strain, the non-concentric nature of the folding and the extremely highly deformed shear zones across the entire region make any accurate restoration impossible. However, the exercise is still a useful one in that it can delineate the relative positions of each thrust sheet and the depths (using pressures derived from thermobarometry). We have used the measured stratigraphic thicknesses of Le Métour et al. (1986) in the western part of Saih Hatat and along Jebel Abu Dhaud in northeastern Saih Hatat to constrain our depth profiles. Deformation was certainly not plane strain within this section. Displacements, both contractional and extensional, occurred in and out of the line of section. The section is internally consistent with the known surface structural data; unfortunately, as yet, there is no geophysical data to constrain the sub-surface. The main aim of constructing the section was to show how each structural unit fits in with neighbouring units, and then to use the geometry to attempt a restoration of the whole continental margin prior to late Cretaceous ophiolite emplacement events. The cross-section (Fig. 4) should be examined together with the restored section (Fig. 5) in order to ease interpretation of the complex structures.

Our structures differ from those in Gregory et al. (1998) and Miller et al. (1998, 2002) in three ways. Firstly, they mapped one major detachment, the Upper plate–Lower plate discontinuity, which overlies both the Hulw and As Sifah windows. The Hulw unit consists of chloritoid-bearing meta-pelites and crossite- and epidote-bearing meta-basalts, and is considerably lower pressure than the eclogite facies As Sifah unit. No garnet or clinopyroxene occurs within the Hulw window, in contrast to the As Sifah unit, which has garnet + chloritoid + glaucophane + phengite in meta-pelites and garnet + clinopyroxene + glaucophane + phengite in meta-basic units. Rocks below and above the Upper–Lower plate discontinuity show similar P–T conditions (7–10 kbar) so although it is a major ductile shear zone truncated by a late brittle fault, it cannot have much vertical throw along it. The major shear zone which overlies the As Sifah unit is structurally lower, and is a very large scale detachment with a 6–10 kbar pressure jump across it (Searle et al., 1994). Secondly, we do not support their extrapolation of the Upper plate–Lower plate discontinuity shear zone down to the mantle. From surface geology it can only be traced down to the top of the Proterozoic (Figs. 4 and 5), and this does not support SW-dipping subduction beneath the Oman passive margin. Thirdly, they did not recognise several of the higher shear zones, notably the Al Khuyran and Yenkit shear zones.

3.2. As Sifah eclogites

The As Sifah dome is the deepest exposed part of the Oman mountains and plunges north towards Muscat and south towards Quriat (Figs. 2 and 3). Fig. 7 shows a photo and sketch section across the eclogite dome as viewed from the sea. Garnet + clinopyroxene + glaucophane + phengite eclogites, which were formed at pressures of around 20 kbar form the core of the dome. They are surrounded above by highly deformed calc-schists interpreted as metamorphosed Saiq Formation, and below by equally highly deformed quartz mica schists, interpreted as metamorphosed Amdeh Formation (Am on Fig. 5; mapped as Lqms on the map of Miller et al. (2002)). The meta-basic eclogites on the beach north of As Sifah are most likely to be metamorphosed Saiq 1 volcanics (Sq1v on Fig. 5). Meta-pelitic eclogites garnet, glaucophane, phengite and clinopyroxene, and a few bands of psammitic quartz + phengite + garnet schists are interlayered within the meta-basic eclogites. Clockwise P–T paths were determined from the As Sifah eclogites from inclusions of lawsonite, retrograded to epidote + paragonite, enclosed in garnet, and from the garnet–clinopyroxene–phengite barometer (Waters and Martin, 1993; Searle et al., 1994). Maximum P–T conditions reported are 540 ± 75 °C and ~20 kbar (Searle et al., 1994).

Subduction-exhumation related simple shear has resulted in intense isoclinal and tight folding and a strong extensional crenulation schistosity (Platt and Vissers, 1980) showing top-to-NNE sense of shear, together with coaxial flattening fabrics resulting in NNE–SSW boudinage of the mafic pods (Fig. 7). The same fabrics are seen in the surrounding calc-schists (calcite + ankerite ± quartz ± phengite). Stretching lineations are aligned NE–SW consistent with exhumation of footwall HP rocks along the NE-dipping subduction zone. Fig. 8a and b shows the style of the tight to isoclinal folds in the As Sifah eclogites and Fig. 8c is a 3D sketch of the large-scale sheath folds in the upper plate rocks along Wadi Mayh.

Fig. 9a shows the restored geometry of the Oman subduction zone with the temperatures and particle paths of eclogite rocks during burial and exhumation, together with the characteristic fabric geometry, and Fig. 9b shows the depths of each structural unit as derived from peak pressures. The temperatures show that this narrow subduction channel was extremely low-temperature compared with the surrounding mantle rocks. This is in effect a narrow channel, where crustal material must have flowed in a ductile fashion down to ~80 km depth within the mantle, where HP metamorphism occurs at ~20 kbar and then, due to buoyancy forces was expelled back up the same narrow zone. We surmise that the trigger for exhumation was the sudden break-off of the eclogitised root, which originally anchored the slab and pulled it down the subduction zone. Top-to-NE 'extensional' fabrics in the eclogites reflect exhumation of the deeper footwall rocks in a wholly

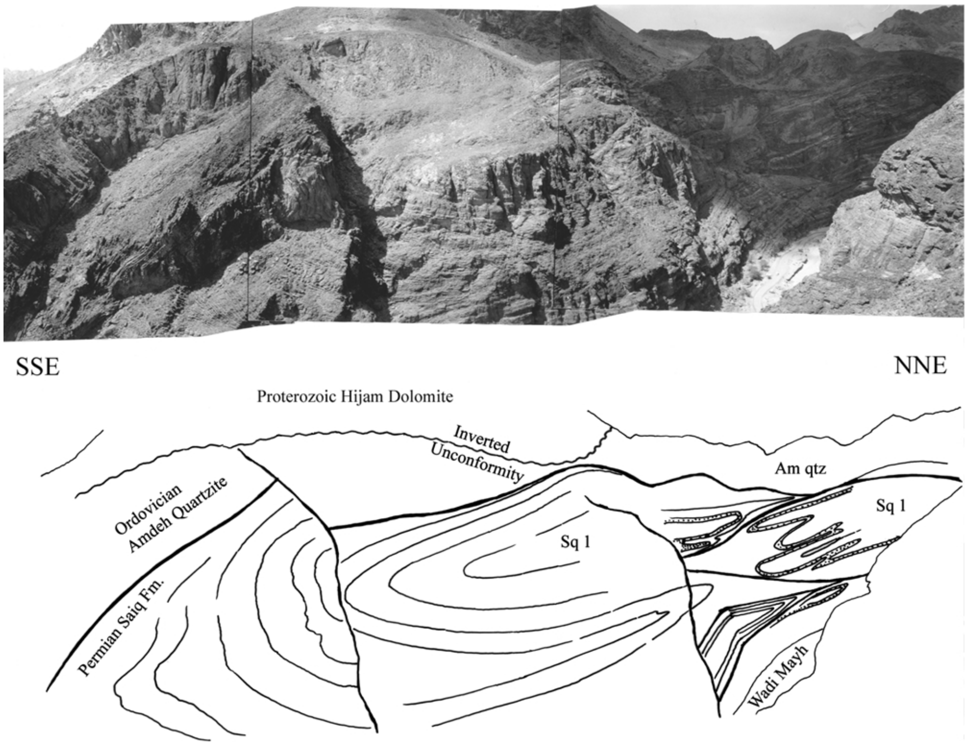


Fig. 10. Photograph and sketch section across the Wadi Mayh sheath fold showing the complex internal folding in Saiq 1 Formation shelf carbonates.

compressive tectonic setting. The hanging-wall remains static whilst the footwall rocks move up, creating down-to-N 'extensional' microstructures.

3.3. Hulw unit

The Hulw unit forms another domal culmination, but at higher structural levels than the As Sifah dome. Gregory et al. (1998) and Miller et al. (1998, 2002) placed both units in the footwall to their Upper plate–Lower plate discontinuity. In contrast, we have mapped a large-scale shear zone separating the two (Figs. 3 and 4). The large difference in P–T conditions supports our contention that the two windows are not in the same structural unit. Whereas the As Sifah unit was metamorphosed at pressures around 20 kbar, the Hulw unit shows only transitional greenschist–blueschist rocks, metamorphosed at pressures of ~6–8 kbar. The upper margin of the Hulw unit is the large-scale shear zone termed the Upper plate–Lower plate discontinuity by Miller et al. (1998, 2002).

Folds within the Hulw unit are very complex. Strong non-coaxial shearing has resulted in dominantly NE-facing folds, compatible with SW-directed, thrust-related extrusion of footwall HP rocks (Fig. 4). Two large-scale syncline and anticline fold closures mapped in the southwestern part of the window have numerous parasitic folds which are all NE-facing, and have axes that either merge into the Upper plate–Lower plate discontinuity, or are cut by later brittle faulting along it. Shear fabrics show top-to-NE sense of shear. Miller et al. (2002) describe refolding of these rocks by a later set of upright, north-trending folds. The Hulw unit is dominated by recumbent folds, refolded by NNE aligned sheath folds with ubiquitous NNE–SSW-trending stretching lineations, and late doming.

Miller et al. (1998, 2002) also mapped a sliver of 'upper plate' rocks between the Hulw and As Sifah windows. These rocks are Saiq 1 Formation dolomites with well-preserved Permian reef corals (Le Métour et al., 1986). These rocks contain carpholite and must have formed at pressures of ~7 kbar (Goffé et al., 1988) and were therefore at an equivalent structural depth to the Hulw unit. All structural units above the As Sifah unit were metamorphosed at similar pressures. The shear zone above the As Sifah dome (Fig. 4) corresponds to the major structural and metamorphic break in the region.

Restoration of the section (Fig. 5) suggests that the crossite-bearing meta-basaltic units along Wadi Mayh are metamorphosed Saiq Formation volcanics, as are the massive meta-volcanic units with the Hulw unit. The overlying calc schists in Hulw (mapped as Lc or Ldl by Miller et al. (2002)) are metamorphosed Saiq Formation dolomite and the underlying quartz mica schists (mapped as Lqms by Miller et al. (2002)) are metamorphosed Amdeh Formation quartzites. The detachment between the Hulw and As Sifah units is a major structural break with a pressure difference across it of up to 8 kbar (about 28–30 km thickness assuming a density gradient of 3.5–3.7 km $kbar^{-1}$ for continental crustal rocks).

3.4. Upper plate–Lower plate discontinuity

Gregory et al. (1998) and Miller et al. (1998, 2002) mapped a major, regional, low-angle structural break, which they termed the Upper plate–Lower plate discontinuity, separating rocks of different stratigraphy, metamorphic grade, structural style and strain. This structure is a ductile shear zone truncated by a later brittle fault which wraps around the Hulw window, separating highly deformed Permian shelf carbonates, some containing the high-P mineral carpholite, above from greenschist–blueschist facies rocks below. Parts of this shear zone have been mapped previously by Le Métour et al. (1986), Searle et al. (1994) and Michard et al. (1984). Gregory et al. (1998) and Miller et al. (1998, 2002) mapped the same contact above both the Hulw window and the As Sifah window, whereas Searle et al. (1994) separated the two, based on structural mapping and differences in P–T conditions. Peak metamorphism in the Hulw window rocks was around 400 °C and 7–8 kbar (Goffé et al., 1988), whereas the As Sifah eclogites were metamorphosed at ~540 °C and 20 kbar (Searle et al., 1994). On metamorphic criteria alone these two units must have been separated by a large post-metamorphic detachment.

In contrast to the mapping of Miller et al. (2002), we therefore distinguish these two shear zones on our map (Fig. 3) and cross-section (Fig. 4). Restoration of the Upper plate–Lower plate discontinuity around the Hulw window (Fig. 5) suggests that the highest structural levels reached were in the Saiq 2 Formation limestones, and the deepest levels were into the Proterozoic Hatat 1 Formation schists. Spectacular mylonites are present along the Upper plate–Lower plate discontinuity, which shows transposition foliation with high strain. *X/Z* strain ratios up to 170:1 have been documented by Miller et al. (1998, 2002) using pressure shadows around pyrite crystals. Brittle faults have truncated these ductile mylonites and the detachment has been later folded around the Hulw dome. Small gossans indicate the lead–zinc hydrothermal ore deposition along the fault. There is no evidence from surface geology that this shear zone penetrated down into the lower crust, let alone into the mantle, as suggested by Gregory et al. (1998) and Gray et al. (2000).

In summary, the Upper plate–Lower plate discontinuity is a major ductile shear zone but, in contrast to the interpretation of Gregory et al. (1998) and Miller et al. (1998, 2002), it has similar metamorphic grade above and below, and planes out horizontally in the Saiq 1 and 2 formations around the Hulw window, then descends to the Hatat schists to the SW (Fig. 5). NNE-aligned sheath folds and stretching lineations are present both above (Fig. 10) and below. In a few places, early south-vergent asymmetric folds with C′ shear bands have been overprinted by NNE-vergent folds, crenulation cleavage and brittle faults, consistent with the evolution through time of subduction-related fabrics on the descending, prograde particle path followed by relative extension during the ascending exhumation path (e.g. Fig. 9a). The temperature at this detachment was probably initially around 300–400 °C, which equates approximately to the major mechanical discontinuity between the brittle upper crust and the ductile lower crust. Regional scale north-trending sheath folds, elongated in the direction of transport, such as those seen in the upper structural units along Wadi Mayh for example, have deformed earlier fabrics. Late stage doming affects all units and is probably related to final SW-directed ramp anticline culmination of the Saih Hatat dome as depicted on Fig. 4.

3.5. Upper plate sheath folds

Spectacular NNE-aligned sheath folds are present in the upper plate rocks along Wadi Mayh (Fig. 4), also called Wadi Meeh by Miller et al. (2002). Sheath folds with a similar orientation are also present throughout the structural pile from deepest level eclogites (Fig. 8) through the Hulw unit (Fig. 4) to the upper plate unmetamorphosed sediments (Fig. 10). Glennie et al. (1974), Bailey (1981), Le Métour et al. (1986) and Searle et al. (1994) noted the increase in deformation of the shelf carbonates towards the NE along northern Saih Hatat and noted that several sections showed inversion of the stratigraphy. Gregory et al. (1998) and Miller et al. (2002) mapped out these structures and determined the detailed geometry of these spectacular NE-facing folds. The Wadi Mayh sheath fold, approximately 18 km long, affects the entire Proterozoic to Permian sequence, with the upper limb wrapping around the shelf carbonates at Jebel Qirmadil (Fig. 3).

Fig. 10 shows a photograph and sketch of the complex folds and faults within the nose of the Wadi Mayh sheath fold. The folds and shears in the Permian Saiq 1 Formation shelf carbonates are wrapped around by the massive Ordovician Amdeh Formation quartzites. The unconformity placing Amdeh quartzites above Proterozoic Hijam dolomite and structurally lower Hatat schists is inverted along the upper limb of the Wadi Mayh sheath fold (northeastern part of Saih Hatat window). Along the northwestern part of the Saih Hatat window the sequence is right-way up and the fold axis is aligned NNE, roughly along Wadi Aday (Fig. 3). The basal limbs of the sheath folds are greatly attenuated. The fold axes of the sheath folds have been later folded around the gently plunging anticlinal domes of the Hulw window, suggesting that the latest phase of motion occurred along a structurally deep level detachment, which domed the lower plate window, folding all overlying thrust sheets and folds. The Hulw window and upper plate nappes occupy a large-scale triangle zone bounded to the SW by NE-vergent detachments and NE-facing folds, and bounded to the N and NE by SW-vergent thrusts and SW-facing folds (Fig. 4).

3.6. Intermediate structural units (Wadi Mayh, Al Khuyran units)

Three major structural units have been mapped above the As Sifah and Hulw domes and below the Muscat–Muttrah peridotite. These units are bounded by three major shear zones or faults: the Al Khuyran shear zone, the Yenkit shear zone and the Wadi Kabir fault (Searle et al., 1994). These fault zones affect the Permian Saiq Formation and the Triassic Mahil Formation rocks cutting up through progressively higher stratigraphic units towards the north. All of these upper structural sheets dip towards the north and several of the SW-vergent thrusts have been reactivated by later NE-vergent normal faulting (see next section). The entire Jurassic and Lower Cretaceous shelf carbonate sequence is missing, eroded off below an unconformity that places the Ruwi mélange and unconformably overlying late Palaeocene limestones, over folded Triassic Mahil Formation (Fig. 4).

Carpholite-bearing meta-sediments occur across all the intermediate level thrust sheets including the Wadi Mayh, Al Khuyran, Yiti units (Goffé et al., 1988; Searle et al., 1994) and parts of the upper plate Permian Saiq Formation. The carpholite group of minerals are single-chain silicates that occur in Al-rich, low-temperature and high-pressure metamorphic rocks. Goffé et al. (1988) recorded Fe–Mg carpholite + pyrophyllite + chloritoid ± sudoite ± phengite assemblages (280–340 °C; 4–5 kbar) in the Yiti unit beneath the Muscat peridotite and in a wide belt across northern Saih Hatat from Rija to Quriat (Fig. 2). Fe-rich carpholite + kaolinite + quartz + illite + chlorite ± paragonite assemblages (200–250 °C; 8–10 kbar) occur in the Al Khuyran and Wadi Mayh units. El-Shazly (1995) showed that a systematic downward increase in metamorphic grade can be demonstrated in Fe–Mg carpholite-bearing rocks and that textures were consistent with a clockwise P–T path. Meta-basaltic horizons interlayered within the Permian limestones contain crossite + albite + chlorite ± actinolite ± epidote. Medium grade assemblages with chloritoid and crossite occur in the Hulw window, but high-grade assemblages with garnet and sodic clinopyroxene only occur in the deepest As Sifah unit in addition to glaucophane, phengite and epidote (Searle et al., 1994).

Metamorphism, phase relations and thermobarometry indicate that the entire substrate to the Muscat–Muttrah peridotite, the basal part of the Semail ophiolite around northern Saih Hatat, has been subjected to HP metamorphism. This is in direct contrast to everywhere else exposed in the Oman mountains, including the north, central and southeast Oman mountains where the amphibolites and greenschists of the high-temperature metamorphic sole are present along the base of the ophiolite, and no high-P minerals occur (Searle and Malpas, 1980, 1982). It seems that only the leading edge of the continental margin has been subducted to HP–LT conditions around northern Saih Hatat. Mapping along the base Tertiary unconformity around Saih Hatat also shows that all thrusting and folding, including the late stage sheath folding, occurred prior to the Palaeocene. Up to 5 km thickness of ophiolite and up to 2.3 km thickness of upper shelf carbonates (Triassic–Cretaceous) must have been eroded off during late Cretaceous uplift along northern Saih Hatat. The base-Tertiary unconformity actually cuts down stratigraphy as far as Saiq 3 Formation immediately NW of Quriat (Le Métour et al., 1986).

3.7. Wadi Qanu fault–Yenkit shear zone

A major fault runs along Wadi Qanu from Ruwi to Bandar Khuyran, which was termed the Yenkit shear zone by Searle et al. (1994). This is a north-dipping shear zone showing numerous isoclinal to tight folds and high strain. Strain decreases both structurally upwards and downwards into the Mahil Formation limestones away from the shear zone. Downward, NE-facing folds in Saiq 3 and Mahil Formations limestones with high-P (4–7 kbar) carpholite + pyrophyllite bearing assemblages are consistent with SW-directed exhumation of HP rocks during NE-directed subduction. Fe–Mg carpholite occurs in thin calcareous sandstones within the recrystallised limestones. Along Wadi Qanu, Saiq 3 Formation limestones have been thrust south over Triassic Mahil Formation limestones along the fault (Fig. 4). Along strike towards the Ruwi valley the same fault shows north-dipping normal faulting as the Ruwi mélange has been down-faulted against the Triassic Mahil Formation. Further west the same fault curves around the north-plunging fold axis of the whole Saih Hatat dome.

The Yenkit shear zone–Wadi Qanu fault is interpreted to have multiple episodes of movement: (1) NNE-facing folds related to NNE-directed subduction of the shelf carbonates to ~20 km depth during HP carpholite grade metamorphism, followed by (2) SW-vergent folding and thrusting during exhumation of the shelf carbonates, as seen on our profile (Fig. 4), followed by (3) late-stage normal faulting showing down-to-N throw during culmination of the Saih Hatat dome to the south. It is possible that a final stage (4) occurred after the middle Eocene when folding about N–S axes reactivated the fault. Tertiary rocks around Qurum–Ras al Hamra (Fig. 3) are also folded about N–S axes and appear to have been downthrown to the north around the northern plunging axis of the main Saih Hatat dome. At Bandar Khuyran, the Yenkit shear zone may also have had some reactivation during post-Eocene time, deduced from the differential level of the base Tertiary unconformity either side of the Ras al Khuyran fjord.

3.8. Ruwi mélange

The Ruwi mélange consists of blocks of lawsonite ± pumpellyite-bearing meta-basalts, marbles, psammites and cherts in a matrix of carpholite-bearing mudstones and quartz mica schists. Within the Ruwi unit, well-bedded packages of Hawasina cherts, Triassic exotic limestones and sandstone-limestone sequences are present. These rocks were initially interpreted as part of the late Cretaceous Muti Formation (Robertson, 1987), but Searle et al. (1994) and Searle and Cox (1999) suggested that the structural position immediately beneath the Muttrah peridotite, and the lithologies of the blocks suggested that their origin was more likely to be the distal, late Cretaceous mélange of the Haybi complex. The alkali basaltic, ocean island-type geochemical signatures (El-Shazly et al., 1994) support the contention that the Ruwi unit is a HP equivalent of the Haybi complex. Although the lithologies in Ruwi are similar to mélange units in the Haybi complex (Searle and Malpas, 1980, 1982), nowhere else in the Haybi complex has carpholite or other HP minerals yet been found. The Ruwi unit is restricted to the Ruwi valley (Fig. 3) and is structurally bounded below by the Triassic Mahil Formation shelf carbonates, and above by the peridotites of the Muttrah area.

Carpholite-bearing meta-sediments occur in the Ruwi mélange above the Wadi Qanu fault and also in thin seams within the Triassic Mahil and Permian Saiq Formation limestones beneath. Goffé et al. (1988) estimated metamorphic conditions in the Ruwi unit at <280 °C and >7 kbar based on the Fe–Mg carpholite-bearing metasediments. Phase relations and P–T determinations suggest that the lawsonite-bearing meta-basalts were formed at 280–315 °C and 3–6 kbar (El-Shazly, 1994, 1995). All units beneath the Muscat–Muttrah peridotite were therefore metamorphosed at high-pressure, with P–T conditions increasing with structural depth. Restoration of these thrust sheets beneath the Muscat–Muttrah peridotite is consistent with the NE-directed subduction of sub-ophiolite, continental margin thrust sheets during SW-directed emplacement of the Hawasina, Haybi and Semail ophiolite sheets.

3.9. Wadi Kabir fault

The structurally highest fault in the area is the post-Eocene Wadi Kabir fault, which dips to the north at 45° and separates the Muscat–Muttrah peridotites and unconformably overlying late Palaeocene–Eocene limestones to the north, from Mahil Formation Triassic shelf carbonates to the south (Figs. 3 and 4). An outlier of Palaeocene limestones on top of the folded Mahil Formation south of Wadi Kabir shows that the base Tertiary unconformity has been downthrown to the north by about 450 m. The sub-ophiolite metamorphic sole, Ruwi mélange–Haybi complex and Hawasina thrust sheets are all structurally missing, downthrown to the north beneath the Muscat–Muttrah peridotite. The fault swings around the southern limit of the peridotite in the Ruwi valley. At Darsayt, the fault has similar relationships to the Semail thrust, with peridotite thrust over thin thrust sheets of Haybi complex mélange (blocks of cherts, alkali volcanics and exotic limestones in a mudstone matrix).

The Wadi Kabir fault has at least three periods of motion recorded on it: (1) Cenomanian–Turonian SW-directed thrusting emplacing the ophiolite peridotites over Haybi complex–Ruwi mélange (as seen at Darsayt; Fig. 3), (2) Santonian–Campanian normal sense shearing, placing rocks metamorphosed at 3–6 kbar (Ruwi unit) over rocks metamorphosed at $P > 6.8$ kbar (El-Shazly, 1995), and (3) post-Eocene normal faulting (as seen along Wadi Kabir–Bandar Jissah; Fig. 3) related to uplift along the footwall and doming of Saih Hatat. The Muscat–Muttrah peridotite has been folded about a NNE–SSW axis at a steep angle to the E–W striking faults and shear zones in the Mesozoic rocks below. The Palaeocene–Eocene limestones are also folded gently about NNE striking axes, but not thrust as suggested by Miller et al. (2002, fig. 4a). This fold is a gravity collapse fold along the hanging-wall of the north dipping Wadi Kabir fault.

4. Restoration of the section

The restored section across northern Saih Hatat (Fig. 5) has been constructed using the measured stratigraphic thicknesses of Le Métour et al. (1986) and our structural mapping, as well as that of Miller et al. (2002). Several key points can be summarized as follows:

1. A prominent phase of NE-vergent folding affects all

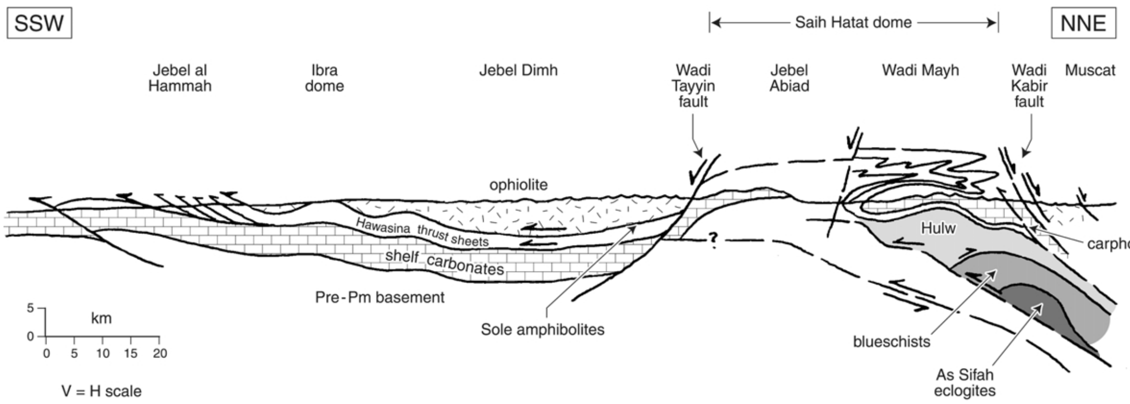


Fig. 11. Geological section across the southeastern part of the Oman mountains including the Saih Hatat window and Ibra ophiolite block.

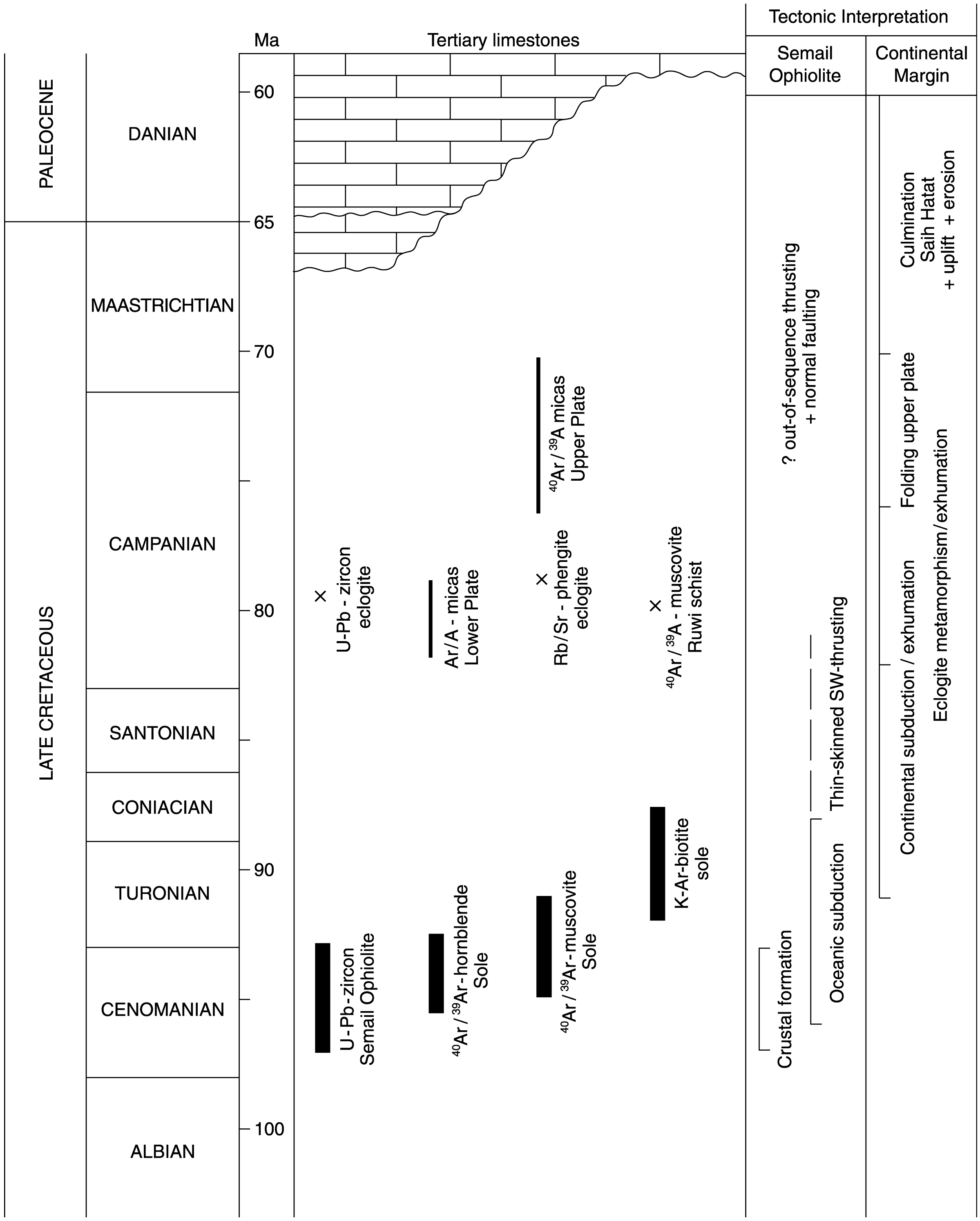


Fig. 12. Time chart summarising all the geochronological data fro m the Oman mountains, together with our interpretation of the tectonic history of the region. U–Pb zircon ages are from Tilton et al. (1981), Warren et al. (2003), $^{40}Ar/^{39}Ar$ data is from Hacker et al. (1996), Lippard et al. (1986), Searle et al. (1994) and Miller et al. (1999). Rb–Sr eclogite data from El Shazly et al. (2001).

pre-Permian rocks and fold axes and cleavage are truncated at the base Permian unconformity (Glennie et al., 1973, 1974).

2. Stratigraphic thickness of the Permian Saiq Formation increases towards the NE.
3. The Jurassic Sahtan and Cretaceous Kahmah and Wasia Groups thin towards the NE, approaching the continental margin.
4. The Late Cretaceous Muti Formation, infilling the Aruma flexural basin, increases thickness towards the

NE, and progressively cuts down-section to the Triassic Mahil Formation.

5. Eclogites in the As Sifah unit are probably metamorphosed Permian Saiq volcanics (El-Shazly et al., 1994; Searle et al., 1994). Overlying calc-schists are likely to be metamorphosed Saiq Formation dolomite, and underlying quartz mica schists are likely to be metamorphosed Amdeh Formation quartzites.
6. Hulw unit rocks are also probably metamorphosed Permian Saiq 2 Formation dolomites and volcanic rocks with underlying psammitic Amdeh quartzites. The shear zone between the As Sifah and Hulw units is a major one, having up to 8 kbar pressure difference across it (= 30 km thickness).
7. The Upper plate–Lower plate discontinuity cuts down-section to the SW only as far as the Hatat schists, not into the lower crust and certainly not into the mantle, as surmised by Gregory et al. (1998), Gray et al. (2000) and Gray and Gregory, 2000).
8. Major thrusts or shear zones above the Upper plate–Lower plate discontinuity (Al Khuyran and Yenkit shear zones, Wadi Kabir and Wadi Qanu faults) show SW vergence. Many faults have been reactivated by later, down-to-N or NE normal faulting, associated with exhumation of HP footwall rocks.
9. The Yenkit shear zone and Wadi Kabir fault cut down-section at least to Saiq 3 Formation. The Wadi Kabir fault certainly has been reactivated during post-Eocene time as a N-dipping normal fault, and it is possible that some Tertiary normal fault motion has also occurred on the Wadi Qanu–Yenkit fault.
10. All tectonic units beneath the Muscat–Muttrah ophiolite peridotites have been subjected to high-pressure metamorphism and exhumed from ca. 10–22 km depth (Ruwi unit; 3–6 kbar), 22–33 km depth (intermediate carpholite-bearing units; 6.5–9 kbar) and from 58–78 km depth (As Sifah eclogites; 15–20 kbar). Exhumation of footwall HP rocks along each shear zone resulted in top-to-NE apparent 'extensional' fabrics, although this relative extension occurred in a purely contractional, subduction zone environment.

5. Semail ophiolite thrust sheet

In the northern and central Oman mountains, the Semail ophiolite generally dips and faces to the NE, such that mantle sequence peridotites lie along the western side of the range and crustal sequence units young towards the NE. The Moho is used as a palaeo-horizontal proxy and the sheeted dykes are palaeo-vertical proxies. Beneath the basal contact of the ophiolite, the Semail thrust, imbricate thrusts and folds show a NE to SW thrusting emplacement direction. The Semail ophiolite has been folded around the Hawasina Window and Jebel Akhdar culminations and affected by late-stage normal faulting around the deeper shelf carbonate ramp anticlines (e.g. Glennie et al., 1974; Searle, 1985; Hanna, 1990). Late normal fault movement along the Semail 'thrust' has been documented around the Sumeini and Asjudi windows in northern Oman (Searle, 1985) and around the Hawasina Window (Searle and Cooper, 1986). Coffield (1990) also mapped late normal faults around the Jebel Nakhl–Fanjah saddle region, resulting from gravity-driven culmination collapse due to over-steepening of the culmination flanks. A similar normal fault now flanks the southern margin of the Saih Hatat shelf carbonate sequence along Wadi Tayin (Fig. 11). The ophiolite has been down-faulted to the south juxtaposed next to the shelf carbonates, with all the underlying Haybi and Hawasina thrust sheets smeared out or structurally buried.

In the southeast Oman mountains, Gregory et al. (1998) noted that the pseudo-stratigraphy of the ophiolite, as well as fold axes, are truncated at the contact known as the Semail thrust around the Dasir and Ibra blocks. This suggests that the final emplacement was related to either out-of-sequence thrusting or normal faulting, truncating the earlier folds. A section across the Ibra–Dasir block ophiolite shows a flat-lying Semail 'thrust' or detachment fault truncating tight folding in the ophiolite. South of the Dasir valley the Moho is actually overturned at right angles to the basal contact. The ophiolite must have undergone large-scale folding during SW-directed emplacement onto the continental margin, and then been truncated by a shallow dipping normal fault during final emplacement (Gregory et al., 1998; Gray et al., 2000; Gray and Gregory, 2000). Considering the very large scale recumbent folding and crustal thickening occurring along northern Saih Hatat during this time (Fig. 4), it is possible that SW-dipping low-angle normal faulting was driven by topographic differences across the margin.

The Muscat–Muttrah peridotite is the only part of the Semail ophiolite preserved along the northern flank of Saih Hatat. The basal contact of this peridotite was originally a late Cretaceous thrust, but was reactivated as a N-dipping normal fault during post-Eocene time (Section 3.8). If this fault was active at the same time as the Wadi Tayin fault, it would suggest that, as Saih Hatat underwent ca. 2000 m of vertical uplift during post-Eocene time, along with the Tertiary jebels of the SE Oman mountains, normal faults dipped away from the uplift along both northern and southern flanks.

6. Tectonic evolution

Mapping relationships, the composite cross-section and the restored cross-section, together with thermobarometric pressure (depth) and temperature constraints, and geochronological timing constraints have been used to deduce the tectonic evolution of the northern continental margin in the Saih Hatat region of Oman. We can divide the whole process into distinct time frames (Fig. 12).

6.1. Ophiolite formation and oceanic subduction

U–Pb zircon ages of plagiogranites from the ophiolite constrain the crystallisation age of the crustal sequence. These ages range from 97.9 to 93.5 Ma with a mean age of ~95 Ma (Tilton et al., 1981). The amphibolite facies metamorphic sole was the first thrust slice to be accreted along the Semail thrust, the fault at the base of the ophiolite. P–T conditions of amphibolites are 870–840 °C and 11.6 ± 1.6 kbar (Gnos, 1998; Searle and Cox, 1999, 2002), equivalent to 50–45 km depth beneath oceanic crust hanging-wall, much deeper than can be accounted for by the thickness of the preserved ophiolite. $^{40}Ar/^{39}Ar$ cooling ages of hornblendes from the amphibolite sole, recording the timing they cooled through 500 °C, are 95–92 Ma (Gnos and Peters, 1993; Hacker, 1994; Hacker et al., 1996). As 50–45-km-deep amphibolites were exhumed, they cooled and were thrust onto lower P–T greenschist facies rocks, which were in turn emplaced onto shallow-level unmetamorphosed distal Tethyan sediments of the Haybi and Hawasina complexes (e.g. Searle, 1985). Thrusting progressed from deep to shallow, from NE to SW with time.

6.2. Thin-skinned SW-verging thrusting onto the passive margin

As the ophiolite was converging with the passive margin of Arabia, deep subduction-related expulsion of HT–MP sub-ophiolite metamorphic sole rocks evolved to thin-skinned thrust emplacement. Restoration of the Hawasina thrust sheets together with minimum emplacement distances of the allochthon suggest that the true width of the Hawasina part of the Tethyan ocean preserved in thrust sheets between the ophiolite and the shelf margin was at least 455 km (Cooper, 1988). At extremely fast plate convergence rates of 50 mm a^{-1} such as the India–Asia convergence, 455 km of convergence would require 9.1 million years; at slow convergence rates of 10 mm a^{-1}, such as the Africa–Europe convergence, 45.5 million years would be needed. Since the entire obduction history spanned ca. 27 Ma (from 95 to 68 Ma), the convergence rate of the Semail ophiolite relative to the passive continental margin could be a minimum of about 17 mm a^{-1}. There is no geological evidence at all for SW-dipping subduction as suggested by Gregory et al. (1998), Gray et al. (2000) and Gray and Gregory (2000). Cretaceous passive margin shelf carbonates exposed around Jebel Akhdar and Saih Hatat are lateral equivalents of the Sumeini Group slope facies carbonates and the proximal Hawasina (Hamrat Duru Group) and distal Hawasina facies (Glennie et al., 1973; Searle et al., 1983).

6.3. Subduction of the continental margin

The passive continental margin of Arabia was a 3-km-thick sequence of Permian–Mesozoic shelf carbonates overlying about 4 km thickness of Ordovician quartzites, overlying Proterozoic basement. The Sumeini Group shelf-slope carbonates and the proximal (Hamrat Duru Group) and distal Hawasina basin sediments are also Permian–Mesozoic and are all the same time-equivalent units as the shelf carbonates, but progressively more distal facies. The distal Hawasina and Haybi thrust sheets were oceanic sediments overlying oceanic crust of Triassic, Jurassic and early Cretaceous age. As the continental margin approached the subduction zone, the thin-skinned thrusts flaked the basin sediments onto the margin, but when the thicker shelf edge met, these massive carbonates must have rapidly choked the subduction zone. However, the thinned leading edge of the Arabian continental crust did subduct to depths of around 80 km, as we can deduce from pressures in the As Sifah eclogites. It seems likely that the continental margin was dragged down the subduction zone by an eclogitised root (the Triassic–Jurassic ocean crust that was attached to the passive continental margin). When this broke off, the eclogitised As Sifah unit, which was mainly low-density, buoyant calc-schist and quartz mica schist, enclosing boudins of meta-basic eclogite, and other HP rocks were rapidly expelled from depth along the same subduction zone (Fig. 9a and b). Recent U–Pb dating of zircons extracted from the as Sifah eclogite constrain the age of peak high-pressure metamorphism at 79.1 ± 0.3 Ma (Warren et al., 2003). This new age confirms that the HP metamorphism was related to the late stage of ophiolite emplacement and was not related to an earlier subduction or collision event.

6.4. Exhumation of the HP rocks

Structural analysis shows that the eclogites at As Sifah originated as meta-basaltic flows within the continental margin, probably in the Middle–Late Permian shelf carbonates. NE Oman is probably the only place in the world where we can be certain that thinned continental crust has been subducted to eclogite facies depths (ca. 78–80 km; 20 kbar) beneath a hanging wall that was, and still is, ophiolite or oceanic crust/mantle. We envisage the subduction zone as a narrow channel where strain is highly focussed, channelling rocks down, and return flow associated with stretching folds, NNE-aligned sheath folds and stretching lineations. We suggest that the extensional crenulation schistosity seen in the lower eclogite and blueschist units in Oman is consistent with SW-directed thrusting and exhumation of footwall HP rocks, as shown in Fig. 9. The extension is relative (between SW-directed upward motion of deeper, HP footwall rocks relative to a static hanging wall) in a convergent subduction zone setting. The carpholite-bearing units show that although pressures were high, temperatures remained very low (<280 °C for the upper units at 7 bar or 25 km depth; ~540 °C for the eclogites at ~20 kbar or 78 km depth).

6.5. NE-facing backfolding and sheath folding

The huge scale of NE-facing backfolds and NE-aligned sheath folds in the upper structural levels in northern Saih Hatat have been used as evidence for SW-directed subduction (Gregory et al., 1998; Gray et al., 2000; Gray and Gregory, 2000). We have shown that there is no evidence of any shear zone cutting down-section to the SW deeper than the upper Proterozoic. We suggest that the NE-facing folds represent antithetic backfolds, which form the upper part of a wedge, balancing the lower part that represents the NE-directed subducted continental margin. Our model is based on the composite cross-section shown in Fig. 4 and its restoration (Fig. 5). These structures must have occurred late in the Late Cretaceous history of the region. The axes of the sheath folds are aligned NNE–SSW, parallel to the subduction and exhumation direction. NNE aligned stretching lineations occur throughout the nappe stack from deep level eclogites up to the upper plate sheath folds. The final stage of folding was related to latest Cretaceous culmination of the Saih Hatat anticline, which domed all the rocks around the Saih Hatat window. This geometry strongly suggests that a flat-lying detachment horizon underlies the whole window and ramps up towards the foreland to the thin-skinned foreland thrust belt, as has also been suggested for Jebel Akhdar (Searle, 1985; Bernoulli and Weissart, 1987). At the culmination of Saih Hatat, as well as during the progression of Jebel Akhdar, normal faulting around the flanks down-faulted the ophiolite blocks around the uplifting shelf carbonate ramp-culminations (Fig. 11). This process should not be described as culmination collapse, because there was no lowering or collapse involved; instead deeper level shelf carbonate anticlines punched through their overlying allochthonous thrust sheets, elevating the footwall windows but leaving the hanging wall at the same structural level.

6.6. Tertiary folding and faulting

Late Cretaceous oceanic subduction, ophiolite obduction and emplacement was completed by the late Maastrichtian, when rudist-bearing Upper Maastrichtian limestones were deposited unconformably over all underlying allochthonous units. Along the northern flank of the mountains, late Palaeocene–early Eocene limestones unconformably overlie all allochthonous units. The deep subduction of the continental margin, eclogite, blueschist and carpholite grade metamorphism, and exhumation of all HP units was also completed by the end of the Cretaceous. A major phase of crustal thickening, folding and erosion occurred around the latest Cretaceous–early Palaeocene, as evidenced by the base Tertiary unconformity cutting down-section through at least 3 km of shelf carbonate stratigraphy. Stable, shallow marine carbonate sedimentation lasted 20–25 million years from middle Palaeocene to late Eocene, before uplift began. Since Oligocene marine carbonates have been recorded on both the northern flank (Rusayl) and the SW flank (Jebel Hafit) of the mountains, this uplift may not have started until the Miocene. At least 2000 m of uplift is recorded in Jebel Abiad, in the southeast mountains, and a similar amount must also have affected Jebel Akhdar and Jebel Nakhl in central Oman.

Both N–S and E–W aligned fold axes in Tertiary structures around Saih Hatat indicate a dome and basin type fold interference pattern as a result of biaxial compression (Searle, 1985). It is not entirely clear what caused the E–W compression. In the northern Oman mountains Searle (1988a,b) suggested that early continent–continent collision in the Musandam mountains may have resulted in late Oligocene–Miocene culmination of the Musandam shelf carbonates and initiation of Zagros-style Tertiary folding.

7. Conclusions

1. All structures in northern Saih Hatat are compatible with SW-directed exhumation and NE-directed subduction during ophiolite obduction, dipping away from the Oman continental margin. We refute previous suggestions that, at any stage of the collision process, a subduction zone dipped SW beneath the Oman margin as suggested by Gregory et al. (1998), Miller et al. (1998, 1999) and Gray et al. (2000).
2. All structural units beneath the Muscat–Muttrah peridotite were metamorphosed at high-pressure, when the thinned leading edge of the continental plate was subducted beneath the obducting Oman ophiolite.
3. The Ruwi schists (lawsonite-bearing alkaline metabasalts and carpholite-bearing metasediments) are metamorphosed equivalents of the late Cretaceous component of the Haybi complex, immediately beneath the ophiolite.
4. Early SW-directed thrusts and SW-facing folds throughout north Oman were related to NE-directed subduction of the continental margin, during SW-directed emplacement of the Semail ophiolite, Haybi and Hawasina thrust sheets.
5. Some of the early SW-directed thrusts were reactivated by later NE-directed normal faulting. All major faults and shear zones appear to be late Cretaceous in age, except for the Wadi Kabir fault, the structurally highest normal fault, which has offset Palaeocene–Eocene limestones. Tertiary rocks have been affected by gentle folds with N–S axes and up to 2000 m of uplift since late Eocene–early Oligocene time.
6. Four major shear zones beneath the Muscat–Muttrah peridotite show SW-facing folds and shear fabrics yet, in most areas, place structurally higher, younger rocks onto lower, older rocks. Structurally higher units contain lawsonite in meta-basalts and carpholite, pyrophyllite, sudoite and kaolinite in meta-sediments (7–10 kbar; 27–39 km depth). Structurally lower

garnet + glaucophane/crossite blueschist units were metamorphosed at 12–15 kbar (= 47–58 km depth). The lowest unit, the As Sifah eclogite contains the assemblage: garnet + clinopyroxene + glaucophane + phengite and was metamorphosed at 15–20 kbar (= 58–78 km depth).

7. The Hulw window lower plate rocks have similar pressures to the carpholite-bearing rocks above the Upper plate–Lower plate detachment. Protoliths of the Hulw unit rocks are Ordovician Amdeh quartzites (= Lqms unit of Miller et al., 2002) and late Permian Saiq Formation (= Lc unit of Miller et al., 2002), with the meta-volcanics derived from the late Permian Saiq volcanics (Sq2v).
8. The As Sifah garnet + glaucophane + phengite blueschists and the structurally lower As Sifah eclogites are probably metamorphosed Saiq 2 and Saiq 1 volcanics, respectively. Calc-schists above the eclogite boudins are metamorphosed Saiq 2 dolomites. Underlying quartz mica schists are probably metamorphosed Amdeh Formation psammites.
9. The Upper plate–Lower plate discontinuity cuts down-structural section to the SW, only as far as the Hijam dolomite, maybe as far as the top of the Hatat schists (Ha4). This does not imply SW-directed subduction, dipping beneath the continental margin, as implied by Gregory et al. (1998) and Gray et al. (2000).
10. There is no evidence of SW-directed subduction beneath an active continental margin along northern Oman before, during or after the obduction of the ophiolite (no I-type granites, no calc-alkaline volcanics, no suture zone above the eclogites). All evidence points to the attempted NE-directed subduction of a thinned, continental margin beneath the SW-emplacing ophiolite during the late Cretaceous.
11. The NE-directed folds, C–S fabrics (extensional crenulation schistosity) and shear zones in the eclogites and blueschists are interpreted as reflecting relative extension during upward movement of footwall HP rocks in a wholly compressional environment. Final shearing placed lower P rocks onto higher P rocks.
12. The major NE-facing sheath folds in the upper structural levels (Wadi Mayh and Wadi Aday, northern Saih Hatat) are interpreted as antithethic back folds, or retro-shears, in a tectonic accretion channel (Engi et al., 2001) above the exhuming subduction zone. These structures are analogous to major backthrust regions in the Alps (Insubric Line and south Alpine nappes) and the Himalayas (N-vergent backthrust and folds along the Zanskar shelf margin). All these hinterland back-thrust zones developed during the later stages of orogeny, whilst the youngest foreland-propagating thrusts were also active, creating divergent orogenic systems.
13. Two phases of tectonic uplift are now well constrained in the Oman Mountains. Although most of the ophiolite obduction/emplacement process occurred below sea level, the latest stages of emplacement resulted in uplift during the late Cretaceous with late-stage ramp culmination of the Saih Hatat and Jebel Akhdar antiforms. The mountains were a positive sub-aerial feature throughout the latest Cretaceous and early Tertiary. The second occurred some time after the Eocene, probably during the late Oligocene–early Miocene, with some 2000 m of uplift of early Tertiary marine carbonates and all underlying rocks, with only minimal compression.

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