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Geometry and significance of internal windows and regional isoclinal folds in northeast Saih Hatat, Sultanate of Oman

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Abstract

Saih Hatat contains tiered sets of low-angle structural breaks that reflect a complex stacking of sheets, which requires multiple upward movement of units within an unstable orogenic wedge in a convergent setting. Early recumbent folds within the Saih Hatat window are subparallel to, but cut by, a major low-angle contractional fault (décollement) that separates lower plate high-pressure rocks (some eclogites) exposed in two windows (Hulw and As Sifah windows) from high-pressure upper plate rocks containing carpholite and lawsonite. Parts of this décollement had been mapped, or speculated upon, to explain the variation in metamorphic grade across Saih Hatat. Upper plate fold-nappes are controlled by the mapped décollement surface. Below the décollement sheath-like lower plate closures formed independently in an intense zone of top-to-the-northeast shearing. Eclogites occur within mafic boudins at the structurally lowest level of the retrograde lower plate shear zone. This zone was responsible for the partial exhumation of the lower plate very early in the observed structural history and has a normal movement sense. The two lower plate windows are essentially foliation domes reflecting fold interference between regional-scale, sheath-like, recumbent isoclines and more open, upright northwest-, north- and northeast-trending fold sets. The early upper plate fold-nappes reflect a major top-to-the-north or -northeast movement of the rocks away from the Oman margin at the same time the ophiolite was being emplaced over the top in the opposite direction (top-to-the-southwest or -south). South-directed faulting and shearing is superimposed on the early recumbent folds in the mountain range. Mapped relationships and structural observations agree with Bureau de Récherches Géologiques et Minières mapping that recognised fold-nappes in this part of the Oman Mountains. All of the mapped structures are associated with exhumation of the high-pressure rocks making reconstruction of the margin during high-pressure metamorphism problematic. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Domal culmination; Fold-nappe; Obduction; Blueschist; Eclogite; Oman

1. Introduction

The presence of high-pressure eclogites in the northeast Saih Hatat window of the Oman Mountains (Fig. 1) has major implications for the tectonic evolution of the Arabian margin (e.g. Lippard, 1983; El-Shazly and Coleman, 1990). The position of the high-pressure rocks in Saih Hatat, and the lack of consensus upon their structural association, has produced varying geometrical interpretations of the window. Various faults and shear zones have either been partially mapped, or speculated upon, to explain the variation in metamorphic grade (Le Metour et al., 1986; Montigny et al., 1988; Goffé et al., 1988; Mann and Hanna, 1990; Michard et al., 1994; Searle et al., 1994; El-Shazly, 1994, 1995; Gregory et al., 1998; Miller et al., 1998, 1999; Searle and Cox, 1999). Kinematic interpretations for the rocks beneath the ophiolite range from south-directed thrusting (e.g. Mann and Hanna, 1990), to northeast-vergent nappes overprinted by south-vergent imbricate faults (Le Metour et al., 1990), to a series of folded units separated by large-scale low-angle extensional detachments (Michard et al., 1994). The controversy on the structural association of the rocks has led to a large number of tectonic/exhumation models (e.g. Goffé et al., 1988; El-Shazly and Coleman, 1990; Le Metour et al., 1990; Michard et al., 1994; Searle et al., 1994; Chemenda et al., 1996). Even though there is close to 100% exposure, many interpretations of the structure have been model-driven, and a lack of agreement on the exact field relationships makes it difficult to resolve which tectonic models are more realistic. For this reason, the structure of the Saih Hatat window, in

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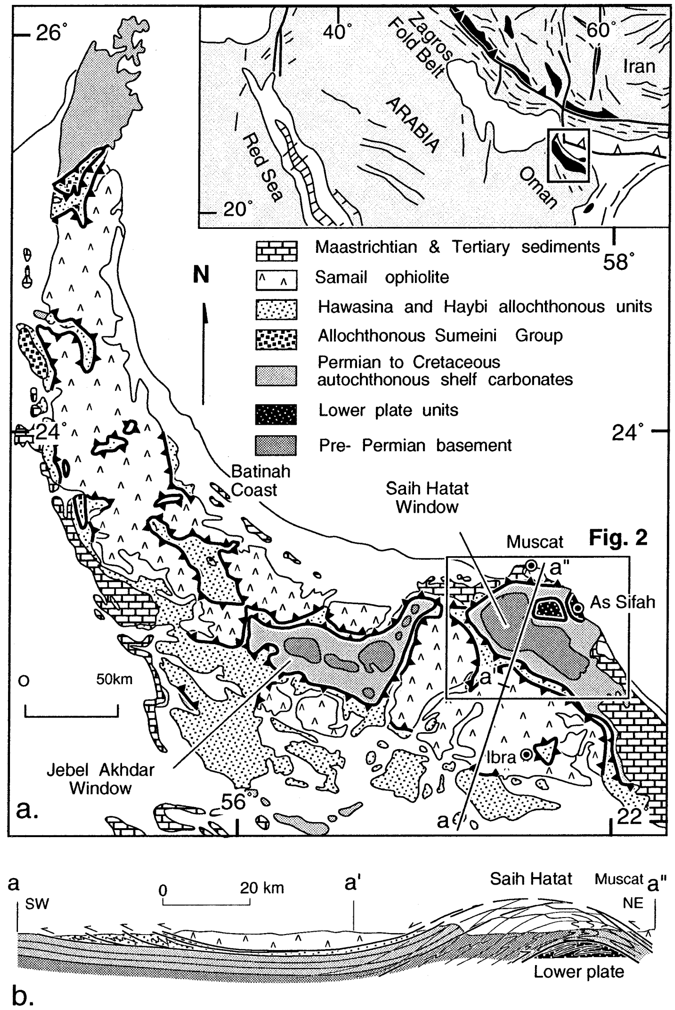


Fig. 1. (a) Geological map of the Oman Mountains (modified from Glennie et al., 1974; inset from Coleman, 1981) showing the locations of the Saih Hatat, Jebel Akhdar and lower plate windows. Location of Fig. 2 is shown. (b) Schematic structural profile through Saih Hatat and Ibra.

particular the northeastern segment, is of major importance for understanding the tectonic evolution of the Oman Mountains and for understanding the mechanisms that ultimately lead to the exhumation of high-pressure rocks.

The recognition of a major structural break in northeast Saih Hatat (see Gregory et al., 1998; Miller et al., 1998, 1999) has led to a greater understanding of the map patterns and metamorphic relationships in the Saih Hatat window. This break, referred to as the upper plate–lower plate discontinuity, separates the higher pressure blueschists and eclogites of As Sifah from less metamorphosed upper plate rocks involving fold-nappes developed in the pre-Permian basement and the Hajar Supergroup. To fully comprehend the geometry of the Saih Hatat window an understanding of the complex refolding of the upper plate–lower plate discontinuity and also the timing of regional folding in both the upper and lower plates is required. This paper: (1) provides detailed justification for this structural break, and (2) documents in detail the structural relations and development of north Saih Hatat. It is based on 1:25,000 scale structural mapping by the authors over five field seasons in Saih Hatat from 1994 to 1999. This mapping utilised the stratigraphy defined by the French Geological Survey (Bureau de Récherches Géologiques et Minières — B.R.G.M.; cf. Le Metour et al., 1986) combined with structural analysis of individual outcrops, and construction of detailed structural profiles (Miller, 1998). The mapping has also shown that northern Saih Hatat is made up of a series of early-formed, regional scale, isoclinal, recumbent folds refolded by later upright northeast-, north-northeast- and northwest-trending more open folds. The map pattern of Saih Hatat is dominated by dome and basin interference within the flat-lying layering and schistosity of the early recumbent folds. Refolding of the décollement surface has produced two, now eroded, regional-scale foliation domes that create internal windows into this lower plate within the Saih Hatat window proper.

2. Geological background

In northern Oman, a 700-km-long arcuate mountain chain that is parallel to the Batinah coast is made up primarily of the obducted Cretaceous Samail Ophiolite slab (Fig. 1). Local elevations are up to 3000 m. The ophiolite is the structurally highest sheet within a thrust-stack of former Tethyan Ocean basinal remnants, including shelf carbonates (Sumeini Group), basinal sediments and sea floor volcanics (Hawasina and Haybi units) (Glennie et al., 1974; Searle and Malpas, 1980; Lippard et al., 1986). These overlie para-autochthonous continental shelf carbonates (Hajar Supergroup) and pre-Permian basement units (Hatat Schist). Onlapping Maastrichtian to Miocene sediments, dominated by shallow water carbonates, overlie the thrust-stack and provide a minimum emplacement age for the ophiolite (Coleman, 1981).

The eroded Saih Hatat domal culmination due south of Muscat (Fig. 2a) is the easternmost window through the Samail Ophiolite thrust sheet (Fig. 1). Rimmed by carbonates, it is a large (70 km × 50 km), recessively weathered, L-shaped tectonic window that exposes some of the deepest level rocks in the Oman Mountains. Large tracts of overturned rocks on the eastern limb of the Saih Hatat dome (Figs. 2 and 3) were identified initially by Glennie et al. (1974) and also by Bailey (1981) and Le Metour et al. (1986). This overturned section is part of the common limb between a regional, northeast-facing anticlinal fold-nappe and a large synformal isocline exposed in Wadi Meeh gorge (Figs. 2b and c and 3). The pre-Permian Hatat schist, which is exposed in the centre of the Saih Hatat window, represents the core of this regional anticlinal closure. These pre-Permian rocks are strongly deformed with transposition layering, and exhibit a well-developed lineation that parallels the regional Cretaceous lineation. Any pre-Permian deformation has been thoroughly overprinted by the Cretaceous event. The upper limb of the major upper plate anticlinal closure is tectonically overlain by the allochthonous Haybi, Hawasina and ophiolite sequences (Fig. 1). These oceanic units have been emplaced via an opposing shear sense to the deformation that results in the shelf carbonates being deformed into fold-nappes (i.e. top-to-the-south as opposed to top-to-the-northeast).

The regional isoclinal fold-pair that dominates Saih Hatat is subparallel to, but truncated by, a major crustal discontinuity that separates the region into upper and lower plates (Figs. 2a and 3). These upper and lower plates display differences in metamorphic grade and structural style (see Gregory et al., 1998; Miller et al., 1998). The structurally lowest parts of the Saih Hatat dome are within the lower plate exposures of the Hulw and As Sifah windows, and not the pre-Permian units that form basement to the platform upper plate shelf carbonates. The lower plate is characterised by intense transposition foliation, and regional recumbent closures in quartz–mica schist, mafic schist and calc schist. Eclogites occur within mafic boudins (El-Shazly and Coleman, 1990) exposed in the easternmost exposure of the lower plate (As Sifah window).

The domal form of Saih Hatat is the result of interference between several fold sets with the two main fold sets having axes that trend to the northwest and north (Fig. 2a). The Tertiary is also often folded with broad closures having northwest-trending axial surface traces (fold traces identified by Glennie et al. (1974) are marked on Fig. 2a). In some areas the Tertiary units are in fault, and not stratigraphic contact, with the underlying units, and have associated northwest-trending ramp antiforms (Fig. 4a).

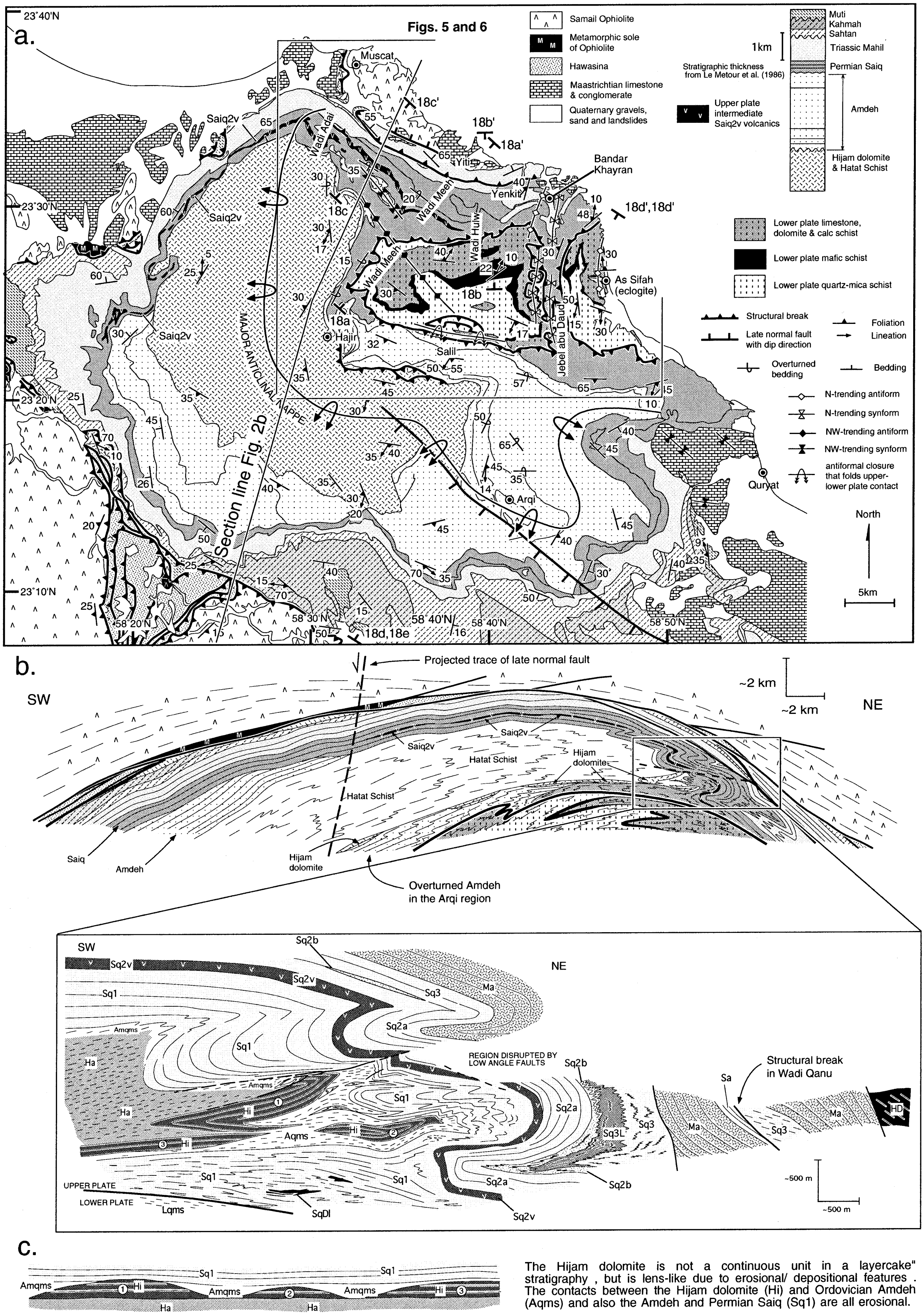
3. Stratigraphic relationships within Saih Hatat dome

The oldest rocks in the Saih Hatat window belong to the pre-Permian Hatat Schist, which ranges from mafic schist to meta-siliciclastic rocks. This is overlain by the Hijam Formation, consisting of dolomite and limestone with minor interlayered clastic sediments, and the Ordovician Amdeh Group, predominantly quartzite but also containing pelitic layers and conglomerate. The Amdeh Group shows marked variations in stratigraphic thickness, and is thicker to the east but appears to have been largely faulted out on the northern side of the dome, or is strongly attenuated due to depositional or erosional processes prior to the deposition of shelf carbonates (Fig. 2c). The Permian Saiq Formation overlies the pre-Permian rocks, and is a carbonate unit that forms many of the high ridgelines within Saih Hatat. Locally siliciclastic at its base, the Saiq formation consists largely of limestone and dolomite, foetid black limestone and thin-bedded limestone and dolomitic marl. The Saiq Formation also contains layers of intermediate volcanics (Saiq 2v) and mafic sills, and shows lateral variation in facies across the Saih Hatat window (Rabu et al., 1990). The Triassic Mahil and Sahtan Formations overlie the Saiq. On the northern side of the Saih Hatat dome, Jurassic and Cretaceous stable platform sediments are absent with 'Muti' Formation or Hawasina melange in fault contact against Sahtan or the Mahil.

In the lower plate As Sifah and Hulw windows there is a common occurrence of meta-quartzites, overlain by mafic schist which in turn is overlain by limestone, dolomite (with occasional interbedded quartz–mica schist) and calc schist. In many areas these units are not laterally continuous. The majority of the calc schists and dolomites within the lower plate have negative $\delta^{13}C$ values inconsistent with a Permian age (R.T. Gregory, unpublished data). Compared with the As Sifah lower plate window, the rocks in the Hulw window preserve more original features: relict pillows and deformed amygdules in the mafic schist, deformed fossils in the limestones, and some relic sedimentary features such as graded bedding in the clastic rocks.

4. The upper plate–lower plate discontinuity

The upper plate–lower plate discontinuity is a brittle fault marked by bleaching alteration and localised occurrences of Pb–Zn and Cu mineralisation in northeast Saih Hatat. The



a.
23°40'N
23°30'N
23°20'N
23°10'N
58°20'N
58°30'N
58°40'N
58°50'N
Figs. 5 and 6
Muscat
Saiq2v
Wadi Adai
Wadi Meeh
Wadi Hulw
Yiti
Yenkit
Bandar Khayran
18c'
18b'
18a'
18d',18d'
18c
18b
18a
18d,18e
Hajir
Salil
As Sifah (eclogite)
Jebel abu Daud
MAJOR ANTICLINAL NAPPE
Section line Fig. 2b
Arqi
Quryat
Samail Ophiolite
Metamorphic sole of Ophiolite
Hawasina
Maastrichtian limestone & conglomerate
Quaternary gravels, sand and landslides
Upper plate intermediate Saiq2v volcanics
1km
Stratigraphic thickness from Le Metour et al. (1986)
Muti
Kahmah
Sahtan
Triassic Mahil
Permian Saiq
Amdeh
Hijam dolomite & Hatat Schist
Lower plate limestone, dolomite & calc schist
Lower plate mafic schist
Lower plate quartz-mica schist
Structural break
Late normal fault with dip direction
Foliation
Lineation
Overturned bedding
Bedding
N-trending antiform
N-trending synform
NW-trending antiform
NW-trending synform
antiformal closure that folds upper-lower plate contact
North
5km
b.
Projected trace of late normal fault
SW
NE
~2 km
~2 km
Saiq2v
Hatat Schist
Hijam dolomite
Saiq
Amdeh
Hijam dolomite
Overturned Amdeh in the Arqi region
SW
NE
Sq2b
Sq2v
Sq1
Sq3
Ma
Sq2a
Amqms
Ha
Hi
Aqms
REGION DISRUPTED BY LOW ANGLE FAULTS
Sq3L
Sa
Structural break in Wadi Qanu
HD
UPPER PLATE
LOWER PLATE
Lqms
SqDl
~500 m
~500 m
c.
Sq1
Amqms
Hi
Ha
The Hijam dolomite is not a continuous unit in a layercake" stratigraphy , but is lens-like due to erosional/ depositional features . The contacts between the Hijam dolomite (Hi) and Ordovician Amdeh (Aqms) and also the Amdeh and Permian Saiq (Sq1) are all erosional.

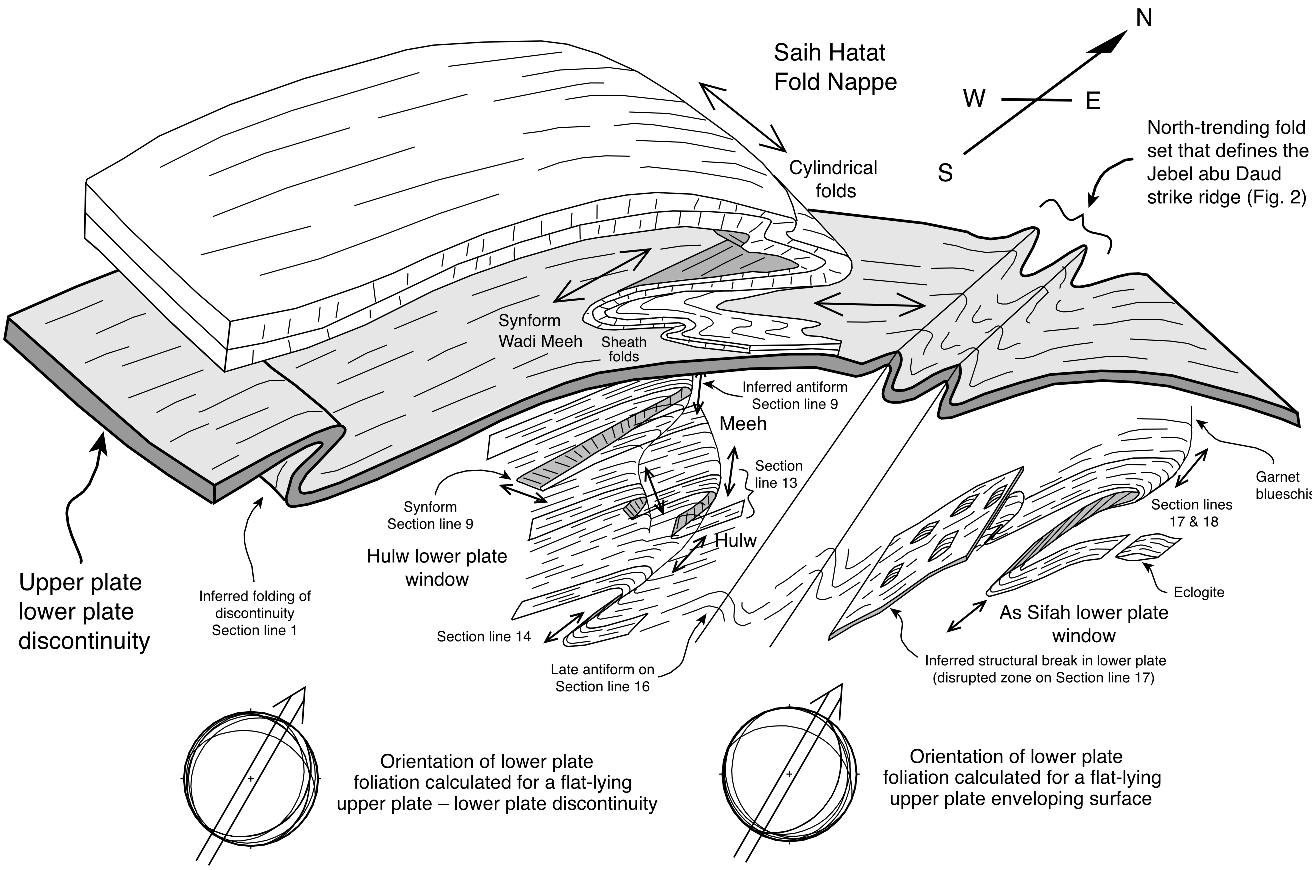


Fig. 3. (a) Block diagram of structure within Saih Hatat. The lower plate closures are a series of macro-scale sheath folds. The eclogites at As Sifah are at the structurally lowest level of this projection such that the westernmost units of the As Sifah lower plate window structurally underlie the structures in the Hulw lower plate window. Relevant section lines used to construct the projection are marked. (b) Great circles defining the unfolded form of the lower plate schistosities. The rotations were done in regions where there was also a measurement of the upper plate enveloping surface, and the upper–lower plate discontinuity. The large arrow indicates the transport direction in the lower plate (top-to-the-northeast).

outcrop trace of the fault in map view defines two ovoid shaped windows, and clearly truncates both stratigraphic and structural features of the overlying (upper) and underlying (lower) plates (Fig. 3). In the upper plate there is a significant increase in strain towards the structural break (in some areas X:Z ratios change from 16:1 to over 100:1; cf. Miller et al., 1998), such that it has the character of a major ductile shear zone truncated by a late brittle fault. It is therefore difficult to distinguish the tectonic break in some sections, particularly when the contact juxtaposes upper and lower plate carbonates. Locally, there can be imbrication and infolding of upper and lower plate sequences, resulting in fault-bounded klippen of upper plate units surrounded by lower plate units (the southern region of Figs. 5 and 6). This is often associated with the development of late north-vergent crenulation cleavages.

The upper plate–lower plate discontinuity does not repeat identical shelf sequences. The lower plate quartzites are overlain by a bimodal metavolcanic sequence dominated by metabasalt, thinly interbedded mud, sandstone and dolomite layers, pre-Permian calc schist and occasional lenses of Permian limestone. In contrast, the upper plate contains Hatat schist overlain by Hijam dolomite, Amdeh quartzite and then an extensive sequence of Permian limestones and dolomites with occasional intermediate volcanic units (Saiq 2v Formation). The Saiq Formation is overlain

Fig. 2. (a) Geological map of Saih Hatat (modified from Le Metour et al., 1986; Béchennec et al., 1992; Le Metour et al., 1992). The domal shape of the lower plate windows is controlled by later north- and northwest-trending fold sets. Some of the fold sets also occur in the Maastrichtian sequences (cf. Quryat region). The trace of the major anticlinal nappe can be identified by large areas of completely overturned sequences in the centre of the Saih Hatat window (e.g. overturned Amdeh at Arqi). The location of Fig. 6 is marked as are the profile bars for the sections in Fig. 18. (b) Structural projection of northeast Saih Hatat. The inset is a compilation of the detailed section lines presented in Fig. 11. Explanation of rock codes (e.g. Saiq 2v) is listed in Fig. 5. (c) Diagram illustrating the lens-like nature of the pre-Permian units below the Saiq formation, this markedly complicates structural analysis. The numbers on individual Hijam dolomite lenses correspond to the numbers marked in (b).

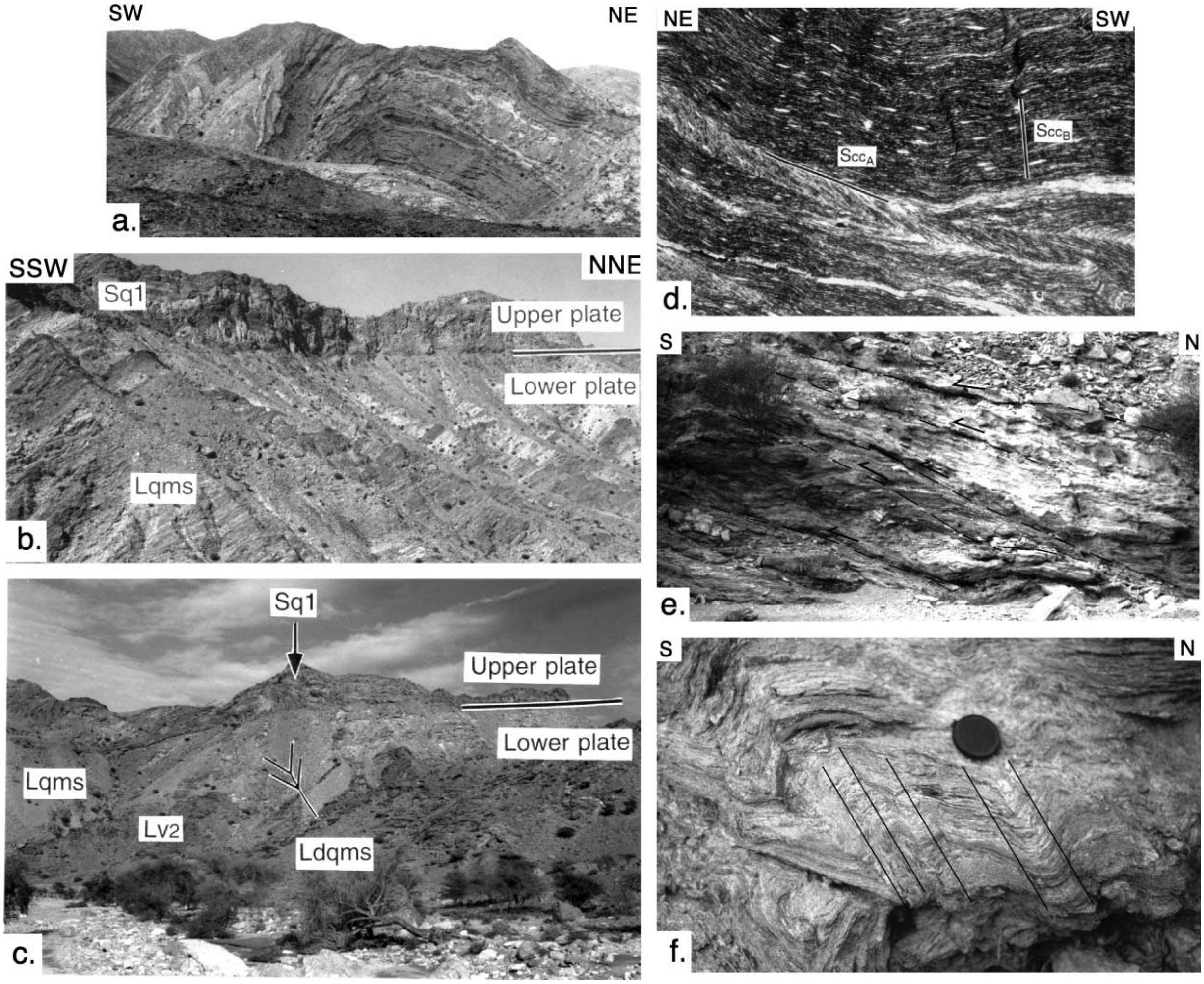


Fig. 4. (a) Ramp antiform defined by Maastrichtian sediments in the Yiti region. Field of view approximately 100 m. (b) Upper plate–lower plate contact on the western side of the As Sifah lower plate window, the discontinuity dips to the west. Upper plate units are Saiq 1 limestones (Sq1), lower plate units are predominantly quartz–mica schist (Lqms) with some mafic boudins. Field of view approximately 500 m. (c) Upper plate–lower plate contact on the northern side of the Hulw lower plate window, the discontinuity dips to the north. Folded upper plate Saiq 1 (Sq1) carbonates are truncated against the lower plate. The dolomite layers are disrupted into large boudins. The lower plate stratigraphy is overturned at this location with quartz–mica schist (Lqms) overlying mafic schist (Lv2) which overlies dolomite interbedded with quartz–mica schist (Ldqms). Approximate field of view 200 m. (d) North-vergent crenulation cleavage (Scc_A) being refolded by a more upright crenulation cleavage (Scc_B). Plane polarised light, base of photomicrograph 5 mm. (e) Late low-angle imbricate faults in lower plate quartz–mica schist just below the upper–lower plate contact in Wadi Hulw (breaks are located on Fig. 13b). Field of view approximately 20 m. (f) South-vergent crenulation cleavage associated with late brittle faults.

by massive Mahil dolomite. The differences in stratigraphy between the two plates indicate a significant component of displacement across this ductile break.

In the As Sifah window, the southern part of the western side is defined by a clear structural break that crops out in an escarpment west of As Sifah with upper plate limestone and dolomite juxtaposed against lower plate quartz–mica schist (Fig. 4b). West of Dhiqdah (Fig. 5) the two lower plate windows are only separated by a thin sliver of upper plate Saiq 1 limestone. To the north this contact is more difficult to identify because it juxtaposes strongly deformed, thinly bedded upper plate Saiq 3 dolomite with strongly deformed lower plate dolomites and quartz–mica schist.

In the Hulw Window, the upper–lower plate contact is sharply defined in the northern and western extremities, where overturned lower plate quartz–mica schist is juxtaposed against upper plate Saiq 1 limestone (Fig. 4c). The same contact is folded in the southern region with upper plate Ordovician Amdeh quartzite and siltstone juxtaposed with lower plate quartz–mica schists and thinly bedded dolomite. The folded nature of the contact, combined with the lithological similarities between some upper and lower plate units, made mapping this region of northeast Saih Hatat difficult. The eastern side of the Hulw window is marked by a region of higher topography where erosion has produced upper plate klippe in Saiq 1 limestone.

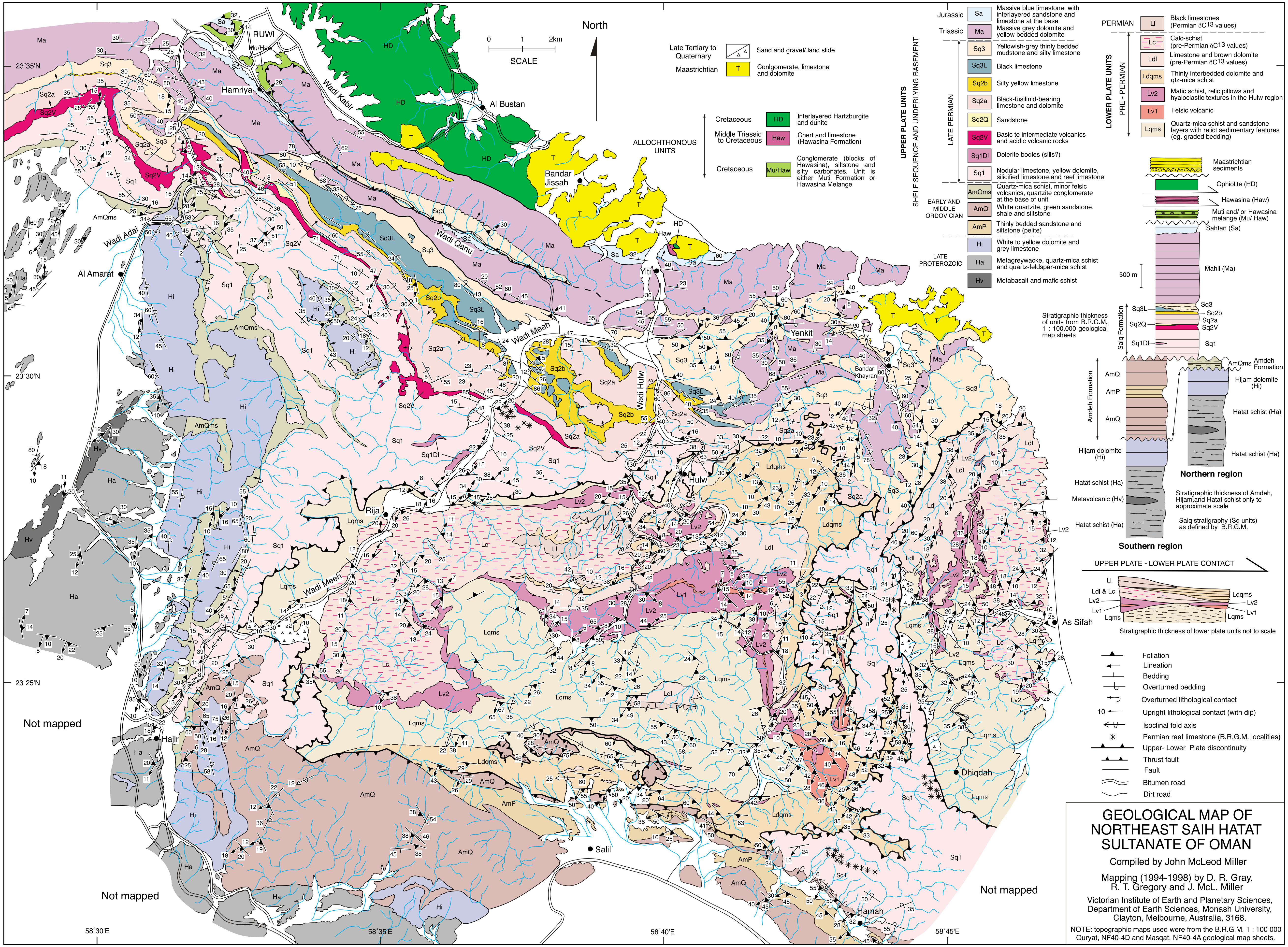


Fig. 5. Geological map of NE Saih Hatat based on 1:25,000 scale mapping onto aerial photographs.

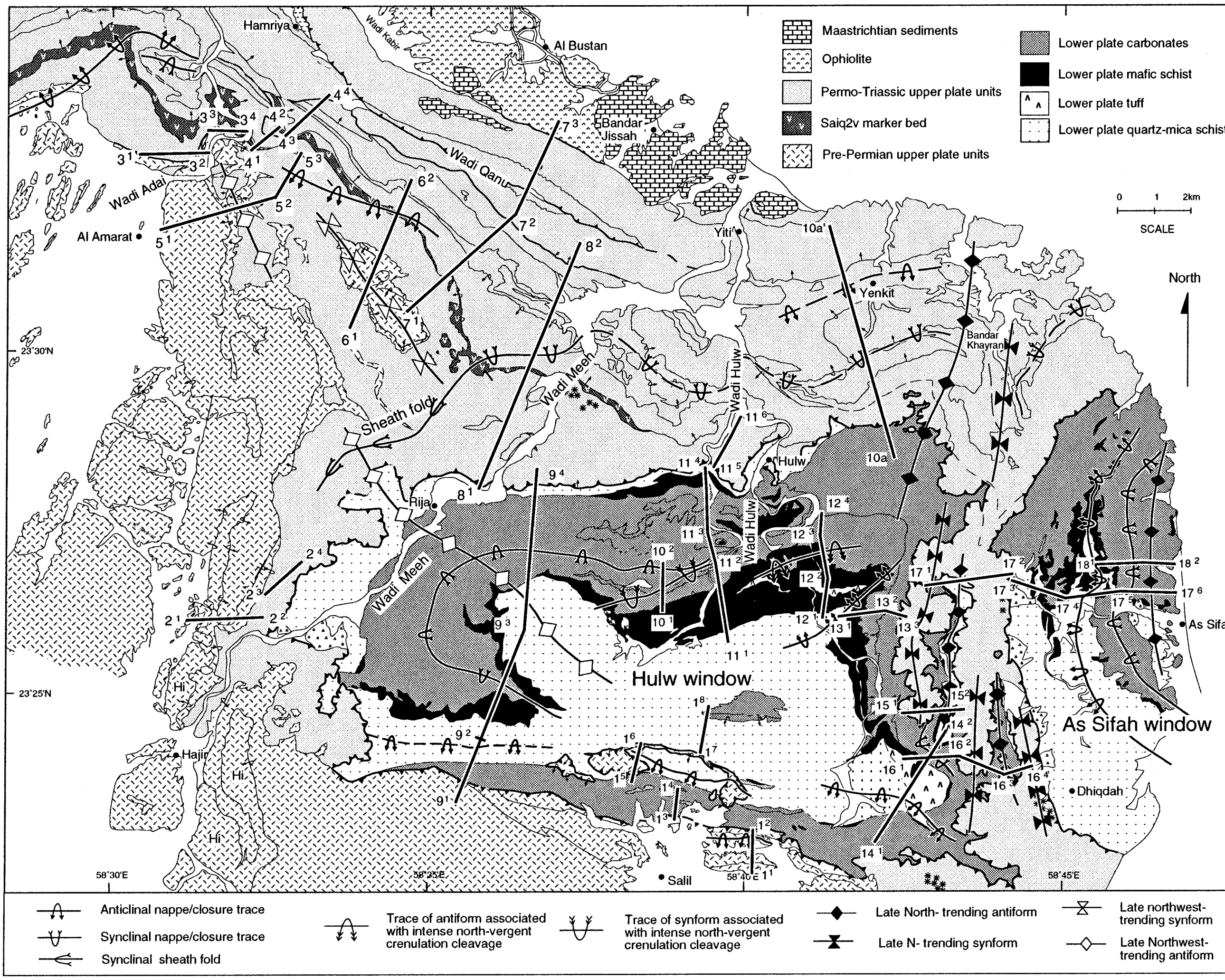


Fig. 6. Structural map of NE Saih Hatat showing positions of section lines for Figs. 8–11, 13, 14 and 16. Full description of lithologies (and abbreviations) are given in Fig. 5.

5. Structures associated with the reactivation of the upper–lower plate discontinuity

The upper–lower plate discontinuity appears to have had more than one generation of movement and, locally, there is imbrication and infolding of upper and lower plate sequences, resulting in fault-bounded slivers of upper plate units, surrounded by lower plate units (cf. the southern region of Figs. 5 and 6). This reactivation is associated with the development of north- and northeast-vergent asymmetric crenulation cleavages (Fig. 4d), and occasionally the development of macro-scale asymmetric closures.

The upper plate–lower plate contact on the southern side of the Meeh lower plate window is not a simple planar contact. The contact is defined by a series of klippe or inliers of upper plate Amdeh Formation (i.e. in-folded fault-bounded slivers surrounded by lower plate units; see Fig. 7). The upper plate Amdeh Quartzite units contain frequent low-angle imbricate faults, and rare C'-type shear bands that verge to the northeast. The lower plate sequences near these Amdeh inliers are in a very complex zone, with lenses of limestone, mafic schist and dolomite occurring sporadically with no stratigraphic continuity of units (unlike the lower plate sequences in other regions). Le Metour et al. (1986) explained the Amdeh outcrop pattern in this area via a series of imbricate faults producing massive Amdeh Quartzite inliers. Our mapping suggests that these upper plate inliers represent folded klippen defined by the hinges of synformal closures that refold the upper–lower plate discontinuity (as shown on section line 1, Fig. 7), but these hinges have been disrupted by later imbricate faulting.

The whole southern region of the Hulw lower plate window has developed north- or northeast-vergent closures associated with axial planar crenulation cleavages (Fig. 4d); this is particularly marked near the contact with the upper plate. There appear to be several generations of crenulation cleavages, the dominant set being inclined to the south. These are overprinted by later, more upright cleavages (Fig. 4d) that can also be found in the upper plate. The inclined crenulation cleavages are associated with extensive

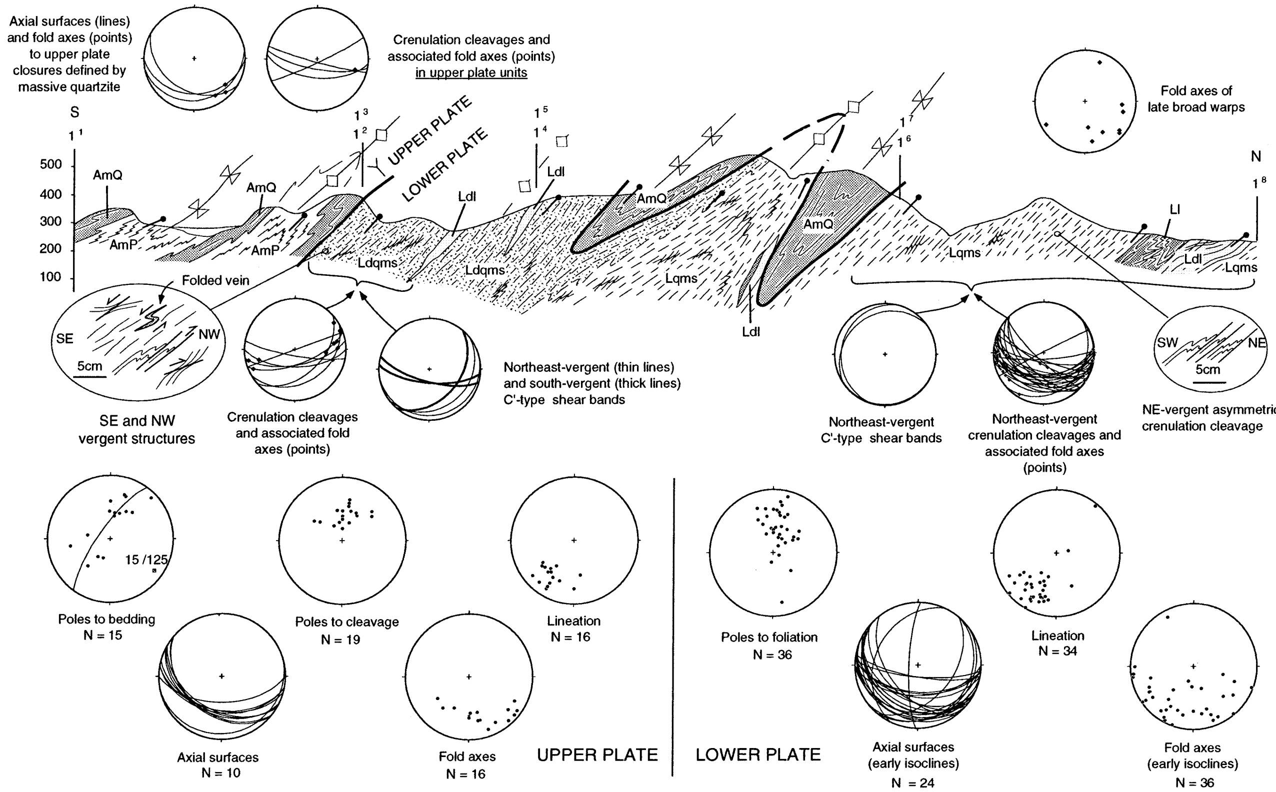


Fig. 7. Section line 1^1–1^7 highlighting the structural style on the southern side of the Hulw lower plate window. In map view the upper plate Amdeh Formation outcrops as fault-bounded slivers, these have been mapped as synformal closures disrupted by later brittle faulting. The lower plate rocks have extensive north-vergent crenulation cleavages, and in the direct vicinity of the upper plate there are also some south-vergent structures. Closures within upper plate pelitic units (AmP) have variably oriented hinges, while closures defined by massive Amdeh Formation quartzite (AmQ) are more cylindrical with hinges perpendicular to the upper plate lineation. The upper plate also contains some weak, steeply dipping, crenulation cleavages.

new mica growth and this is most prevalent in crenulation cleavages axial planar to the major north-vergent asymmetric refolds in the Hulw region. Quartz deformed by these closures shows signs of dynamic recrystallisation, but lacks evidence for later static recovery (and in this sense is similar to the rocks in the upper plate; cf. Fig. 8h).

Occasionally, in the immediate vicinity of the contact with the upper plate on the southern margin of the Hulw window, there are rare south-vergent asymmetric folds, and C′-type shear bands (section line 1, Fig. 7). These south-vergent structures can also be found along the southern margin of the lower plate in the upper plate Saiq 1. The Saiq 1 carbonates are disrupted by a series of low-angle imbricates, which often have south-vergent geometry (see detailed blowout on Fig. 9 — these low-angle south-vergent faults were also identified by Mann and Hanna (1990)). Late south-vergent structures are far more prominent on the northern side of the Hulw window (in Wadi Hulw itself; Wadi = dry river) where lower plate units in the direct footwall of the upper–lower plate discontinuity are disrupted by brittle faults that dip gently north (Fig. 4e). South-vergent, asymmetric crenulation cleavages are extensively developed in association with these faults (Fig. 4f), but they die out approximately 500 m away from the contact with the upper plate. These crenulation cleavages fold earlier sodic–calcic amphiboles and chlorite and thus texturally post-date the retrograde overprint in the lower plate associated with the formation of the regional lower plate closures. Small zones of cataclastic deformation in the footwall zone of the upper–lower plate discontinuity are also common.

6. Structural style of the upper plate

6.1. Early recumbent folds

Structures within the upper plate consist of a series of regional recumbent folds that initially substantially thicken the stratigraphy, but at lower structural levels become more attenuated and sheath-like (Fig. 3). Deformation associated with the early recumbent closures has produced a consistent north- to northeast-trending stretching lineation in the upper plate (Fig. 5). This is defined by pressure shadows on framboidal pyrites, the long axes of deformed clasts in conglomerate units, mineral lineations defined by white mica, and more rarely by the long axes of pencils that form in units adjacent to the Saiq 2v volcanics.

In the vicinity of the lower plate, the upper plate carbonates are deformed into recumbent, isoclinal folds (Fig. 8a).

Transposition foliation develops with pressure shadows on pyrite indicative of high strain (Miller et al., 1998), with dolomite layers disrupted into large boudins (Fig. 4b). The folds within the upper plate limestones and dolomites have limbs extending for several kilometres (Fig. 6), and strong axial planar fabrics. These folds have cylindrical form with fold axes at high-angles to the stretching lineation at the highest structural levels, but the lower closures are sheath-like and have hinges sub-parallel to the stretching lineation (Fig. 3). These changes are accompanied by a marked increase in *X*/*Z* strain with values up to 170:1 for limestone at the base of the upper plate (Miller et al., 1998). The thickness of the upper plate nappes between the contact with the lower plate in Wadi Meeh and the tectonic contact with the overlying Hawasina and ophiolite sequence, is no more than 5 km (Fig. 2b).

The current orientations of the axial surfaces (and fold axes) of upper plate structures directly reflect the geometry of the tectonic windows that expose the lower plate units. In the Wadi Adai region (Fig. 5), the majority of the axial surfaces of parastic folds on the limbs of the regional closures dip to the northwest or west. In the region south of the Hulw lower plate window (Fig. 5) the axial planes dip to the south, whereas in the Bandar Khayran region (Fig. 5) they dip to the north. This has resulted in the early recumbent closures having both upwards and downwards facing attitudes, depending on their position with respect to the lower plate windows. This is reflected by closures in the Bandar Khayran region where lithological and mesoscopic structural relationships between the Saiq 3, and the Mahil dolomite, suggests the region contains a series of large, downwards facing, closures (Fig. 10). There is also significant loss of upper plate stratigraphic section in the Bandar Khayran with Saiq 2a and Saiq 3 juxtaposed with the lower plate, whereas further south Amdeh and Saiq 1 are truncated against the lower plate (Fig. 10).

The upper limb of the regional anticlinal closure that encompasses the majority of Saih Hatat is defined by a large asymmetric closure that encompasses the entire hillside of Jebel Qirmadil (Fig. 8b; this closure is projected above section line 3 in Fig. 11). Below this is a complex zone with extensive low-angle imbricate faults, isoclinal closures and variable stratigraphic units (section line 3, Fig. 11). In the Wadi Adai area dark grey Saiq 1 limestone is disrupted into large boudins, which contain tight to isoclinal closures cut by a series of faults that are at a low-angle to bedding and the enveloping surface between the limestone and quartz–mica schist. The overall gross anticlinal structure is most easily identified by the change in dip (and stratigraphic younging) of the Saiq 2v volcanic unit (cf. Sq2v in Fig. 11). This unit is a useful 'marker bed' because it has acted as a stiff competent layer, unlike the carbonate sequences, which form tighter, isoclinal closures. Furthermore it can be traced across the entire northern side of the Saih Hatat Window (Fig. 2).

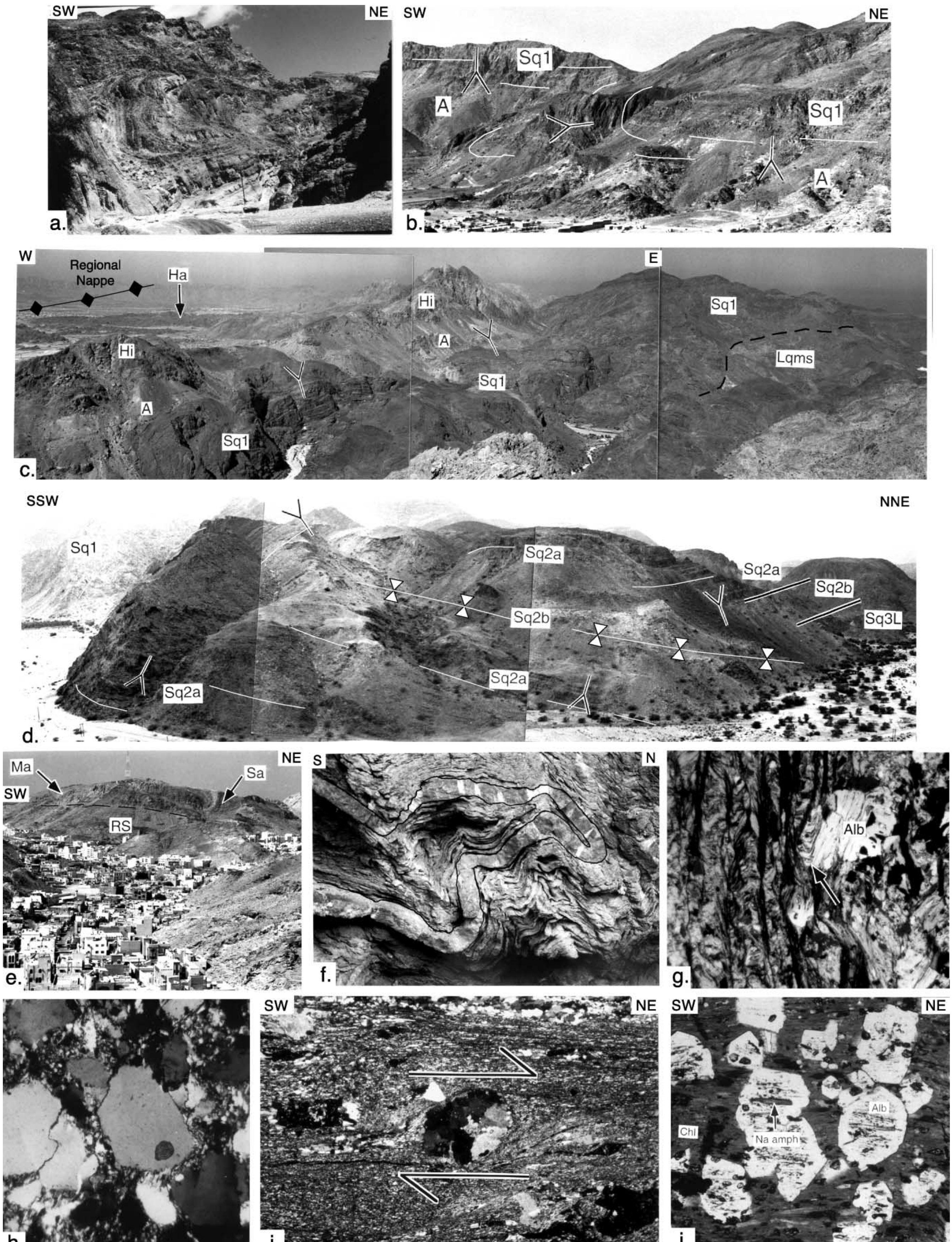
Below the complex anticlinal hinge zone is a major recumbent syncline (Fig. 9 and section lines 6–8, Fig. 11), which is the dominant structure in this region of the upper plate. A large expanse of Hatat schist and Hijam dolomite defines the overturned limb of this syncline on the most southwestern extremity of Wadi Meeh (Figs. 8c and 9). The lower limb of this closure is truncated by the upper–lower plate discontinuity. The closures in the Saiq 1 limestone are sheath-like and have axes with variable orientations with some parallel to the stretching lineation (stereonets, Figs. 2, 9 and 11). These closures are disrupted by a series of low-angle faults that have a duplex-like form with a top-to-the-south movement sense (inset Fig. 9 — faults also identified by Mann and Hanna (1990)).

This major synclinal closure can be traced across the western side of the Wadi Hulw lower plate window, and part of the upper limb is defined by isolated inliers of overturned Hijam dolomite (section line 6, Fig. 11). The hinge of the regional recumbent synclinal closure is again exposed at Wadi level in the northern part of Wadi Meeh (Fig. 8d and Section line 8, Fig. 11). The Saiq 2v volcanics defining the hinge are disrupted by a series of late brittle faults that dip steeply to the northeast.

Not all of the closures with variably oriented axes can be related to the units' proximity with the lower plate. In some areas thinner bedded units show folds with extreme fold axis variability, while more massive units have cylindrical hinges. This occurs on the southern flank of the Hulw lower plate window, where upper plate Amdeh units have been folded into a series of isoclinal closures, whose lower limbs are generally truncated against the contact with the lower plate. The pelitic units 'sandwiched' between the quartzite layers contain extensive mesoscopic closures with variably oriented fold axes, while the quartzites form major, macroscale hinges with cylindrical form and axes perpendicular to the stretching lineation (stereonets, Fig. 7). Similar features are also observed in the Bandar Khayran region, where thinner bedded Saiq 3 units, surrounded by massive Mahil dolomite (Fig. 10), have closures with markedly varying directions.

6.2. Late faulting within the upper plate

A major northeast-dipping break separates the shelf carbonate succession from the overlying ophiolite and imbricated slivers of Hawasina (Fig. 5). Slickensides on the fault surface have both steep and flat-lying attitudes. Structurally below this major break, north of the lower plate windows, earlier ductile features associated with the early recumbent closures are truncated by northeast-dipping faults. The largest of these faults is a major, northeast-dipping, break in the Ruwi area that emplaces Mahil and Sahtan units over the top of intensely deformed mudstone and siltstone (Figs. 5 and 8e). There is paucity of shear sense indicators associated with this break, although previous workers have argued it has a top-to-the-south movement sense (Michard et al., 1984; Le Metour et al., 1986), and


SW
NE
a.
SW
NE
Sq1
A
Sq1
A
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W
Regional
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Lqms
A
Sq1
Sq1
c.
SSW
NNE
Sq1
Sq2a
Sq2a
Sq2b
Sq2b
Sq3L
Sq2a
Sq2a
d.
Ma
NE
Sa
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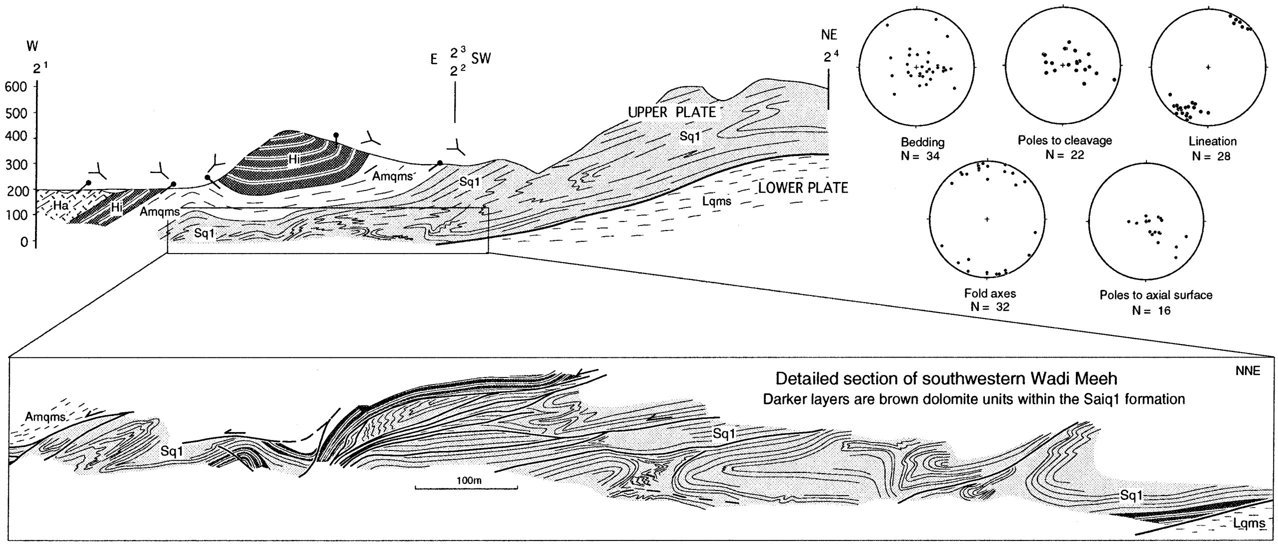


Fig. 9. Structural section and detailed blowout of upper plate units in southern Wadi Meeh (also covered by photos in Fig. 8c) in fault contact with lower plate quartz–mica schist (Lqms). Pre-Permian units (Hatat schist — Ha; Hijam dolomite — Hi; Amdeh quartz–mica schist — Amqms) clearly overlie the Permian Saiq limestones (Sq1). Note the south-vergent faults and fold hinges with variably oriented axes. Stereonets are equal area projections. Full description of lithologies (and abbreviations) is given in Fig. 5.

the break does cause repetition of Mahil and Saiq 3 units. The break runs south of Hamriya along Wadi Qanu (cf. Section line 7, Fig. 11), where it either dies out or is obscured by the monotonous sequences of Mahil Formation near Yiti (Fig. 5). Isolated slivers of serpentinite, surrounded by strongly foliated dolomite, occur in the footwall region of this fault in the northern Wadi Adai area. These serpentine units require similar structural breaks in Mahil or Sahtan units below the major break in Wadi Qanu that were not identified by the 1:25,000 mapping (or alternatively a series of splays off the major fault). In some regions some of these northeast-dipping faults can be identified by stratigraphic repetition of Saiq 2v volcanics (e.g. section lines 3 and 4, Fig. 11), but the faults often appear to lose displacement and 'die out' along strike.

There are also a series of more steeply dipping faults that disrupt the hinge of the major synclinal closure in Wadi Meeh; the largest of these juxtaposes Mahil dolomite against older Saiq 3 units (section line 8, Fig. 11). The footwall is disrupted by a series of smaller brittle breaks that are associated with inclined closures that refold the earlier recumbent closures (Fig. 8f and detail on section line 8, Fig. 11). The other northeast-dipping breaks with shallower dips do not show this style of deformation in the footwall. The asymmetry of these folds in the footwall suggests the larger fault has reverse displacement

Fig. 8. (a) Recumbent folds defined by upper plate Saiq 1 limestone in southern Wadi Meeh close to the contact with the lower plate. Telegraph pole provides scale. (b) Asymmetric closure within Saiq 1 limestone (Sq1) defining the upper part of the regional anticlinal structure in Saih Hatat. This closure dominates the northwestern flank of the Saih Hatat window. (c) Overturned lower limb of the regional anticline in the upper plate (the trace of which is marked on Fig. 2). The view is looking northwest into southern Wadi Meeh. Note that the stratigraphy is completely overturned, the Hatat Schist (Hi) and Hijam dolomite (Hi) are pre-Permian, while the Saiq 1 (Sq1) is Permian. Lower plate quartz–mica schist (Lqms) is also shown, but the upper–lower plate contact is obscured by rubble. (d) Outcrop exposure of the regional synclinal hinge (which in this area is cored by Saiq 2b dolomite) in northern Wadi Meeh. This collage of photos depicts the central part of section line 8 (Fig. 11). (e) Major structural break in the Hamriya region. Lawsonite bearing Ruwi Schist (RS) is tectonically overlain by folded Triassic Mahil dolomite (Ma) and Jurassic Sahtan limestone and dolomite (Sa). (f) Early recumbent folds refolded by a south-vergent fold set. These south-vergent closures are below the steeply dipping fault that separates the Mahil from the Saiq 3 on section line 8 (cf. structural blowout in Fig. 11). Field of view approximately 1 m. (g) Crenulation cleavage axial planar to parasitic folds within the pre-Permian Amdeh Formation (on the lower limb of an upper plate regional closure). Albite porphyroblasts (Alb) have overgrown the folded layers (see area highlighted by arrow) and do not pre-date this cleavage forming event, although some of the pressure solution appears to post-date albite growth. Crossed polars, base of photomicrograph approximately 2.3 mm. (h) Photomicrograph of a sandstone layer interbedded with Saiq 2a carbonate in the Wadi Adai region. Note grain size reduction from dynamic recrystallisation and also pressure solution along the grain boundaries of detrital quartz grains. Crossed polars, base of photomicrograph approximately 2.3 mm. (i) Asymmetric strain shadows around quartz/carbonate porphyroblasts from a sample of the Amdeh Formation (quartz–mica schist unit in the Wadi Adai region), these give a top-to-the-northeast shear sense. Crossed polars, base of photomicrograph approximately 2.3 mm. (j) Photomicrograph of a mafic unit infolded with upper plate carbonates in the northern Wadi Meeh region. These mafic bodies (SqDl) in the upper plate are located on section line 8 (Fig. 11). Chlorite (Chl) and sphene are the dominant minerals in the matrix. Relict sodic amphibole (Na amph) is included in the albite porphroblasts. Plane polarised light, base of photomicrograph approximately 2.3 mm.

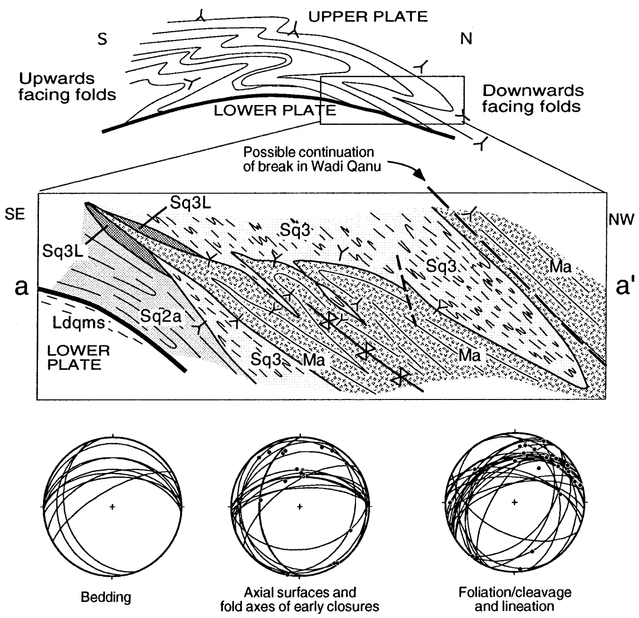


Fig. 10. Schematic profile for the Yenkit and Bandar Khayran regions. Section line marked as 10a–10a′ in Fig. 6. Earlier structures are refolded by late north-trending folds, which are highlighted by the outcrop pattern of the Mahil dolomite (Ma) in this region. Reversals in stratigraphic relationships in this region suggest that a series of tight to isoclinal folds have produced overturned and upright contacts between the Saiq 3 (Sq3) and Mahil Formations. Dome and basin fold interference pattern has reoriented these earlier closures into downwards facing attitudes. Note the variable fold axis and lineation trends on the stereonets (equal area projections).

(top-to-the-southwest). These later closures are cylindrical, have axes that plunge to the southeast (stereonets on section line 8, Fig. 11), and are associated with a northwesterly dipping crenulation cleavage that is extensively developed in the Saiq 3 dolomite in this region of the upper plate.

Finally, there is a late set of steeply dipping normal faults that occur sporadically throughout northeast Saih Hatat. These generally trend due north, dip steeply to the west, have minor displacement, and locally disrupt the Hawasina Formation exposed near Yiti.

6.3. Microstructure and metamorphism associated with upper plate structures

Upper plate peak assemblages are distinguished by the presence of carpholite, lawsonite and sodic amphibole; garnet is not present. Based on the absence of aragonite and the inferred stability fields of magnesio–carpholite, ferro–carpholite and chloritoid, El-Shazly (1994, 1995) argues that these upper plate units were metamorphosed between 6.8 and 9 kbar and 315 and 435°C. Alternatively, for most of the upper plate, Goffé et al. (1988) estimate *P–T* conditions ranging from 8 to 10 kbar and 180 to 250°C for carpholite–kaolinite assemblages and approximately 6 to 8 kbar and 250 to 350°C for Fe/Mg carpholite–pyrophyllite assemblages.

6.3.1. Microstructure of pre-Permian units

Pre-Permian units (Hatat Schist and Amdeh Formation) contain extensive crenulation cleavages that are axial planar to the upper plate nappes and are associated with extensive new mica growth and pressure solution. Inclusion trails in albite porphyroblasts suggest that albite growth occurred after some of the deformation related to the formation of the crenulation cleavage had occurred (Fig. 8g). Unlike many of the lower plate quartzites, quartz-grains show extensive undulose extinction, have irregular grain boundaries, and extensive sub-grains with little sign of static recovery processes.

6.3.2. Microstructure of Permian units

Permian units show similar deformation microstructures to the pre-Permian sequences with pressure solution, and dynamic recrystallisation being the dominant deformation mechanism affecting both calcite and quartz. Coarse grained metagreywackes have detrital sedimentary grains that have been affected by pressure solution and mica growth, with minor effects from dynamic recrystallisation (Fig. 8h). In carbonate units, grain boundary migration has produced elongate calcite grains that are accentuated by pressure solution. Asymmetric shear sense indicators are rare, but some limestone units at the base of the nappe pile, close to the contact with the lower plate, have asymmetric pressure shadows on framboidal pyrite and asymmetrically sheared clasts that suggest a top-to-the-northeast sense of shear (Fig. 8i). Crenulation cleavages define axial planar fabrics to some regional nappes associated with axial planar mica growth.

6.3.3. Microstructure of mafic units

Mafic units that are interleaved and folded with Saiq 1 limestones in the Wadi Adai region (SqDl on section line 8, Fig. 11), have textural relationships that suggest the recumbent folds formed during decreasing pressure (or at least at a lower pressure with respect to the peak metamorphic pressure recorded by minerals such as sodic amphibole and carpholite). Chlorite defines the axial planar fabric to these regional fold-nappes, with sodic amphibole included as relicts within the albite porphyroblasts (Fig. 8j). Sphene is also a common matrix mineral in these mafic schists. The included amphibole is aligned in a similar orientation to the minerals in the matrix, and the fabric within the albite porphyroblasts appears to be continuous into the matrix with some relic sodic amphibole occasionally preserved with the matrix minerals. Chlorite, which is ubiquitous in the matrix, is rarely preserved as inclusions within the albite porphyroblasts.

7. Structural style of the lower plate

The lower plate shows the pervasive effects of intense, northeast-directed non-coaxial shear which has produced

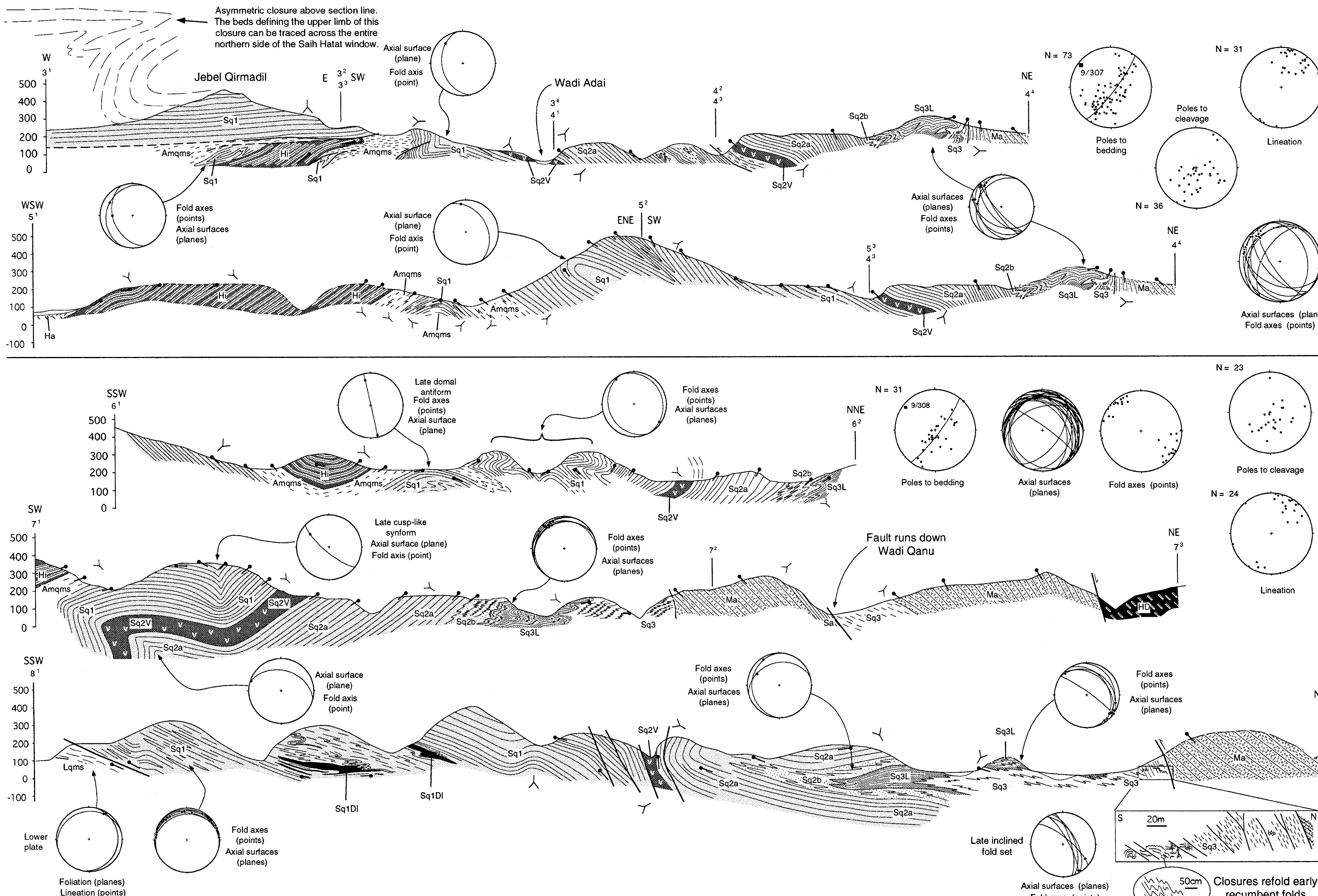


Fig. 11. Section lines depicting upper plate structures between Wadi Adai and Wadi Meeh. Note the variation in fold axis trends along section line 8. Stereonets are equal area projections.

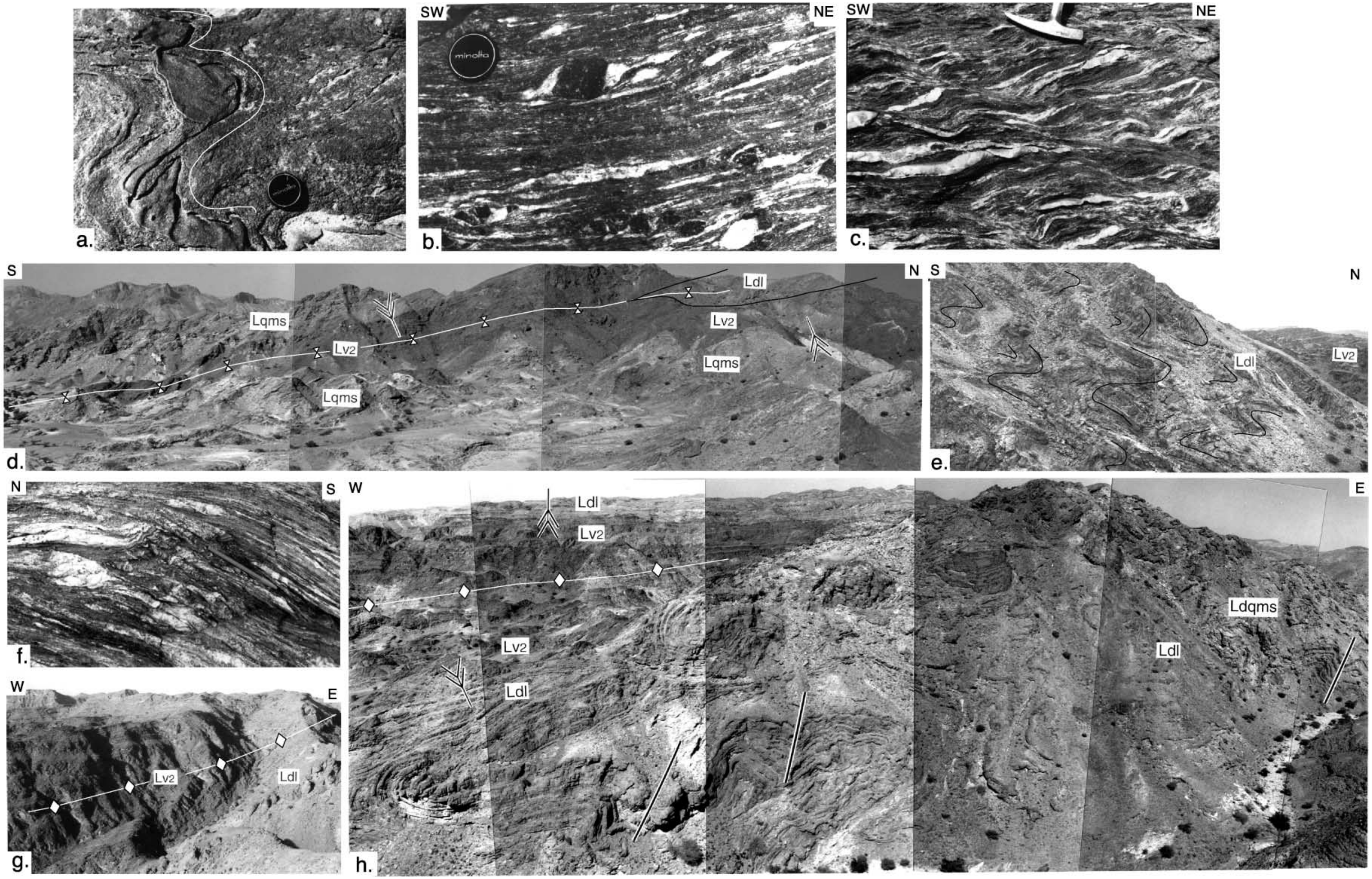


Fig. 12. (a) Sheath folds within lower plate calc schist (Wadi Meeh). Lens cap is 5 cm in diameter. (b) Asymmetric pressure shadows around limestone clasts in a calc-schist from Wadi Meeh that have a top-to-the-northeast shear sense. Lens cap is 5 cm in diameter. (c) C′-type shear bands in a calc-schist (As Sifah region). Geological hammer head for scale. (d) Regional synclinal closure in the Hulw lower plate window (depicted on section line 9, Fig. 13a). Field of view approximately 600 m. (e) 'Cascading' folds associated with the major north-vergent asymmetric fold (depicted on section lines 10–12, Fig. 13b). Field of view approximately 200 m. (f) North-vergent crenulation cleavage in a lower plate quartz–mica schist. Pencil for scale. (g) Hinge of regional anticlinal closure that is the dominant structure in the northeastern part of the Hulw lower plate window (depicted on section line 13, Fig. 14a). Field of view approximately 200 m. (h) Collage of photos depicting the lower limb of the anticlinal structure in the previous figure. The upper limb can be seen in the background. The earlier closures are refolded by later north-trending closures (marked with lines on the photo). Note the different colour of the two lower plate carbonate units, i.e. the dolomite and carbonate unit (Ldl) versus the dolomite interbedded with quartz–mica schist (Ldqms). Field of view approximately 500 m.

schistose L–S tectonite fabrics, and sheath-folds at all scales (Fig. 12a). Shear sense indicators include C- and C′- shear bands (cf. Passchier and Trouw, 1996), asymmetrically sheared clasts and pressure shadows around porphyroblasts (Fig. 12b and c). Deformed conglomerates and calc schists within the lower plate indicate a component of flattening accompanied by marked stretch in *X*, the maximum principal elongation direction. This produces flattened 'cigar-like' forms and extensive shear bands.

The lower plate tectonostratigraphy is folded by a series of sheath-like regional recumbent folds (e.g. Fig. 12d). Structural analysis of the lower plate is complicated in some regions by major lensing of the volcanic and carbonate units. High strain is associated with tight to isoclinal, sheath-like parasitic folds on the limbs of the closures (Miller et al., 1998), which makes using fold asymmetry to define the gross structure unreliable. The early regional closures are readily identified by the outcrop trace of the lower plate mafic units and also by reversals in the lower plate tectonostratigraphic stacking order of the sequences (i.e. carbonates overlying mafic units which overlie quartz–mica schist) (Figs. 5 and 6). The terms synclinal and anticlinal are used to reflect changes in the 'younging' of the lower plate tectonostratigraphy (marked as a doubled headed inverted Y on the section lines). The early closures in the lower plate can also be distinguished by the strong axial planar schistosity, as later folds have a closely spaced axial surface crenulation cleavage. In both exposed lower plate windows, these regional closures are associated with a marked northeast-trending stretching lineation (Fig. 5), that is marked by fibres within pulled-apart limestone clasts and boudin-necks, vein sets orthogonal to the lineation, and pressure shadows on pyrite. The sheath-like nature of the regional closures has resulted in north–south outcrop traces for these closures in the As Sifah region, which are sub-parallel to the stretching lineation (Fig. 6). Outcrop traces of regional closures in the Wadi Meeh and Hulw subdomain window of the lower plate reflect strong fold interference (Fig. 6).

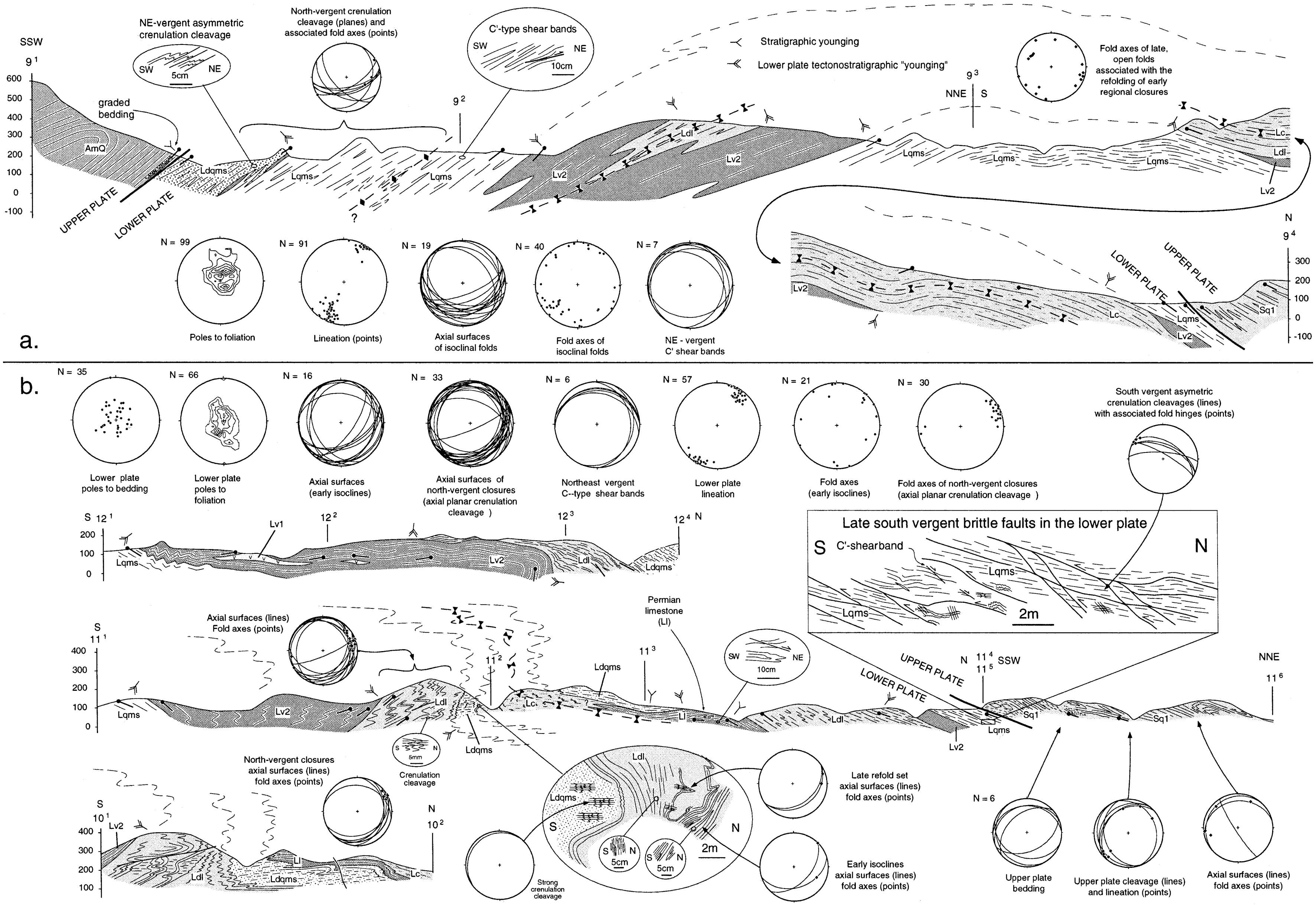
A schematic section that incorporates the observed variations in lower plate structure in the Hulw window, as well as linking the two lower plate windows through Jebel abu Daud is shown on Fig. 3. This diagram highlights the difficulty of producing 2D sections summarising the lower plate closures (and also for the upper plate nappe structure). The lower plate closures have formed in a very broad zone of intense non-coaxial shear, with thinner-bedded units deforming at a totally different wavelength to the mafic units; i.e. the different formations have structures reflecting intense non-coaxial shearing, but at different scales. As a result, the axial surfaces of these closures are difficult to trace along strike into adjacent quartz–mica schist and carbonate units. The only areas where fold vergence appears to have any reliability is where the closures are defined by mafic units. The regional lower plate closures are non-cylindrical, with discontinuous hinges. The As Sifah closures are at the lowest structural level, with a major synclinal closure in the Hulw window being at a higher level with respect to the enveloping surface of the lower plate (Fig. 3). Mafic boudins that contain the eclogites in the As Sifah window are at the structurally lowest level. There appears to be a structural break in the lower plate defined by a disturbed zone in the western region of the As Sifah lower plate window (Fig. 3). This is associated with what appears to be a significant change in metamorphic grade ('garnet in' isograd of Le Metour et al. (1990)).

7.1. Hulw lower plate window

The dominant structure in the western part of the Hulw window is a large synclinal closure (Figs. 5, 12d and 13a (section line 9) — synclinal closure also identified by Le Metour et al. (1986, 1992)). This is cored by a calc schist that has extensive northeast-vergent asymmetric closures, pull-apart limestones and C- and C′-type shear bands that all give top-to-the-northeast sense of shear. The synclinal closure is folded over a broad, doubly-plunging, domal antiform that has a general northwest trend. The tectonostratigraphic units to the south of this closure change back to a 'right-way up' orientation which suggests there may be an anticlinal closure structurally above this syncline, that is largely faulted out by the upper–lower plate discontinuity.

Further to the east in Wadi Hulw proper, the position of the synclinal hinge can be identified by a change in lower plate younging (section line 11, Fig. 13b — compare the start and finish of the profile). The inferred hinge zone is a major lens of dark grey to black limestone that is stratigraphically similar to some of the Permian upper plate limestone. This limestone also has Permian $\delta^{13}C$ values (R.T. Gregory, unpublished data), but unlike the upper plate limestone it has undergone strong non-coaxial shear. The current structural position of this unit, being surrounded by pre-Permian sequences, is consistent with its inferred position in the hinge of major lower plate syncline. This synclinal closure is refolded in the Hulw region by a major asymmetric closure (Figs. 5, 6 and 13b (section lines 10, 11 and 12)). This refolding has produced a spectacular series of 'cascading' closures in the dolomite layers that have axes that plunge to the east (Fig. 12e), with strong axial planar crenulation cleavages. North-vergent asymmetric crenulation cleavages are commonly developed in adjacent quartz–mica schist (Fig. 12f).

Further to the east the regional synclinal closure is underlain by a large anticlinal closure within mafic units (Figs. 12g and h and 14a (section line 13)). A series of tight to isoclinal closures in the carbonates on the overturned lower limb of this closure define a synclinal closure, which makes the overall geometry asymmetric in form. These closures are refolded by a later, upright, north-trending fold set (Fig. 12h). The axial surface of this major asymmetric closure can be traced along strike to the south. In the most southwestern corner of the Hulw lower plate window, the


a.
SSW
NNE
S
N
UPPER PLATE
LOWER PLATE
graded bedding
AmQ
Ldqms
Lqms
Lv2
Ldl
Lc
Sq1
NE-vergent asymmetric crenulation cleavage
SW
NE
5cm
North-vergent crenulation cleavage (planes) and associated fold axes (points)
C'-type shear bands
10cm
Stratigraphic younging
Lower plate tectonostratigraphic "younging"
Fold axes of late, open folds associated with the refolding of early regional closures
N = 99
Poles to foliation
N = 91
Lineation (points)
N = 19
Axial surfaces of isoclinal folds
N = 40
Fold axes of isoclinal folds
N = 7
NE - vergent C' shear bands
b.
N = 35
Lower plate poles to bedding
N = 66
Lower plate poles to foliation
N = 16
Axial surfaces (early isoclines)
N = 33
Axial surfaces of north-vergent closures (axial planar crenulation cleavage)
N = 6
Northeast vergent C--type shear bands
N = 57
Lower plate lineation
N = 21
Fold axes (early isoclines)
N = 30
Fold axes of north-vergent closures (axial planar crenulation cleavage)
South vergent asymetric crenulation cleavages (lines) with associated fold hinges (points)
Late south vergent brittle faults in the lower plate
C'-shearband
2m
Lv1
Permian limestone (Ll)
Ll
Axial surfaces (lines) Fold axes (points)
Crenulation cleavage
5mm
North-vergent closures axial surfaces (lines) fold axes (points)
Strong crenulation cleavage
Late refold set axial surfaces (lines) fold axes (points)
Early isoclines axial surfaces (lines) fold axes (points)
N = 6
Upper plate bedding
Upper plate cleavage (lines) and lineation (points)
Axial surfaces (lines) fold axes (points)

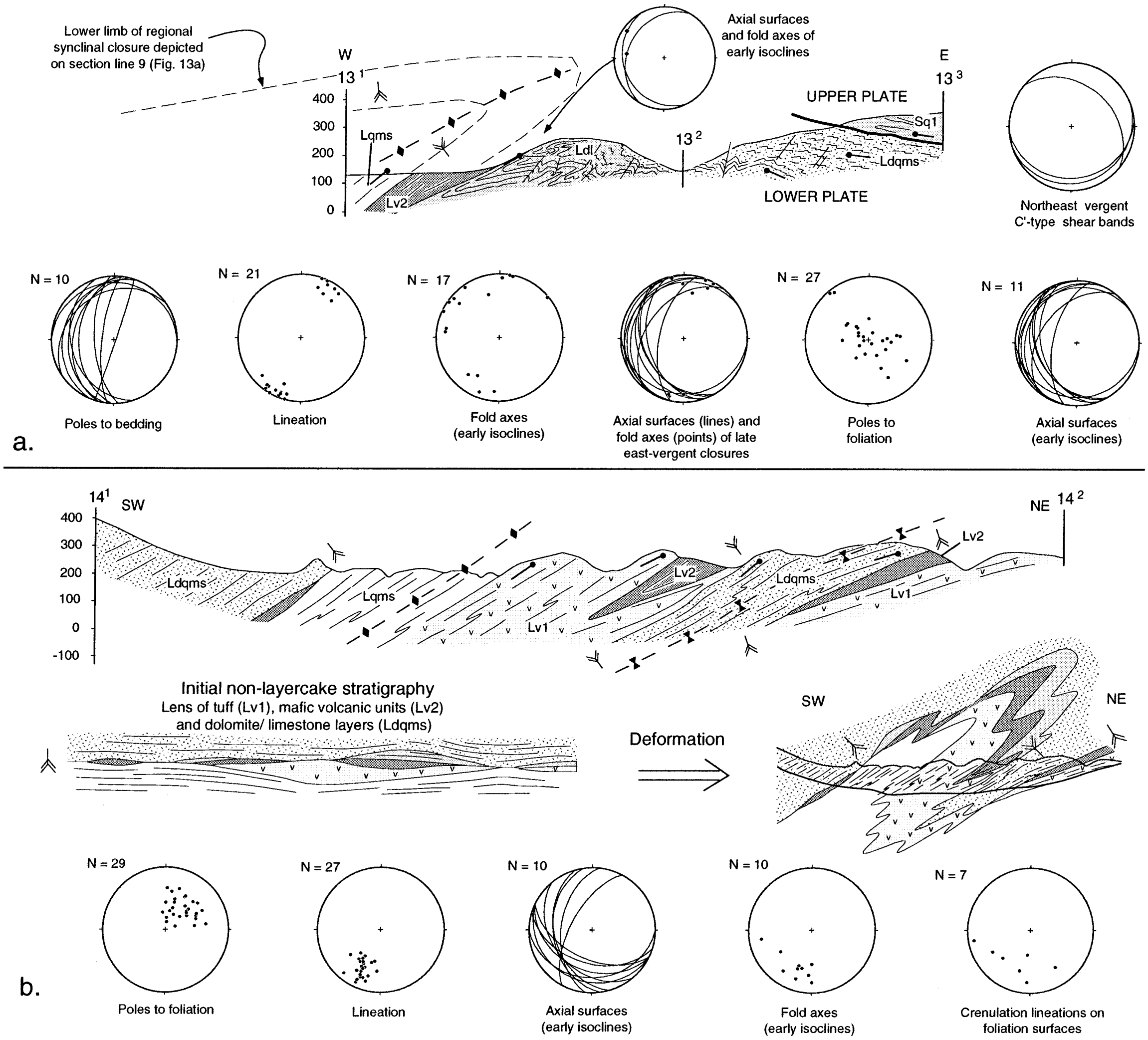


Fig. 14. (a) Section line summarising the lower limb of the regional closure in the northeastern part of the Hulw lower plate window. The projected hinge above the section is the same as that shown in Fig. 12g, and the majority of this section is also summarised by the collage of photos in Fig. 12h. (b) Section line depicting large asymmetric closure in the eastern part of the Hulw window. The geometry is 'obscured' by the lens-like nature of the lower plate tectonostratigraphy.

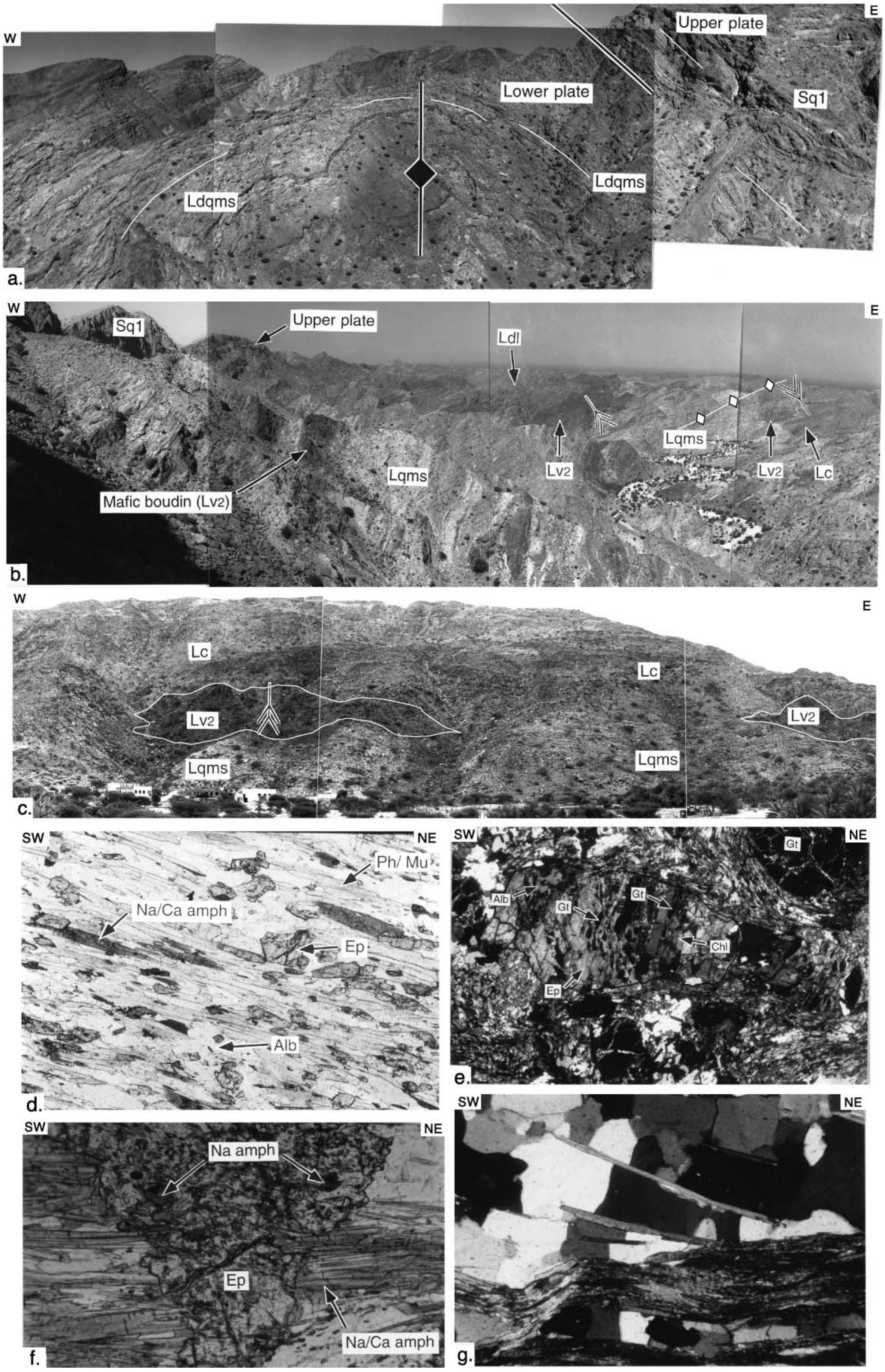
overall geometry is still that of a major asymmetric fold that verges to the northeast, although the structure is complicated by the non-layercake nature of the stratigraphy (section line 14, Fig. 14b).

From west to east across the Hulw window there is a lack of continuity of some of the major closures in the lower plate. For example tracing the axial surface of the regional synclinal closure along strike is problematical, and this hinge is not present on the eastern side of the window (the projected position runs through the anticlinal structure on section line 14, Fig. 14b). Part of the difficulty is due to the change in wavelength of deformation between mafic units and the adjacent quartz–mica schists and carbonates (which have deformed at a much smaller wavelength).

7.2. Region between the two lower plate windows

The two lower plate exposures, are separated by a

Fig. 13. (a) Structural profile through the western side of the Hulw lower plate window. The dominant structure is a synclinal closure that is refolded over a later broad antiform. Parasitic folds in the lower plate are sheath-like (stereonets are equal area, stereonet contour interval 2%/1% area). (b) Section through the northern part of the Hulw lower plate window along Wadi Hulw west. The dominant structural feature is a major, north-vergent, asymmetric fold that refolds an earlier synclinal closure. These asymmetric refolds are associated with a strong crenulation cleavage. The inferred earlier synclinal closure is identified by a change in the 'younging' of the lower plate tectonostratigraphy (see 'younging' indicators on the section line). On the southern part of the section the units are 'right-way up' while on the northern side, just below the contact with the upper plate, they are overturned (these overturned units are also shown in Fig. 4c). The core of the inferred synclinal closure is defined by a limestone unit (Ll) that has Permian δC^{13} values. South-vergent low-angle brittle faults occur in the direct vicinity of the contact with the upper plate.


W
E
Upper plate
Lower plate
Sq1
Ldqms
Ldqms
a.
W
Sq1
Upper plate
Ldl
E
Lqms
Lv2
Lv2
Lc
Mafic boudin (Lv2)
Lqms
b.
W
E
Lc
Lc
Lv2
Lv2
Lqms
Lqms
c.
SW
NE
Ph/ Mu
Na/Ca amph
Ep
Alb
d.
SW
NE
Gt
Alb
Gt
Gt
Chl
Ep
e.
SW
NE
Na amph
Ep
Na/Ca amph
f.
SW
NE
g.

topographic high comprised of upper plate carbonates (Figs. 5, 15a and b and 16). The two lower plate windows are at similar topographic levels, and in some regions the two lower plate exposures are only separated by a thin sliver of upper plate rocks. The relatively flat-lying schistosity in the Hulw window is at a similar structural level to the lower plate quartz–mica schist in the westernmost exposure of the As Sifah lower plate window (section line 17, Fig. 16).

The zone that separates the two lower plate closures has outcrop trends that are controlled by a strong north–south trending fold set that refolds the earlier closures (Figs. 15a and 16). The closures that refold the earlier structures have upright to inclined, north-trending, axial surfaces, and fold axes that plunge to the north (stereonets, Fig. 16). Upper plate klippe have complex internal structure as a result of fold interference between earlier isoclinal folds and the north-trending fold set. The north-trending closures become tighter from west to east, and the tighter closures are associated with strong crenulation cleavages. In places the upper plate–lower plate contact is overturned.

The overall geometry of the later refold set is a large east-vergent asymmetric closure. This is clearly illustrated further to the north where the Saiq 3 and Mahil dolomites are refolded into a large asymmetric fold with a rounded antiformal hinge, and a tighter synformal closure (note the outcrop pattern of Mahil dolomite in Fig. 5). This refold pattern of the upper plate units is responsible for the gross refolding of the lower plate schistosity, that results in the units re-emerging, in the As Sifah window.

7.3. As Sifah lower plate window

The westernmost exposure of the lower plate at As Sifah (Fig. 5) is marked by a disturbed zone that has isolated boudins of mafic schist (Figs. 15b and 16 (section line 17)), and marks the first appearance of garnet in the lower plate. This disturbed zone is underlain by a continuous layer of mafic volcanic and dolomite units that are folded into a series of closures that have rounded antiforms and cusp-like synforms. These smaller wavelength closures are on the western limb of a major anticlinal closure that is cored by intensely deformed quartz–mica schist, which has extensive non-coaxial shear indicators giving top-to-the-northeast shear sense. Closures in mafic units on the lower limb of this closure have asymmetry consistent with the lower limb of a regional anticline (section lines 17 and 18, Fig. 16). Underlying the regional anticlinal closure is a synclinal closure that folds a series of mafic boudins. The lower limb of this syncline can clearly be demonstrated to have upright lower plate stratigraphy (i.e. carbonate overlying mafic schist, which in turn overlies quartz–mica schist — Figs. 15c and 16 (section line 17)). This closure is cored by intensely deformed calc schist (similar to that in the core of the major synclinal closure in the Hulw lower plate window; cf. Fig. 12d). Eclogitic rocks are exposed as boudins in the deepest levels of the lower plate at As Sifah. These occur along a shear zone that defines the lower limb of the synclinal structure (Fig. 15c). The megaboudins not only preserve the highest grade metamorphic assemblages, but also earlier structural features, that are completely overprinted outside the boudins. They are bounded by strongly deformed calc schist and quartz–mica schist, which show intense transposition layering and a marked northeast-trending lineation.

The outcrop traces of the regional closures in the As Sifah window of the lower plate are not strongly affected by later fold interference. As a result the north–south strike of these closures is a direct reflection of their sheath-like nature. The only significant later deformation has produced a broad north-trending antiform (As Sifah dome) that refolds both the major anticlinal and synclinal closures (eastern part of section line 17, Fig. 16).

7.4. Microstructure and metamorphism associated with major lower plate structures

A pressure (and temperature) difference distinguishes the

Fig. 15. (a) Collage of photographs that depict a north-trending antiform that refolds transposed layering in the lower plate and the upper–lower plate discontinuity. This closure is located on section line 16 (Fig. 16) between section bars 16^1 and 16^2. Note that the upper–lower plate discontinuity dips to the east. The units on the eastern part of the photo define the start of the upper plate topographic high that separates the two lower plate windows. Approximate field of view 200 m. (b) As Sifah lower plate window. The western side is bounded by upper plate Saiq 1 limestone and dolomite that defines part of the topographic high separating the two lower plate windows; note that the upper plate units dip to the west (the *opposite* to the Saiq 1 carbonates in (a)). The initial lower plate units define a disrupted zone of quartz–mica schist and mafic boudins. Further to the east the lower plate stratigraphy is 'right-way up' (see 'younging' indicator on the figure). The core of the regional anticline in the As Sifah lower plate window is clearly defined by quartz–mica schist, which is underlain by overturned mafic schist (Lv2) and calc schist (see overturned indicator on the figure). (c) Mafic megaboudins (Lv2) in Wadi As Sifah (houses for scale). Note the boudin is overlain by calc schist (Lc) and underlain by quartz–mica schist (lighter coloured unit — Lqms), this indicates the lower plate tectonostratigraphy is upright at this locality, the units are on the lower limb of the regional syncline at As Sifah. Eclogite sample locality. (d) Retrograde fabric element in the As Sifah lower plate window. The long axes of sodic/calcic amphibole and mica define a strong northeast-trending lineation. Mica (Mu/Ph) within this fabric is intergrown with albite (Alb) porphyroblasts. Plane polarised light, base of photomicrograph approximately 2.3 mm. (e) 'Pulled apart' remnant garnets (Gt) in the hinge of a parasitic fold from the regional anticlinal closure in the As Sifah lower plate window. The resulting fractures have growth of epidote, chlorite, hematite and albite. Similar minerals also grow axial planar to these folds. The earlier higher grade assemblages are folded by this parasitic closure. Crossed polars, base of photomicrograph approximately 2.3 mm. (f) Sodic/calcic amphibole (Na/Ca amph), and chlorite defining the axial planar fabric to a regional closure in the Hulw lower plate window (sample is from the hinge of the anticlinal closure depicted in Fig. 12g). Sodic amphibole (Na amph) is preserved as inclusions inside epidote porphyroblasts (Ep). Plane polarised light, base of photomicrograph is approximately 1 mm. (g) Polygonal quartz grains from a lower plate metapelite in the Hulw region, grain size is controlled by interlayered white mica. Note the major difference in deformation microstructure between this sample compared with the upper plate units (Fig. 8h). Crossed polars, base of photomicrograph is approximately 1 mm.

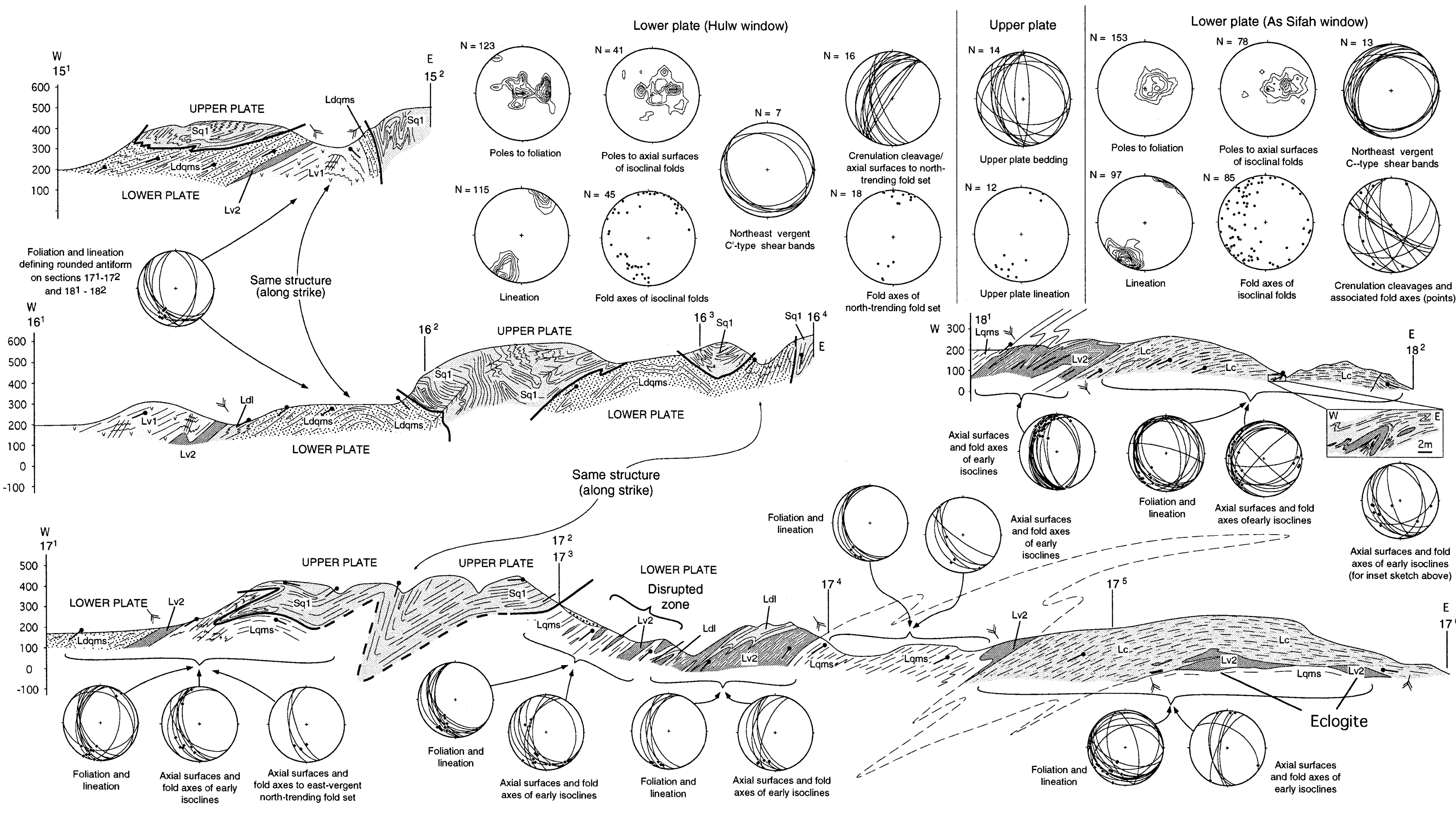


Fig. 16. Sections for the As Sifah lower plate window and the strike ridge connecting the Hulw and As Sifah windows. Stereonets are equal area projections (stereonet contour interval 2%/1% area). These sections highlight the folding of the upper–lower plate discontinuity by north-trending closures (associated with a strong crenulation cleavage). The upper plate rocks define a topographic high with both lower plate windows being at similar topographic levels. The western side of the As Sifah lower plate window contains a disrupted zone mainly comprised of quartz–mica schist (section line 17), but also containing boudins of mafic schist (Lv2). The lower plate tectonostratigraphy is folded into an anticlinal closure that overlies a synclinal hinge. The lower limb of the synclinal structure has a series of mafic boudins that contain eclogite assemblages. The schistosity in the As Sifah lower plate window is folded over a broad antiformal closure.

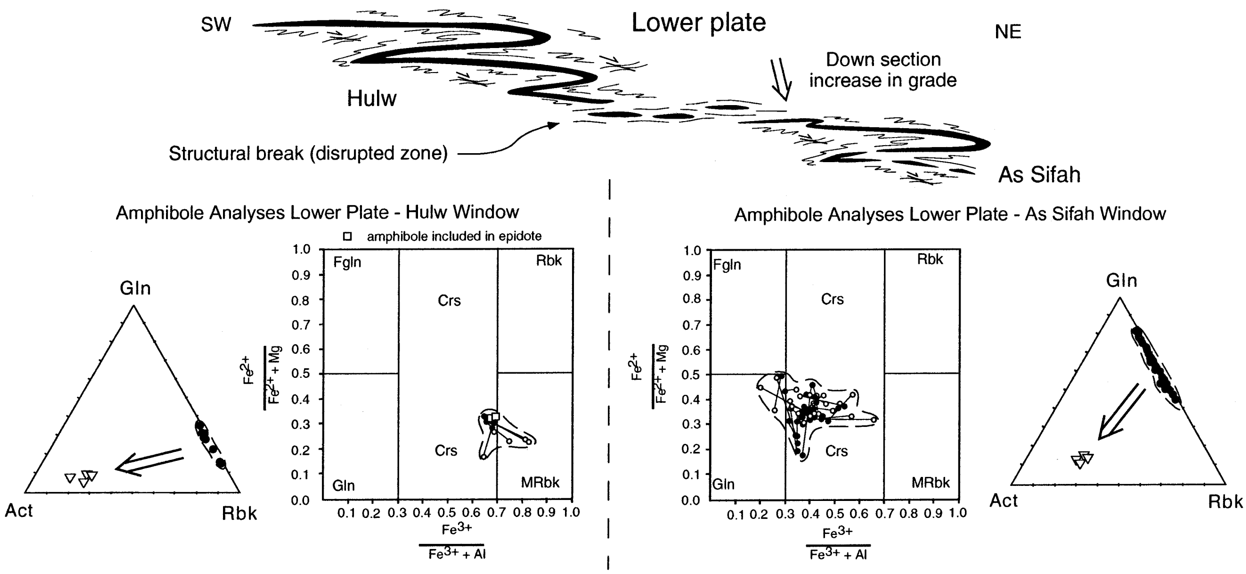


Fig. 17. Compositional data for amphibole in the two lower plate windows (from Miller, 1998; Miller et al., 1999). Early sodic amphibole is represented by circles (white = amphibole rim, black = amphibole core). Squares are amphibole included in epidote (from the Hulw lower plate window — this generation of amphibole is depicted in Fig. 15f). Ternary diagrams represent analyses on late sodic/calcic amphibole triangles and early sodic amphibole (solid circle). Probe data is normalised to 13 cations (excluding K, Ca and Na) with ferric iron calculated by charge balance.

highest pressure upper plate units from the highest pressure lower plate glaucophane–eclogites. Eclogite assemblages are only found as relicts in boudins that occur in the As Sifah subdomain of the lower plate. The eclogite facies metabasites exposed in the easternmost exposure of the lower plate at As Sifah record minimum pressures of approximately 10–12 kbar (El-Shazly et al., 1990). Peak temperatures were estimated at 500–580°C (El-Shazly et al., 1990). Application of a new garnet–pyroxene–phengite barometer by Wills et al. (1991) and Searle et al. (1994) and numerically modelling of radial fractures around quartz inclusions in garnet (Wendt et al., 1993) have both resulted in calculated pressure values of higher than 20 kbar for the lower plate eclogites. However, El-Shazly et al. (1997) argue that these estimates are too high and that metamorphic peak pressures were probably about 15 kbar.

Peak metamorphic conditions appear to have been different for the two subdomains within the lower plate. No garnet or pyroxene has been found within the Hulw lower plate window, in marked contrast to the As Sifah window. There is no evidence that the rocks in the Hulw/Meeh region of the lower plate were ever metamorphosed at pressures (or temperatures) close to that of the As Sifah lower plate window. This variation in grade is also highlighted by the difference in sodic amphibole composition (El-Shazly and Coleman, 1990; El-Shazly et al. 1990; Miller 1998; Miller et al., 1998) between the two regions (Fig. 17). El-Shazly et al. (1990) obtained pressures in the Hulw lower plate window (equivalent to their region III, zone A) of 4.5–5.5 kbar.

Outside the megaboudins at As Sifah, peak metamorphic assemblages associated with the earlier structures are almost completely overprinted by intense deformation, which culminated in the formation of the regional recumbent closures. A progressive decrease in metamorphic grade is recorded by assemblages that are consistently oriented around the northeast–southwest stretching lineation (Fig. 15d) (Miller et al., 1999). The lowest grade assemblages are synchronous with the formation of the regional sheath-like recumbent folds, which fold the earlier higher grade assemblages. 'Pulled apart' remnant garnets in the hinges of parasitic folds associated with these recumbent folds have epidote, chlorite, hematite and albite in the resulting fractures (Fig. 15e).

In the Wadi Meeh and Hulw regions, similar low grade assemblages (epidote, sodic/calcic amphibole, albite, actinolite, hematite and chlorite) define axial planar fabrics to parasitic folds in mafic units (Fig. 15f). Quartz grains in the matrix show signs of static recovery processes, with the size of the quartz crystals being controlled by interlayered muscovite (Fig. 15g). Pelite units have chloritoid porphyroblasts that are intensely retrogressed, and which have partially broken down to paragonite, muscovite, chlorite and biotite; asymmetric shear sense indicators also give top-to-the-northeast shear sense. Unlike the earlier sodic amphiboles, sodic/calcic amphibole that grew during the retrograde overprint has a similar composition in both lower plate windows (Fig. 17).

8. Discussion — the Significance of northeast Saih Hatat

8.1. Geometry/correlation with previous work

One very distinct feature of northeast Saih Hatat, is the structural differences between the upper and lower plates.

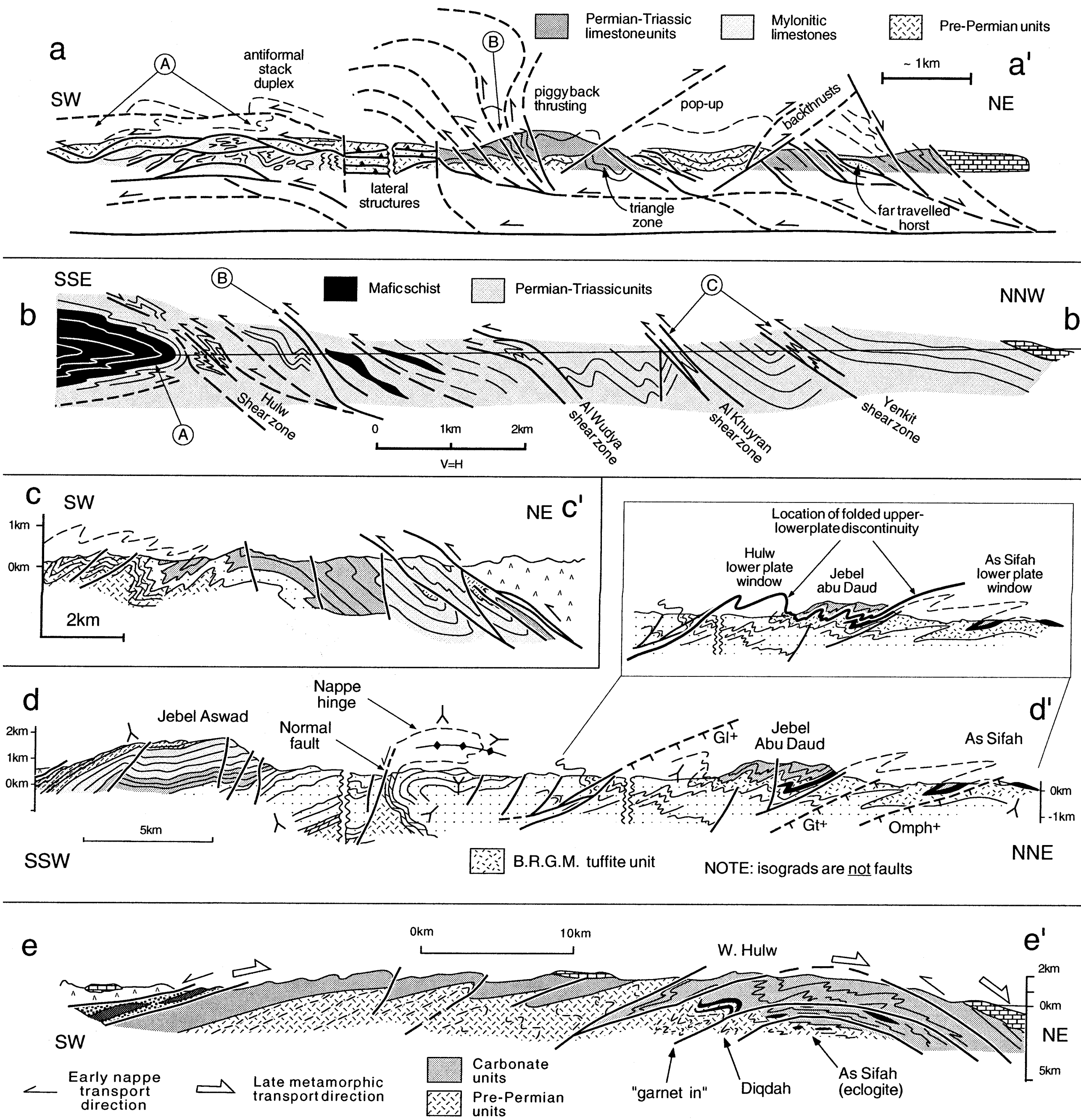


Fig. 18. Previous structural profiles through Saih Hatat, where possible stratigraphy has been 'normalised' to the stratigraphic units in Fig. 2 (section bars are marked in Fig. 2, i.e. as 18a–18a′). For some profiles this was not possible, and these have the alternative stratigraphic units marked with the section line. (a) Structural profile down Wadi Meeh by Mann and Hanna (1990). Region marked (A) corresponds to south-vergent faults in Wadi Meeh depicted by the detailed 'blow out' for section line 2 (Fig. 9). 'Piggy back thrusts' marked (B) correspond to steep reverse faults that disrupted the Saiq 2v on section line 8, Fig. 11. Mann and Hanna (1990) also recognised other major differences in structural style along Wadi Meeh and argued that the south-directed thrust units in the centre part of Wadi Meeh actually overthrust intensely deformed pre-Permian Hatat schists (which have been mapped in this study as the Wadi Meeh part of the lower plate). (b) Structural profile down Wadi Hulw from Searle et al. (1994). Recumbent fold marked (A) is the upper part of the asymmetric closure depicted in section line 12 (Fig. 13b). South-vergent structures marked (B) correspond to faults depicted in Fig. 4e and section line 11 in Fig. 13b. Shear zones marked (C) are within thinly bedded Saiq 3 dolomite. This incompetent unit has tight parasitic folds related to nappe formation and extensive later south-vergent structures (e.g. Fig. 8f). (c) Structural profile from Le Metour et al. (1986). (d) Structural profile from Le Metour et al. (1990). Section at top right depicts the refolded upper–lower plate discontinuity incorporated with their structural profile. The tuffite unit is mapped as Lv1 in this study (in the Hulw window); the unit almost certainly occurs in the As Sifah window but was not delineated by this study. (e) Structural profile from Michard et al. (1994).

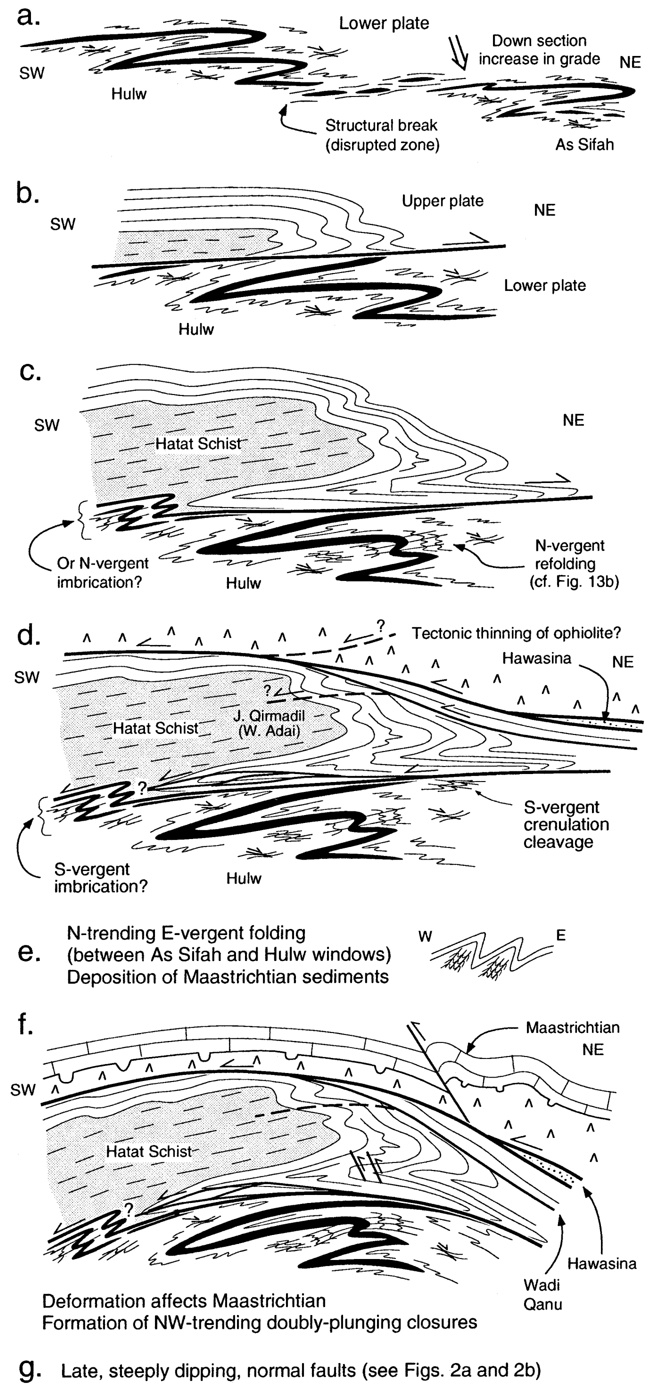


Fig. 19. Schematic structural evolution of northeast Saih Hatat. (a) Formation of regional closures in the lower plate associated with intense non-coaxial shear and growth of sodic/calcic amphibole, epidote, chlorite, albite and hematite. (b) and (c) Progressive juxtaposition of the upper plate resulting in reactivation of the lower plate with the formation of strong north- and northeast-vergent crenulation cleavages and folding of the upper–lower plate discontinuity. Nappe formation in the upper plate is associated with a strain gradient and change in fold style, and also post-dates peak metamorphic pressures. (d) South-vergent faulting resulting in the emplacement of the ophiolite and Hawasina Complex, low-angle imbricate faulting in the shelf carbonates (and pre-Permian), and reactivation of the upper–lower plate discontinuity. (e) East-vergent, north-trending folding that dominates on the western side of the Hulw lower plate window. This is associated with the formation of crenulation cleavages that have extensive pressure solution, and may have predated the deposition of the Maastrichtian limestone sequences. (f) Steeply dipping reverse faulting and formation of northwest-trending doubly plunging closures producing a dome and basin fold interference pattern. (g) Late normal faulting that affected all units.

The lower plate shear zone has extensive non-coaxial shear indicators, whereas the most extensive non-coaxial shear sense indicators in the upper plate are normally associated with later movement on brittle faults. Just viewing these later shear sense indicators in isolation gives the appearance that all of the upper plate sequences have been deformed by top-to-the-south shearing, when this represents only part of the overall structural evolution. These south-vergent structures in the northeast Saih Hatat window (Mann and Hanna, 1990; Searle et al., 1994) have been interpreted to represent a series of thrust-bound units within the Permian shelf carbonates of northeast Saih Hatat (Fig. 18a and b).

B.R.G.M. mapping and structural profiles show clear evidence for south-directed brittle faulting, which they related to the emplacement of the ophiolite and Hawasina sequences. These workers also identified northeast-vergent structures in the platform shelf units that they argued were overprinted by the south-directed brittle faults (Fig. 18c). They also mapped many of the lower plate closures defined by mafic schist and recognised the second generation north-verging folds in the lower plate (this refolding is depicted on section lines 10–12, Fig. 13). Importantly, B.R.G.M. recognised the same stratigraphic units in the Hulw and As Sifah windows and because of the apparent continuity in stratigraphy between the Hulw and As Sifah windows they argued that all of the units below the break in Wadi Qanu were conformable with no major tectonic breaks and thus termed all of the units autochthonous (Fig. 18d).

In marked contrast to B.R.G.M., Michard et al. (1994) presented a structural profile that depicts Saih Hatat as a foliation dome with a series of low-angle extensional faults separating the eclogites at As Sifah from the structurally higher units that are less metamorphosed (Fig. 18e). These workers argued that major low-angle breaks must exist because of the large variations in metamorphic grade. Michard et al. (1994) argue for early south-directed nappe transport followed by late northeast-directed transport, the opposite to that of B.R.G.M.

This study has also identified the south-vergent structures documented by Mann and Hanna (1990) and Searle et al. (1994) (in particular note the annotation in Fig. 18a and b). However, these south-vergent structures depicted in Fig. 4e and f clearly overprint northeast-verging lower plate structures in the Wadi Hulw area. We have also been able to map out regional upper plate closures across the south-vergent shear zones of Mann and Hanna (1990) and Searle et al. (1994). In many areas there are large expanses of overturned Permian stratigraphy disrupted, or refolded by, south-vergent structures (cf. Fig. 8f). Some regions previously mapped as shear zones are actually deformation partitioned into thinly bedded incompetent Saiq 3 stratigraphic units 'sandwiched' between layers of massive Mahil dolomite (cf. Figs. 10 and 18b). We find no evidence to support the timing relationships of Michard et al. (1994); however their south-directed nappe transport (Fig. 18e) refers to deformation synchronous with high-pressure metamorphism (a shear sense not constrained by this study), which pre-dates all of the major structures mapped in northeast Saih Hatat.

Even though the overprinting relationships documented in this study are similar to B.R.G.M., one clear difference is the identification and mapping of the upper–lower plate discontinuity, the control it has on the upper plate structures and the later fold sets that produce the domal lower plate windows. It should be noted that the upper plate–lower plate discontinuity is strongly folded by late north-trending closures between the two lower plate windows (Jebel abu Daud) and thus, apart from the upper–lower plate discontinuity, the section of B.R.G.M. is an accurate depiction of the geometry (Fig. 18d). This study has also more accurately delineated the lower plate geometry, in particular the lower plate closures. Unlike the upper plate regional folds (which have markedly attenuated lower limbs), the lower plate closures are not nappes in a strict sense as they have formed in a zone of strong non-coaxial shear, because of their sheath-like form, they are best depicted via a 3D block diagram (Fig. 3).

8.2. Overall geometry and relative chronology of deformation

The lower plate closures formed via intense, pervasive, northeast-directed non-coaxial shear (Fig. 19a). There appears to be a down section increase in grade with respect to the enveloping surface of the schistosity within the lower-plate. This suggests that the shear zone has a 'normal' movement sense and is either extensional in character or the bounding fault along the top of an upward moving block. This down section increase in grade appears related to an apparent structural break marked by disrupted lithologies within the lower plate at As Sifah. The similar retrograde assemblages associated with the lower plate closures (epidote, albite, chlorite and sodic/calcic amphibole with similar compositions in both lower plate windows; Fig. 17) suggests that the units attained similar crustal levels (i.e. a similar metamorphic field), during intense top-to-the-northeast shearing. Thus, partial exhumation of the lower-plate units occurred during this northeast-directed shearing event (Miller et al., 1998, 1999). This shearing event appears to have initiated while high-pressure metamorphism was still occurring in the lower-plate with initial shear sense indicators either defined by high-Si phengite or overgrown by later sodic amphibole (Miller, 1998; Miller et al., 1999).

The lower plate regional closures are clearly truncated by the upper–lower plate discontinuity (Fig. 19b), indicating they predate at least the final stages of movement along this structural break. There is no apparent correlation of structural levels within the lower plate with particular respect to distance from the upper–lower plate discontinuity (i.e. deeper levels are not further away from the discontinuity). The upper–lower plate discontinuity appears to progressively 'cut' down into deeper lower plate structural levels from west to east. This feature implies that any variation with metamorphic grade in the lower plate existed prior to the formation of the upper–lower plate discontinuity and either reflects the dip of lower plate units prior to development of the discontinuity (i.e. they were part of a west-dipping shear zone), or the dip of the upper–lower plate discontinuity itself (i.e. dipping to the east). Ascertaining the initial orientation, or dip, of the lower plate shear zone is not possible, except to say that it was at a low-angle to the upper–lower plate discontinuity (cf. Fig. 3).

The variation in structural style of the upper plate with deeper structural level suggests that the upper–lower plate discontinuity has a direct control on the development of the upper plate. Axial planar mineral assemblages to the upper-plate fold-nappes (chlorite–albite–sphene for mafic units containing relict high-pressure minerals) indicate the fold-nappes formed during decreasing pressure (i.e. post the formation of sodic amphibole). The overall fold geometry, rare asymmetric shear sense indicators, and the stretching lineation within the upper plate indicate that these nappes have been emplaced from the southwest (top-to-the-northeast sense of shear). This requires that these upper plate fold-nappes moved away from the Oman margin.

Part of the key to putting the upper plate structures into context is an understanding of when specific mineral assemblages were stable in the upper and lower plates. Most workers focus solely on the eclogites in the lower plate, and their implication for large scale extensional breaks, without constraining the timing and regional structures related to retrograde metamorphism of the entire lower plate. The entire lower plate appears to have been at shallower crustal levels (evidenced by the timing of retrograde assemblages) prior to juxtaposition with the upper plate. It is also very difficult to argue that the upper–lower plate contact is a major extensional break when one makes a comparison of the recorded peak minerals occurring in the upper plate rocks (magnesio–carpholite, lawsonite and glaucophane) and those in the Hulw lower plate window (epidote, crossite to magnesioriebeckite, chlorite, albite — no garnet, omphacite, or glaucophane). El-Shazly and Coleman (1990) and El-Shazly et al. (1990) obtained pressure estimates of 4.5–5.5 kbar for the Hulw lower plate window (equivalent to their Region III, zone A) while they argue that the presence of magnesio–carpholite indicates pressures where in excess of 5.5–6 kbar for the upper plate rocks (equivalent to their Region II). Goffé et al. (1988) obtained similar relative pressure differences (cf. Hulw vs. Muscat nappes in Fig. 16 of Goffé et al. (1988)). The results from both metamorphic studies suggest the peak metamorphic pressure obtained by the Hulw lower plate rocks was lower than the carpholite-bearing upper plate rocks.

The upper plate nappe-like geometry, and the mineral assemblages, indicate that the upper–lower plate discontinuity is best described as a contractional décollement surface (rather than an extensional detachment) that has had possible later, brittle, extensional reactivation. Pre-Permian basement rocks (Hatat Schist etc.) have been emplaced over lower plate sequences that contain at least some younger Permian shelf sequences (lower plate limestone unit Ll; cf. Fig. 5). The décollement bounding the two plates has transposed two terranes with different tectono-metamorphic histories.

The folding and imbrication of the upper–lower plate contact in the southern part of the Hulw window is believed to represent deformation related to the progressive emplacement of the upper plate (Fig. 19b and c). The large asymmetric closures in the northern part of the Hulw lower plate window (Section lines 10–12, Fig. 13) that refolds the earlier regional syncline in the northern part of the Hulw window is probably the same generation structure.

The upper plate nappes are overprinted by later northeast-dipping faults (e.g. Wadi Qanu, Fig. 5). This may have occurred synchronously with the movement along the breaks emplacing the ophiolite and Hawasina sequences (top-to-the-southeast). This has resulted in some reactivation of the upper–lower plate contact producing south-vergent crenulation cleavages in the lower plate units associated with low-angle brittle faults (Fig. 19d).

The domal shape of the lower plate windows is controlled by later north- and northwest-trending fold sets. The north-trending folds that dominate the Jebel abu Daud region have strong axial planar crenulation cleavages associated marked pressure solution (Miller, 1998). The northwest-trending folds have no apparent associated fabric development and also occur within Maastrichtian units. Based on the differing styles of axial planar cleavages associated with these structures the north-trending set is believed to have formed prior to the deposition of the Maastrichtian (Miller, 1998), as are some of the steeply dipping faults that disrupt the hinge of the regional syncline in Wadi Meeh (Fig. 19e). The later fold sets are considered to be Tertiary structures that also affect the Maastrichtian limestones (Fig. 19f). The last distinct deformation is probably the steeply dipping normal faults (Fig. 19g), which disrupt upper and lower plate rocks, the Hawasina sequences as well as the Maastrichtian units (Mann and Hanna, 1990). These steeply dipping faults significantly disrupt the regional upper plate nappe in the southeastern sector of Saih Hatat (Figs. 2b and 18d).

8.3. Tectonic evolution

The age of high-pressure metamorphism of the lower plate is controversial and is not, as yet, totally resolved. Some workers relate all metamorphism to the obduction of the Samail ophiolite (metamorphism less than 95 Ma, e.g. Michard et al., 1994; Searle et al., 1994) while others invoke an earlier phase of underthrusting (eclogites 140–120 Ma, e.g. El-Shazly and Coleman, 1990). The youngest cooling ages on high-pressure phengite in the lower plate at As Sifah give 82 Ma $^{40}Ar/^{39}Ar$ plateau ages, $^{40}Ar/^{39}Ar$ ages on mica extracted from low-pressure fabric elements in the lower plate (e.g. the calc-schist) give ages of 82–79 Ma (Miller et al., 1999). This indicates the exhumation of the high-pressure rocks at As Sifah occurred after the initial stage of thrusting associated with the emplacement of the Samail ophiolite, which has 94–93 Ma $^{40}Ar/^{39}Ar$ cooling ages on hornblende in its metamorphic sole (Hacker et al., 1996). The earliest mappable structures in Saih Hatat (i.e. the folds within the lower plate shear zone) are related to the exhumation of the high-pressure rocks, this means that there is very little information that can be obtained on the geometry of the system that produced high-pressure metamorphism of the lower plate. The current age constraint on the upper plate metamorphism is a 80 Ma crystallisation $^{40}Ar/^{39}Ar$ age on a lawsonite schist in El-Shazly and Lanphere (1992). This suggests the exhumation of the lower plate could have been synchronous with the high-pressure metamorphism of the upper plate (Miller et al., 1999). Other constraints on the timing of high-pressure metamorphism of the upper plate are; (1) the high-pressure metamorphism of the upper plate also affects syn-tectonic Muti/Hawasina melange sequences (El-Shazly et al., 1990; Michard et al., 1994), (2) there is clear evidence that the upper plate carbonates underwent significant disruption at approximately 95 Ma, resulting in the formation of the Wasia–Aruma break (Glennie et al., 1974; Rabu et al., 1990; Warbuton et al., 1990) and, (3) overthrusting of the shelf carbonates by the Hawasina is constrained by the imbrication of Late Santonian (~86–84 Ma) Fiqa Formation with Hawasina units (Warbuton et al., 1990).

The markedly different stratigraphy observed in the lower plate, which has no equivalence elsewhere in the Oman Mountains, suggests the As Sifah rocks were probably part of a promontory that was under thrust long before any of the upper plate shelf carbonates (cf. Hacker and Gnos, 1997). The differences in geothermal gradient between the As Sifah high-pressure rocks and the assemblages preserved in the sole thrust of the Samail ophiolite suggest that the high-pressure metamorphism of the As Sifah rocks is not as a result of them being directly underthrust beneath the Samail ophiolite (Hacker and Gnos, 1997).

A two stage mechanism appears to be responsible for the exhumation of the high-pressure rocks (Miller et al., 1999). The first stage is the partial exhumation of the lower-plate to shallower crustal levels during intense non-coaxial shear, the second is the exhumation of the upper plate. Multiple processes appear to have combined to exhume the As Sifah eclogites and the various models/mechanisms that are proposed for the exhumation of high-pressure rocks should not be viewed as mutually exclusive (e.g. Wheeler, 1991).

The down section increase in metamorphic grade in the lower plate shear zone is consistent with the lower-plate being part of shear zone associated with a 'normal' movement sense as either the upper-part of a buoyancy driven slab (i.e. model of Chemenda et al., 1996), or part of an extensional shear zone (model of Michard et al., 1994), or extensional processes in a localised region (part of the model of Searle et al., 1994). Whether the exhumation of the lower plate occurred in the same zone of underthrusting that resulted in high-pressure metamorphism of the upper plate is difficult to prove. We believe that the markedly different styles of metamorphism between the two plates (i.e. carpholite and lawsonite growth versus greenschist/amphibolite facies overprint) suggests exhumation may have occurred along a separate zone of underthrusting to that which produced the high-pressure metamorphism of the upper plate. The lower plate is only exposed as two small tectonic windows truncated by a later discontinuity and one does not see the entire system directly related to the exhumation of the lower plate rocks. Because of this the choice of exhumation model comes down to theoretical questions — such as the relaxing of the geotherm during extension vs. whether buoyancy driven uplift is a viable means for exhuming high-pressure rocks. The field relationships in Oman alone will not resolve the issue.

There are much tighter structural controls on the exhumation of the high-pressure rocks containing lawsonite and carpholite in the upper plate and, unlike the lower plate, it is possible to document the characteristics of the entire package associated with exhumation. The upper plate exhumation style is a strong candidate for deeper level thrusting synchronous with higher level normal faulting and/or rapid erosion, resulting in the exhumation of the high-pressure rocks (e.g. Fig. 3 in Carmignani and Kligfield, 1990; Inger and Ramsbotham, 1997). This type of model fits the field observations of the exhumed upper plate rocks having initial deeper level 'thrust' related structures (nappe formation), which are overprinted by shallower brittle faults with an opposite sense of shear. Evidence for synchronous erosion of the structural pile is supported by detritus shed from the overlying units that was deposited in sedimentary basins at the end of the Campanian, when the ophiolite was subjected to deep, sub-areal lateritic weathering (Coleman, 1981; Hopson et al., 1981). $^{40}Ar/^{39}Ar$ dating by Miller et al. (1999) indicates upper plate nappe formation occurred late and appears to have been synchronous with higher level normal faulting/erosion between 76 and 70 Ma. In many cases the $^{40}Ar/^{39}Ar$ ages on mica extracted from the upper plate nappes are younger, or the same age as, zircon fission track ages from the same region (Saddiqi et al., 1995). Lower plate units in the direct footwall of the ductile-brittle upper–lower plate discontinuity also have 76 Ma $^{40}Ar/^{39}Ar$ ages (El-Shazly and Lanphere, 1992). These have been interpreted by Miller et al. (1999) to represent mica growth/resetting due to footwall deformation of the lower plate during the emplacement of the upper plate (i.e. the north-vergent refolds depicted in Fig. 19c). The deformation associated with the exhumation of the upper plate also represents the final exhumation stage of the lower plate.

If the high-pressure metamorphism of the upper plate was related to an underthrusting event directed away from the margin, the emplacement of the upper plate nappes would have a back-thrust geometry within the complex. An alternate geometry could have involved underthrusting directed back towards the margin (Gregory et al., 1998). This would explain the formation of the Wasia–Aruma break that marks the end of upper plate carbonate deposition (Glennie et al., 1974; Rabu et al., 1990; Warbuton et al., 1990), and the formation of the Muti intra-shelf basin (Rabu et al., 1990). One of the implications of such a model is that it would require a tectonic break between Saih Hatat and the shelf carbonates of the autochthon further inland. Such a proposed tectonic break could explain why the carbonates in Jebel Akhdar do not contain high-pressure minerals, and the relatively poor correlation between the pre-Permian units exposed in the different tectonic windows.

The late stage deformation in Oman (Fig. 19b–d) probably reflects deformation within an unstable over-thickened orogenic wedge (Platt, 1986, 1987; Wallis et al., 1993). The overthrusting of the Samail ophiolite over a subduction zone that dipped either towards, or away from, the Oman margin, appears to have been a key factor that produced an unstable wedge geometry. The low-angle south-directed faults within the shelf sequences (Fig. 19c), and the late transport on the Samail ophiolite, are interpreted to reflect extension of the orogenic wedge in an attempt to maintain gravitational stability. In contrast, the upper plate nappe transport reflects deformation within the orogenic wedge that accommodates the known convergence still occurring at the time. The formation of these fold-nappes, and the resultant thickening of deeper levels of the orogenic wedge, would have further facilitated (and/or driven) the rapid higher level erosion and normal faulting.

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References

Bailey, E.H., 1981. Geological map of the Muscat–Ibra area, Sultanate of Oman. Journal of Geophysical Research 86, B4 pocket map.

Béchennec, F., Roger, J., Le Metour, J., Wyns, R., 1992. Geological map of Seeb, sheet NF40-03, scale 1:250000. Ministry of Petroleum and Minerals, Directorate General of Minerals, Sultanate of Oman.

Carmignani, L., Kligfield, R., 1990. Crustal extension in the northern Appennines: the transition from compression to extension in the Alpi Apuane Core Complex. Tectonics 9, 1275–1303.

Chemenda, A.I., Mattauer, M., Bokun, A.N., 1996. Continental subduction and a mechanism for exhumation of high-pressure metamorphic rocks: new modelling and field data from Oman. Earth and Planetary Science Letters 143, 173–182.

Coleman, R.G., 1981. Tectonic setting for ophiolite obduction in Oman. Journal of Geophysical Research 86, 2497–2508.

El-Shazly, A.K., 1994. Petrology of lawsonite-, pumpellyite- and sodic amphibole-bearing metabasites from NE Oman. Journal of Metamorphic Geology 12, 23–48.

El-Shazly, A.K., 1995. Petrology of Fe–Mg-carpholite-bearing metasediments from NE Oman. Journal of Metamorphic Geology 13, 379–396.

El-Shazly, A.K., Coleman, R.G., 1990. Metamorphism in the Oman Mountains in relation to the Semail ophiolite emplacement. In: Robertson, A.H., Searle, M.P., Ries, A.C. (Eds.). The Geology and Tectonics of the Oman Region. Geological Society of London Special Publication 49, pp. 473–493.

El-Shazly, A.K., Lanphere, M.A., 1992. Two high pressure Metamorphic events in NE Oman: evidence from ^{40}Ar–^{39}Ar dating and petrological data. The Journal of Geology 100, 731–751.

El-Shazly, A.K., Coleman, R.G., Liou, J.G., 1990. Eclogites and blueschists from NE Oman: petrology and P–T evolution. Journal of Petrology 31, 629–666.

El-Shazly, A.K., Worthing, M.A., Liou, J.G., 1997. Interlayered eclogites, blueschists, and epidote amphibolites from NE Oman: a record of protolith compositional control and limited fluid infiltration. Journal of Petrology 38, 1461–1487.

Glennie, K.W., Hughes Clarke, M.W., Boeuf, M.G., Pilaar, W.F., Reinhardt, B.M., 1974. Geology of the Oman Mountains, p. 423 Verhandelingen van het Koninklinjk Nederlands geolgisch minjbouwkundig Genootsschap, Amsterdam 31.

Goffé, B., Michard, A., Kienast, J.R., Le Mer, O., 1988. A case of obduction-related high pressure, low temperature metamorphism in upper crustal nappes, Arabian continental margin, Oman. Tectonophysics 151, 363–386.

Gregory, R.T., Gray, D.R., Miller, J.McL., 1998. Tectonics of the Arabian Margin associated with the emplacement of the Oman Margin along the Ibra Transect: new evidence from NE Saih Hatat. Tectonics 17, 657–670.

Hacker, B.R., Gnos, E., 1997. The conundrum of samail: explaining the metamorphic history. Tectonophysics 279, 215–226.

Hacker, B.R., Mosenfelder, J.L., Gnos, E., 1996. Rapid emplacement of the Oman ophiolite: thermal and geochronological constraints. Tectonics 15, 1230–1247.

Hopson, C.A., Coleman, R.G., Gregory, R.T., Pallister, J.S., Bailey, E.H., 1981. Geologic section through the Samail Ophiolite and associated rocks along the Muscat–Ibra transect, southeastern Oman Mountains. Journal of Geophysical Research 86, 2527–2544.

Inger, I., Ramsbotham, W., 1997. Syn-convergent exhumation implied by progressive deformation and metamorphism in the Valle dell'Orco transect, NW Italian Alps. Journal of the Geological Society, London 154, 667–677.

Le Metour, J., de Gramont, X., Villey, M., 1986. Geological map of Masqat and Quryat, sheets NF40-4A, NF40-4D, scale 1:100000. Explanatory notes, Ministry of Petroleum and Minerals, Directorate General of Minerals, Sultanate of Oman.

Le Metour, J., Rabu, D., Tegyey, M., Béchennec, F., Beurrier, M., Villey, M., 1990. Subduction and obduction: two stages in the Eo–Alpine tectonometamorphic evolution of the Oman Mountains. In: Robertson, A.H., Searle, M.P., Ries, A.C. (Eds.). The Geology and Tectonics of the

Oman Region. Geological Society of London Special Publication 49, pp. 327–339.

Le Metour, J., Béchennec, F., Roger, J., Wyns, R., 1992. Geological map of Muscat sheet NF40-04, scale 1:250000. Ministry of Petroleum and Minerals, Directorate General of Minerals, Sultanate of Oman.

Lippard, S.J., 1983. Cretaceous high pressure metamorphism in NE Oman and its relationship to subduction and ophiolite nappe emplacement. Journal of the Geological Society, London 140, 97–104.

Lippard, S.J., Shelton, A.W., Gass, I.G., 1986. The ophiolite of northern Oman. Geological Society of London, Memoir, 11.

Mann, A., Hanna, S.S., 1990. The tectonic evolution of pre-Permian rocks, Central and Southeastern Oman Mountains. In: Robertson, A.H., Searle, M.P., Ries, A.C. (Eds.). The Geology and Tectonics of the Oman Region. Geological Society of London Special Publication 49, pp. 307–325.

Michard, A., Bouchez, J.L., Ouazzani-Touhami, M., 1984. Obduction related planar and linear fabrics. Journal of Structural Geology 6, 39–49.

Michard, A., Goffé, B., Saddiqi, O., Oberhänsli, R., Wendt, A.S., 1994. Late Cretaceous exhumation of the Oman blueschists and eclogites: a two stage extensional mechanism. Terra Nova 6, 404–413.

Miller, J.McL., 1998. The structure, metamorphism and $^{40}Ar/^{39}Ar$ geochronology of northeast Saih Hatat, Oman: implications for the formation and preservation of high pressure rocks. Unpublished PhD thesis, Monash University, Clayton, Melbourne, Australia.

Miller, J.McL., Gray, D.R., Gregory, R.T., 1998. Exhumation of high-pressure rocks, northeastern Oman. Geology 26, 235–238.

Miller, J.McL., Gray, D.R., Gregory, R.T., 1999. Geological and geochronological constraints on the exhumation of a high-pressure metamorphic terrane, Oman. In: Ring, U., Brandon, M.T., Lister, G.S., Willet, S.D. (Eds.). Exhumation Processes: Normal Faulting, Ductile Flow and Erosion. Geological Society of London Special Publication 154, pp. 241–260.

Montigny, R., Le Mer, O., Whitechurch, H., 1988. K–Ar and $^{40}Ar/^{39}Ar$ study of metamorphic rocks associated with the Oman ophiolite: tectonic implications. Tectonophysics 151, 345–362.

Passchier, C.W., Trouw, R.A.J., 1996. Microtectonics. Springer-Verlag, Berlin, 289pp.

Platt, J.P., 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Geological Society of America, Bulletin 97, 1037–1053.

Platt, J.P., 1987. The uplift of high-pressure–low-temperature metamorphic rocks. Philosophical Transactions of the Royal Society A 321, 87–103.

Rabu, D., Le Metour, J., Béchennec, F., Beurrier, M., de Grissac, C.H., 1990. Sedimentary aspects of the Eo–Alpine cycle on the NE edge of the Arabian platform. In: Robertson, A.H., Searle, M.P., Ries, A.C. (Eds.). The Geology and Tectonics of the Oman Region. Geological Society of London Special Publication 49, pp. 49–68.

Saddiqi, O., Poupeau, G., Michard, A., Goffé, B., Oberhänsli, R., 1995. Exhumation des roches métamorphiques HP–BT d'Oman: datation par traces de fission sur zircons. Comptes Rendus de l'Académie des Sciences, Paris 320, 1071–1077.

Searle, M.P., Malpas, J., 1980. Structure and metamorphism of rocks beneath the Semail ophiolite of Oman and their tectonic significance in ophiolite obduction. Transactions of the Royal Society of Edinburgh 71, 247–262.

Searle, M.P., Cox, J., 1999. Tectonic setting, origin and obduction of the Oman ophiolite. Geological Society of America, Bulletin 111, 104–122.

Searle, M.P., Waters, D.J., Martin, H.N., Rex, D.C., 1994. Structure and metamorphism of blueschist–eclogite facies rocks from the NE Oman Mountains. Journal of the Geological Society, London 151, 555–576.

Wallis, S.R., Platt, J.P., Knott, S.D., 1993. Recognition of syn-convergence extension in accretionary wedges with examples from the Calabrian Arc and the Eastern Alps. American Journal of Science 293, 463–495.

Warbuton, J., Burnhill, T.J., Graham, R.H., Isaac, K.P., 1990. The evolution of the Oman Mountains Foreland basin. In: Robertson, A.H., Searle, M.P., Ries, A.C. (Eds.). The Geology and Tectonics of the Oman Region. , pp. 419–427 Geological Society of London Special Publication 49.

Wendt, A.S., D'Arco, P., Goffé, B., Oberhänsli, R., 1993. Radial cracks around _-quartz inclusions in Almandine: constraints on the metamorphic history of the Oman mountains. Earth and Planetary Science Letters 114, 449–461.

Wheeler, J., 1991. Structural evolution of a subducted continental slither: the northern Dora Maira massif, Italian Alps. Journal of the Geological Society, London 148, 1101–1113.

Wills, H.N., Waters, D.J., Searle, M.P., 1991. A clockwise P–T path at $P > 20$ kbar for eclogite and High-P schist beneath the Semail ophiolite, Oman. Terra Abstracts 3, 98.