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Structural evolution of the Hawasina Window, Oman Mountains

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ABSTRACT

This paper presents field observations and measurements from the Hawasina Window, Oman Mountains. An updated geological map is based partly on previous publications and four NE-trending cross-sections. Along each cross-section key structural features are described, illustrated and interpreted. Based on these (and other) observations several differences between our interpretation and the former published geological maps and cross sections were noted as follows.

(1) Late Cretaceous original (Hamrat Duru; Haybi) nappes that formed during intra-oceanic obduction underwent out-of-sequence thrusting beneath the Semail thrust. The repetitions of the nappe complexes are out-of-sequence because: (a) repetition of original nappe packages; (b) the presence of Haybi-derived lenses along boundaries between two Hamrat Duru nappes; (c) the presence of sheared serpentinite in the same nappe boundaries. The Hamrat Duru and Haybi nappes are repeated three times.

(2) The tectonic boundaries of the Hawasina Window are steep, normal- or strike-slip faults, unconformable to, and cutting the original nappe boundaries. A main strike-slip corridor at the southern edge of the Hawasina structure was mapped. The northern edge is a top-north thrust.

(3) Ductile-brittle extension created mega-boudins of preserved nappe units and areas where complete nappe units are missing. Extension is present in Sumeini and Hamrat Duru units; therefore it is post-out-of-sequence thrusting.

(4) Two main antiforms were recognised inside the Hawasina Window (Jabal Rais and its northward and southward continuations in Hamrat Duru units, and Jabals Mawq - Matid). Several folding phases were recognised and the two antiforms are the result of interference. A main, sub-horizontal axial plane, syn-regional cleavage folding is present in the whole Window. This folding gives top NE or N regional shear.

(5) Structural dips of regional cleavage suggest a major NW-striking dome beneath the Hawasina Window. This dome would correspond to the upwarp of the Autochthon, similar to Al Jabal al-Akhdar. In the southern zone of this dome we observed several occurrences of small gypsum diapirs. The best outcrops of these features are in the Wadi ad Dil-Wadi Hawasina area, where the evaporite bodies rise from beneath the Hawasina nappes. We suggest that they originate from the underlying Arabian Platform, or they form the basal detachment of the Sumeini units.

Our observations are fit into a proposed deformation scenario resulting from plate-tectonic events occurring at the Arabian Plate margin during Cretaceous – Tertiary time.

INTRODUCTION

Between 2006 and 2008 MOL geologists and consultants made a series of geological field trips and three longer campaigns to study the geology and structures of the Hawasina Window in the Central Oman Mountains. Three main structural units build up these mountains: the uppermost Semail Ophiolite, the middle Hawasina (oceanic) nappes and the lower Arabian Platform, the Autochton (e.g. Glennie et al., 1974; Figure 1). The study area is known as the Hawasina Window ("Window"

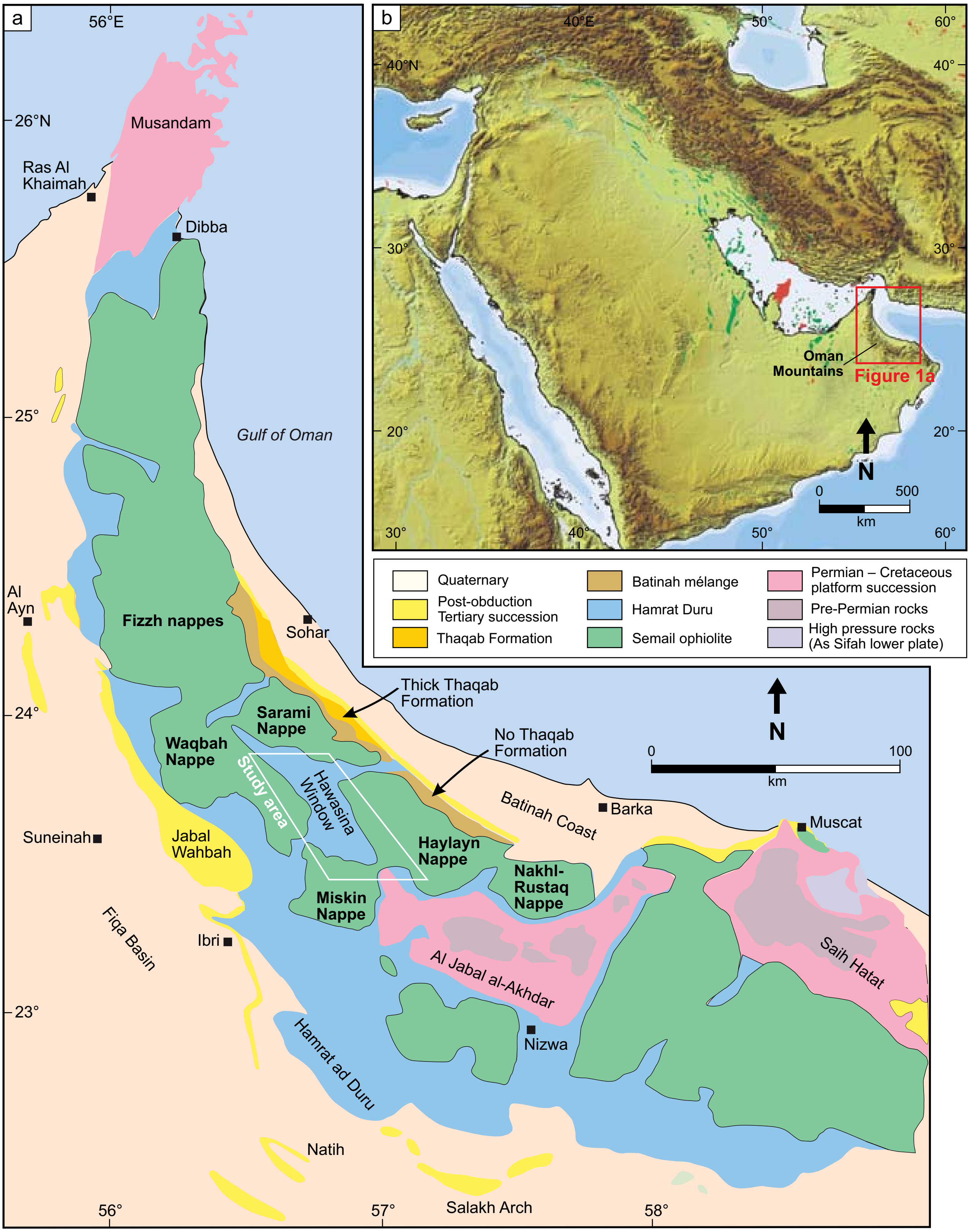


Figure 1: (a) Tectonic units of the Central and Northern Oman Mountains (modified after Glennie et al., 1974). (b) Reprocessed Digital Elevation Model (DEM) of Arabian Peninsula, originally from NASA.

throughout the paper) because the middle tectonic unit, the Hawasina nappes, comes to the surface from beneath the ophiolites (e.g. Robertson et al., 1990). For the sake of comparison, the neighbouring tip of Al Jabal al-Akhdar, a large window of the Arabian Platform was added to this study.

While numerous former works deal with the same region (Lees, 1928; Allemann and Peters, 1972; Glennie et al., 1974; Searle and Cooper, 1986; Villey et al., 1986; Béchennec, 1988; Cooper, 1988; Grey and Gregory, 2003), systematic outcrop description from a structural point of view and a structural study based on field measurements is practically absent in previous publications. Therefore our study, which is based on detailed structural information, may bring new results in the otherwise much studied geology of the Oman Mountains.

The presented work is based on field structural analysis. Measurements of bedding and cleavage attitude, fold-axis trends and fault-slip data were recorded (Figure 2). Whenever tectonic transport could be seen, that was also noted. We did not perform stress-tensor calculations for several reasons. First, slickenside data collected at individual outcrops were often not numerous enough to perform a statistically correct analysis. Second, we observed a multitude of deformations with several phases of tilting in the ductile oceanic formations. Since fault-slip analysis is strongly dependent on the reconstruction of later tilt, the complicated structural history inhibited such calculations. On the other hand, such calculations were possible at several sites of Al Jabal al-Akhdar, where rocks are much less deformed and were subject to a limited number of tilt steps. This study is subject of a different paper (Fodor, in preperation).

In this paper the description and documentation of key exposures in the Window is made along four dip-oriented traverses (A to D from south to north, see Enclosure 1). This method was chosen for the sake of effective comparison with former tectonic models. Cross-section and outcrop descriptions are followed by analysis of map-scale features. A structural summary (including relative timing of events) is followed by a discussion and comparison with earlier work, notably with Searle and Cooper (1986), Villey et al. (1986) and Grey and Gregory (2003).

STRATIGRAPHIC NOMENCLATURE

The stratigraphy of the area was given by earlier work (Searle and Cooper,1986; Villey et al., 1986; Béchennec, 1988; Béchennec et al., 1990; Cooper, 1988, 1990; a summary is given in Rabu et al. (1990) or Searle, 2007). Basic structural and stratigraphic terms are summarised and compared in Figure 3, and the terms used throughout this paper are marked in red. Stratigraphic terms were defined and used from the beginning of mapping (Lees, 1928; Allemann and Peters, 1972; Glennie et al., 1974), however, some were subsequently redefined or revised. We adopt the BRGM's nomenclature (Béchennec, 1988; Béchennec et al., 1990) because it is widely used and provides a workable stratigraphic framework for our purpose. The work of Pillevuit (1993) on the exotic limestone blocks was also taken into consideration. For structural terms we used the nomenclature developed by Glennie et al. (1974) and Searle and Cooper (1986). Therefore we call Haybi Nappe the sheared unit containing dismembered fragments of oceanic islands, their cover and their talus cone. These rocks build up the (reconstructed) stratigraphic Umar, Al Aridh and Kawr successions of Béchennec (1988). We did not separate the different members of Umar, Khawr and Aridh units, because quite often the different stratigraphies had a chaotic, tectonic contact. Some exotic lenses could be easily separated, but more often, thinner-thicker limestone layers and lenses were mixed with other lithologies within the resolution of the map. Since Hamrat Duru units are repeated, the Upper, Middle, Lower Hamrat Duru units designate the tectonic positions of these formations and not startigraphic subdivisions. This paper does not discuss in detail stratigraphic aspects, except for two successions, the "Sumeini exposures" and an evaporite body unknown so far. Both have structural importance.

TRAVERSE A: IBAT- HAWASINA SECTION (ENCLOSURE 2)

The long W-E Traverse A stretches from the Ibat Gorge to the eastern border of the Hawasina Window (Enclosures 1 and 2). On the surface, three superposed Hamrat Duru units (Lower, Middle and Upper) can be identified: all three contain mainly Matbat and Al Jil formations, and in the eastern part of the section a Haybi Unit. The contact of the different Hamrat Duru units is frequently (but not exclusively) underlined by sheared serpentinite lenses or banks. Several superposed sheared

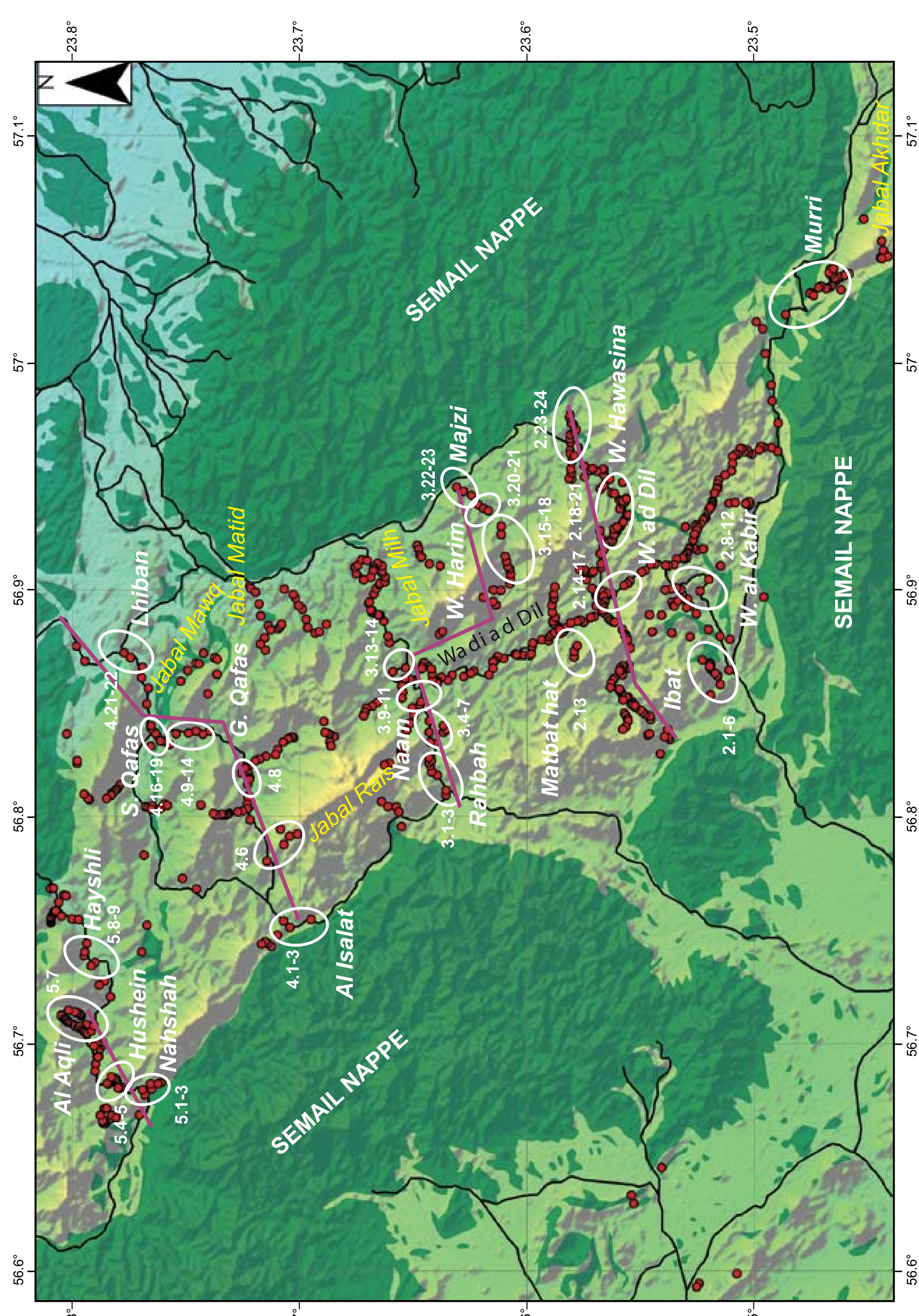


Figure 2: Digital elevation map (DEM) of the Hawasina Window (proprietary data) and visited exposures (red dots). Regions encircled in white indicate the key exposures described under indicated by numbers.

serpentinite horizons can be identified. These are thought to be out-of-sequence nappe boundaries (see below). Other repetitions within the Al Jil and Matbat formations may be imbrications of less importance and less offset.

While general dip, and also the dip of the nappe boundaries, is towards the west in the western part of the section, these dips become eastwards tilted in the eastern portion of the cross section. This suggests a broad doming at the central part of the section, which is why Sumeini units were interpreted at depth in this segment. These units are projected from the north beneath the lowest Hamrat Duru Nappe (Enclosures 3 and 4). Another peculiar feature of the section is the presence of evaporite fingers, i.e. smaller intrusions from beneath the Lower Hamrat Duru Unit.

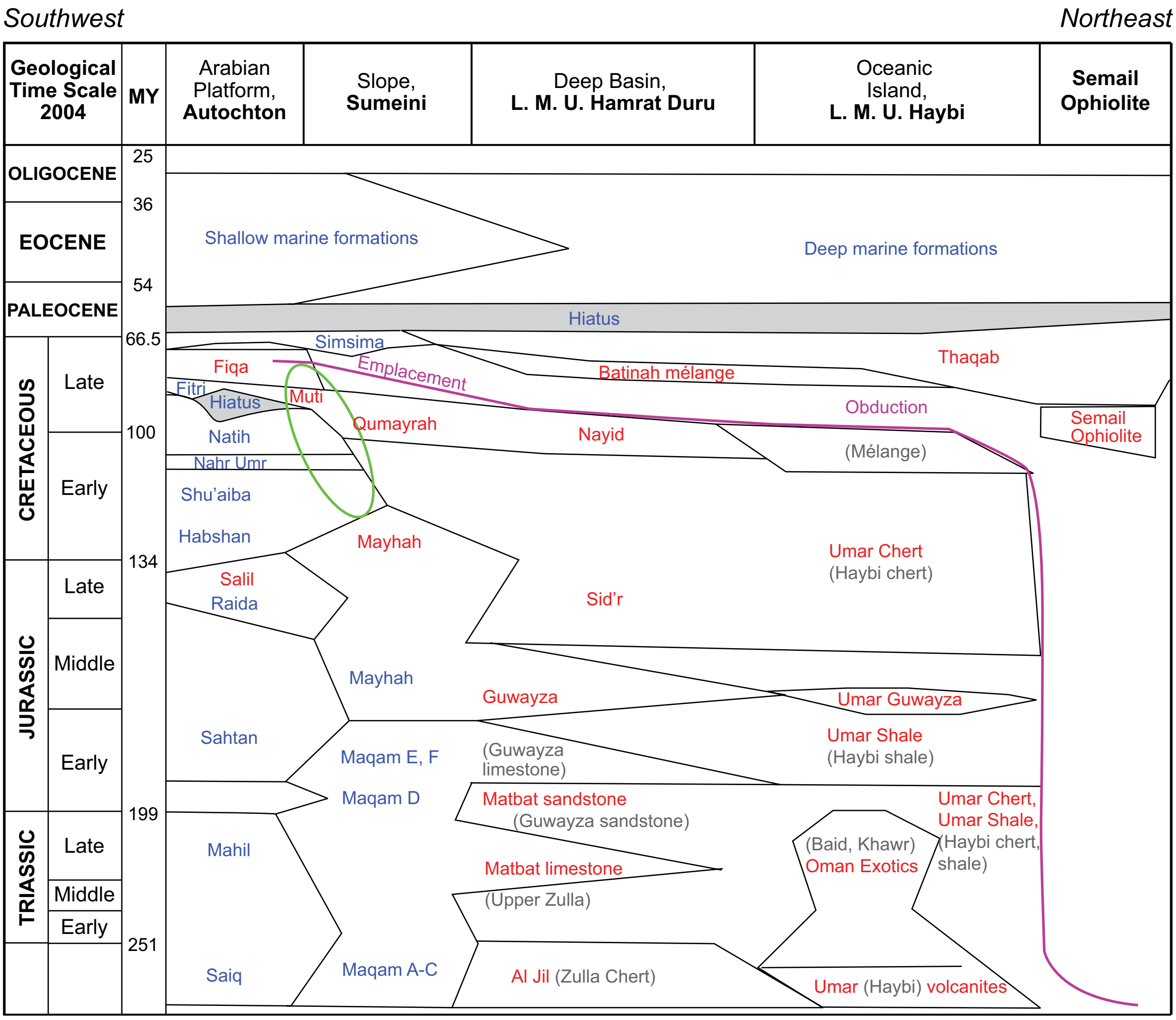


Figure 3: Simplified stratigraphic chart of the Oman Mountains. Formation names used in this paper are marked in red. Formation names used by other authors for the target area and not used in this paper are marked in grey and in parantheses. Formations outside of target area (Autochton) are marked in blue. Red and blue letters are mainly derived from the BRGM terminology (e.g. Béchennec, 1988; Rabu et al., 1990), while grey are derived from other authors (e.g. Glennie et al., 1974; Robertson, 1987; Searle, 2007; Pilevuit, 1993; Watts, 1990). Tectonic unit names in bold capitals in headings after Glennie et al. (1974), Searle and Cooper (1986) and Searle (2007). Regular capitals indicate facies zones (mostly after Glennie et al., 1974; Béchennec, 1988). Green ellipse indicates the transitional lithologies found in the 'Sumeini' exposures and at Murri.

Surroundings of Ibat Mountain

Description 1: In the road section, which crosscuts the Mountain front at Wadi Ibat, a sequence of Semail Ophiolite - Matbat Formation - Nayid, Sid'r, and Guwayza formations is exposed (Enclosure 2.1). The Lower Hamrat Duru Unit is tectonically covered, first by the Matbat Formation belonging to a Middle (or Upper?) Hamrat Duru Nappe, and second by the Semail Ophiolite. The contact between Middle (Upper?) Hamrat Duru and Semail Ophiolite has a steep attitude (Enclosure 2.2).

Interpretation 1: The occurrence of weak superposed slickensides suggest a later normal faulting downdip towards SW (Enclosure 2.3).

Description 2: The Middle/Lower Hamrat Duru Nappe boundary is folded as clearly seen in the landscape (Enclosure 2.1). At outcrop the highly tectonised shaly contact was investigated but no tectonic transport direction was found. The Ibat Mountain region is built-up of a complete Mesozoic succession of the Lower Hamrat Duru Unit. The Nayid Formation is easily distinguished as a thin, lighter carbonate layer on top of darker Sid'r Formation. This horizon appears three times at the entry of Wadi Ibat and one of the layers shows signs of tight folding (Enclosure 2.4). At several sites this original flat, SW-facing synform is refolded by NE-verging F2 folds (Enclosure 2.5). These folds are also very tight and have an axial plane cleavage, steeply dipping to the SW.

Interpretation 2: When seen on a satellite image, it appears that the Nayid Formation is folded in flat axial surface folds, the limbs of which cover the whole mountain. The hinges are found respectively at the NE and SW terminations of Ibat Mountain. It is concluded that at least the upper part of the Hamrat Duru succession is folded in large isoclinal folds (F1). Most of these folds seem to be SW-facing (see also Searle and Cooper, 1986). A second, NE-facing, syn-cleavage folding phase post-dates the SW-facing folding (F2).

Wadi al Kabir Region

Description 3: The Ibat Mountain ends in an abrupt cliff towards the east. In exposures close to M'Kerr village, the tectonic boundary between these two regions is very sharp.

Interpretation 3: The abrupt termination strongly suggests a late normal fault (Enclosure 2.6). The hangingwall of this supposed fault contains sheared serpentinite and overlies the Matbat Formation. Several, opposite transport directions can be observed in this sheared serpentinite. A first, top-SW shear is followed by a second, top-N shear (Enclosure 2.7).

Wadi al Kabir Large Curve

Description 4: Although not intersecting Traverse A, the Wadi al Kabir "large curve" of the wadi-road (Figure 2) merits a more detailed description. The large curve has several facets displaying different structural aspects. On the NW wall of Wadi al Kabir, high on the hillside, the Matbat sandstone is subhorizontally over-ridden by a 2-m-thick sheared serpentinite zone, topped by folded Matbat sandstone (Enclosure 2.8). The lower Matbat beds are sheared in a top-NE sense. Layering is gradually turned subparallel to the shear zone. The contact is indicated by a ferruginous thick bank.

Interpretation 4: The serpentinite displays S/C cleavage with top-NE sense of shear (Enclosure 2.9). Both measured lineations on the main shear surface and transport direction constructed from the intersection of S and C planes indicate top-NE shear (Enclosure 2.10). The upper thrust unit is folded and ductile serpentinite flows into the hinge of that fold (Enclosure 2.8). Folding asymmetry is compatible with top-NE shear.

Description 5: A steep southern wall of Wadi al Kabir large curve offers another set of exposures. The wall exposes Matbat sandstone, Guwayza limestone and Sid'r chert (Enclosure 2.11). Guwayza and Sid'r are in tectonic contact with Matbat sandstone along a major fault, which can be followed up-flank for several 10s of metres. Outcrop-scale offset shows normal faulting. On the fault surface clear dip-slip and oblique normal slickensides are perfectly preserved. Three motions could be differentiated based on superposed slickensides (Enclosure 2.12): a first southwards (dextral), a second southeastwards (pure dip-slip normal) and a third northeastwards (normal-sinistral) one.

On top of the hill formed by Sid'r, a cherty and silicified limestone (also member of Sid'r) is topped by serpentinite. This sheared serpentinite can be also found on the opposite, northwestern side of the main wadi, where it overrides the Matbat sandstone of the normal fault footwall (see previous exposure).

Interpretation 5: Sheared serpentinite tectonically covers both the Matbat and Sid'r formations; therefore the normal fault dies out in the ductile detachment formed by the serpentinite. An alternative interpretation is that normal faulting preceeded out-of-sequence nappe formation, marked by sheared serpentinite.

Matbat Hat

Description 6: The Middle Hamrat Duru Nappe is mostly represented by the Matbat Formation. However, near the western shoulders of Wadi ad Dil, another Matbat exposure is found on top of a hill, with an entirely different dip from its Matbat substratum (Enclosure 2.13). A roughly horizontal surface separates the subhorizontal- and the subvertical-bedded Matbat Formation. This peculiar feature named as "Matbat hat" makes up yet a higher (Upper) Hamrat Duru Nappe.

Wadi ad Dil

Description 7: Wadi ad Dil is a deformed zone in the Lower Hamrat Duru Unit, characterised by dominantly very steeply dipping beds. Along a linear, open valley segment with NNW strike rounded hills entwine a broader basin. The bottom of this little basin is filled by sheets of Quaternary gravel. The sudden topographic change has a geologic basis, which is revealed by fresh road cuts at the pass of Wadi ad Dil. There a greyish, soft rock surrounded by its pinkish, brownish alteration zone is exposed (Enclosure 2.14). A strong sulphurous smell and many gypsum veins and smaller crystals indicate that the grey and soft rock is microcrystalline gypsum. The region is gently uplifted with respect to its neighbourhood; the pinkish oxidized gypsum is topped by Al Jil radiolarite and shale. Internal layering of these is always somewhat discordant to the gypsum boundary and is upwards dragged by the gypsum. Gypsum bodies are always broader downwards and are found in the core of regional folds. The contact can be qualified as intrusive; i.e. gypsum protrudes from below and uplifts the Al Jil Formation above (Enclosures 2.16 and 2.17). Gypsum forms fingers in the order of 100 m diameter.

The internal structure of the gypsum intrusions is marked by xenoliths embedded in soft gypsum and by cm-thick gypsum veins. The xenoliths/clasts are often aligned and arranged into parallel sets (Enclosure 2.15). These are marked by an incipient subvertical cleavage and by the long axis of the non-gypsum clasts. From an exposure in the junction of Wadi Hawasina it is clear that the cleavage and alignment of the xenoliths marks flow paths. Neither identified Mesozoic rocks of the Autochthon, nor members of the Hamrat Duru Nappe were found as clasts in the gypsum. Most clasts are formed by coarse siliciclastics and shales, with some organic-rich limestones. All show strong flattening and pre-emplacement cleavage.

Interpretation 7: The gypsum fingers may have originated from a larger evaporite stock at depth. The stock might also contain halite and cover-salts, because several gypsum finger samples tasted halite/ sylvine. Because of the linear arrangement, it is probable that gypsum intrudes a pre-existing tectonic zone (i.e. a fault). The xenoliths brought up by the evaporites should be found in the immediate vicinity of salt layers or within them as sedimentary clasts. Several studies (including palynology) were done in order to reveal the age of the gypsum; so far all efforts proved to be in vain. After some still-pending studies are concluded, separate papers will be devoted to the origin of these evaporites.

Wadi Hawasina Serpentinite Shear Zone

Description 8: In the central part of Wadi Hawasina (Figure 2), the thrust contact between two Hamrat Duru units is marked by sheared serpentinite. It can be traced from Wadi Bani Kalban towards the north (Enclosure 1.1), where the generally E-W striking nappe boundary turns N-S and is marked by a western lower plate and an eastern upper plate.

The northern wall of Wadi Hawasina shows a greenish, E-dipping serpentinite horizon between the two Hamrat Duru units. In a northern side valley, the main thrust indicated by serpentinite can be followed towards the north (Enclosure 2.18). The serpentinite is gradually sheared-out and replaced by sheared shale. Near the lower contact three major Oman exotic limestone boulders are found embedded in sheared shale.

Adjacent to the main valley a small exposure illustrates the complexity of shear deformation in serpentinite. This exposure was buried by recent road construction. The lower plate Matbat Formation has a steep dip, but layering is flexed and turned parallel to the main thrust boundary of the serpentinite (Enclosure 2.19). Smaller thrusts parallel to this main tectonic boundary have a clear top-SE offset; several lenses or sheared, rotated clasts corroborate this observation. On top of Matbat, cm-thick sheared black clay was found with mylonitic fabric, small sheared lenses, and sigma clasts. These gave a uniform, top-NNW shear sense, i.e. opposite of those preserved in the lower plate (Enclosure 2.20). The black shale-mylonite is topped by a cemented, sheared serpentinite. Probably magnesite formed a thicker off-white, ochre impregnation and preserved shear structures in serpentinite.

Interpretation 8: S/C cleavage gave top-N sense of shear (Enclosure 2.22). Unfortunately no lineation was associated with either shear direction, but transport direction was constructed from the S/C relationship. Shear zones measured further up-valley do fit the two general shear directions. A first top-SSE shear, followed by second top-north shear is suggested (Enclosure 1.4).

Description 9: In a small side-valley to the east, serpentinite is found on top of a rusty limestone and shale formation (Enclosure 2.21). All rocks are impregnated by ferruginous fluids. The footwall of the serpentinite is probably the Matbat Formation. The contact is easily followed in the exposure and shows well-developed drag folds. A penetrative subvertical cleavage affects the footwall (serpentinite forms just a small erosional fragment) and transposes sedimentary lenses parallel to cleavage. This steeply dipping cleavage is parallel to the axial plane of the drag folds. The axial trace of the original fold trends NW; the asymmetry of the fold (F1?) indicates a SW vergence (Enclosure 2.21). The whole structure is re-folded by a later folding event (F2), so the region forms an involute synform with sheared serpentinite in the core. Some of these later folds have northwards trending axes.

Description 10: Following the section in the Wadi Hawasina, at the junction towards Al Ayan, a very tectonised zone can be observed with sheared shale, Fe-impregnated boulders and many shear indicators. Serpentinite is found along the northern continuation of the same shear zone. There, at the eastern termination of Jabal Milh, the Nayid Formation is tectonically covered by the Al Jil Formation (Enclosure 1.1). Although this contact is not so spectacular in Wadi Hawasina, it was identified as the contact of the Middle and Upper Hamrat Duru nappes. The thrust surface between these nappes can be seen in the landscape and also on the satellite image. Dip data and smaller repetitions suggest that there might be several imbrications within the Upper Hamrat Duru Nappe.

Along the road Al Jil radiolarites of the Upper Hamrat Duru Nappe are overthrust by reddish-greenish cherts, radiolarites of the (Upper) Haybi Nappe. It is very difficult to distinguish between these very similar radiolarites. However, at the eastern termination of Jabal Milh, i.e. further to the north, several exposures show a more complete succession of the Upper Hamrat Duru Nappe (Enclosure 2.23), including the Guwayza Formation. These are also overthrust by the Umar cherts, so the situation is clear there.

Description 11: At the eastern termination of the cross section the pillow basalts of the Haybi Nappe are covered by some metre-thick, much sheared serpentinite, which is overlain by the Semail Ophiolite (Enclosure 2.24). The thrust contact can be seen in the outcrops and also in the landscape. Several imbricates of shale and basalt lenses are found in this zone.

TRAVERSE B: RAHBAH-MAJZI SECTION (ENCLOSURE 3)

This Traverse starts at Rahbah, ends near Naam and is broken at Wadi ad Dil. It continues in a more southerly location through Jabal Milh, through Wadi Harim. In the east it ends near the village of Majzi, at the asphalted road (Enclosure 3; Figure 2).

In the western segment the Semail Nappe is underlain by a vast Haybi Nappe, in turn underlain by a Lower Hamrat Duru Unit. Although these certainly had a primary nappe thrust contact, the present contacts are steep and have normal and strike-slip fault character. The same applies to the contact of the folded Hamrat Duru and Sumeini units. This latter is exposed as a major antiform in the Jabal Rais. The eastern limb of the fold is again covered by a Lower Hamrat Duru Nappe. It is to be noted that in the main part of Jabal Rais, cleavage is generally flatly dipping to the west. This general attitude is locally steepened, especially in the limestone crest transected by the Naam Gorge.

The eastern part of the Traverse begins in the higher elevated regions on Jabal Milh. Near Wadi ad Dil the Lower and Middle Hamrat Duru boundary runs within a thick Al Jil Formation. Several potential nappe surfaces were identified, but these lacked sheared serpentinite, so the continuation of the nappe boundary is uncertain here. In the bulk of the section a continuous Hamrat Duru succession is found from the western, stratigraphically lowest Al Jil to the highest Nayid Formation in the east. An isoclinal fold with Guwayza core is observed within this succession. Near the centre of this transect segment, Al Jil chert of the Upper Hamrat Duru Unit is found tectonically above and to the east of the Nayid Formation of the Middle Hamrat Duru Unit. Both units show signs of intense, tight to isoclinal folding.

At the northeastern end of the section the tightly folded Hamrat Duru Group is cross-cut by several post-folding thrust faults. Their main vergence is top to the southwest, but several smaller top to the northeast thrusts are also observed. This Hamrat Duru Nappe is overthrust by a southwest verging Haybi Unit consisting of exotic limestone and intensely folded shale and chert. This nappe contact is apparently not folded. The Semail Ophiolite, as the uppermost tectonic unit, is emplaced upon the Haybi Nappe. Sheared serpentinite near the contact shows signs of various tectonic transport directions, but map-scale (late?) normal faulting seems to dominate.

Sites near Rahbah

Description 1: A palm grove west of Rahbah gives excellent opportunity to observe the contact of the Semail Nappe with Haybi Unit (Enclosure 3). The sheared serpentinite at the base of the Semail Nappe is in direct contact with carbonates of the Haybi Group. The sheared lithologies are arranged in steeply west-dipping "layers" with prominent shear directions. S/C cleavage is the most dominant feature (Enclosure 3.1).

Interpretation 1: All the indicators give a right-lateral, i.e. top-N shear (Enclosure 3.2). The steeply dipping nature and the strike-slip shear suggest that the original Semail thrust fault was strongly tilted and overprinted by later movements. The steep and tectonically discordant nature of the serpentinite can be followed throughout the western boundary of the Hawasina Window.

Description 2: In the Gorge between Rahbah and Naam (Figure 2, Enclosure 1.1) a complete Hamrat Duru Nappe cover is found above the Sumeini and below the Umar succession. In Rahbah, the Haybi/Lower Hamrat Duru Nappe boundary is subvertical (Enclosure 3.3). Unfortunately no shear indicator was found there, but several similar attitude left-lateral shear zones were found in the Lower Hamrat Duru succession further east. The Lower Hamrat Duru succession is folded by syn-cleavage tight folds (F2), with a SW-dipping general cleavage (Enclosure 3.4).

Interpretation 2: These folds affect layers which suffered earlier top-SW layer-parallel shear, evidenced by remains of small drag folds (F1) and thrusts in cherts and clay layers (Enclosure 3.5). These drags cannot be associated to syn-cleavage F2 folding.

Description 3: In northerly areas the nappe boundary between Hamrat Duru and Sumeini nappes is conformable to the general dip of Sumeini beds (ca. 40° towards the SW) and is underlined by a haematitic shear surface. However, at the western entry of Naam Gorge this relatively flat nappe boundary is not found. Instead, the Matbat Formation makes a syn-cleavage synform, which is cut by a subvertical fault against steeply dipping layers of the Sumeini carbonates (Enclosure 3.6). The Sumeini carbonates show signs of en echelon folds, superposed on the major antiform.

Interpretation 3: The arrangement of these *en echelon* folds suggests right lateral shear. An important exposure (Enclosure 3.7) along the subvertical fault, on the other hand, shows several slickensides and indicators of left lateral movement (Enclosure 3.8). The subvertical fault zone continues towards the SE, and defines the linear segments of Wadi ad Dil (Enclosure 1).

Naam Gorge

Description 4: Partly departing from earlier descriptions (e.g. Searle and Cooper, 1986), the oldest exposed stratigraphic member of the Sumeini succession is a dark grey, well-layered, micritic limestone of possible Late Jurassic – Cretaceous age (Figure 4). No fossils are found in this formation. The dark micritic layers are separated by thin shale or clay layers. Some layers may contain chert or dolomite lenses, horizons forming a black, resistant bed in the micrite. No redeposited elements are found in this thick horizon.

Interpretation 4: This micrite is not equivalent to the Mayhah Formation, which seldom contains redeposited elements (Figure 3). It is rather similar to certain Natih facies of the Autochton. No older term was observed (as also stated by Searle and Cooper, 1986), so a detachment is inferred below the dark micrite.

Description 4a: A purplish (originally black-grey) shale-marl horizon is frequently found at the top of the micrite. This is followed by a generally several-metre-thick limestone breccia bed or beds. This bed is composed of clasts of dark limestone, occasionally chert or dolomite and even sandstone. Some horizons may contain a rich, but deformed fauna of rudist shells or *Actaeonella*- and *Nerinea*-like gastropod sections (Figure 4c). The limestone breccia grades to dark marl, which weathers to purple or yellowish brown. This marl is often sandy and regularly encloses thinner-thicker clastic limestone beds (Figure 4d). These are echinoderm-limestones or micro-conglomerates, calcirudites with often graded bedding. Chert lenses are frequently found within the marl. The formation is crossed by oxidized iron-rich calcite gashes.

Interpretation 4a: The marl is most probably Late Cretaceous in age and equivalent to the Qumayrah or Muti formations. It has indeed redeposited elements (Searle and Cooper, 1986; Rabu et al., 1990).

The above described stratigraphy of the whole succession is also found in Jabals Mawq and Matid. It closely resembles the lithologies and platform-like (and not slope-like) facies found at Murri, at the tip of Al Jabal al-Akhdar. Therefore these Hawasina Window "Sumeini" jabals might have more affinity to the Arabian carbonate platform facies realm rather than to the slope. Therefore we suggest that the exposed formations constitute a certain transition from platform to slope environment, schematically indicated by the green ellipse in Figure 3. This part of the platform may have been sheared off during nappe emplacement, so these jabals may still be part of the Sumeini tectonic unit (i.e. the lowest position Hawasina Nappe, above the Autochton). However, during field work no basal shear plane was detected beneath these units.

Description 5: Both "Sumeini" grey micrites and tectonically overlying Matbat sandstone are folded in a major fold with flatter, west-dipping western and subvertical to overturned eastern limbs, this being the central fold of Jabal Rais (Enclosure 3.9). In the Naam Gorge the fold within the Sumeini carbonates is upright, the axial surface is near vertical. This steep axial plane antiform is best seen from a distance, from the western slope, or in side-gorges. There is a steeply dipping penetrative cleavage, which is around the axial surface of this major fold (Enclosure 1.4). The strike of the cleavage is also rotated with the axis of the fold.

In the narrows of the Gorge an unconformity of tectonic nature is found within well-layered grey micrites (Enclosure 3.10). When taking a closer look, it appears that a steep and gently curving fault cuts off layers obliquely from the SW compartment and is parallel to the layering of the NE compartment. The thrust fault dips to the NE, but dip angle may change (Enclosure 3.12). Moreover, the SW compartment is very tightly folded (F1). Calcite-filled gashes parallel to and along the fault plane are ptygmatically folded and deformed by the regional cleavage (Enclosure 3.11).

Interpretation 5: This observation suggests that there was internal imbrication within the "Sumeini" succession synchronous to, or after a tight-isoclinal first folding (F1). Then the whole primary folded-imbricated structure was refolded by the major, syn-cleavage fold (F2).

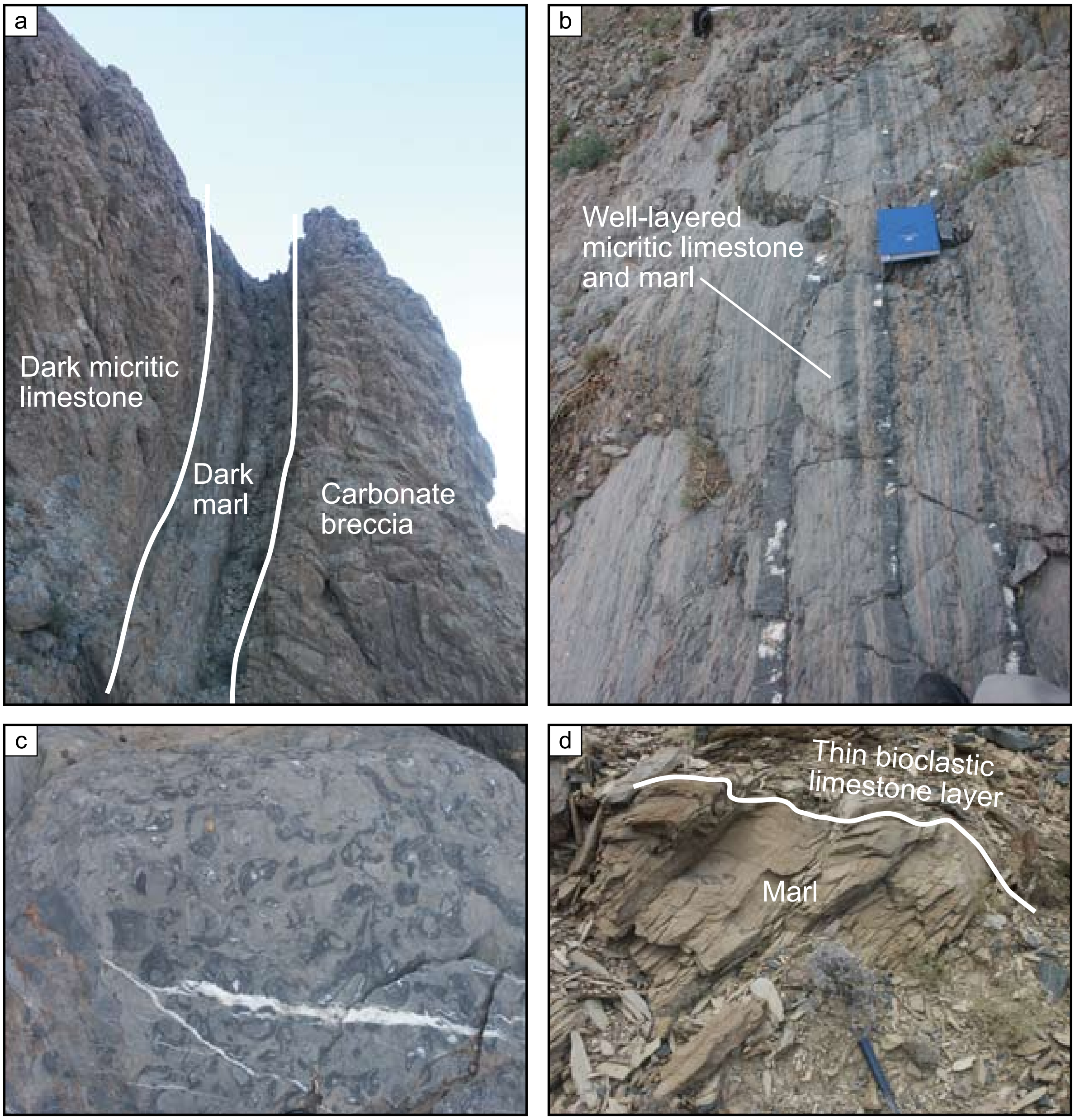


Figure 4: Main lithologies of the "Sumeini" Unit. (a) Micritic limestone, marl, clastic carbonate succession right beneath the Qumayrah marl. (b) Close-up view of clast-free limestone, marly micritic limestone. (c) Boulder with rudist fragments from the carbonate breccia bank. (d) Qumayrah marl with ferruginous calcarenite giving the layering. Cleavage is well distinguished.

East of Naam

Description 6: On the eastern limb of the Jabal Rais antiform, Qumayrah shale/marl is tectonically covered by the Lower Hamrat Duru Nappe. In the exposures at the eastern end of the Gorge, near Naam village (Figure 2) bluish grey Al Jil shale and yellowish thin limestone form thin alternations. The limestone layers form continuous marker beds, so complex folding is easily followed (Enclosures 3.13 and 3.14). The exposure is dominated by tight to isoclinal upright F1 folds, re-folded by syn-cleavage small wavelength F2 folds and crosscut by penetrative, subhorizontal cleavage. There is no apparent cleavage associated to the first folding phase, although folding is very tight. Hinges of the F1 folds are crosscut by the main cleavage (Enclosure 3.14). The two axial surfaces are almost perpendicular and the first axial surface is folded together with layering by the F2 folds. While no facing could be observed for the first generation folds, the syn-cleavage F2 folds have a top-NE vergency. These are accompanied by top-NE thrusts which are almost parallel to the main cleavage and which have decimetre offsets.

Interpretation 6: This top-NE shear is clearly associated to the F2 folds and cleavage formation; most probably they represent a later phase of glide along, or at small angle to the already formed cleavage.

Jabal Milh, Wadi Harim

Description 7: Jabal Milh is composed of major flat lying folds. This structure is best revealed in the Wadi Harim (Figure 2), where km-size and outcrop-size folds are found. On the northern slope the Guwayza and Sid'r formations are folded in a tight antiform and synform (Enclosure 3.16). The southern slope shows km-size major folds with flat axial planes (Enclosure 3.15). These are best seen in Al Jil Formation. All folds tend to be cylindrical with parallel axes.

Outcrop-scale folds are equally spectacular. At the SW end of the Wadi Harim many smaller or decametre-size folds are seen in the Matbat Formation. The folds have flat axial plane parallel to a penetrative cleavage (Enclosure 3.17). Cleavage is often planar, very penetrative, and also present in more competent formations. Planar minerals and clasts, lenses are rotated parallel to the plane perpendicular to main shortening.

Interpretation 7: The gentle tilt of cleavage may be due to later folding. This late folding (F5) has a gently SE-dipping axis (Enclosure 3.19, constructed axis as red barbed asterisk).

Description 7a: In outcrops the folds have two slightly oblique lineations. The first is bent around the hinge of the fold, while the second is parallel to it (Enclosure 3.18). This feature is seen in many exposures of the Jabal, but possibly the most spectacular example is found in an eastern side valley to the Wadi ad Dil. There a tight fold supports boudinage-like or mullion-like lineations around the hinge.

Interpretation 7a: The first lineation may be related to incipient folding, or to an early boudinage; the second is clearly parallel to the axis of the finite fold form. Stretching lineations are also slightly oblique to the fold axis.

Narrows of Wadi Harim

Description 8: In the narrows of Wadi Harim (Figure 2) the Sid'r exposures are interrupted by the appearance of grey, oolithic, turbiditic limestone (Enclosure 3.20). This characteristic Guwayza Formation is unexpected, because, coming from the west, one can see a folded, but eastwards-younging sedimentary succession of the Hamrat Duru Nappe. The contact of this "internal" Guwayza exposure does not seem to be much faulted. There are some small local faults, with occasionally crushed chert, but no major thrusting or large offset between the formations is apparent. Upper layers of shalier Guwayza are followed upwards and eastwards, then they can be tracked downwards in both walls of the Gorge.

Interpretation 8: The "internal" Guwayza forms an early, tight F1 fold, which was later re-folded by a flat axial surface, syn-cleavage F2 fold. It is probable that the Sid'r is also folded in a tight F1 synform, but this is not evident in the nearby Gorge.

Description 9: In the middle part of Wadi Harim, where its strike slightly breaks, Al Jil Formation (Middle Hamrat Duru Nappe) is thrust upon the Nayid Formation (Lower Hamrat Duru Nappe; Enclosure 3.21; see also Béchennec 1988, his Figure 129). The nappe contact is folded in a synform verging towards the NE. The axial surface is subhorizontal to gently NE-tilted. The same nappe boundary contains sheared serpentinite and a sheared shale zone further to the SE, near Wadi Hawasina. Further north, in Wadi Harmali, the contact is even more spectacular. There folds become very tight and also correspond to F2 folds.

Majzi

Description 10: At the entrance of Wadi Harim, near Majzi village (Figure 2), a set of exposures documents the contact of Semail serpentinites, Haybi Unit and Hamrat Duru Unit. The wadi cuts through a smaller tower of serpentinite, then through Umar cherts and limestones, and finally runs into Matbat Formation of a Hamrat Duru Nappe (Enclosure 3.22).

The Haybi Nappe directly below the sheared serpentinite is composed of slab-like lithologies with tectonic contacts. Not a single sedimentary contact between the different lithologies was found. The lowermost formation is shale with a top-to-SW shear zone (Enclosure 3.24, red plane and transport arrow). In the footwall of this shear zone, already in Upper Hamrat Duru nappe formations, a first, top-SW thrusting and a second top-NE normal faulting was recorded along the same inclined planes (Enclosure 3.24).

The small tower of serpentinite is in fact separated into three compartments by subhorizontal tectonic surfaces (Enclosure 3.23). Between two relatively intact serpentinite blocks an intensely sheared serpentinite "layer" is found. This is thought to be an important mylonitic zone with well-developed S/C cleavage and overprinting brittle shear surfaces. These shear indicators suggest several motions, including a top-S and a top-N shear (Enclosure 3.24). The tower is separated from the neighbouring Umar chert block by a 60° ENE-dipping normal fault. This surface bears a number of slickensides and other shear indicators. Some of the brittle fault features fit into a NE-SW extension, which corresponds to the main normal fault visible at the outcrop (Enclosure 3.24). It is interesting to note that a similar NE-SW extension along semi-ductile shear zones exists in the serpentinite as well. However, NW-SE extension can be also recorded in brittle fault zones (Enclosure 3.24). Slickensides also preserved the indications of a NE-SW to N-S compression.

Interpretation 10: These observations suggest that after top-SW shear and nappe stacking, a top N shear event followed. Of the several extensional phases affecting the eastern border zone of the Window NE-directed normal faulting seems to be dominant.

TRAVERSE C: AL ISALAT-LHIBAN SECTION (ENCLOSURE 4)

The Traverse (Enclosure 4) is dominated by two antiforms, in the core of which "Sumeini" rocks are exposed (see also Searle and Cooper, 1986, their section XS-2; their figure 7b). These constitute the high peaks of Jabals Rais and Mawq. The sector between these antiforms is occupied by a synform, where Hamrat Duru and Umar lithologies are exposed. Jabal Mawq Sumeini Unit is directly covered by sheared serpentinite and a thicker Haybi Nappe. This Haybi Nappe is also found on the northern limb of the Jabal Mawq antiform. Towards the north a smaller synform, then an antiform follow. In the north, the section ends with a top-north thrust of the Umar rocks on the possibly overturned Haybi-Semail Ophiolite contact (Searle and Cooper, 1986).

Al Isalat

Description 1: The westernmost part of Traverse C at Al Isalat shows the steep contact of the Semail Nappe with Hamrat Duru units. This is a late contact, since it obliquely dissects several formations and is subvertical (Enclosure 1). Along a NNW-oriented surface semi-ductile, left-lateral slip was observed (Enclosures 4.1 and 4.5; green shear plane and transport arrow).

Regionally the Sumeini Unit is tectonically covered by the Lower Hamrat Duru Nappe. These rocks are folded into an isoclinal fold (F1). The fold is seen at the crest above Al Isalat village (Enclosure 4.2).

Interpretation 1: North of the village both limbs of this fold are preserved, but further north the northeastern limb is cut by the overlying Middle Hamrat Duru tectonic boundary. Near the village, the southwestern limb of the fold is also cut by the left-lateral shear surface of the steep Semail overthrust (Enclosure 4.4).

Description 2: In the village, at a smaller gorge cut by the creek, exposures of Nayid, Sid'r and Guwayza formations in the Lower Hamrat Duru Nappe were found. These exposures are located on the eastern limb of the main isoclinal fold (Enclosure 4.4). They are now partly covered by scree from road construction. It is to be noted that the Nayid Formation is tectonically followed by the Matbat Formation on its external (eastern) side. The exposures show a fold train with axial plane cleavage (F2 folds; Enclosure 4.3). Even clasts within Nayid Formation were aligned parallel to the penetrative cleavage (transposition). This particular site showed cleavage planes dipping towards the NE (Enclosure 4.5). Fold asymmetry was conformable with that dip.

Interpretation 2: The syn-cleavage fold (F2) refolded the original isoclinal upright fold (F1). The tectonically higher Matbat Formation (Middle Hamrat Duru Nappe) was probably also affected by the isoclinal F1 fold and the subsequent F2 fold (Enclosure 4.4).

Saddle in New Road across Jabal Rais

Description 3: The Sumeini rocks in the core of Jabal Rais antiform show tight folds. A spectacular fold train is found at the saddle (relay tower) and a little palm grove near the saddle, on the northern slope. The folds have an E-W axial direction and axial surface dipping flatly towards the south or west (Enclosure 4.6).

Interpretation 3: This fold train is the uninterrupted continuation of the main Jabal Rais antiform, but at this segment the axial direction is flexed. From south to north fold hinges are turned from a general SE-NW to E-W strike. An intensive axial plane cleavage is found in the core of the folds and is also flexed with the axes (Enclosure 4.7).

Northern Slope of Jabal Rais

Description 4: The Lower and Middle Hamrat Duru nappes are amply preserved on the northern, eastern limb of the Jabal Rais antiform. At the contact of Lower and Middle Hamrat Duru units, a thin sheared serpentinite lense and a mafic intrusive body were found (projected into Traverse).

Interpretation 4: Based on cleavage/bedding relations, the Middle Hamrat Duru formations are overturned (Enclosure 4.8).

Description 5: The tight synform in Umar rocks between the Jabal Rais and Jabal Mawq is not readily seen along road cuts in the Traverse. However, some exposures to the north, in the direct continuation of the structure show a flat axial surface synform, affecting both Hamrat Duru and Umar lithologies (Figure 5). These structures are best expressed along a sinuous road between Al Isalat and Al Ghuwajz, at the abandoned village of Masan.

Interpretation 6: In the northern continuation of the main Traverse, a Sumeini Unit is exposed in Jabal Mawq, but it lacks Hamrat Duru tectonic cover. Instead, it has a thicker sheared serpentinite on its northern limb (Transect C; Enclosure 1.1), followed by a Haybi Unit. This latter is in continuity with the Haybi Unit covering the Jabal Rais antiform. Therefore, if all nappe units were "cylindrically" covering their respective tectonic basements, at least the Lower and Middle Hamrat Duru nappes would be missing in Jabal Mawq. It is interesting to note that there are small remains of Lower or Middle Hamrat Duru preserved along the eastern edge of Jabal Matid (Enclosure 1; immediately SE of Jabal Mawq).

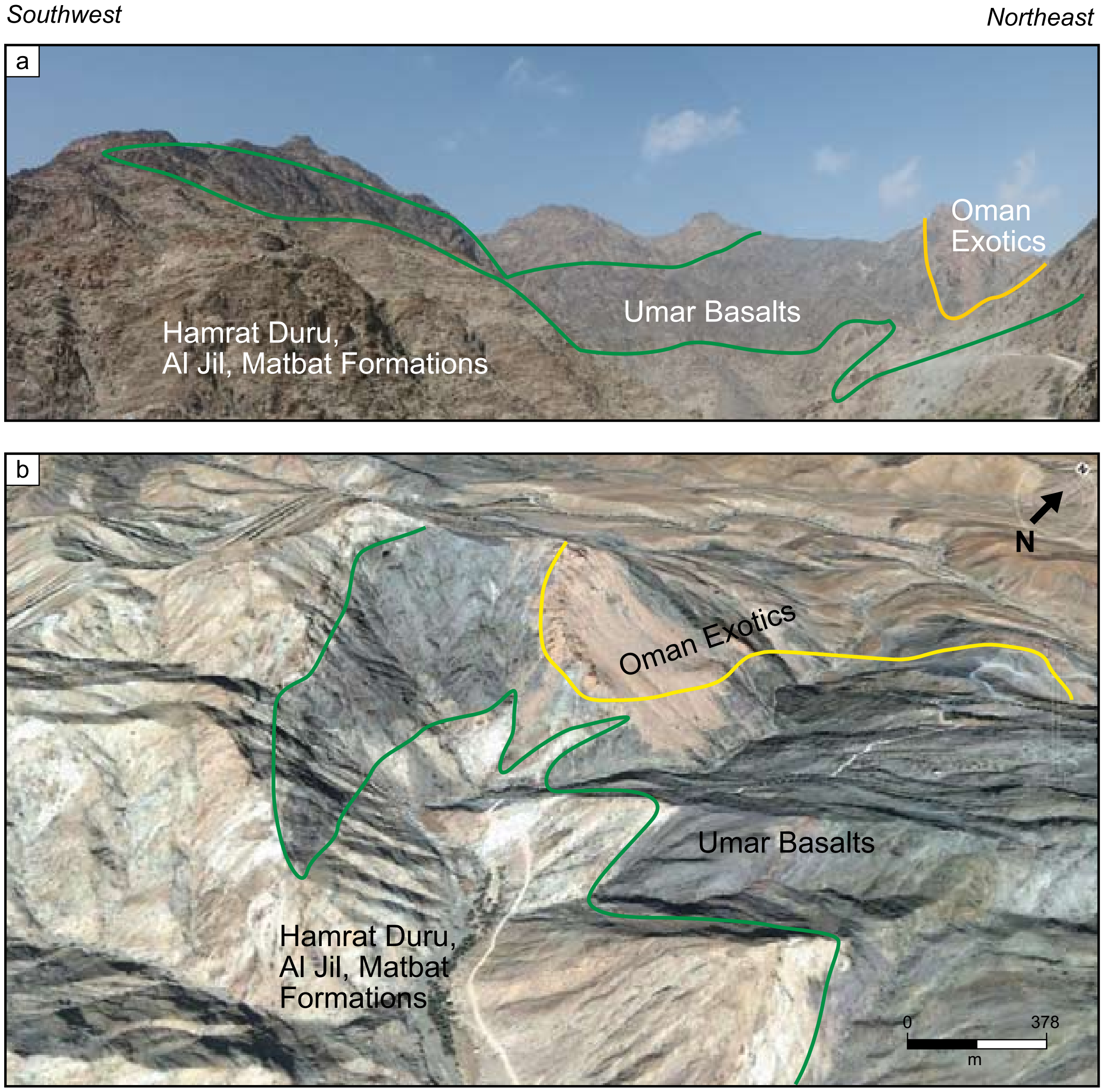


Figure 5: Synform of a Haybi Nappe fragment north of Jabal Rais, along the Al Isalat-Al Ghuwiz road. (a) Basalts and Oman Exotics in the core of a synform formed by Hamrat Duru sediments. Width of photo landscape 1.5 km. Photo taken from the road in the lower central segment of the picture. (b) Oblique Google Earth view of the area with the main lithologies.

Jabal Mawq, Greater Qafas Gorge

Description 7: Jabal Mawq is cross-cut by the greater and smaller Wadi Qafas gorges (Figure 2). These offer excellent exposures in Sumeini rocks. The "Sumeini" carbonates at the southern end of the greater Gorge have an abrupt contact towards the southern body of slightly metamorphosed basalts of the Hajbi Nappe (Enclosure 1.1). A side-wadi branching off the main Wadi Qafas runs along the contact of these carbonates and Umar basalts, shales and cherts. In this side-wadi the projected dip of the carbonate would continue in Umar rocks. In other words a fault contact between the Sumeini and Haybi nappes is inferred. This fault is exposed higher in the side-wadi. The average 20° southwesterly dip of Sumeini limestone layers is cross-cut by the 45° southerly dipping normal fault surface.

Description 7a: Folds are dominant deformation features in the Qafas Gorge. The best examples are found within the great Gorge. All of them are flat lying, with almost horizontal axial planes, and ENE- to E-trending axes (Enclosures 4.9 and 4.11). Most of the syn-cleavage F2 folds have northwards, northeastwards vergency. The folded layering shows signs of flattening and layer-parallel asymmetric shear (Enclosure 4.10). Therefore syn-cleavage folding post-dates layer-parallel flattening and shear.

Description 7b: Normal faulting features are also exposed in the Wadi Qafas greater Gorge. Normal faulting and thinning of rocks is evidenced by many structures. First, the "Sumeini" succession is thinned by faults dissecting the layering at very low angles (Enclosure 4.12). These low-angle faults cut out a marly part of the succession, bringing the top of the clastic limestone closer to the grey micrite. Second, some thin limestone layers are dragged along inclined planes, which do not cut through the entire succession, but form shear zones detached at ductile layers. The offset and drag along these shear zones is clearly normal (Enclosure 4.13). Some more competent carbonate layers are boudinaged; the lenses are asymmetrically back-tilted and the inclined, dragged tail indicates ductile normal faulting (Enclosure 4.14). These lenses form asymmetric boudins. This feature is quite common in metamorphic rocks subject to extension.

Interpretation 7b: The bulk of these normal faults and semi-brittle to ductile normal shear zones dips to the south or SSE, but south-westerly dips (Enclosure 4.15), as well as some conjugate, N-dipping surfaces were also recorded. In very rare cases slickenside lineations point to the south. It is important to note that the conjugate fault planes have the extension direction (N-S) in their acute bissectrix. This is again a characteristic of ductile faulting. The whole ductile normal fault set is gently northwards tilted. This is not due to syn-cleavage folding, because these folds and their axial plane cleavage are also frequently northwards tilted (see later).

Description 7c: Between the two gorges a spectacular view of a map-scale fold is seen (Enclosure 4.16). This fold follows the uppermost limestone layers in a smaller secondary *en echelon* fold to the major Jabal Mawq structure (Enclosure 1).

Interpretation 7c: Although the origins of this fold were formed during F2 folding, the finite structure is due to a later F3 folding, which gently tilts the cleavage in both gorges (Enclosures 4.11 and 4.20; red ticks for constructed fold axes). The (constructed) axis of this F3 fold gently plunges towards the NW.

Smaller Qafas Gorge

Description 8: The most ductile deformation in the Window is observed at the northern end of the smaller Qafas Gorge (Figure 2). There the grey marble contains clasts of different origin and size (submarine debris flow). These are seriously flattened parallel to the macroscopic layering (layer-parallel cleavage, S0/S1). Isoclinal F1 folds parallel to macroscopic layering are rarely seen (Enclosure 4.17). A rough clast-elongation lineation is also visible and trends north-westwards (Enclosure 4.20). The clasts also show signs of asymmetric shear. Unfortunately, no unequivocal shear direction can be defined. Most of the sigma and delta clasts seem to be sheared top southeast (Enclosure 4.18), but opposite shear senses are also visible. Transposed layering is folded in syn-S2 cleavage F2 folds (Enclosure 4.19).

Interpretation 8: The first, very ductile and supposedly higher-temperature deformation is most visible in the stratigraphically higher part of the "Sumeini" succession. In the eastern part of Jabal Mawq the same clastic carbonate contains skarn minerals in contact with sheared serpentinite. There are flow folds, strong boudinage and stretching-related shear in this topmost part of the succession. This very ductile deformation seems to be less intensive downwards, in the "Mayhah" carbonates. This difference might reflect an inverted metamorphic gradient, but the difference might also be due to the lack of prominent marker beds and clasts.

Description 8a: An important structural feature is found at the hot spring at the northern mouth of smaller Qafas Gorge. Intense faulting affects the steep, slightly overturned northern limb of the Jabal Mawq fold (more precisely its northern parasitic fold; Enclosure 4.19). Folding is clearly syn-cleavage. The fold limb is offset by a thrust of couple of metres. The thrust has slickensides giving a top-NW tectonic transport (Enclosure 4.20). Considered with the other outcrop-scale faults the main shortening during this post-folding thrusting was probably top-N. The thrust fault is cut and offset by an E-W strike-slip fault with oblique left-lateral motion in several phases.

Lhiban

Description 9: At the junction of the Lhiban-Doqal and the Koria roads late folding is spectacular. There Umar radiolarites are twisted around steep to subvertical axes. The fold limbs are oriented E-W (parallel to the main trend of Jabal Abyad) and NNE-SSW (parallel to the main valley trend; Enclosure 1). All formations suffer map-scale refolding. Individual olistolithic or basaltic layers draw these major steep-axis folds in the landscape. At an outcrop scale, steep-axis folding is best documented in thin layered radiolarites (Enclosure 4.21). The measurable axes tend to dip steeply to the SE, although other steep dips are equally possible (Enclosure 4.23).

Interpretation 9: Steep-axis folding in this part of the Window is related to strike-slip shear. All lithological and structural boundaries are offset along a N-S left-lateral shear zone (Enclosure 1). Several similar zones are found within the Window.

Description 10: The northern edge of the Hawasina Window at Lhiban (Figure 2) is E-W striking. It is a spectacular thrust boundary between Haybi and Semail nappes. However, Semail is not on top of Haybi, as usually expected, but the opposite is found (Enclosure 4.22).

Interpretation 10: An overturned succession of amphibolite sole and tectonised serpentinite suggests that the original nappe contact was overturned to the north. The same interpretation was given by Searle and Cooper (1986). All this is best explained by a major antiform with an overturned and sheared, overthrust northern limb. From dip data between Jabal Mawq and Lhiban, a synformal structure, then an antiform at Lhiban can be constructed. This antiform might be later overthrust upon its overturned limb. The offset along this thrust remains unknown.

TRAVERSE D: NAKHSHAH-AL AQLI SECTION (ENCLOSURE 5)

This E-W trending Traverse (Enclosure 5) is characterised by the four main tectonic units of this region: the Lower and Middle Hamrat Duru units, the Haybi Unit and the Semail Ophiolite (see also Searle and Cooper (1986), their XS-1; their figure 7a). In the western termination of this section the contact between the Semail Ophiolite and the Hamrat Duru units can be investigated. The major synform character of the section can be understood only after map analysis (Enclosure 1). The whole mountain belt in the Nakhshah region can be described as a three times folded nappe structure.

Nakhshah

Description 1: Near the western termination of the Nakhshah Gorge the contact of the Semail Ophiolite with the Matbat Formation seems to be subvertical (Enclosure 5.1), which suggests more complex tectonic relations than a simple nappe thrusting or gravity gliding. The subvertical contact can be followed as far south as Al Isalat (Traverse C) and Rahbah (Traverse B) (Enclosure 1). The limestone beds of the Matbat Formation are totally sheared and folded; in the shaly parts pencil cleavage can be observed. The Matbat forms a general tectonic cover of the Nayid Formation. At the contact, both the Matbat and Nayid formations are heavily tectonised, and cleavage can be observed in the limestone (Enclosure 5.2). No striae have been found.

Interpretation 1: Matbat Formation above the Nayid Formation can be explained as a nappe boundary between the Lower and Middle Hamrat Duru nappes.

Description 1a: In the road cut of the western segment of Nakhshah Gorge, the Matbat sandstone in lower position is overlain by the sheared, shaly and cherty Nayid Formation (Enclosure 5.3). On top of the neighbouring hills, the contact of the same Matbat Formation in upper, and Nayid Formation in lower structural position can be observed (Enclosure 5.2).

Interpretation 1a: The Hamrat Duru nappes are refolded together by a tight F2 fold with subhorizontal axial surface. The core of this flat fold is also seen on one of the hillsides: there Guwayza limestone forms a tight synform towards the east. The normal and also the inverted limbs seem to be sheared.

Hushein

Description 2: East of Nakhshah Gorge at Hushein (Wadi Shafan) a famous outcrop is found (Searle 1985; Searle and Cooper, 1986) (Figure 2). There Guwayza limestone and Sid'r Formation are spectacularly folded (Enclosure 5.4). The folds are upright, tight. They probably belong to the F1 generation. Axes generally trend northwestwards (Enclosure 5.6). Most folds are truncated and offset by flat thrust surfaces. These thrusts deform the hinges of folds and drag those south-westwards. Small lenses are also found along the shear surfaces. The thrusts have minimal offset: in most cases lithological boundaries across them are found within a metre. Closer inspection of one of the thrust surfaces revealed that the first top-SW motion was followed by a backthrust top-NNE (Enclosure 5.5). This movement left measurable slickensides, and also dragged the layering (Enclosure 5.6). Other faults were mainly of strike-slip nature. Some late normal faults were also measured.

Interpretation 2: Thrusts are apparently not associated to fold formation: they neither follow a fault-bend fold, nor fault-propagation fold geometry. They post-date upright (possibly F1) folding. Several motion phases along these thrusts may result in minimal offset.

Interpretation 3: A Matbat tectonic cover is also found in the easternmost part of the Nakhshah Gorge. There this formation follows the Lower Hamrat Duru Nappe successions in an apparent stratigraphic order (Enclosure 1). However, two facts suggest that it belongs to the Middle and not to the Lower Hamrat Duru Nappe. The first is that in the southern continuity, at Al Isalat, an eastward-younging, complete Lower Hamrat Duru succession (up to Cretaceous) is covered by the same Matbat rock body (Enclosure 4.4). The second is that it is underlain by a sheared serpentinite zone at Wadi Shafan (Enclosure 1). This Middle Hamrat Duru Matbat Formation is thus folded in a pre-syn-cleavage isoclinal fold (F1) with steep axial surface. The same fold was already described at Al Isalat (Enclosure 4.4).

Al Aqli

Interpretation 4: The major fold of Lower Hamrat Duru succession topped by Middle Hamrat Duru Matbat Formation forms a semi-circular mountain range seen in the landscape, on the satellite image and also on the geological map (Enclosure 1). This constitutes a late, map-scale folding phase (F4?). In fact the eastern part of the section is a mirror structure of that on the west. The map-scale late folding can be explained by north-south shortening or by lateral drag along an E-W oriented steep surface.

Description 5: In the eastern part of the Traverse the contact of the Haybi Unit towards the Hamrat Duru units is sharp: the steep contact can be clearly seen in the landscape (Enclosure 5.7). The shear zone between the Lower Hamrat Duru and Haybi nappes is characterised by yellowish-brownish, sheared shale, very similar to the Matbat shale.

Interpretation 5: This sheared shale might be the equivalent of Middle Hamrat Duru Nappe, on the external limb of the first fold. The Hajbi Nappe boundary is relatively planar and cross-cuts several lithologies, therefore it appears to be a relatively young and not an old (i.e. original nappe boundary, cf. Searle and Cooper, 1986) tectonic surface.

Wadi Shafan, Haylshi

Description 6: In the bowl-shaped central part of the Nakhshah region, somewhat off and to the east of Transect line, the area is mainly covered by the Matbat Formation. However, in smaller erosional windows along the main road of Wadi Shafan, sheared serpentinite is exposed. This serpentinite is clearly related to the vast serpentinite exposures at the northern limb of the Jabal Mawq antiform (Enclosure 1). Therefore the sheared serpentinite would be tectonically above "Sumeini" rocks. Near Haylshi, in a small wadi close to the road, the flat-lying sheared serpentinite is tectonically covered by a thin slice of Middle Hamrat Duru Matbat shale and limestone (Enclosure 5.8). This formation gently dips to NW and SE, and folds with a NE-trending axis are seen. The Matbat Formation is itself tectonically covered by a shaly succession containing thick limestone lenses and layers of reef or reef talus olistoliths. A thicker massive carbonate crowns the top of the hill. The succession above

Matbat reflects Umar lithologies; therefore there is a nappe boundary between Hamrat Duru and Haybi nappes. Both tectonic boundaries below and above Matbat are cut and offset by smaller normal faults (Enclosure 5.8). A salt water spring is found at the lower nappe boundary.

Going around the hill towards Al Aqli a similar geometry is found, with some variations. The upper part of the tectonic succession remains unchanged: it is formed by olistolithic Umar shales and massive Oman Exotic limestone. However, at some parts sheared serpentinite is directly in contact with the Haybi Nappe: the thin Matbat Formation is sheared out (Enclosure 5.9). This latter reappears as a slice of Matbat Sandstone together with a patch of basalt between the sheared serpentinite and the Umar rocks. Near the saddle Umar (and Matbat) rocks form an antiform. Massive Oman Exotic limestone is preserved in synform cores, while Matbat and sheared serpentinite appear in the core of the antiform. Towards the east the Matbat Formation is accompanied by the Al Jil, Guwayza and Sid'r formations, so an almost complete Hamrat Duru Nappe succession is found there, beneath a Haybi Nappe (Enclosure 1).

Interpretation 6: Two different extension styles are found in this set of exposures. A first layer- or nappe-parallel stretching completely cuts out the Hamrat Duru Nappe in some places, while preserving it at full development/thickness in some others. This feature is very similar to boudinage. The ductile detachment surfaces required for this process are given by the lower and upper nappe boundaries (sheared serpentinite and Umar shale, respectively). The second extensional style is characterized by a brittle normal faulting, dissecting and offsetting the nappe boundaries along discrete planes.

IMPORTANT EXPOSURES IN JABAL AL-AKHDAR AND BATINAH PLAIN

Wadi Bani Kharous and Wadi Bani Awf

Description 1: Although the formations of the Al Jabal al-Akhdar Autochthon do not show signs of isoclinal folding, they do show indications of strong, practically layer-parallel flattening. Two formations were examined in a quick study: the Habshan oolithic limestone and the Shu'aiba rudist limestone at Wadi Bani Kharous. Both originally contain more or less circular sections (of ooliths and rudists), which are flattened into ellipses. A standard R_f/Phi method was not conducted, but measurements of R_f values on these sections gave values between 2.59 and 1.35, with two maxima at 2.5 and 1.42 (Figure 6a).

Description 2: A spectacular fold is found in the Wadi Bani Awf in Salil shales (Figure 6b). The structure is tight, asymmetrical, with a flat axial surface. This axial surface gently dips to the north, but is not exactly parallel to the general dip. A cleavage associated with folding is found roughly parallel to the axial surface. Folding only affects the ductile formations; it is not seen in the over- and underlying stiff and thick carbonates. These on the other hand make up the gently north-dipping limb of the major Jabal al-Akhdar Dome.

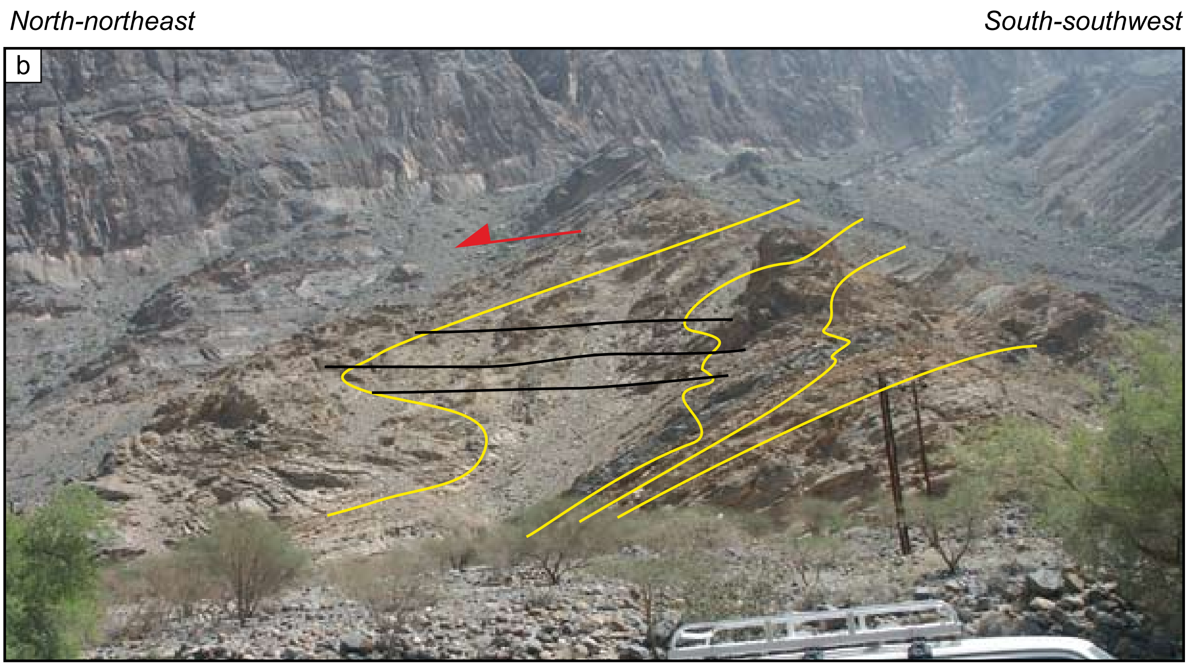
Interpretation 2: This fold is clearly a shear-related feature. Shear was layer-parallel and directed top NNE according to the asymmetry of the fold and to the bedding-cleavage relationships. The asymmetry of the fold is the contrary of that expected on the NNE limb of the Jabal al-Akhdar Dome. Therefore the described syn-cleavage fold either predates, and is unrelated to doming, or is related to a normal shear downdip along the northern flank of the Jabal al-Akhdar antiform (Al Wardi and Butler, 2007).

Similar to cleavage, tilted normal and thrust fault sets are observed on both the southern and northern limbs of the Jabal al-Akhdar Dome (Breton et al., 2004; Al-Wardi and Butler, 2007; Fodor, in prep.). These tilted fault sets define oblique stress fields, principal stress directions of which are parallel/perpendicular to the tilted beds. We interpret these fault sets as generated by the same stress fields, prior to doming, still in the subhorizontal position of layers. A NNW-SSE to NW-SE extension episode and N- to NNE-verging thrusting was differentiated prior to doming.

Murri

Description 3: The tip of Al Jabal al-Akhdar antiform at Murri (Figure 2) shows an example of pre-doming normal faulting. The stratigraphic horizons can be followed because top Natih (orange on Figures 7a and 7b) is a characteristic hardground also expressed in topography and because Muti Formation contains several horizons of clastic and micritic limestone (coloured lines on Figure 7b). These are also exposed as outstanding ridges in topography. The fold of Al Jabal al-Akhdar can be easily followed by the top Natih boundary (Figure 7b, orange). In the SW limb of the antiform, near the village, there are at least three parallel, thicker limestone banks in the marl. Their number decreases towards the apex and the NNE limb of the fold. Even more, the upper limestone horizons (all with characteristic coarse, but different grain size facies) come closer towards the NNE limb (Figures 7a

Figure 6: Tectonic features in Al Jabal al-Akhdar.
(a) Flattened Cretaceous carbonate at Jabal al-Akhdar, Wadi Bani Kharous. Note that ooliths are flattened. Scale is 5 cm.
(b) NE-vergent syn-cleavage fold in Salil Formation, Wadi Bani Awf. Note the marked asymmetry of the fold and tilted cleavage. Yellow marks layering, black marks cleavage. Roof of car for scale.



and 7b). Near the axis of the fold, already on the NNE limb, the stratigraphically highest horizon of clastic limestone (red on Figures 7a and 7b) is offset by a shear zone and is shifted towards the top Natih boundary, while lower (green and yellow) horizons are tectonically omitted.

Interpretation 3: This feature is explained by normal faulting within Muti marl, most probably detaching at the base of Muti. An obvious detachment is indeed exposed near the top Natih boundary on the SW limb (marked in blue on stereoplot Figure 7c; measured on the western limb). The fault was later refolded.

Description 3a: At the saddle above the village a major normal fault can be inferred between the Muti marl and the directly overlying serpentinite. This boundary has a mylonitic zone with strong banded layering, with an alternation of sheared serpentinite and strongly boudinaged sedimentary lenses. In spite of a strong ferruginous impregnation it seems these lenses were derived from the underlying Muti marl. All lenses are strongly boudinaged, elongated, then later folded into tight folds. Tight folding remains within the shear zone. Here the Semail serpentinite is in direct contact with the Autochton, which means the complete omission of all Hamrat Duru and Haybi nappes, which are otherwise preserved in the NE, near Sinni.

Interpretation 3a: Ephemeral preservation and absence of structural units can be only explained by a large-scale boudinage or normal fault cut-off of the Hamrat Duru and Haybi nappes. The strong boudinage in the mylonitic zone probably indicates this extensional event.

Description 3b: Several post-folding normal faults can be seen in the top-Natih horizon. These dip towards the core of the fold and are transversal to the axis of the fold (thin black lines in Figure 7b). Walking along the plunging axis the top-Natih horizon becomes increasingly steeper, and E-W faults become increasingly flatter. It seems that after formation of the normal faults (probably partly synchronous with their activity) a transversal folding phase acted. This folded the axis of the major fold and rotated the E-W normal faults along an E-W axis.

Interpretation 3b: Transversal folding could have been caused by a normal fault roll-over. In this case the flat listric normal fault should dip towards the SSE, i.e. just the opposite of potential normal faults proposed by Searle (2007; p. 115). Although not documented and seen, these N-dipping normal faults would seem logical in that they may have uncovered the Hawasina nappes from above the Autochton and offset them NW into the Hawasina Window. Based on our observations we infer a tectonic denudation of different direction.

Two extensional directions may be derived from the fault-slip map pattern and fault-attitude data (Figure 7c). One has NNE-SSW extension direction; the other has a W-E extension direction. However, the faults fitting in NNE-SSW extension were arranged *en echelon* along E-W striking zones with apparent right-lateral offsets. Such right-lateral faults were indeed measured. It is to be noted that differently arranged *en echelon* tension gashes defined both right- and left-lateral shear along E-W zones.

Transversal folding and rotated normal faults could also have been generated by a compressional fold. In this case, the flattening of normal faults together with gradual steepening along the plunge would require a flat thrust dipping SSE and a drag during top-north thrust of Al Jabal al-Akhdar along this thrust on top of Hawasina Window. Since no such thrust is exposed, that structure should be blind. Such a thrust could have been generated by a regional north-south shortening and top-N shear. Such a tectonic episode should post-date the rotated normal faults.

Description 3c: At Murri folds are also observed in the Muti marl, and cleavage affects both Muti and Natih formations. Folds are mostly related to ramps, or shear zones across the marl (Figure 8B). Ramps to folds offset index horizons in the Muti marl by some metres. Several slickenslides indicate two or even three major shortening directions. Superposition of striae including a main detachment surface near base Muti marl suggest that the first thrusting was towards the east, the second was towards the north and the last one was towards the NE (Figure 7c). The majority of fold axes have a NW to NNW trend, but there are also quite numerous folds with E-W to WNW-ESE axis (Figure 7c).

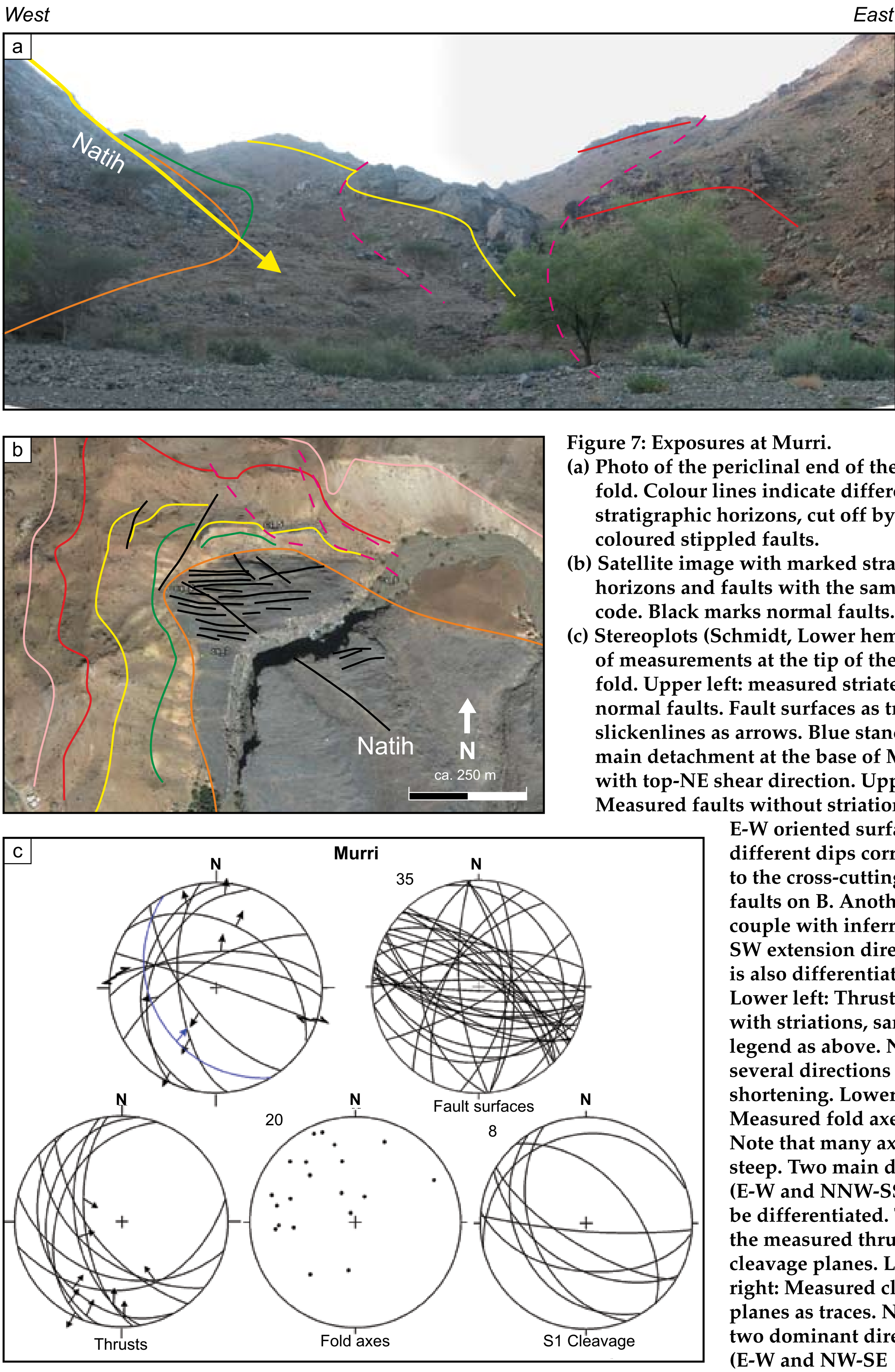


Figure 7: Exposures at Murri.
(a) Photo of the periclinal end of the major fold. Colour lines indicate different stratigraphic horizons, cut off by purple coloured stippled faults.
(b) Satellite image with marked stratigraphic horizons and faults with the same colour code. Black marks normal faults.
(c) Stereoplots (Schmidt, Lower hemisphere) of measurements at the tip of the main fold. Upper left: measured striated normal faults. Fault surfaces as traces, slickenlines as arrows. Blue stands for main detachment at the base of Muti marl with top-NE shear direction. Upper right: Measured faults without striations. E-W oriented surfaces with different dips correspond to the cross-cutting normal faults on B. Another Mohr couple with inferred NE-SW extension directions is also differentiated. Lower left: Thrust faults with striations, same legend as above. Note the several directions of main shortening. Lower centre: Measured fold axes as dots. Note that many axes are steep. Two main directions (E-W and NNW-SSE) may be differentiated. These fit the measured thrusts and cleavage planes. Lower right: Measured cleavage planes as traces. Note the two dominant directions (E-W and NW-SE orientations).

Interpretation 3c: It is interesting to note that many steep axis folds were measured in this region. This points to the effect of steep shear zones, which might re-orient or drag earlier structures or create steep drag folds. Some of the steep axes were buckled earlier fold axes, which were gradually steepened by N-S shortening.

Description 3d: Two cleavage sets were observed (Figure 7c). A west- to southwest-dipping cleavage was measured in Muti marls. This cleavage is compatible with NNW-trending fold axes. A second cleavage was also measured in Muti marl and Natih limestone. This was south- to south-southwest dipping and was clearly transversal to the major fold. Smaller E-W folds measured in Muti marl were compatible with transversal cleavage.

Interpretation 3e: The whole Al Jabal al-Akhdar region is dominated by a major, long-ranging fold, which is evident in the landscape around Murri and on the digital elevation-assisted satellite map (Figure 8a). The axial trace of the fold trends SE, but in the background, i.e. towards the main part of the Al Jabal al-Akhdar it is distorted towards the ESE and later to the E.

Exposures near Al Risfah and Al Shia, NW Batinah Plain

Description 4: The supra-ophiolite Maastrichtian Thaqab Formation (Nolan et al., 1990) was also investigated. The bulk of the Formation has a general medium dip towards the NE; however, at several places subvertical to slightly overturned beds were recorded (Figure 9a). Folds were rarely seen, but sudden dip changes in well-defined regions suggested the presence of folds.

Interpretation 4: The axis of these suspected folds was constructed in a stereoplot (Figure 9b). Most of these axes strikes NW-SE, but some have a clear N-S trend. A smaller group showed an ESE-WNW direction. Most axes had a medium dip; some were steeper.

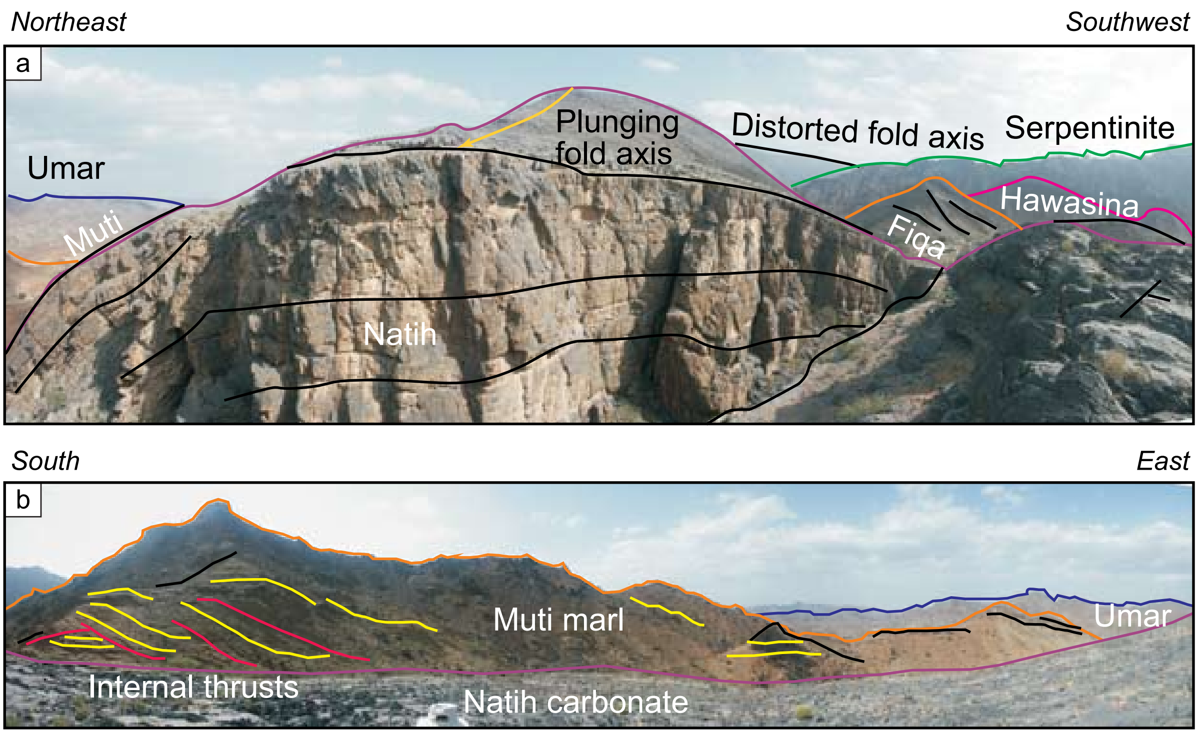


Figure 8: Folds and thrusts of the Muti marl and Natih limestone at Murri.
(a) Tip of the main Al Jabal al-Akhdar antiform Width of Gorge is 500 m.
(b) Photo of Muti marl on the SW limb. Note oppositely dipping thrust faults (red). For stereoplot see Figure 7. Width of the photo landscape ca. 500 m.

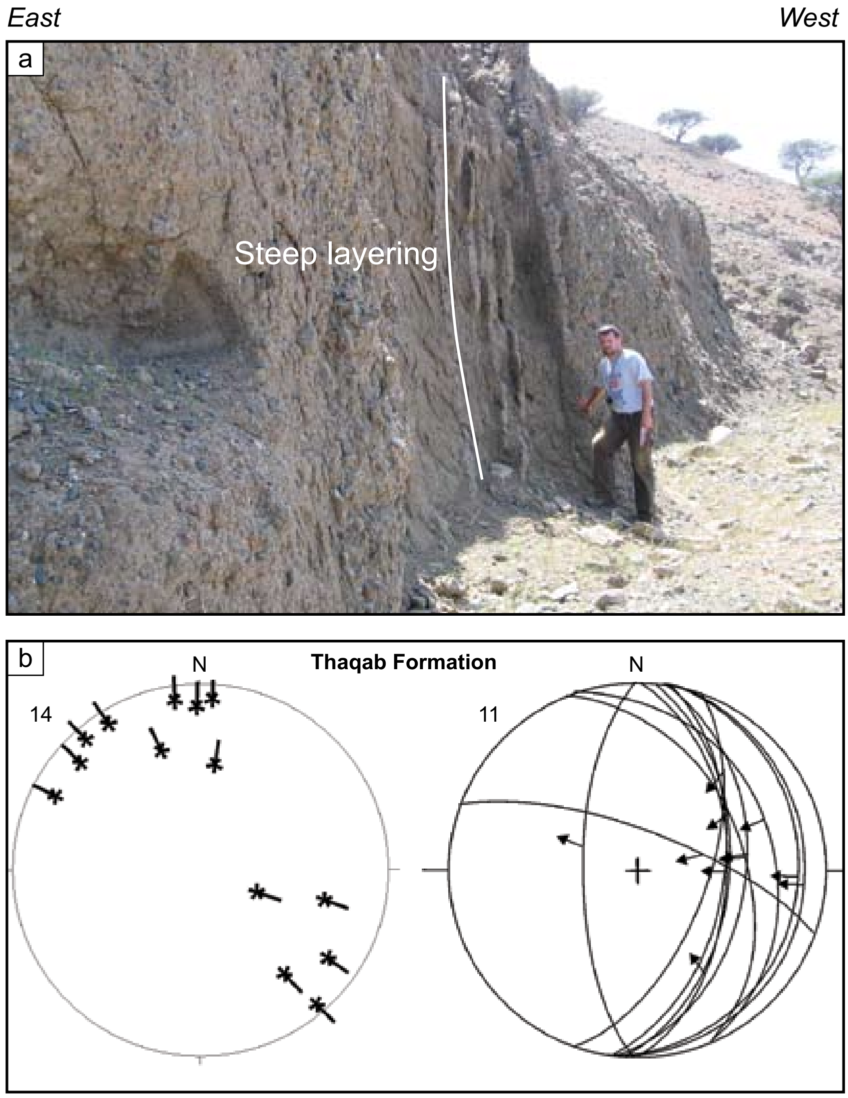


Figure 9: Exposures of Thaqab Formation on the Batinah Plain.
(a) Steeply dipping layers of Late Cretaceous Thaqab Formation.
(b) Stereoplot of structural data in Thaqab. Left: constructed fold axes as barbed crosses. Note the dominance of NW-SE and N-S axes. Right: measured thrust faults as traces, with slickenslides as arrows. Measured tectonic transport directions are in agreement with the folds.

In the same regions of changing dip, striated surfaces were also measured. The majority of these gave thrust movements. The striated and non-striated flat faults define a NE-SW and an E-W compression (Figure 9b). These data are compatible with constructed fold axes.

MAP ANALYSIS AND GENERALISED CROSS SECTION

In this section we summarise the main novelties we found during mapping referring to the geological map, (Enclosure 1.1) and section construction. Map-scale features are analysed. A generalised cross section was also produced (Enclosure 6). This is a modification of Nicolas et al. (2000) and Searle (2007) sections. The new features deduced from map analysis are also drawn on this section, and differences with respect to former sections are highlighted.

Repetitions of Hamrat Duru Nappes

At several places we observed a complete repetition of the classical nappe superposition. The valleys into Jabal Matid show a good example. These nappe repetitions are partly identical to those indicated by Searle and Cooper (1986) and Béchennec (1988), but in fact there are many more repetitions than they suggested (Enclosure 1.2). Sheared serpentinite lenses or layer-like horizons frequently occur between different nappe packages. In the generalised section (Enclosure 6) three repetitions of Hamrat Duru and Haybi nappes were drawn above the Sumeini Unit. These represent the Lower, Middle and Upper nappes. Sheared serpentinite horizons were too thin to be represented along these boundaries.

Shear Directions along Nappe Boundaries

All available ductile or semi-ductile shear indications were plotted on a structural sketch of the Hawasina Window (Enclosure 1.3). These include mostly S/C cleavage in sheared serpentinite and shear-related features at or close to nappe boundaries. As seen in the detailed description of exposures, several superposed generations with often divergent, or opposite shear directions were observed. It is to be noted that most of the older shear indicators show a top-southerly tectonic transport (red arrows on Enclosure 1.3). This is more southwesterly in the southern part of the Window and more south-southeasterly in the north. When superposition was clear, a later shear was indicating mostly northerly tectonic transport (blue arrows on Enclosure 1.3). In western parts of the Window this was more north-easterly, in eastern parts it was more in northerly direction. Finally, presumably late shear indicators pointed to an easterly tectonic transport (green arrows on Enclosure 1.3). At several sites ductile strike-slip shear in both sinistral (orange arrows on Enclosure 1.3) and dextral (black arrows on Enclosure 1.3) sense were recorded along northerly striking shear zones. These features might be created as original strike-slip zones, or as originally flat-lying shear zones which were later tilted (folded) into vertical position. It seemed that dextral slip along NNW-SSE oriented zones preceded sinistral slip. A remarkable link exists between the fold axes of syn-cleavage F2 folds and the top northerly (blue, green) shear directions. Both are dispersed together and shear direction is sub-perpendicular to (therefore apparently attached to) the F2 fold axes.

Cutoffs: Shortening and Extension

Cutoffs may indicate tectonic transport direction. In this respect no clear shear direction may be deduced. Supposedly original nappe contacts of Hamrat Duru and Haybi nappes (e.g. western borders of the Window) show inconclusive cutoffs with mostly Nayid Formation in contact with Haybi Nappe (Enclosure 1). The contact of the Hamrat Duru Nappe with the underlying Sumeini Unit in the western border region cuts up towards the west in the hangingwall (Al Jil Formation in the east, Matbat Formation in the west of Jabal Rais). However, in the footwall, it seems to cut down in the same direction (Qumayrah Formation in the east, "Mayhah" Formation in the west; see Transect B, Enclosure 3). Since the western limb of Jabal Rais is affected by faults, it is possible that the down-west cutoff is due to later normal/strike-slip faulting. If that reasoning is true, then the cutoff of the hangingwall would suggest top to the SW transport. The cutoff along the eastern limb of the isoclinal fold at Al Isalat suggests a top to the SE nappe transport (prior to isoclinal folding), since the Matbat Formation cuts upsection first on Guwayza, then on Nayid Formation.

Cutoff pattern at several nappe boundaries strongly suggests a pre-overthrust folding or boudinage. This is the case of Middle/Upper Hamrat Duru boundary at the eastern slope of Jabal Milh. The thrust surface cuts upsection in both northern and southern sides. It is interesting to note that pre-overthrust folding had possibly a roughly E-W axial trace trend. Alternatively extension created major boudins of E-W axis.

The regular superposition of nappes is sometimes disrupted. The most complete succession of Lower, Middle and Upper Hamrat Duru units is found in the south and around Jabal Rais and Milh (Enclosure 1.2). In the north very similar tectonic units are exposed, but they are less numerous than their southern neighbours. Several tectonic omissions can be deduced from the map, e.g. at the southern border of Jabal Matid. There seems to be a regional cutoff zone of NW direction, ranging from Wadi Shafan, Al Aqli towards Jabal Matid. Along this oblique boundary practically all Hamrat Duru nappes are sheared off between the Sumeini units and the Middle Haybi Nappe. When observed in detail, the cutoff does not occur along a single fault and layers are not cut off in a consequent way. The different successions rather seem to thin out and then thicken again, forming major boudins. These boudin-like features are also somewhat folded along roughly E-W axis folds.

On the general cross section (Enclosure 6) the semi-ductile, boudinage-like extensional features were schematically imaged as an ephemerally disappearing, thinning Middle Hamrat Duru Nappe. This is not completely correct, since there are some places where several of these nappes are cut out, but this is a compromise between imaging the general nappe stack pattern (of three times repeated nappes) and the extensional features.

Major Folds

Folds were mapped by Searle and Cooper (1986) and the BRGM team, and in consent, we propose two regional antiforms (Enclosure 1). The main difference in interpretation is that we suggest folding of the entire nappe succession. The longest regional antiform is that exposed in Jabal Rais. It starts in fact as an isoclinal fold near Nakhshah, and continues south until the Window axial part along Wadi ad Dil. It has a number of parasites. At the southern termination of Jabal Rais its axial surface is steeply W-dipping, but it has a gradually flattening axial surface towards the north and east. In several out-of-sequence nappes around Jabal Rais the E-facing antiform continues along Wadi ad Dil to have flatter and flatter axial surfaces in Jabal Milh. A second regional antiform is found locally at Jabal Matid and Mawq. In fact these Jabals form WNW-striking *en echelon* folds continuing in an EW-strike fold along Wadi Shafan, but they also define a regional uplift of NNW-strike. Tight synforms (marked by white lines) are located between these regional antiforms.

In the generalised section (Enclosure 6) two main syn-cleavage, northeast vergent and NE-facing antiforms were drawn. These refold earlier structures, including earlier tight folds and out-of-sequence nappes. Sumeini exposures form the core of these antiforms. In the section separation of F1 and F2 folds was impossible, partly because their axes are parallel. The two folds intend to stand for the major folds observed in Jabals Rais and Milh. A third fold was added for sake of preservation of wavelength.

Regional Fold Axial Trend Distribution and Map-Scale Post-Cleavage Folds

All the fold axes measured in the field were plotted on a map (Enclosure 1.4). The diagram is colour-coded: flat axes are indicated by cooler colours (green), while steep axes are coded in warm colours (red). The dominant part of the data was measured on syn-cleavage folds, but other types (see above) were also added.

All exposed units in the Window have dominantly NW axial direction folds. These are almost all flat axis folds (green and yellow). As apparent already from the BRGM map, the formations often show a zigzag pattern (Enclosure 1). Some of these can be explained by topographic effects, but others need more subtle explanation. At some parts (best seen along Wadi ad Dil) the map-scale (syn-cleavage) folds change strike to continue in a different, WNW, EW, or even NS direction. These zigzags, deflections can be explained by post-cleavage F4 folds, some of which may be related to drag along strike-slip faults (e.g. at the southern termination of the Window, near Jabal Ibat). The EW deflection of the general axial trend of Jabal Rais in the north and at Jabal Mawq is spectacular and possibly related to a deep EW-oriented ramp.

There is also a NE fold axial direction recorded in the Window. These folds are generally moderately to steeply dipping. Although these are also generally widespread, we can see a greater concentration of them along or near Window borders.

Regional Cleavage Distribution

Although cleaved rocks are very abundant in the Hawasina Window, cleavage is not always observed. Most rocks are quite flattened and isoclinal folding should have created a strong cleavage practically parallel to layering. In some rare cases, such cleavage planes are observed. However, the most frequently recorded cleavage is related to F2 folding (Enclosure 1.5) and is oblique to layering. Most folds have a clear-cut NE-vergency and NE-facing and a dominant SE dip of the cleavage. However, some examples (central Wadi Hawasina; Wadi Ibat; Wadi Isalat) show oppositely verging folds and consequently NE-dipping cleavage planes.

The continuous sections in Jabal Milh strongly suggest that the originally flat, gently SW-dipping cleavage and axial surfaces become eastwards dipping as approaching the eastern Semail contact (Enclosure 1.5). Similarly, when the sections across Jabals Rais and Mawq (Enclosures 3 and 4) are observed, the original flat, gently southerly dipping cleavage planes become strongly SW-dipping as approaching the western Semail contact. Eastern exposures show dominantly E-dipping cleavage, while western exposures show dominantly W-dipping cleavage.

In the general section (Enclosure 6) the axial surface of the folds (equal to regional cleavage) was intentionally drawn to be steeply W-dipping in the west and flatly E-dipping in the east. The tilted axial surfaces define a broad dome. Similarly, all important structural surfaces dip towards the Window western and eastern borders, defining the same dome.

Large-wavelength doming might be due to a mega-duplex formed by the Hawasina Complex lying above a relatively flat Autochton, as suggested by Villey et al. (1986) or Searle (2007). However, the fact that doming seems to be general and a relatively late structural feature rather suggests that it is formed by upwarped Autochthon or a salt dome beneath the Window. This solution is also suggested by the crustal thickening demonstrated by Ravaut (1997). In our generalised section (Enclosure 6) this doming is imagined as an analogue of the Jabal al-Akhdar Dome.

Evaporite Plugs

A series of smaller evaporite plugs (Enclosures 1 and 1.2) do not appear on the older maps (Searle and Cooper, 1986; Villey et al., 1986), probably because they were discovered along freshly bulldozed road segments. The 100-m-diameter plugs rise from beneath formations of the Lower Hamrat Duru Nappe and are located along two, more-or-less linear segments. One of them is in the axis of Wadi ad Dil, running SSE, in continuation of Jabal Rais, i.e. parallel to the main F1+F2 antiform of the Window. This zone also corresponds to the axis of late doming of cleavage. Several other occurrences indicating salt at depth were recorded. These include salt-leached and mineralized plugs (Wadi ad Dil central sector and Jabal Matid; Wadi Shafan, near Al Ghuwiz) and several salty springs around the Jabals.

RELATIVE CHRONOLOGY OF THE STRUCTURAL EVENTS

The key for relative timing is syn-cleavage F2 folding, which can be observed in most exposures of the Window. Regional cleavage dissects and deforms isoclinal F1 folds and nappe boundaries. Even nappe boundaries with sheared serpentinite are affected by this type of F2 folding. In some cases (mainly in the west) nappe boundaries are also folded by F1 isoclinal folds.

N-S shortening-related structures may be quite old in the sequence of tectonic events. E-W folds characteristic for the Window northern part and for the NE Window border region may preceed out-of-sequence thrusting of Unit III (Upper Hamrat Duru+Upper Hajbi). Such E-W folds (or alternatively mega-boudins) cut by the out-of-sequence boundary can be seen in Jabals Milh and Matid.

Ductile normal faults cut and offset transposed beds, thus they cut isoclinal folds. In Qafas Gorge they apparently cut syn-cleavage F2 folds, too. Major boudinage-like extensional features have ambiguous relation to nappe Formation. As highlighted by several exposures these normal faults do not cross nappe boundaries, but may detach in the ductile zones (within sheared shale and serpentinite).

There are two types of later folding. Regional cleavage is gently folded by broader F3, F5 folds of gently plunging axes. These folds are en echelon (F3) at some places. Cleavage is also affected by a broad doming (F5). This folding may be assigned to a Late Cretaceous or Tertiary shortening phase. Late folds with subvertical axes (F4) mostly deform previously generated syn-cleavage F2 folds along subvertical shear zones.

The succession of structural events in a more-or-less well-established chronological order is thus:

1) original nappe stacking (intra-oceanic; Hamrat Duru, Haybi and Semail nappes) shear zones,
2) flattening, isoclinal folding, transposition in Sumeini units and Autochton,
3a) emplacement of original nappes onto continental margin, involvement of Sumeini units,
3b) out-of-sequence nappe formation, shear zones (mainly in the west),

4) isoclinal-tight F1 folding of all stacked units,
5) syn-cleavage F2 folding, top E-NE thrusting,
6) top-N thrusting along Window northern border and, NNW right-lateral shear along the Window's eastern border, formation of F3 folds,
7) semi-ductile extension in N-S to NE direction,
8) renewed out-of-sequence thrusting (mainly in the east).

The following deformational features are collected by their style and kinematics. Very often their timing cannot be precisely given. Moreover, several deformation features, e.g. strike-slip and normal faults can be generated during the same deformation event.

1) late (brittle) normal faulting (NE- and NW-directed extension).
2) strike-slip faulting (mainly southern and western borders). F4 steep axis folding,
3) F5 doming.
4) post-cleavage thrusting (mainly top-SW directed),
5) halokinesis.

DISCUSSION

Some of the described structures, structural events seem not to be new, since previous publications dealt with the topic. In this section the differences between the previous and our new views are highlighted. These concern: (1) nappes of the region, (2) the major folds, (3) ductile extension, (4) the borders of the Window, and (5) the evaporites.

Nappes

Helvetic Nappes
Searle and Cooper (1986) describe three 'Helvetic nappes' in the Jabal Milh (their Figure 9a). These are in fact Hamrat Duru layers flatly folded in 100–500 m amplitude isoclinal folds without associated thrusts. In our view these structures are not comparable to the pluri-kilometric Helvetic or Penninic nappes underlain by well mappable thrusts. These folds were interpreted as F1 folds, which are re-folded by the also flat axial surface F2 folds.

Number of Nappes
Jabal Milh does contain true nappes. These nappes repeat whole or nearly whole Hamrat Duru succesions, have well-documented shear zones at their basis and sheared serpentinites in these shear zones. Repetition of whole succesions along wide shear zones implies major thrusting; therefore these objects should be really called nappes. Only one ('Upper Hamrat Duru complex') is shown in Searle and Cooper's map (their figure 2), while we mapped several such units in different parts of the window. Although nappe superposition was noted by Villey et al. (1986) as well, they show only some non-conclusive and non-continuous thrust boundaries on their map.

Another difference of Searle and Cooper (1986) and our interpretation is in the number and position of Haybi nappes. We argue for the presence of the Haybi Nappe in central, southern, northern, eastern and southwestern part of the Window, in several tectonic positions. The out-of-sequence Haybi Nappe of Searle and Cooper (1986) forms a single, uppermost sheet and is mostly present at the eastern and northern limits of the window. Their Haybi Nappe wedges-out somewhere above the Window.

Out-of-Sequence Nappes
Searle (1985) and Searle and Cooper (1986) were amongst the first to introduce the term 'out-of-sequence' for the Oman Mountains. They used the Wadi Shafan-Haylshi exposure (Enclosure 5.4) to demonstrate their case. The Wadi Shafan exposure does not contain any in-sequence thrusting; nor does it contain any feature related to original nappe formation. Folds might be related to original nappe formation, but this is not demonstrated in the cited (nor in later) works and it cannot be demonstrated at the outcrop. In short, the relative timing of the described thrusts with respect to original nappe formation is not seen. All that can be inferred is that because of their post-folding nature and because

of their relatively flat attitudes, the thrusts were certainly generated after folding and probably late in the succession of structural events. They may even be of Miocene age, since at that time there was major Tertiary shortening in all of the Oman Mountains (e.g. Glennie et al., 1974; Carbon, 1996). In other words, they might be related to a structural process totally different from Cretaceous nappe stacking, i.e. the 'Zagros event' of Searle (2007).

Repetition of whole nappe sequences and large-amplitude thrusting (contrasting minor thrusts of Wadi Shafan) merits to be called out-of-sequence, if temporal relations with respect to original nappe formation can be successfully demonstrated. That is why we think some shear zones documented in our work merit attention. Several of these shear zones contain tectonic clasts of Oman Exotics, Umar volcanics. There is only one plausible way to incorporate different Haybi-Umar elements in the shear zone separating different Hamrat Duru units: by supposing a former original nappe contact (Haybi on top of Hamrat Duru) later cut and repeated by thrusts with large offset. These later thrusts should be really 'out-of-sequence', since they cross-cut and duplicate an already amalgamated thrust pile, the result of an original, in-sequence nappe emplacement.

Sheared serpentinites between different younging-upward Hamrat Duru nappes cannot be interpreted in simple, within-Hamrat Duru duplexing terms. According to our knowledge no publication has addressed this question so far. These bodies are partly present on the map of Searle and Cooper (1986) and Villey et al. (1986) without any explanation, and often with inconclusive interpretation of the (necessarily tectonic) boundaries. There are two places for serpentinites to occur: at the bases of the Semail and Haybi nappes (Searle and Cooper, 1986; Villey et al., 1986; own observations). In case of the latter the mid-crustal section seems to be missing, or lavas and intrusives were serpentinised. In either case the serpentinites now found in between Hamrat Duru units should have been located tectonically above the Hamrat Duru succession, at the bases of an original Haybi or Semail Nappe. Their present position strongly suggests repetition of that original structural pile by a later, out-of-sequence thrust. Therefore sheared serpentinites reproduce the same kind of arguments as for the exotic (tectonic) clasts in shear zones.

In the light of the above, the repetition of the Hamrat Duru units cannot be identical to the scheme suggested by Searle and Cooper (1986, their figures 2 and 10) and Béchennec (1988, his Figure 128). These authors suggest an in-sequence SW-propagating model for individual Hamrat Duru duplexes beneath a major upper detachment formed by the Haybi Nappe. We have shown that Haybi units have participated in the repeated nappe successions (east of Jabal Matid). Moreover, presence of Haybi-derived rocks in-between Hamrat Duru Nappe units cannot be explained by a detachment above these duplex structures.

On the other hand, the Semail Nappe can be really out-of-sequence. The problem with this is twofold: first, Searle and Cooper (1986) do not describe field evidence relative to this feature; they just mention downcutting of the Semail boundary, observed by all the other mappers as well. Second, the same downcutting can be achieved by normal faulting. The ductile-brittle strike-slip faulting and extension we documented can be a viable alternative to the out-of-sequence Semail Nappe. In a way the late gravity glide of the Semail Nappe, proposed by many (e.g. Cooper, 1988) can be an out-of-sequence nappe west of the Window.

Folding

The three main "Sumeini" exposures were documented by all earlier mappers of the region (Glennie et al., 1974; Searle and Cooper, 1986; Villey et al., 1986). Most of them interpreted these as antiforms. Earlier authors suggested a gentle, broad (and somewhat disharmonic) doming of all structural units above the Sumeini cores. This feature can be compared to our late doming. Our observations suggest that the Sumeini, Hamrat Duru and Hajbi out-of-sequence nappe stacks were together subjected to very tight folding, including F1 isoclinal and F2 NE-vergent asymmetric folding (compare the structures of Searle and Cooper, 1986, XS-2 or XS-4 to our Transects B and C). Unlike in the sections XS-1 and XS-4 (especially Jabal Milh), but like XS-2 and XS-3 of Searle and Cooper (1986) and like Béchennec (1988; his figure 130A) and Villey et al. 1986 (their figure 11) the main nappe boundaries were also tightly folded together with the whole nappe pile.

Jabal Rais antiform is a combination of early isoclinal F1 folding and later F2 syn-cleavage folding, which we think is unrelated to a deeper ramp. The *en echelon* Jabal Mawq-Jabal Matid F2-F3 antiforms may lie above a deeper ramp, as suggested by Searle and Cooper (1986). However, we propose a different orientation and nature for this ramp (see below). We do not see any evidence for support of lateral ramps transversal across the Window (Searle and Cooper, 1986). On the other hand, cutoff relations may suggest early, pre-thrusting E-W axis folding and subsequent erosion, or alternatively NS oriented semi-ductile extension.

Folding and cleavage are dominant deformation features of the Window. Several styles and several distinct episodes of folding were described and these can give a relative chronological order of important deformations. Isoclinal F1 folds clearly pre-date regional cleavage and intensive F2 folding related to this cleavage. NE- and N-vergent, syn-cleavage F2 folding is found everywhere in the Window, including Wadi Shafan, Jabal Milh, Wadi Ibat etc. This deformation style is not restrained to the "Hawasina Window promontory", the transversal NE- striking central zone suggested by Searle and Cooper (1986). It can also be found in Jabal al-Akhdar northern limb (see also Breton et al., 2004).

The local tilt of the cleavage planes opposite to the general trend and F2 folds with SW vergency might be due to two factors: (1) eventually a SW vergent syn-cleavage fold set was created under the same thermal conditions as the general NE-vergent one (fan shaped pattern of Searle and Cooper 1986); or alternatively (2) the originally NE-vergent fold and associated cleavage were tilted in opposite direction by a later folding of NW-SE axis, or by later rotational faulting.

Ductile Extension

Boudinage-like smaller and greater structures, subtractive cutoffs strongly suggest that the complete absence of several out-of-sequence nappes is mainly due to extension. According to our measurements this extension may be first NS-oriented and may change later towards NE-SW extension.

At the tip of Jabal al-Akhdar local observations and mapping suggests that the original nappe pile was effectively thinned, to be locally completely cut off. These normal fault structures link major detachments. Based on map analysis Searle (2007) proposed a major normal faulting from above Al Jabal al-Akhdar towards NW, in direction of the Hawasina Window (i.e. N-S or NW-SE extension direction, not explicitely mentioned by him). We found rather signs of NE-SW extension there (see at outcrop descriptions). Because of measurements in the Hawasina Window, the N-S extension (northward directed) hypothesis may be also valid (but purely hypothetical). However, analysis of rotating normal faults affecting the northern tip of Al Jabal al-Akhdar, a top-south extension (or rather, a top north blind thrusting) would better fit observations (see detailed description and interpretation at Murri).

Boundaries of the Window

The boundaries of the Window were partly documented by Searle and Cooper (1986) or Villey et al. (1986). We described several points and presented structural data of the boundary with conclusions partly fitting the conclusions of cited works.

Northern Window Boundary

As already mentioned in the cross section descriptions (Enclosure 5) the northern boundary of the Window differs from all others, because the Sarami Nappe of the Semail Ophiolite (Figure 1; Nicolas et al., 2000) is in a tectonically lower position with respect to a Haybi Unit. The different shallower zones of the ophiolite also follow in a reverse order further north. As Searle and Cooper (1986) already suggested, this situation is best explained by the inverted limb of an overturned fold (implying also the Semail serpentinite). However, this inverted limb and especially the Sarami Ophiolite, may be deeper underthrust beneath the Hawasina Window with a southern dip. That deeper ramp would explain the uplift of Jabals Mawq and Matid, which would be sitting on top of that ramp. This ramp is not identical to the blind ramp supposed by Searle and Cooper (1986), dipping basically westwards beneath the Jabals Mawq, Matid, and Rais, within Sumeini units.

In a more regional context it is interesting to note that the Upper Cretaceous sediments seem to be missing or very thin east of the Hawasina Window, above the Haylayn Semail Nappe, while thick Upper Cretaceous Thaqab Formation is preserved north of the northern boundary thrust, on top of the Sarami and Fizzh nappes (Figure 1). Moreover, this northern Thaqab Formation is of deep-marine origin (Nolan et al., 1990; own observations), while only continental-deltaic synchronous sediments (Al Khawd Formation) exist much further to the south, on top of the Nakhl-Rustaq (or alternatively, Semail *sensu stricto*) nappe. This whole setting is sealed by a linear, monoclinally NE-dipping row of exposures of Eocene Seeb Limestone. The above described setting suggests that the region of the Hawasina Window (and the Haylayn Ophiolite Nappe above) were uplifted relative to the Sarami Nappe fragment in the north. This uplift can be the result of northwards thrusting and E-W folding. Analysing the structures near Murri we also concluded that the Jabal al-Akhdar Unit is possibly overthust towards the north on the Hawasina Window by a deep, blind ramp. In this manner, the Hawasina and al-Akhdar windows would form relative uplifts with respect to their northern neighbours. Thaqab Formation could be pre-kinematic or syn-post-kinematic with respect to the folding. Dip measurements in the critical southern part of the Sarami depression suggest that Thaqab filled an existing relative low and it is not folded in the required directions there. Therefore the age of the top-north thrusting is possibly pre-Maastrichtian.

Northwards thrusting of the Hawasina Window would explain a peculiar feature of the internal structural arrangement. The general NW-SE trend of all major structures, but also of individual, smaller structures changes to EW or WNW near Jabals Mawq and Matid, and along Wadi Shafan. Such a change in fold axis trends could be well explained by a deeper, EW-oriented ramp beneath the mentioned region.

The eastwards flexure of the Nakhshah fold trend is a relatively late deformational feature that could also be explained by N-S shortening. Observations showed that the Haybi Nappe was overthrust on top of the Nakhshah fold. This steep thrust could be followed towards the north, to reach the southern termination of the Haybi corridor. That could be an oblique lateral ramp with respect to top-north thrusting.

Western Boundary of the Window

The western boundary fault of the Window north of Rahbah seems to cut a regional promontory, as suggested by Searle and Cooper (1986). However, all studied segments of the western Semail thrust contact showed signs of either strike-slip, or normal faulting. In most areas the tectonic contact is strongly discordant, cutting several formations and structural units, often at high angles.

The Lower Hamrat Duru Nappe shows very similar lithological and structural characters in the NW and the SW along the western border and there is no logical reason to suggest its absence in the central sector, immediately west of Jabal Rais. Instead of a central swell, and a gradual replacement of Hamrat Duru units by the Sumeini Unit (a kind of facies explanation; Searle and Cooper, 1986), we suggest that Jabal Rais had its original Hamrat Duru tectonic cover (most probably several Hamrat Duru out-of-sequence nappes, since these are preserved to the east), as well as respective Hajbi Nappe(s). Due to later folding this structural assemblage acquired a topography that was later cut and tectonically truncated by the reactivated Semail Nappe boundary. This reactivation should certainly have had an important strike-slip component. From the map it appears that a possibly E-W axis fold could play an important role in the westward protrusion of the respective tectonic units, prior to truncation.

Multiple Strike-Slip Zones at Southern Border

The southern boundary of the window is complex. In a WNW-trending portion behind the Ibat Hill the steep Matbat-serpentinite boundary shows lateral motion and SW-trending normal faulting (Enclosures 2.1 and 2.3). Along the E-W trending boundary, the steeply south-dipping to subvertical boundary has lateral shear components. Shear indicators at out-of-sequence nappe boundaries are roughly parallel to window borders and show lateral offset. The structural directions generally trending NW-SE in the internal parts of the Window become dragged towards the west, suggesting an important right-lateral offset along the southern border (Enclosure 1). On the other hand, an *en echelon* fold pattern of the southernmost part of the window is suggested by mapping. These steep axial surface folds are tightly arranged and compatible with a left-lateral shear along the EW-oriented southern border of the Window. Fault measurements at Murri also suggest a left-lateral motion.

Evaporites

Evaporites are not known at the base of Hamrat Duru succession. Moreover, evaporites do not fit into a deep-marine, radiolaritic (oceanic) environment. Thus we propose that the evaporitic fingers rose from a lower structural unit. Although the extent and age of this evaporite body are not known yet, three alternative positions seem plausible based on general considerations (Enclosure 6). The evaporite may rise from a deeper level of the Autochthon. From regional analogues this (stratigraphic) level may be of Infra-Cambrian (i.e. Ara), or Permian (i.e. Khuff) age. As a second variant, the evaporite may be also located right beneath the Sumeini Unit. This hypothesis suggests that the evaporite forms a detachment sheet, which is also the main gliding surface of all Hawasina nappes. Originally this evaporite might have been a stratigraphic unit at the base of Sumeini succession or at the highest (i.e. Upper Cretaceous) position of the Autochthonous. Finally, the third theoretical position of the evaporite is between Sumeini and Hamrat Duru nappes. In this perspective the evaporite may be of any age. No evaporite was found at any interface of Sumeini and Hamrat Duru rocks in the Window, so this solution is not probable.

From these three possibilities, we prefer the second solution. The widespread indication of evaporites, combined with the distant surface exposures suggests the existence of a more developed, widespread sheet of evaporites. The limited size of intrusions (Hawasina Window) and the stratiform nature (Qumayrah Half-window) suggest a relatively thin body. These imply the existence of a detachment horizon, which could explain the mobility of the nappes, as well as the geometrical requirements to create the Sumeini structures.

PLATE-TECTONIC MODEL OF THE HAWASINA WINDOW

This section summarises the tectonic events in a conceptual model (Figure 10). Because of the many uncertainties, this is to be considered a working hypothesis. Field data and exhumation theories led to two concurrent plate tectonic models: a single subduction and a two-subduction model (Glennie et al., 1974; Searle et al., 1994, 2007; *versus* Le Métour et al., 1990; Breton et al., 2004, Miller et al., 1998). Although we have our preference, we do not wish to enter into this debate since the deformations experienced in the Hawasina Window mostly post-date the critical emplacement of the oceanic nappes, after which the two models do not differ.

The tectonic evolution starts with the formation and almost immediate obduction of the Semail Ophiolite (Tilton et al., 1981; Hacker and Mosenfelder, 1996; Nicolas et al., 2000; Warren et al., 2003). The process starting at ca. 95 Ma rapidly evolved and a nappe stack of scraped-off oceanic sediments developed. Since major rotation of the Semail Ophiolite is measured during this Cenomanian – Turonian time (Perrin et al., 1994), the bulldozing of oceanic sediments should have occurred in a curvilinear trend. Therefore the meaning of original tectonic transport directions (and also sedimentary transport directions; see Béchennec, 1988; Cooper, 1990) should be reconsidered. It is proposed that during the original nappe assembly very tight-to-isoclinal folding (F1) and internal imbrication under anchimetamorphic conditions affected the oceanic sediments. Very possibly still in the oceanic domain tectonic thinning of the obducted Semail oceanic plate began. This means that its original thickness should have been reduced by internal normal faulting. The same is valid for the underlying tectonic wedge.

These processes are to be separated from early structural events recorded in the Arabian margin (Autochthon; Sumeini Unit) since these units came in contact with the oceanic units quite late: after emplacement of the latter on the margin, not earlier than 85 Ma (Warburton et al., 1990). These units experienced strong layer-parallel flattening, ductile folding under variable, southwestwards decreasing metamorphic conditions. These events should be linked to the subduction of the Arabian margin, regardless of the age of this subduction (see Le Métour et al., 1990; Miller et al., 2002; Gray et al., 2004, 2005; Grey and Gregory, 2004 arguing for an early subduction, *versus* Searle et al., 1994; Warren et al., 2003; Searle et al., 2007, arguing for a late subduction).

Tectonic thinning, unroofing, or a much less probable erosion event could have triggered formation of out-of-sequence nappes. Alternatively, the out-of-sequence nappes began to form when the tectonic wedge reached the Arabian margin. In any case, these nappes multiplied the original thickness of

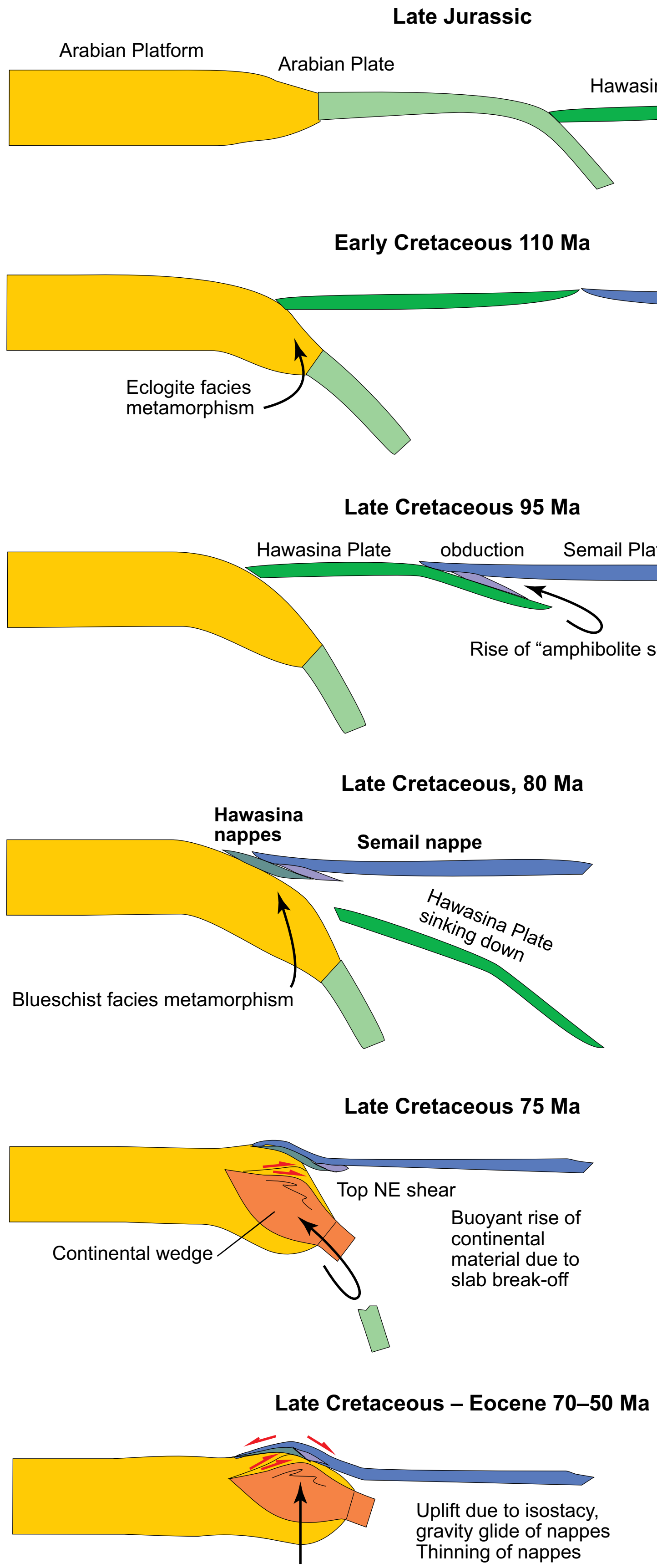


Figure 10: Schematic cartoon of the Jurassic – Cretaceous plate-tectonic model (modified after Gray et al., 2004; Breton et al., 2004; Chemenda et al., 1996). Subducted oceanic amphibolite (dark blue) and continental wedge (brown) are thrust upwards due to buoyancy. This motion generates a top-NE shear and also tectonic thickening of the lithosphere. Thickening, in turn initiates isostatic uplift and tectonic unroofing of the nappes that ignites renewed isostatic uplift.

the wedge beneath the Semail thrust. Most shear indicators in present-day coordinates indicate a top southeast - top southwest emplacement. South-facing isoclinal F1 folding could have accompanied and partly post-date nappe formation.

Out-of-sequence nappes and Semail Nappe were emplaced onto the Arabian continental margin. The emplacement time around 85 Ma (Boote et al., 1990; Warburton et al., 1990; Breton et al., 2004) is recorded in the Fiqa-Muti "foreland" deposits of the desert front and of the Al Jabal al-Akhdar. Emplacement very possibly occurred towards the SW (suggested by the general trend of the ophiolites). Emplacement was driven most probably not by *push-from-behind* the ophiolite, but by a roll-back of the subducted Arabian margin, which pulled the nappes above the subducted continental part of the margin. During the same period, a NW-SE compressional, NE-SW extensional stress field was recorded by Filbrandt et al. (2006) in the "foreland" part of the Arabian Plate. This fact alone questions the classical foredeep model of the Fiqa-Muti basin and the compressional emplacement of the nappes. A synchronous NE-SW compressive stress and a subsidiary NW-SE compressive stress model of Searle (2007) is not viable in our view, since at time of emplacement a coupling came into effect between the allochtonous nappes and the underthrust Arabian margin. If the Semail Nappe was really emplaced by *push-from-behind*, that NE-SW compressive stress should have propagated and should have been present in the "foreland" as well.

The subsided lower part of the Arabian margin *bounced back* because of buoyancy effects. For example, detachment of the oceanic part of the subducted Arabian Plate from the subsided continental part could have triggered subduction channel backwards flow. This possibly resulted in the underplating of a continental wedge beneath the more internal platform part of the Arabian Plate. The *back-bounced* wedge could have intruded the margin along an internal surface, like a major blind thrust. In this manner, the structures resulting at the upper boundary of the wedge can be viewed as hangingwall backthrusts. It is not important, whether the wedge intruded along discrete fault surfaces or ductile, more diffuse shear zones; the resulting shear senses are important. The above-described process (Mann and Hanna, 1990; Chemenda et al., 1996; Miller et al., 2002; Gray et al., 2004, 2005; Breton et al., 2004) could have led to the formation of top-to-the-NE-vergent structures, including semi-ductile shear zones, asymmetric F2 folds and general, originally flatly SW-dipping regional cleavage development. Since syn-cleavage folding affects the (northern areas of) Autochthon, Sumeini and the Hawasina nappes in the same style and direction, the formation of these structures should post-date the emplacement of nappes onto the continental margin (see also Béchennec et al., 1990; Le Métour et al., 1990). Based on Saih Hattat examples and dating (Miller et al., 2002; Gray et al., 2004, 2005; Breton et al., 2004) this folding and NE-wards shear occurred between 80 and 70 Ma.

Although similar in direction, the top-N thrusting at the northern boundary of the Hawasina Window may have another reason. This direction seems to be quite close to the general principal compressional stress direction proposed for the whole Late Cretaceous by Filbrandt et al. (2006). It is therefore suggested, that the already emplaced and folded area underwent relatively important N-S (NNW-SSE) compression, resulting in partial underthrusting of some already fragmented Semail nappes. A northwards thrust of Al Jabal al-Akhdar on top of the Hawasina Window (along a blind thrust) may also have occurred in this period. The timing of that event is indicated by the occurrence of Thaqab Formation to the north of the Hawasina Window. Therefore, this folding would be pre-Maastrichtian.

Overthickening by out-of-sequence nappe stacking, and by backwards flow of formerly subducted margin, possibly triggered several mechanisms. A burial-driven anchimetamorphism beneath the 5–10 km thick ophiolite was initiated. Tectonic thinning occurred within the nappe stack by boudinage and semi-ductile normal faulting. Thickness of the original overburden was probably quickly reduced by effective tectonic thinning; therefore major heating up did not occur. Isostatic rebound occurred, which uplifted the Hawasina and Semail nappes stationed above the subducted Arabian margin. This uplift may have resulted in a broader upwarp in later Window areas.

The timing of Window formation is much debated in the literature. For some Late Cretaceous (Nolan et al., 1990), for others Miocene uplift is more probable (Breton et al., 2004). Truth may be in between, with both Late Cretaceous and Miocene uplift times. In the Hawasina Window no sensitive fission track (FT) measurements could be made. In the Al Jabal al-Akhdar Window, however, Apatite FT results (Poupeau et al., 1998) suggest a first uplift above 70°C isograde (with isostatic uplift rates) by the Eocene (53 Ma), then a tectonically quiet period until 19 Ma. Later, the Autochthon was gently reheated and subsequently uplifted from 7 Ma until Present. We propose therefore that the main opening of the Hawasina Window occurred between Late Cretaceous and Early Eocene.

Normal faulting both to the NE and NW might have occurred during Paleogene. Since the Eocene rocks recorded this event much better than the Mesozoic ones, we accept the conclusions of Fournier et al. (2006) and Fodor and Kázmér (in preperation) that syn-sedimentary normal faulting occurred mainly towards the north and northwest occurred. That might have contributed to the extensional unroofing of the Hawasina and Al Jabal al-Akhdar Windows.

In many outcrops a late, flat-lying thrust assemblage could be recorded. Most of this thrusting was top-SW, but smaller opposite transport direction was also recorded. This suggests a strong deformation event with main NE-SW shortening direction (Carbon, 1996; Fournier et al., 2006). It is generally suggested that the Miocene "Zagros thrusting" is responsible for this late phase of deformation (e.g. Searle 2007). Late doming, folding of cleavage could also occur during the Cenozoic compressional event. That event is ubiquitous in all Cenozoic outcrops of the Batinah Plain and SW foreland (Carbon 1996). It resulted in tilting in the Batinah Plain and thrust folding in the SW foreland. When dip data are projected towards the Hawasina Window, an important uplift in the order of several kilometres due to ramp thrusting or folding can be suggested for the central part of the Oman Mountains (Searle 1985; Bernoulli and Weissert 1987; Hanna 1990). The main axis of this folding/uplift should be NW-SE, i.e. parallel to the main trend of the mountains.

CONCLUSIONS

During field work in the Hawasina Window and the compilation of the new geological map we noted several differences between our interpretation and the former published geological maps and cross sections (Villey et al., 1986; Searle and Cooper, 1986; Searle, 2007). These are the following:

1) The original Late Cretaceous nappe stack underwent out-of-sequence thrusting. The repetitions of the nappe complexes are called out-of-sequence because: (a) these tectonic surfaces cut original nappe packages; (b) The presence of Haybi-derived lenses along Hamrat Duru Nappe boundaries can be only explained by the gliding of the repeated unit above already amalgamated Hamrat Duru and Haybi nappes. (c) The presence of sheared serpentinite in those nappe boundaries (i.e. between sedimentary formations) cannot be explained by normal original nappe superposition. It seems that serpentinite is attached to the base of Haybi Nappe, therefore serpentinite indicates Haybi Unit between two Hamrat Duru units. The Hamrat Duru and Haybi nappes are repeated in three out-of sequence units (Upper, Middle and Lower Hamrat Duru and respective Haybi units).

2) The tectonic boundaries of the Hawasina Window are steep, normal- or strike-slip faults, cross-cutting the original nappe boundaries. A main strike-slip corridor in the southern edge of the Hawasina structure was mapped. The northern edge is a top-north thrust possibly above the north-lying ophiolite sheet. The Jabals Mawq-Matid structure possibly lies above this ramp, which also causes a deflection of all structures towards an EW.

3) Two main antiforms were recognised inside the Hawasina Window (Jabal Rais and its northward, southward continuations in Hamrat Duru units, and Jabals Mawq - Matid). Jabal Rais is a composite structure of F1 and F2 folds. Jabals Mawq and Matid form an *en echelon* F2-F3 structure near the eastern edge of the Window.

4) The "Sumeini" lithologies found in these areas are quite similar to the autochthonous platform facies near Murri village at the northwestern tip of Jabal al-Akhdar window. Therefore these main positive "Sumeini" features can be part of the (sheared off) autochthonous platform of the Arabian Plate. These units have a Sumeini tectonic position.

5) Ductile-brittle extension created mega-boudins of nappe units and "boudin neck areas" where complete nappe units are missing. Ductile extension is present in Sumeini and Hamrat Duru units, therefore it is post-out-of-sequence thrusting and post-emplacement. Later brittle extension can be separated from this relatively early feature.

6) Structural dips of a regional cleavage suggest a major dome beneath the Hawasina Window. This dome would correspond to the upwarp of the Autochthon, similar to Al Jabal al-Akhdar. The axis of the dome strikes NW-SE.

7) In the southern zone of this dome we observed several occurrences of small gypsum diapirs. The best outcrops of these features are in the Wadi ad Dil-Wadi Hawasina area. The evaporite bodies rise from beneath the Hawasina nappes. We suggest that they originate from the underlying Arabian Platform, or they form the basal detachment of the Sumeini units.

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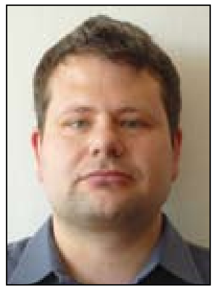

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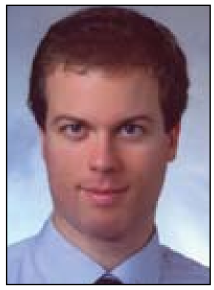

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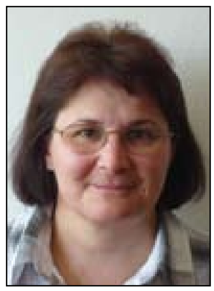

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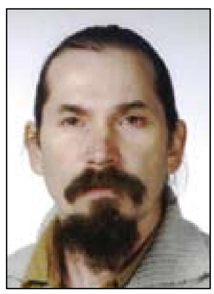

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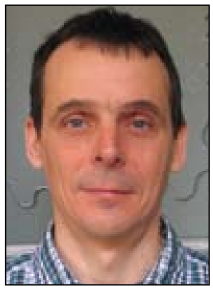

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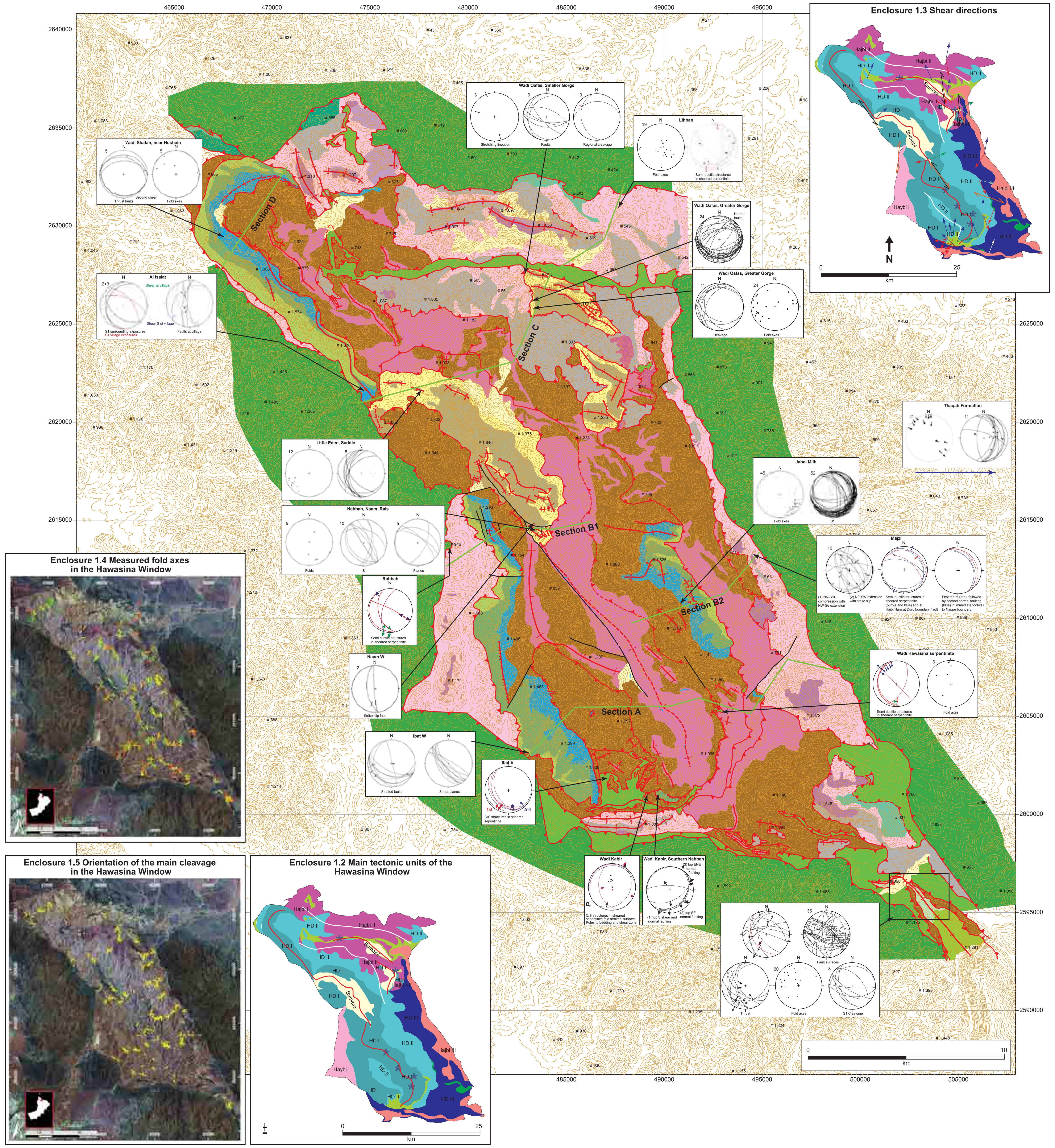
ENCLOSURE 1: GEOLOGICAL MAP OF THE HAWASINA WINDOW, OMAN MOUNTAINS



Enclosure 1.4 Measured fold axes in the Hawasina Window

Enclosure 1.5 Orientation of the main cleavage in the Hawasina Window

Enclosure 1.2 Main tectonic units of the Hawasina Window

Enclosure 1.1: Compilation based on own observation and Villey et al. (1986). Stereoplots show selected measured locations described in the text. Location of measurement is indicated by a arrow. Faults and cleavage represented by traces. Slickenslides represented by shear arrows. Outwards pointing arrows for normal, inwards pointing arrows for thrust movements. Fold axes represented by dots. Constructed fold axes represented by barbed crosses. Different colours help in separating different structural features in same exposure. All plots on Schmidt Lower Hemisphere projection.

Enclosure 1.2: Structural sketch of the Hawasina Window. blue asterisks indicate evaporite fingers. Coloured lines indicate main folds. Different colours correspond to different Sumeini, Hamrat Duru (HD) and Haybi (Hb) units. Lower number indicates lower tectonic position.

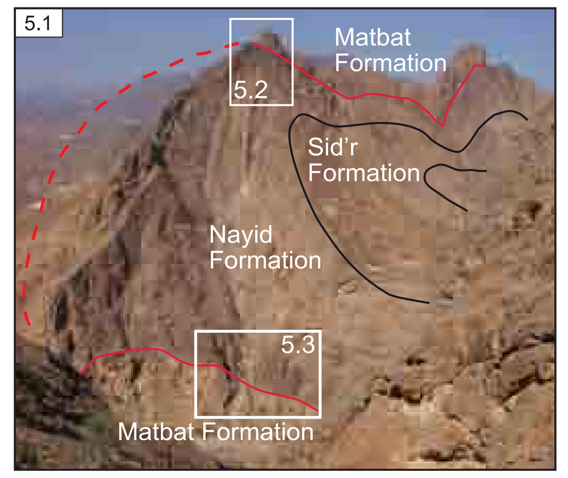
Enclosure 1.3: Measured shear directions at different nappe boundaries. Tectonic transport is indicated by coloured arrows. Different colours correspond to inferred deformation events (red: early, top-southerly event; blue: main out of sequence northerly event; green: late, top-easterly event; black: early (?) left lateral event; orange: late (?) right lateral event). White corresponds to blue on blue background.

Enclosure 1.4: Fold axes on satellite image measured in Hawasina Window. Bars indicate axis strike. Colours correspond to dip domains. Line indicates the strike of fold axis. Green: 0–15° Yellow: 15-30° Red: 75–90°

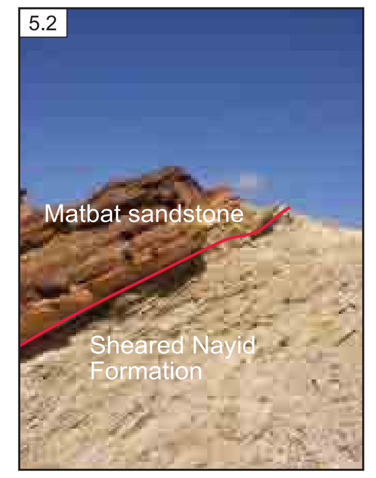
Enclosure 1.5: Orientation of main cleavage in the Hawasina Window. Cleavage indicated by dip ticks. A broad dome indicated by stippled line can be inferred from diverging cleavage.

#	Elev	Q	Quaternary	Ub	Umar Group, pillow basalt
	Elevation line	Diap	Gypsum diapir	Na	Nayid Formation
	Anticline	Sam	Samail ophiolite	Si	Sid'r Formation
	Overturned anticline	Ths	Sheared serpentinite	Gw	Guweyza Formation
	Supposed anticline	Am	Amphibolite	Mb	Matbat Formation
	Normal fault	Rms	Metasediments	Aj	Al Jil Formation
	Strike-slip fault	Um	Umar Group, reef in general	Qu	Qumayrah Formation
	Syncline	Umr	Umar Group, reef limestone	Ma	Mayhah Formation
	Thrust	Umgw	Umar Group, grey bioclastic limestone	Fq	Fiqa Formation
	Overturned thrust	Us	Umar Group, red shale	Nat	Natih Formation
	Supposed thrust				
	Fault (Thrust, normal or strike slip)				
	Nappe boundary				

ENCLOSURE 5, NAHSHAH-AL AQLI TRAVERSE



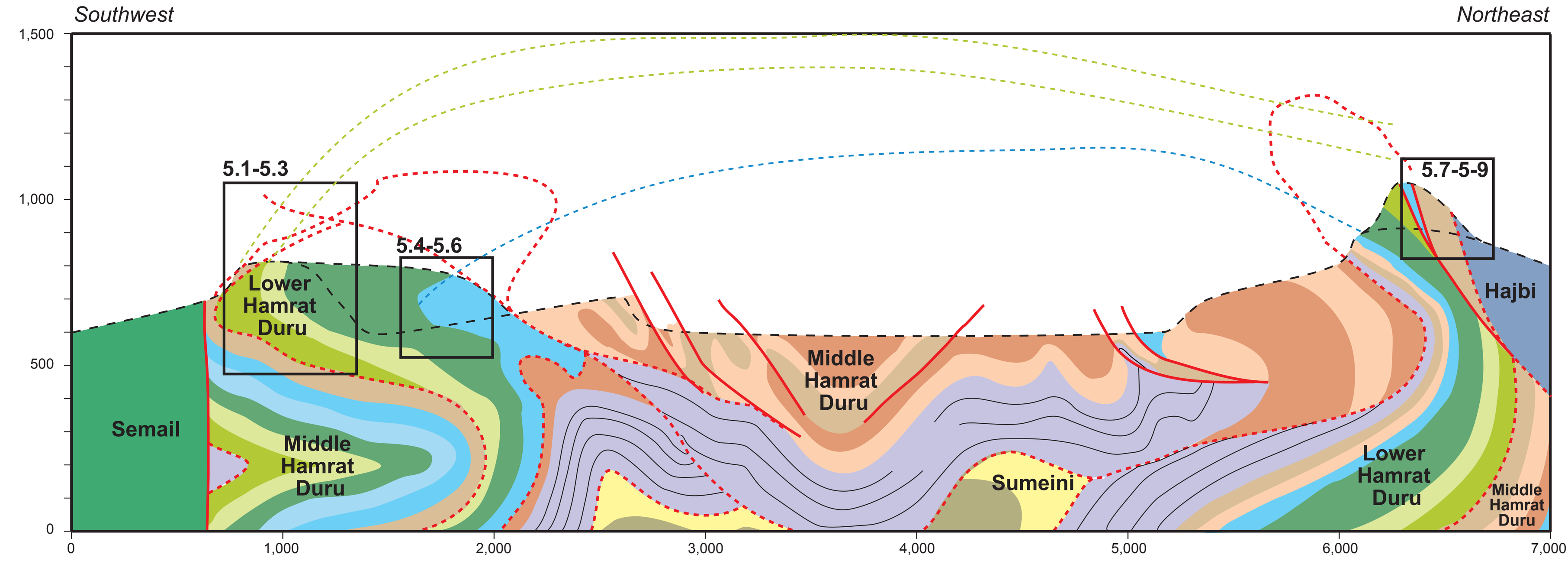
5.1: Nahshah Gorge. Contact of the Lower HD and Middle HD units. Note the overturned Nayid-Matbat contact in lower position in the valley.



5.2: Contact of the Lower Hamrat Duru and Middle Hamrat Duru units on the normal limb of fold. For location see 5.1.

5.3: Nahshah Gorge. Contact of the Lower Hamrat Duru and Middle Hamrat Duru on the overturned limb, in the valley. Matbat Formation belonging to the Middle Hamrat Duru unit is highly sheared.

5.4: Hushein, classical exposure of Guwayza Formation (see Searle 1985, Searle and Cooper 1986). View of the exposure, white indicates layering, red indicates thrust faults, box indicates location of 5.5 . Note that SW-trending thrusts cross-cut (truncate) folds and do not produce large offsets.



LEGEND

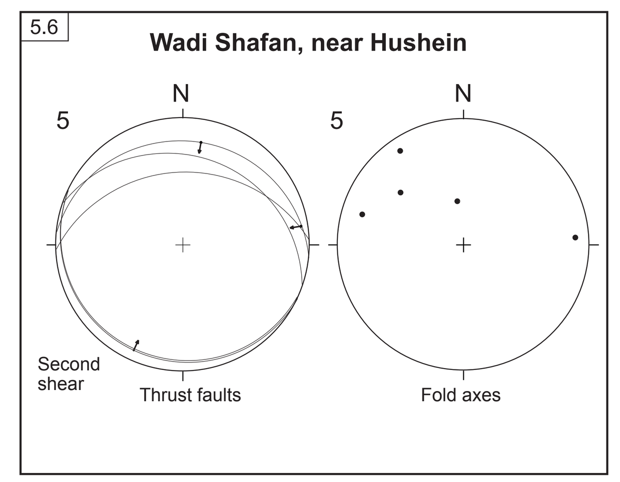
Hamrat Duru Group		
Nayid Formation	Na_2	Massive limestone breccia with calcareous matrix (Nayid Limestone sstr.)
	Na_1	Thick, lithoclastic limestone beds, with silicified limestone and chert interbeds
Sid'r Formation	Si_1	Massive brown radiolarite and silicified limestone
Guweyza Formation	Gw_2	Silicified oolitic limestone, with some layers of chert and shale
	Gw_1	Oolitic limestone
Matbat Formation	Mb_3	Yellow, red shale with thin sandstone layers
	Mb_2	Massive, red sandstone
	Mb_1	Brown, grey thin limestone beds in shale (with filaments)
Al Jil Formation	Aj	Al Jil Formation, undifferentiated

Semail Ophiolite	
Sa	Ophiolite (undifferentiated)
Umar Group	
Ub	Basaltic pillow lavas
Sumeini Group	
Qu	Qumayrah Formation
Ma	Mayhah Formation

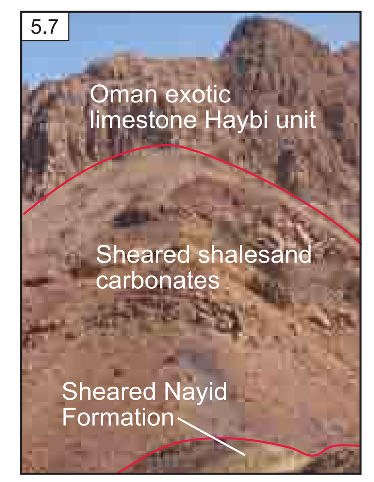
Fault (Thrust, normal or strike slip)

Nappe boundary

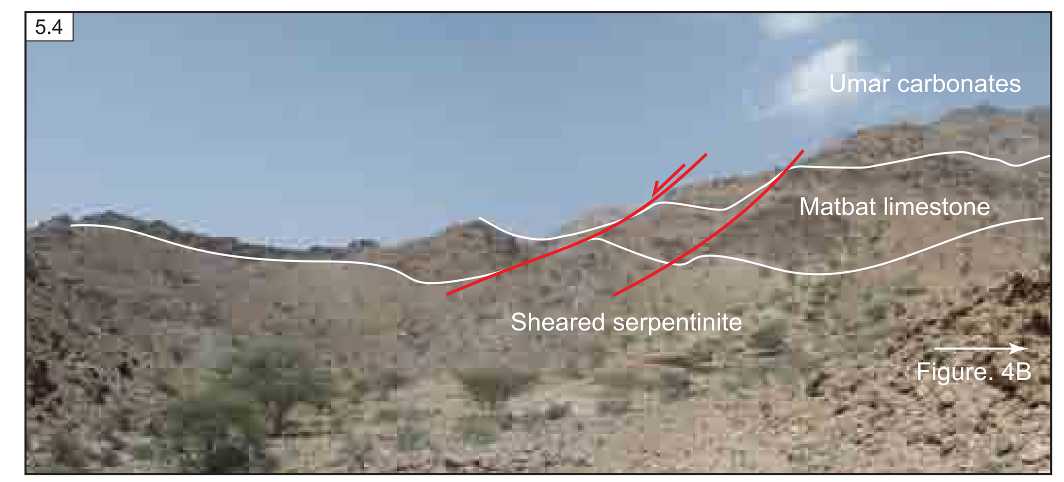
5.5: Hushein Close-up of the lowest thrust fault, indicating opposite (top NE) drag along it. This drag is not compatible with macroscopic offset (top left, i.e. SW)



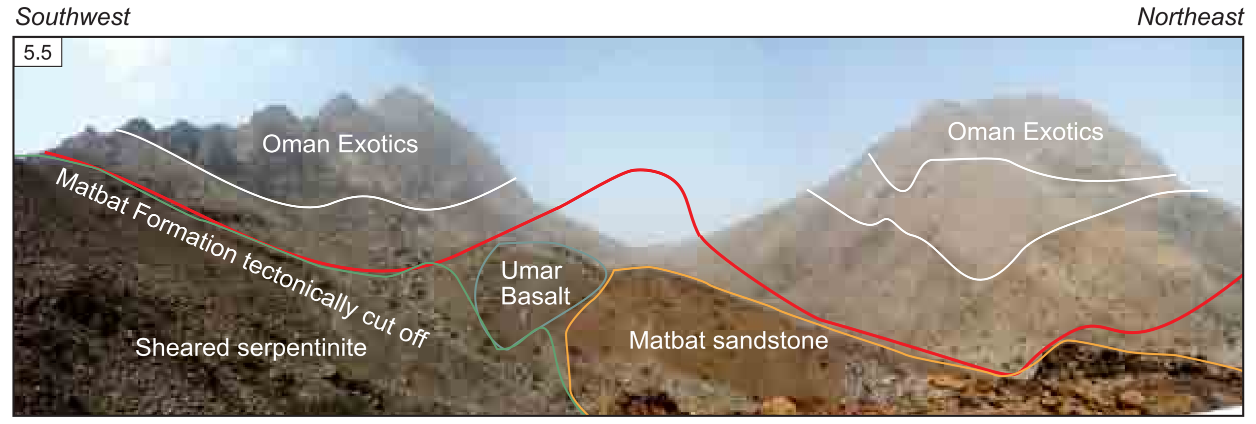
5.6: Stereoplot of measurements at Hushein. Left: faults measured at 5.4. Note top north shear along flat surface, while macroscopic offset is top S. Top S thrust faults were also measured. Right: fold axes as dots. Note general NW axial trend.



5.7: Contact of the Haybi and HD units at the eastern termination of the section unit is highly sheared.

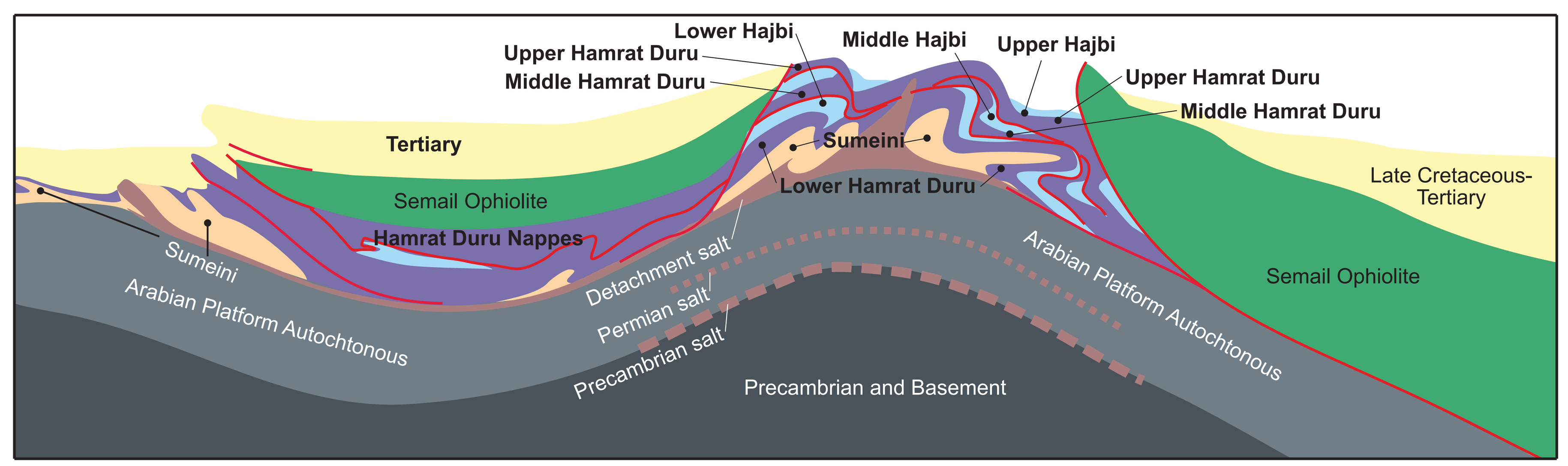


5.8: Exposure at Hayshli, falling out of section line. The relatively flat lying units are all separated by nappe boundaries. lowest unit is a sheared serpentinite, that is tectonically followed by a Hamrat Duru nappe (represented by Matbat Fm) and by Hajbi nappe (represented by Umar shale, carbonate and Oman Exotics). Note late normal faults and tilted blocks.



5.9: Exposure at Hayshli, eastwards continuation of 5.8. Note major synclinal nature of preserved Hajbi nappe succession, with Umar shales, carbonates and Oman Exotics. Umar basalt belonging to Hajbi nappe, and underlying Matbat Formation belonging to a Hamrat Duru nappe are sheared-boudinaged out. This stretching is earlier, than the normal faults seen at 5.8.

ENCLOSURE 6, GENERALIZED SECTION



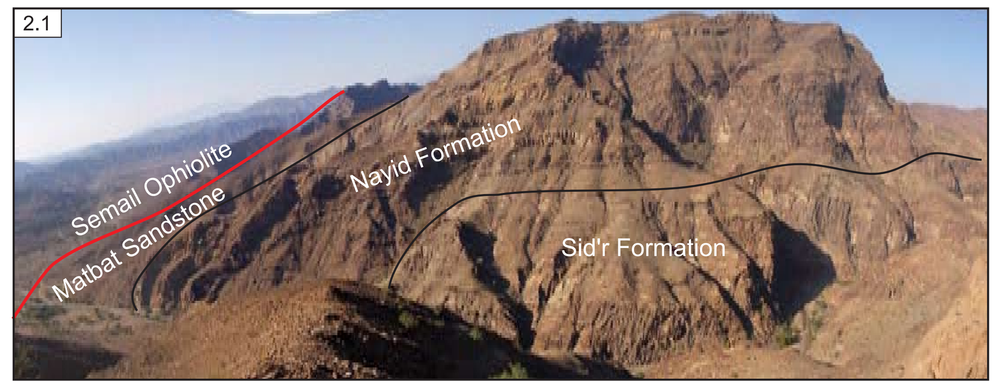
ENCLOSURES 1, 5 and 6

STRUCTURAL EVOLUTION OF THE HAWASINA WINDOW, OMAN MOUNTAINS

László Csontos, Tamás Pocsai, Ágoston Sasvári, Márton Palotai, Gizella Árgyelán-Bagoly, László I. Fodor, Árpád Magyari and Mohammed Al-Wardi

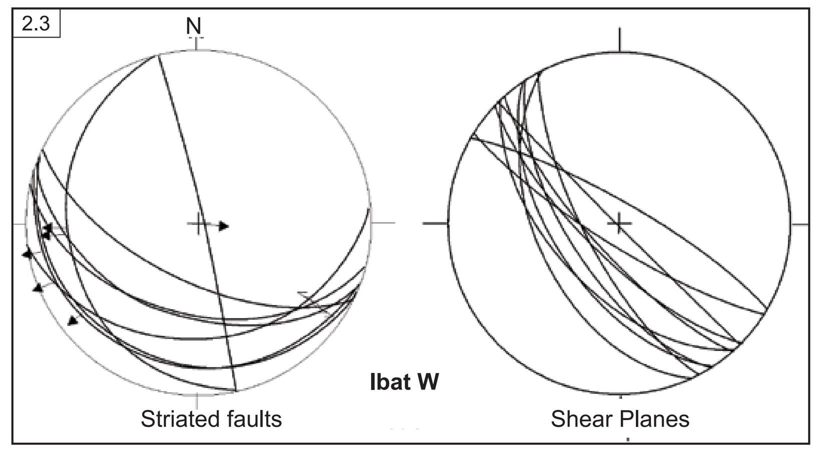
GeoArabia, v. 15, no. 3, 2010, p. 85-124 with 6 enclosures

ENCLOSURE 2: IBAT - HAWASINA TRANSECT

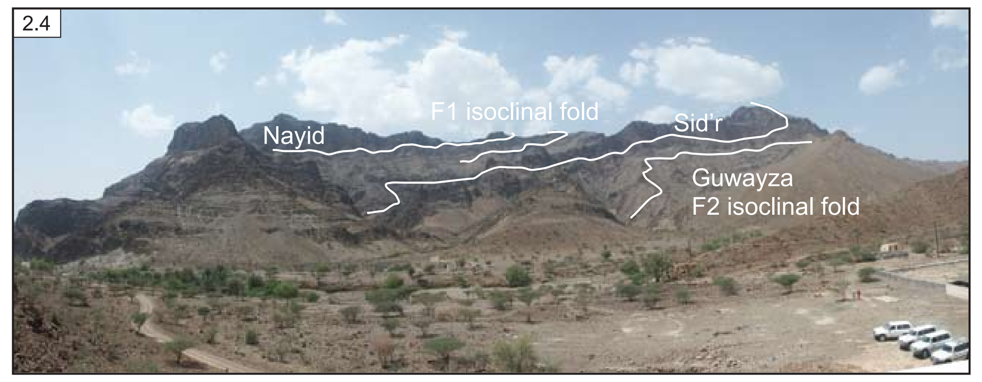


2.1: Ibat Mountain view from south. Note the SW vergency of the mountain scale fold (F1). The Matbat Formation of the Upper Hamrat Duru nappe covers the SW slopes.

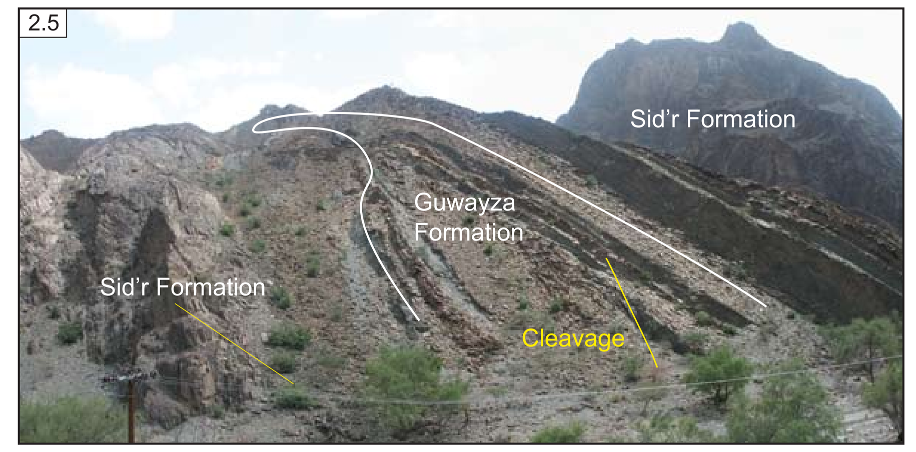
2.2: Steep contact of Matbat Formation with the Semail Ophiolite is a reactivated normal fault.



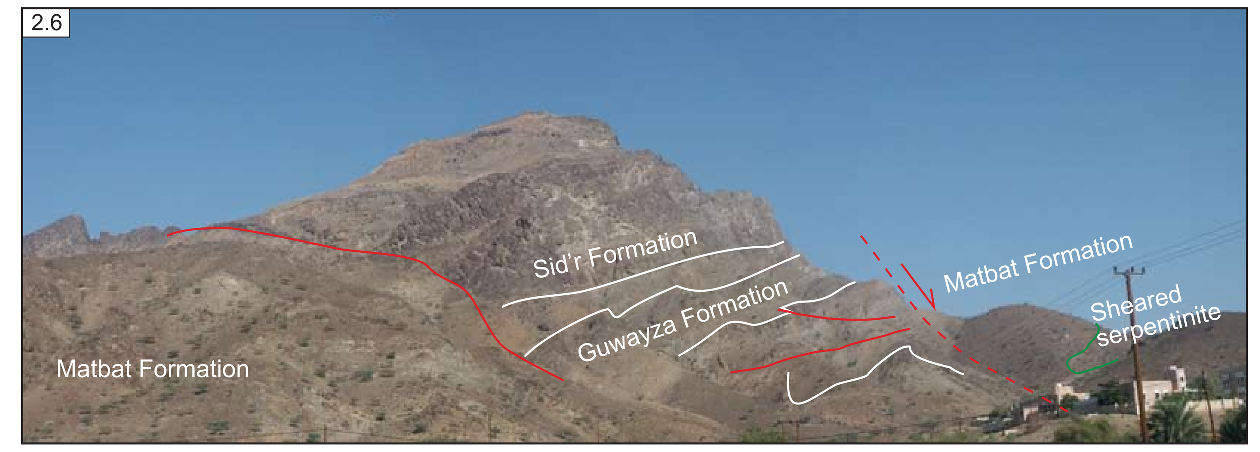
2.3: Stereoplot of steep contact. Striated faults to the left, measured shear planes to the right. Fault planes indicated by traces; outwards pointing arrows indicating normal fault striae with direction of motion.



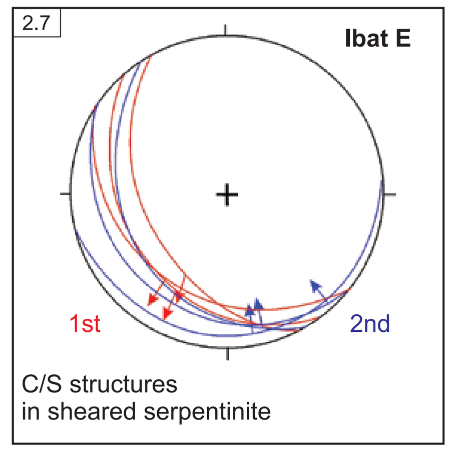
2.4: Tight F1 fold seen from the SE. Wadi Ibat, eastern end of gorge.



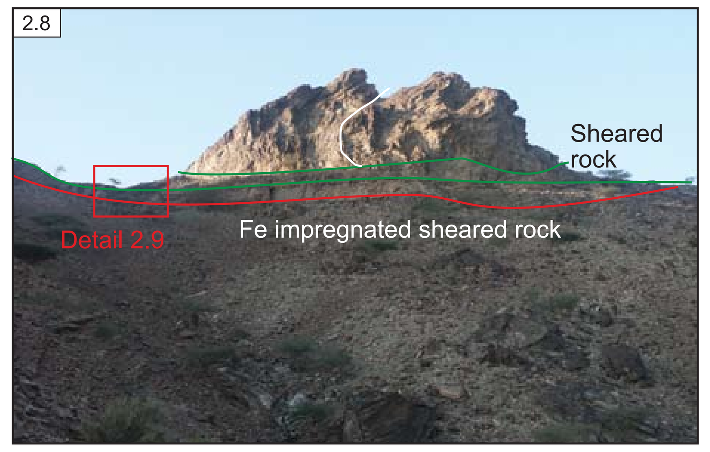
Tight NE vergent F2 fold in Guwayza Formation, Wadi Ibat.



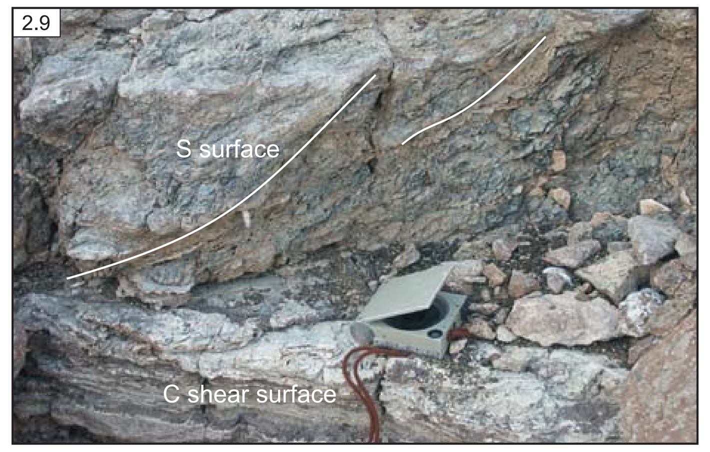
2.6: Possible normal fault at the eastern edge of Ibat Mountain.



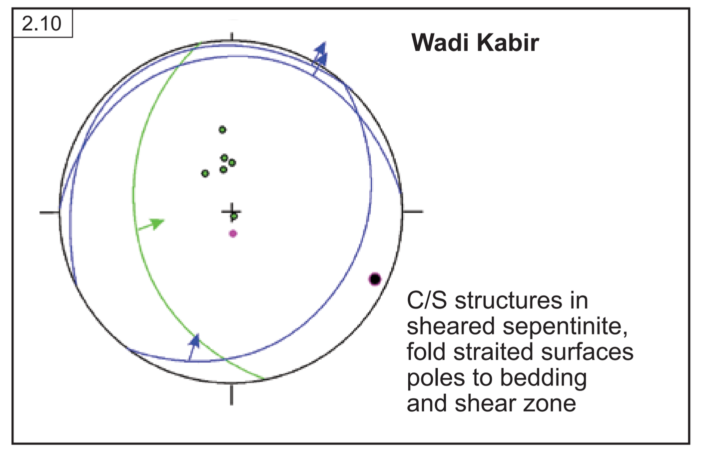
2.7: Stereoplot of shear zones in ophiolites at the eastern feet of Ibat Mountain. Arrows indicate transport directions based on C/S pattern. Red: earlier; blue: later shear. Trace: C surface



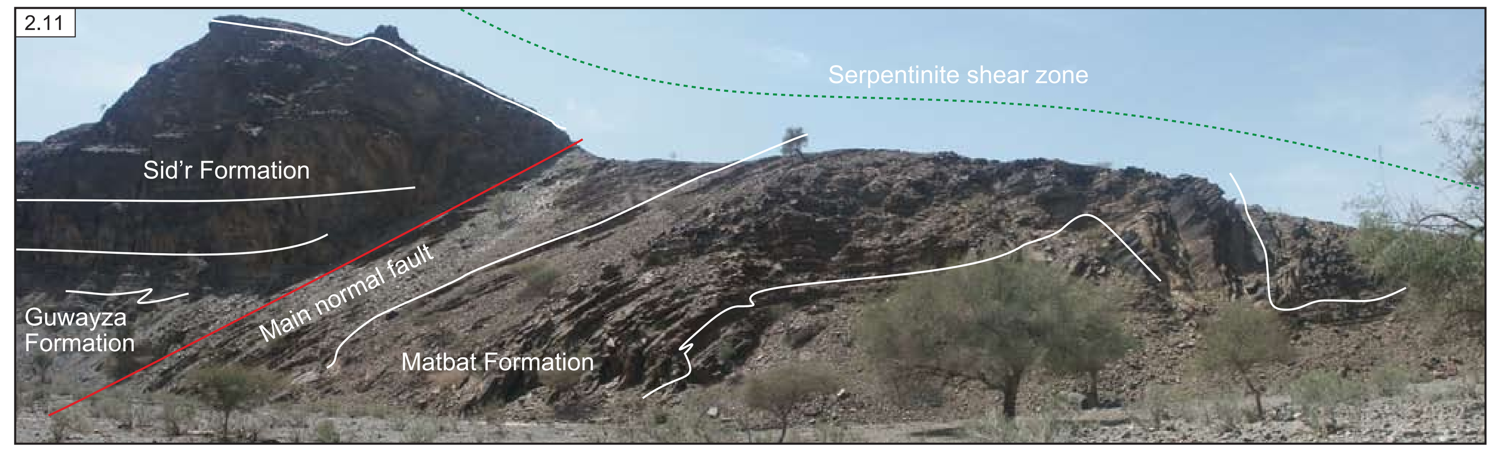
2.8: Wadi Kabir exposure on the NW wall. The higher, folded, and the lower, monoclinally dipping Matbat formations are separated by a subhorizontal, sheared serpentinite with ferruginous banks.



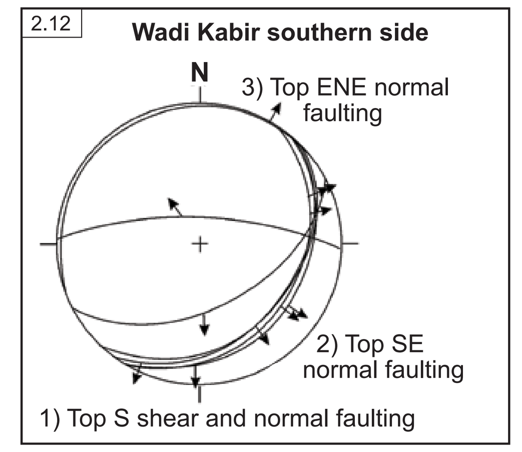
2.9: Close-up of S/C structure in serpentinite. Note top NE shear direction.



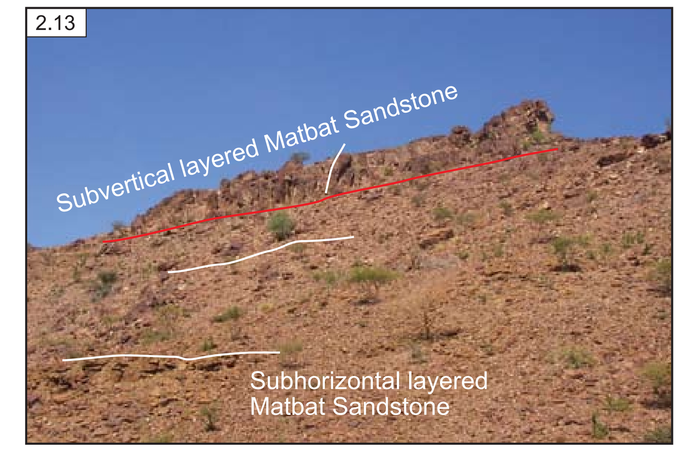
2.10: Stereoplot of S/C shear zones and inferred transport directions. green dots: poles to bedding of Matbat in footwall. Purple dot: pole to shear zone. Footwall dips begin to parallelize shear dip.
Traces: C surfaces. Blue: earlier; green: later motion. Same legend as for 2.7. Thick dot with red ring: constructed fold axis.



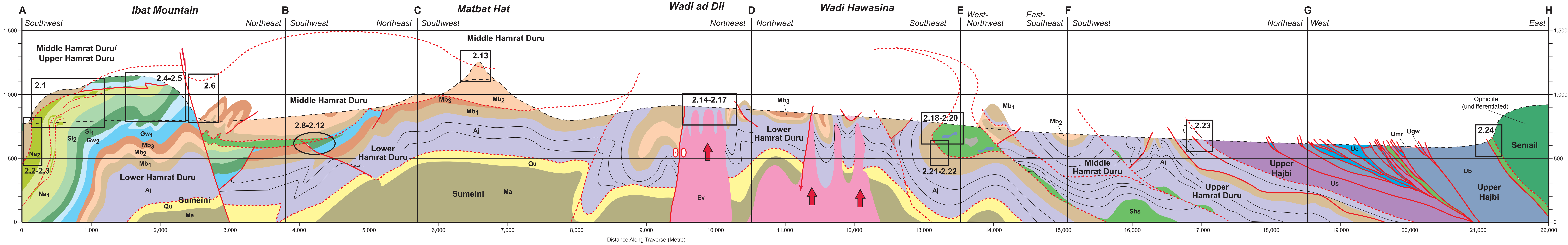
2.11: Exposure of Wadi Kabir southern wall. Main normal fault preserving younger Hamrat Duru formations is marked by red. Sheared serpentinite boundary marked by green. Normal fault detaches on serpentinite boundary fault.

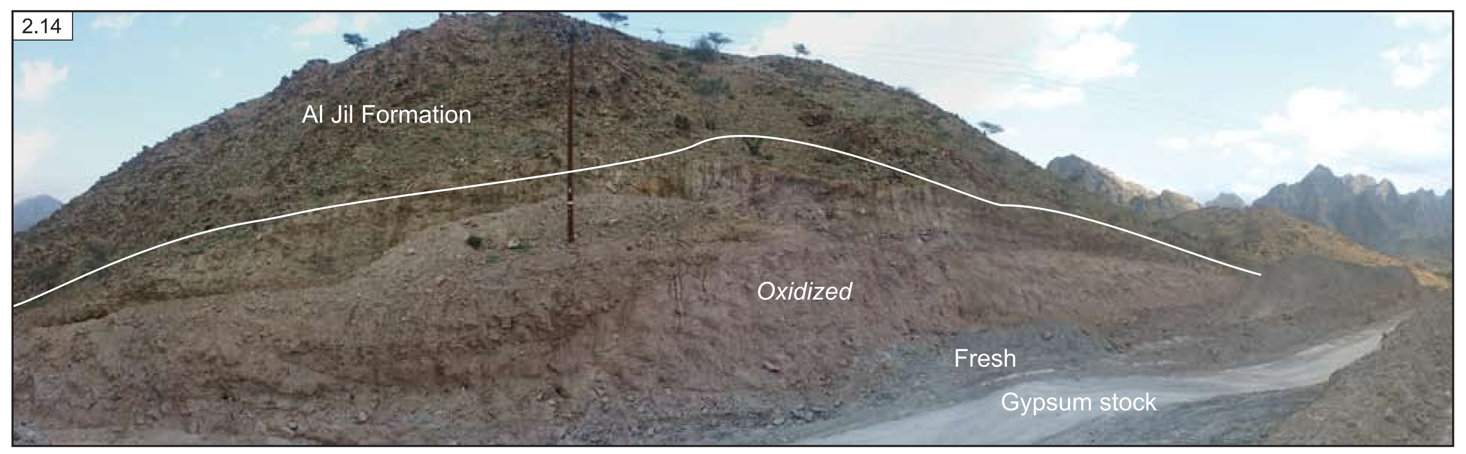


2.12: Stereoplot of successive motions on main normal fault.



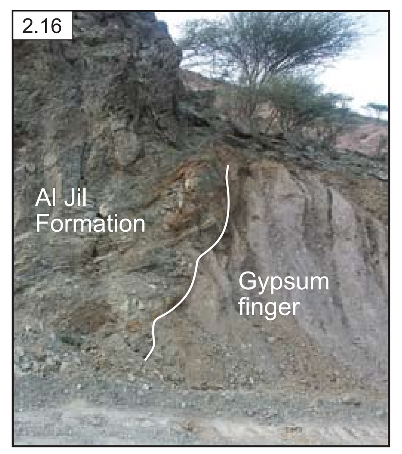
2.13: Matbat 'hat'. Contact of the Middle and Upper Hamrat Duru units. Note that beddings are at right angle.



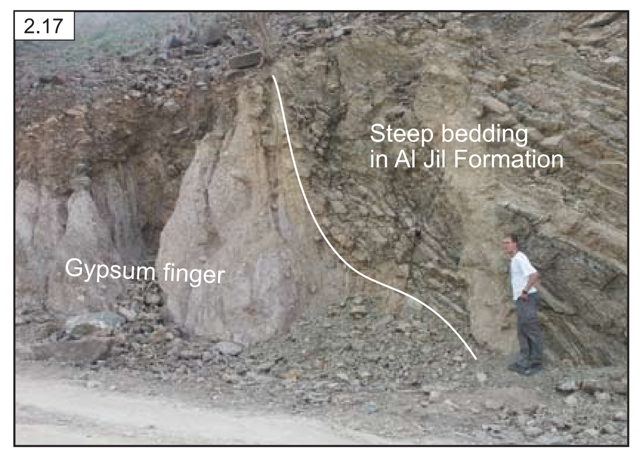


2.14: Diapir in Wadi ad Dil. Note the shape of the gypsum stock.

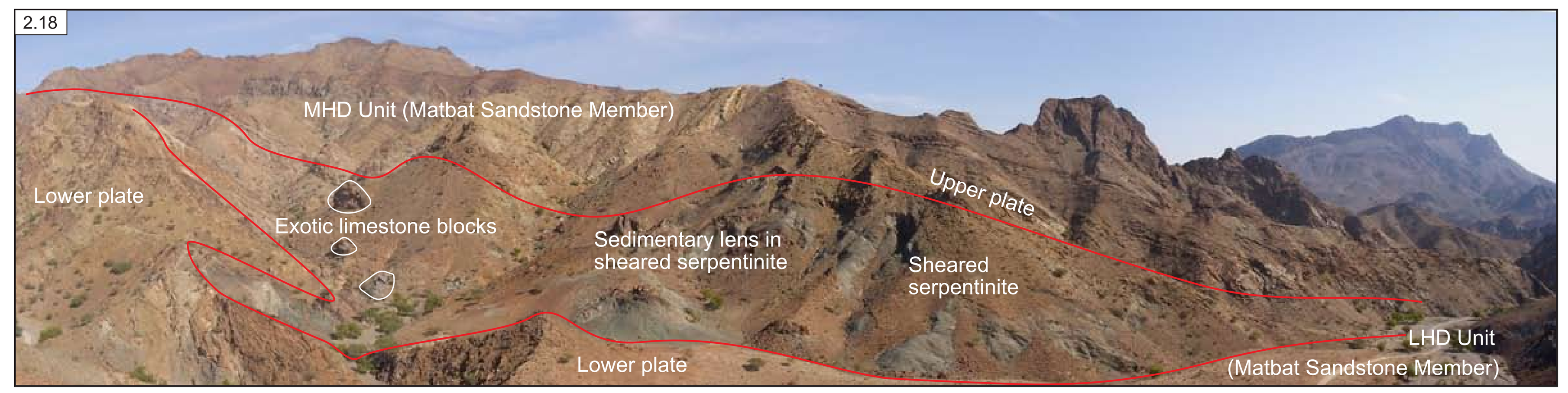
2.15: Polymict clasts brought up by the gypsum finger. Hammer for scale.



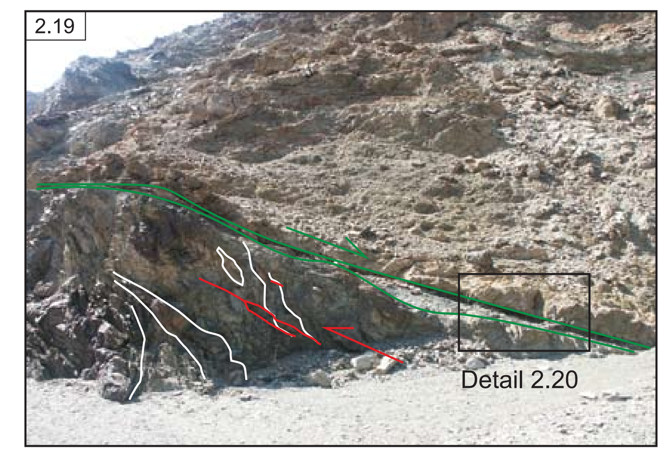
2.16: Intrusive-like contact of gypsum fingers with overlying Al Jil Formation of the Hamrat Duru group sediments, Wadi Hawasina.



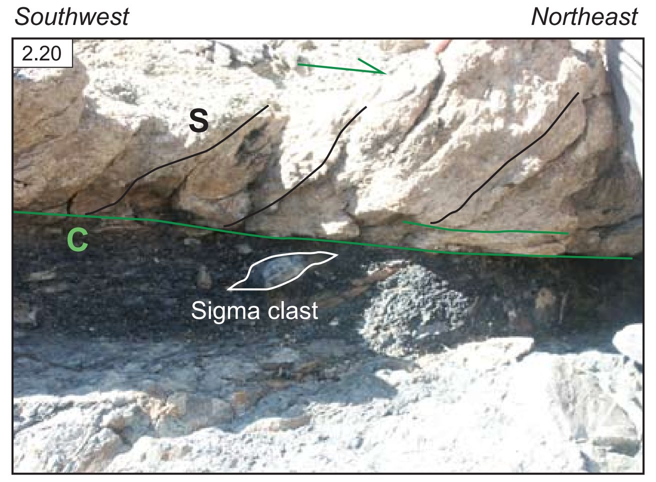
2.17: Same, Wadi ad Dil.



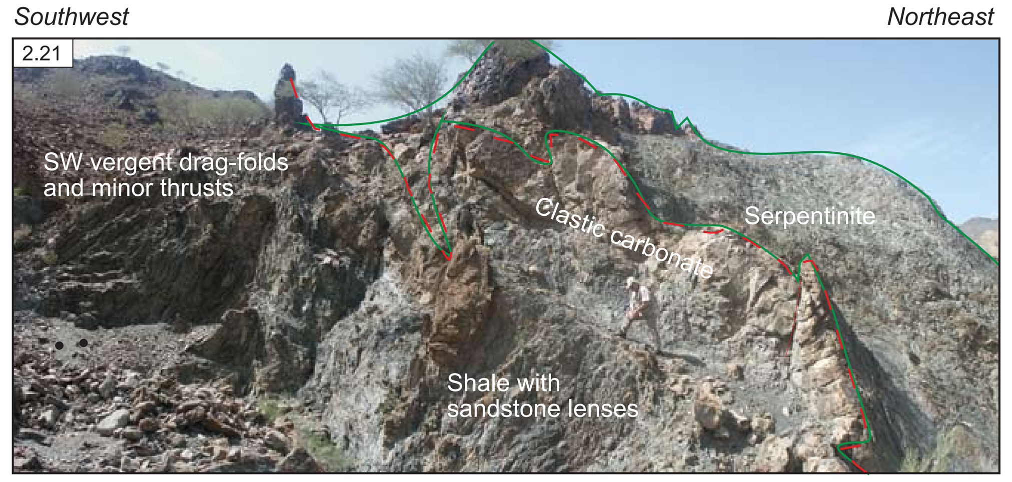
2.18. Sheared serpentinite body in the Wadi Hawasina, that forms the boundary of the Middle HD and Lower HD units. Note large Oman Exotic blocks within the shear zone.



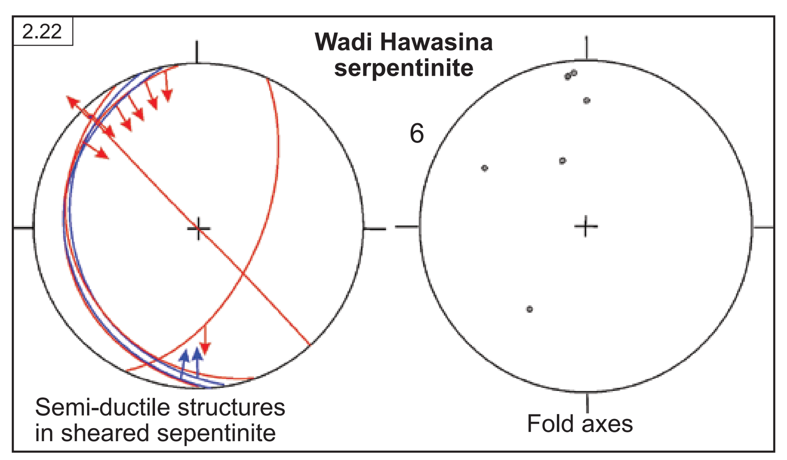
2.19. Nappe boundary in side valley. Note top SW drag on lower Plate structures.



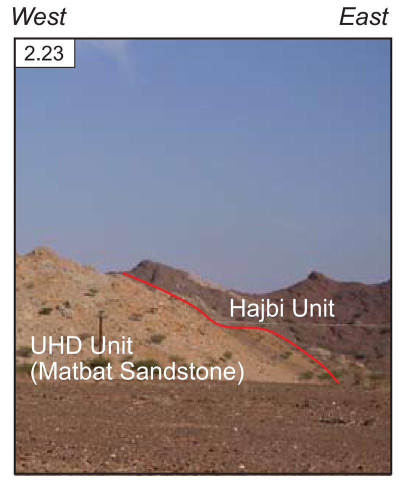
2.20: Shear zone with top NE shear directions in sheared and mineralized serpentinite (white) and dark shale.



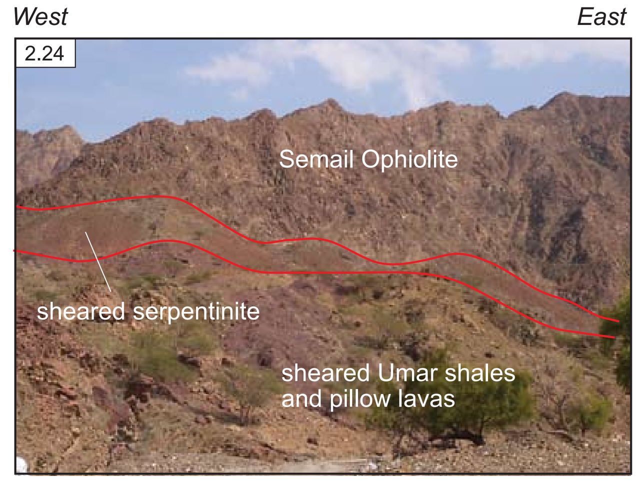
2.21: Folded nappe contact of Lower HD unit and a sheared serpentinite zone. Boundary is folded by drag folds of an upright fold (F1), with weak cleavage at axial surface. This axial surface is folded by a later fold (F2).



2.22: Stereoplot of measured elements in Wadi Hawasina. Left: shear zones and inferred transport directions of nappe boundary. Same legend as for 2.7. Right: folded nappe surface. dots for poles.



2.23: Contact of the Upper HD and Hajbi units. Note conformable layering



2.24: Contact of the Semail Ophiolite and the underlying Umar basalts along the eastern border of the window. Basalts and related shales alternate in several imbricate slices.

LEGEND

Hamrat Duru Group		
Nayid Formation	Na_2	Massive limestone breccia with calcareous matrix (Nayid Limestone sstr.)
	Na_1	Thick, lithoclastic limestone beds, with silicified limestone and chert interbeds
Sid'r Formation	Si_2	Silicified micritic limestone and radiolarian shale
	Si_1	Massive brown radiolarite and silicified limestone
Guweyza Formation	Gw_2	Silicified oolitic limestone, with some layers of chert and shale
	Gw_1	Oolitic limestone
Matabat Formation	Mb_3	Yellow, red shale with thin sandstone layers
	Mb_2	Massive, red sandstone
	Mb_1	Brown, grey thin limestone beds in shale (with filaments)
Al Jil Formation	Aj	Al Jil Formation, undifferentiated

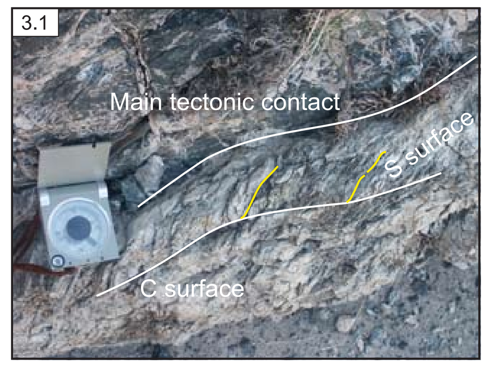
Semail Ophiolite	
Sa	Ophiolite (undifferentiated)
Shs	Sheared serpentinite
Umar Group	
Umr	Massive reef limestone
Ugw	Thick bedded grey limestone, with chert nodules and interbeds ("UmGuw")
Us	Red, green shale
Uc	Varicoloured radiolarian chert
Ub	Basaltic pillow lavas
Sumeini Group	
Qu	Qumayrah Formation
Ma	Mayhah Formation
Ev	Evaporites

ENCLOSURE 2

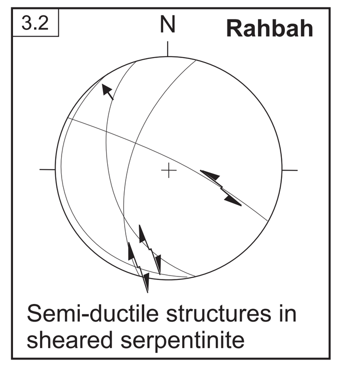
STRUCTURAL EVOLUTION OF THE HAWASINA WINDOW, OMAN MOUNTAINS

László Csontos, Tamás Pocsai, Ágoston Sasvári,
Márton Palotai, Gizella Árgyelán-Bagoly, László I. Fodor,
Árpád Magyari and Mohammed Al-Wardi
GeoArabia, v. 15, no. 3, 2010, p. 85-124 with 6 enclosures

ENCLOSURE 3: RAHBAH - MAJZI TRANSECT

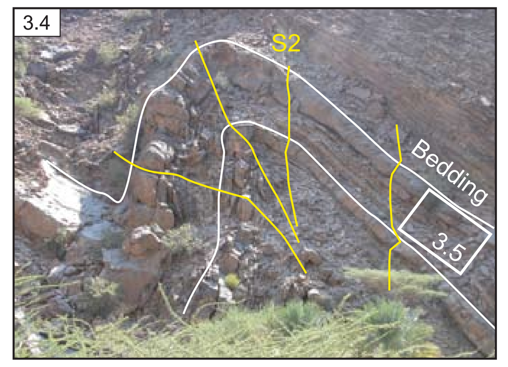


3.1: Rahbah, west of village: Serpentinite-Haybi boundary. Map view. Close-up of the contact with S/C cleavage in sheared serpentinite. Shear is basically right lateral.

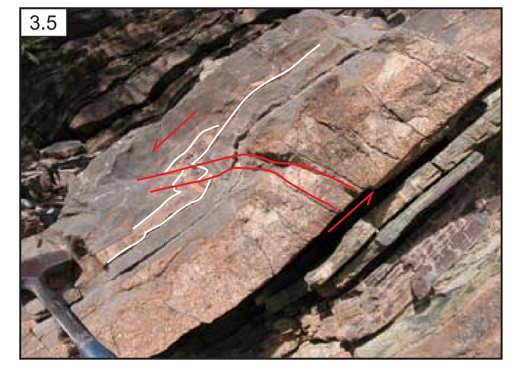


3.2: Stereoplot of serpentinite shear zone with inferred transport directions. These were constructed from C and S surface intersection relations.

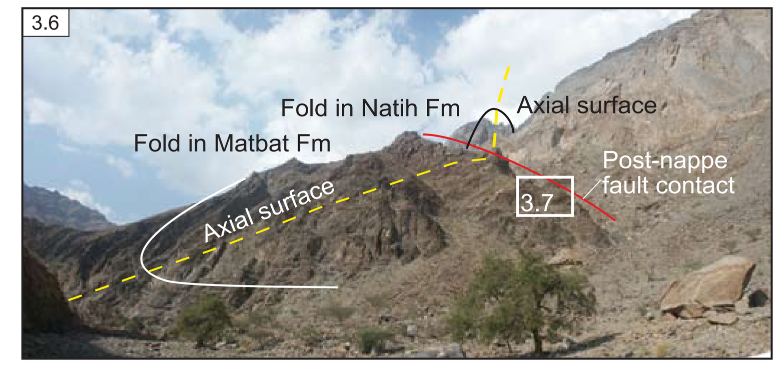
3.3: Rahbah, at entrance of the gorge: Subvertical boundary of Umar radiolarite (Lower Haybi nappe) and marly Nayid Fm of Lower HD nappe.



3.4: Rahbah, inside gorge. NE vergent syn-cleavage (F2) fold in Guwaiza Fm. Trees and bush for scale.

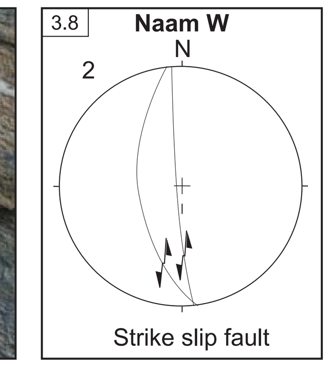


3.5: Close up of previous photo. Top SW shear-related folds (F1) and semi-ductile thrusts within layering, on the normal limb of the fold at 3.4. Shear direction is not competent with any fold mechanism. Note the opposite orientation of the two photos (taken at either side of the valley).



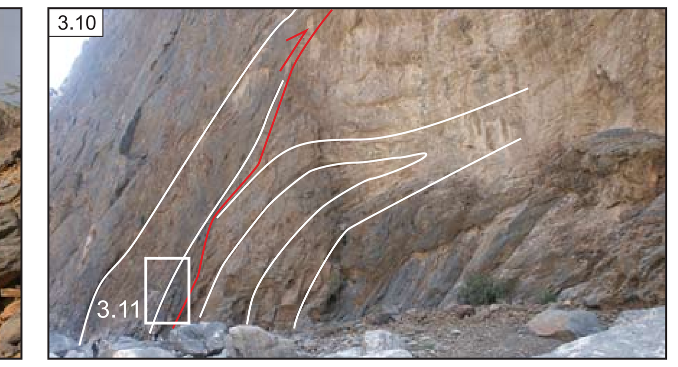
3.6: Western end of Naam Gorge. Contact zone of Matbat Formation and Sumeini carbonate. Note that the synform in Matbat is put against a truncated antiformal normal limb of sumeini.

3.7: Close-up of the fault contact with slickensides indicating oblique left-lateral slip.

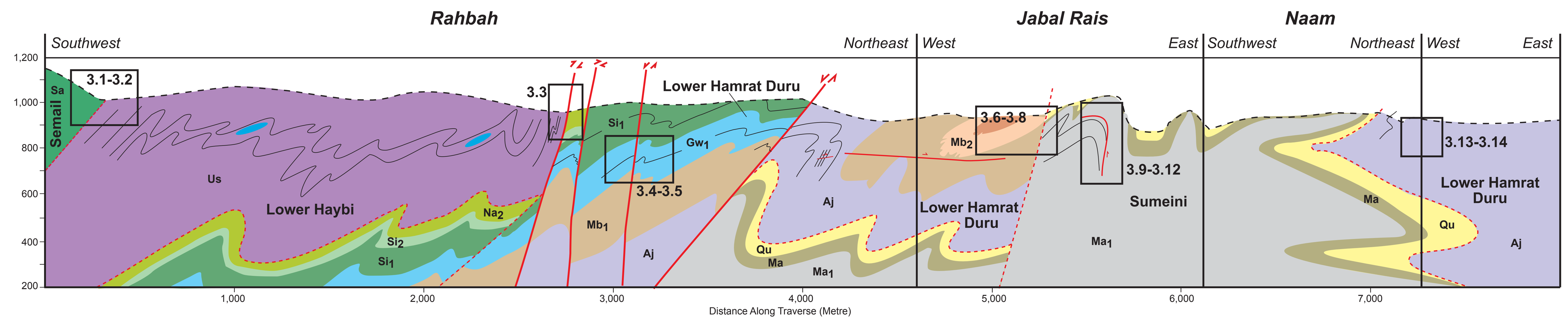


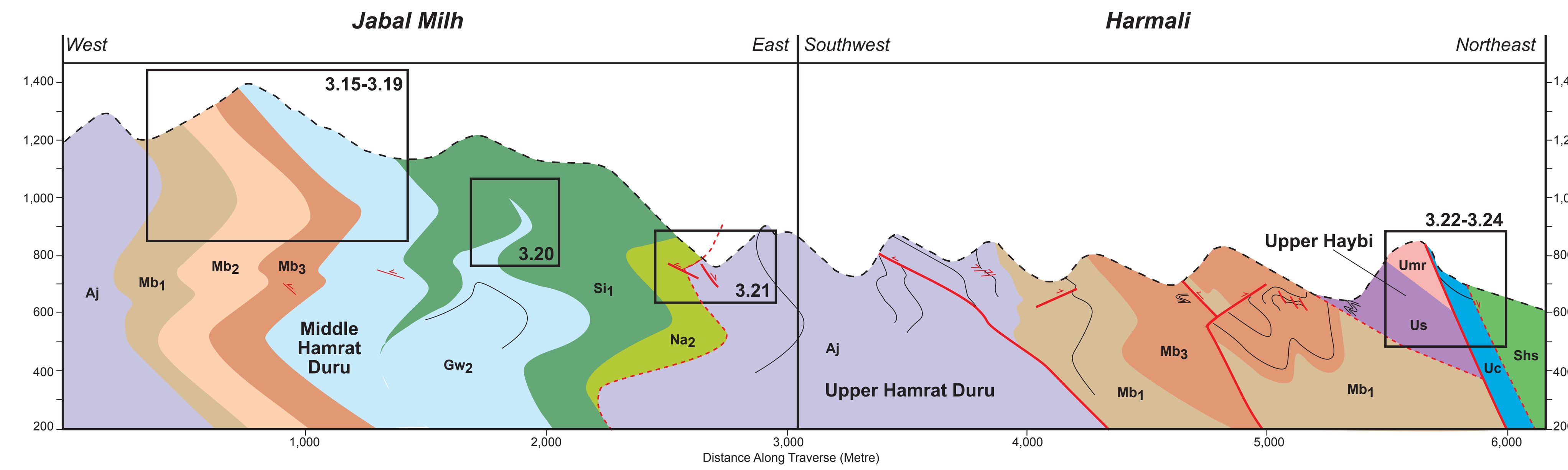
3.8: Stereoplot of left lateral fault at contact. Traces indicate main surface. Arrow indicates measured slickenslide lineation. Shear arrow indicates left lateral movement.

3.9: Naam Gorge. Distant view of the central anticline (F2) of Jabal Rais. Note that fold is upright.

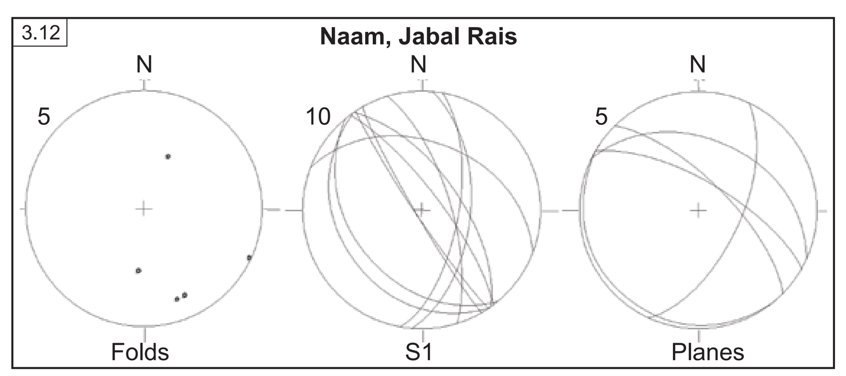


3.10: Inside Naam Gorge. Isoclinal fold (F1) in Sumeini carbonate, cut on its eastern limb by west-vergent curved thrust fault. This structure should pre-date the main F2 anticline, because all surfaces are bent conformable to the main fold.

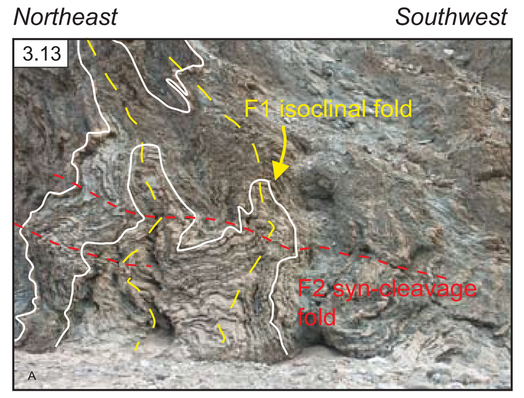




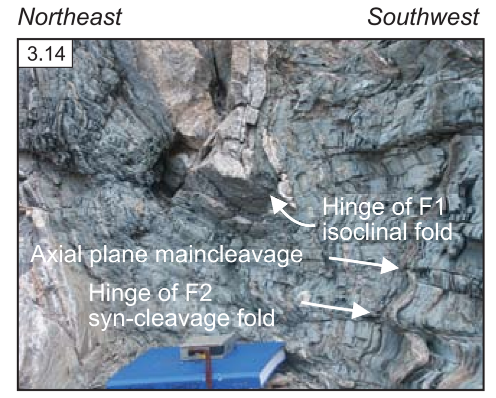
3.11: Ptygmatitic folds with cleavage in calcite vein on the limb of former fold. Note that subvertical cleavage is not compatible with former fold, but with larger main F2 fold.



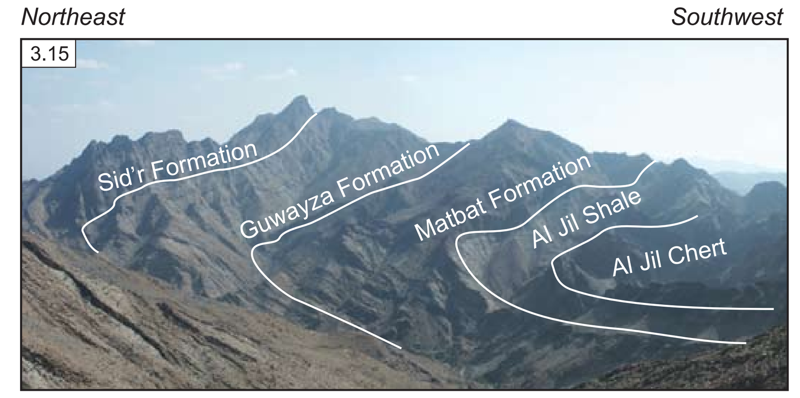
3.12: Stereoplots of Naam gorge. Left: fold axes as dots. Note main SSE axis orientation. Centre: Main cleavage surfaces as traces. Note divergent cleavage. These are compatible with fold axes. Right: shear surfaces (presumed early thrusts) related to the early F1 fold (see 3.10). Most of these dip NE.



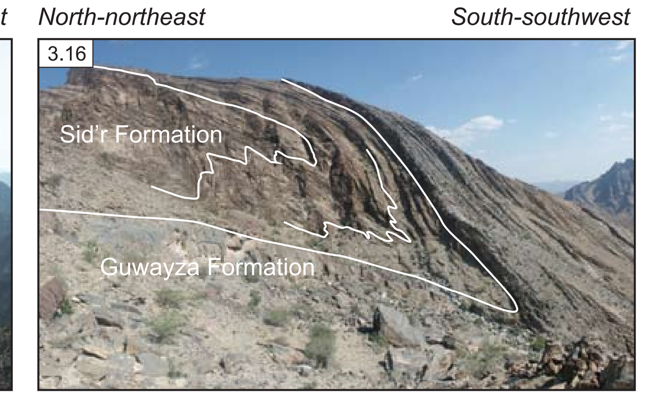
3.13: Eastern end of Naam Gorge, village exposure in Al Jil Formation. Isoclinal upright fold (F1) refolded by flat axial surface (F2) folds. F1 axial surface: yellow; F2 axial surface: red. Note that axial direction of both folds is roughly parallel.



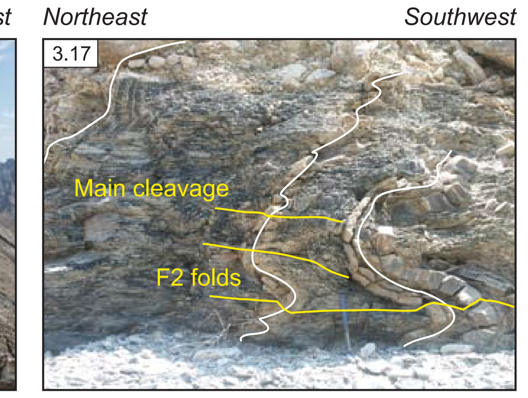
3.14: Close-up of F1 hinge cross-cut by F2 axial surface cleavage. At this scale F2 folds are crenulation-like.



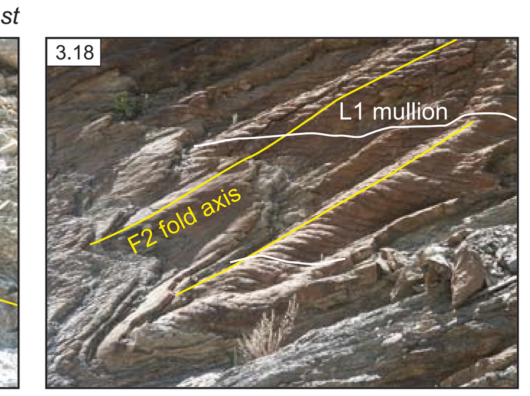
3.15: Jabal Milh, western Wadi Harim. Main Wadi Harim folds. Flat axial surfaces are parallel to regional cleavage.



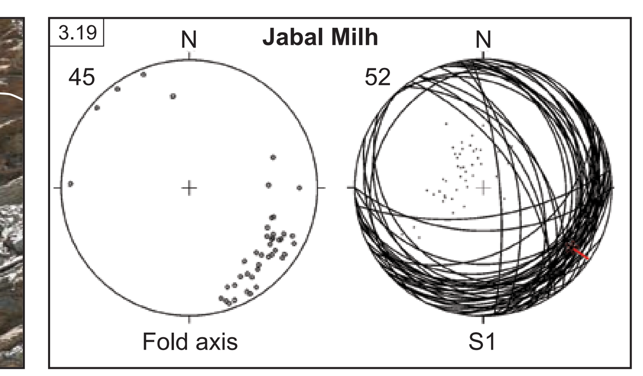
3.16: Synform in Guwayza and Sid'r formations in northern slope. Note that this synform dips below the fold in 3.15.



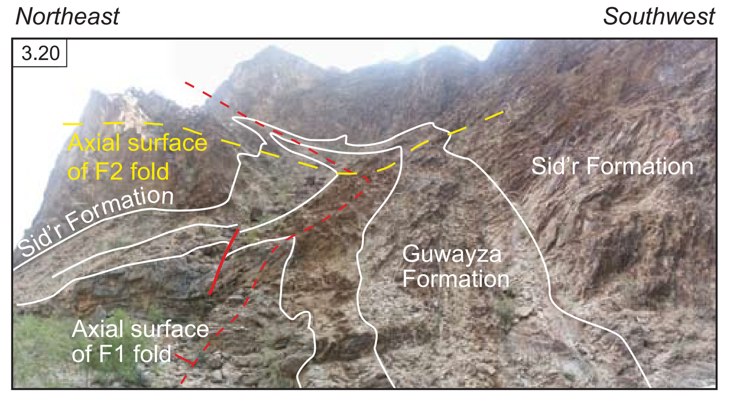
3.17: Outcrop-scale syn-cleavage fold in Matbat Formation. Cleavage is parallel to axial plane.



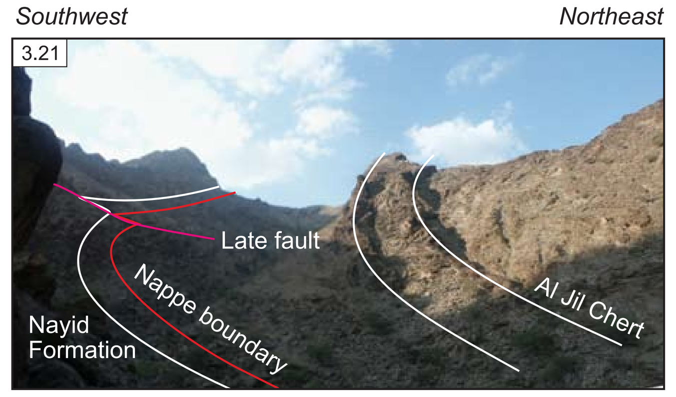
3.18: East of Wadi ad Dil: Two lineations in Matbat Limestone Formation. First (oblique to hinges, white) is a mullion-like feature folded around syn-cleavage fold hinges (yellow).



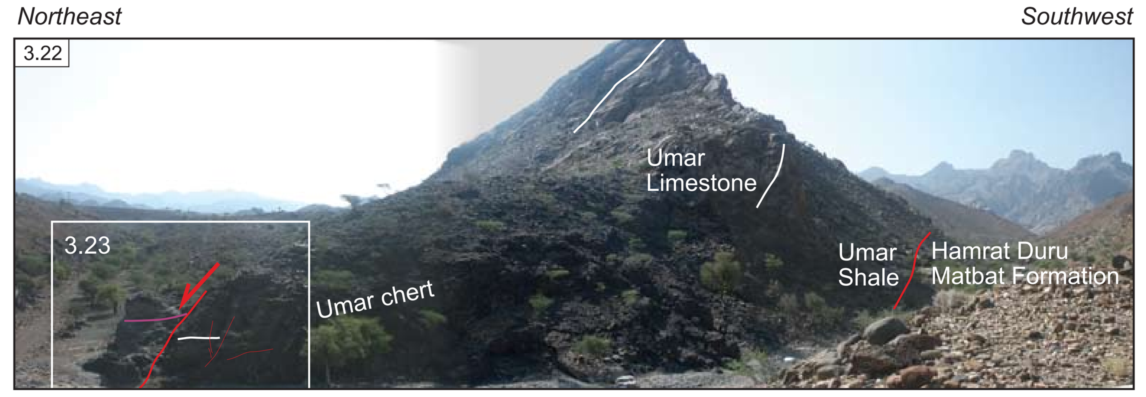
3.19: Stereoplot of measurements in Wadi Harim. Left: measured fold axes as dots. Note clear grouping around SE trending main axial direction. Right: cleavage planes as traces. Note that cleavage is folded. Constructed fold axis is marked in red This later fold axis also trends SE.



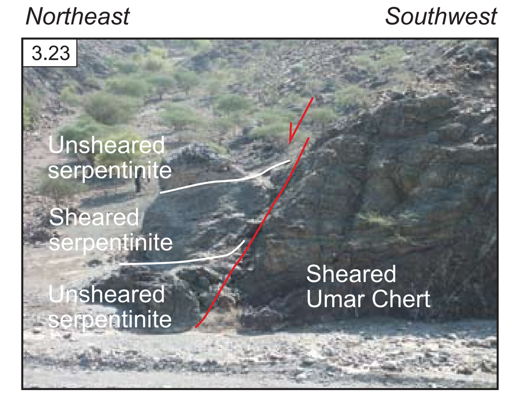
3.20: Narrows of Wadi Harim. View towards higher parts of the slope. Refolded isoclinal F1 fold in Guwayza and Sid'r formations. The second fold is a syn-cleavage F2 fold. F1 axial trace: red. F2 axial trace: purple.



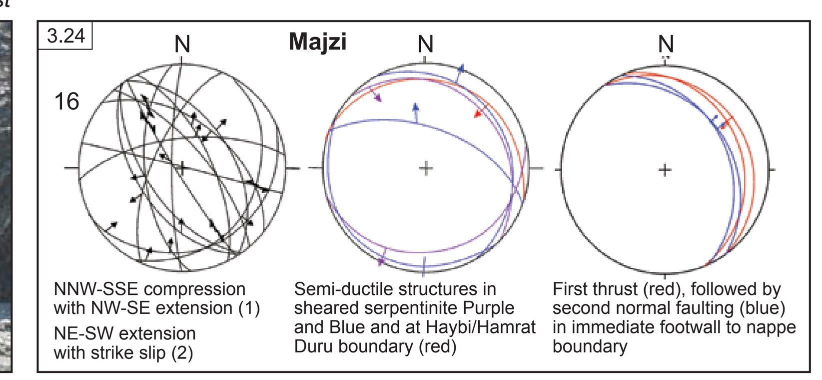
3.21: Eastern exit of Wadi Harim narrows. Folded nappe boundary between Middle and Upper HD nappes. Axial surface of the syn-cleavage fold is subhorizontal.



3.22: Eastern end of wadi Harim. View of the Semail-Haybi and Haybi-Hamrat Duru nappe boundary exposure. The Haybi nappe consists of slabs of different lithologies, assembled by tectonic surfaces.



3.23: Blow-up of the serpentinite-Haybi boundary. Note the steeply dipping normal fault (red). Sheared serpentinite is found in the middle "layer" of hangingwall block.



3.24: Stereoplot of the nappe boundary. Left: brittle faults of the exposure of 3.23. Faults as traces, slickenslides as arrowed dots. Normal faults point outwards, thrust faults point inward. Note several phases of movement. Centre: semi-ductile shear indicators in sheared serpentinite. Main shear surfaces (C) as traces. Shear directions constructed from S/C relationships. Arrows point to shear transport direction. Note two different shear episodes (top southerly marked by warm, top northerly marked by cool colours). Right: shear directions recorded near the Haybi-Hamrat Duru boundary. Early top SW shear (red) was followed by later, top NE shear (apparent normal faulting, blue).

LEGEND

Hamrat Duru Group		
Nayid Formation	Na_2	Massive limestone breccia with calcareous matrix (Nayid Limestone sstr.)
Sid'r Formation	Si_2	Silicified micritic limestone and radiolarian shale
	Si_1	Massive brown radiolarite and silicified limestone
Guweyza Formation	Gw_2	Silicified oolitic limestone, with some layers of chert and shale
	Gw_1	Oolitic limestone
Matbat Formation	Mb_3	Yellow, red shale with thin sandstone layers
	Mb_2	Massive, red sandstone
	Mb_1	Brown, grey thin limestone beds in shale (with filaments)
Al Jil Formation	Aj	Al Jil Formation, undifferentiated

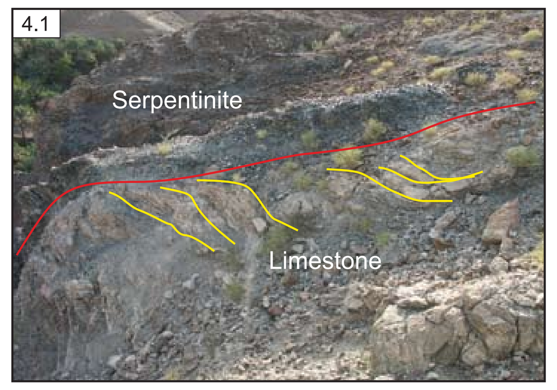
Semail Ophiolite	
Sa	Ophiolite (undifferentiated)
Shs	Sheared serpentinite
Umar Group	
Umr	Massive reef limestone
Us	Red, green shale
Uc	Varicoloured radiolarian chert
Sumeini Group	
Qu	Qumayrah Formation
Ma	Limestone breccia (Mayhah Formation?)
Ma_1	Grey, micritic limestone (Mayhah Formation?)

ENCLOSURE 3

STRUCTURAL EVOLUTION OF THE HAWASINA WINDOW, OMAN MOUNTAINS

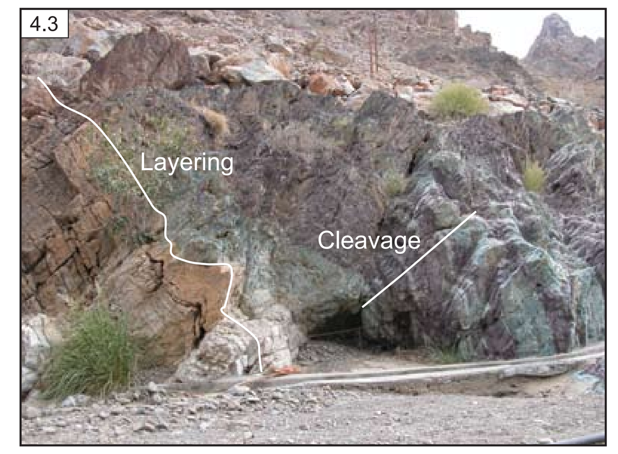
László Csontos, Tamás Pocsai, Ágoston Sasvári, Márton Palotai, Gizella Árgyelán-Bagoly, László I. Fodor, Árpád Magyari and Mohammed Al-Wardi
GeoArabia, v. 15, no. 3, 2010, p. 85-124 with 6 enclosures

ENCLOSURE 4: AL ISALAT-LHIBAN TRANSECT

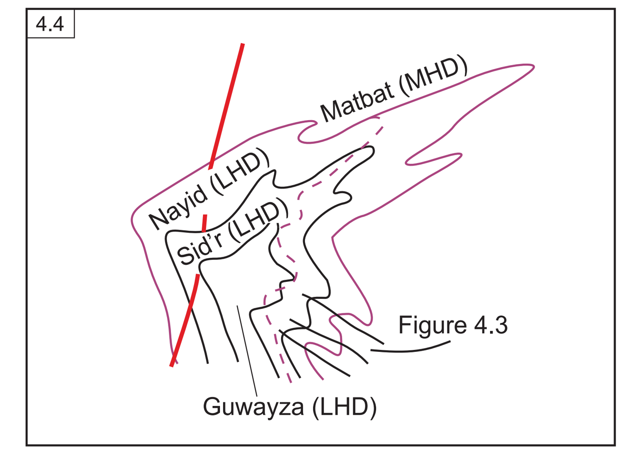


4.1: Serpentinite/Hamrat Duru contact (red) west of Al Isalat. Note sigmoidal shear-related cleavage planes. The shear is left lateral.

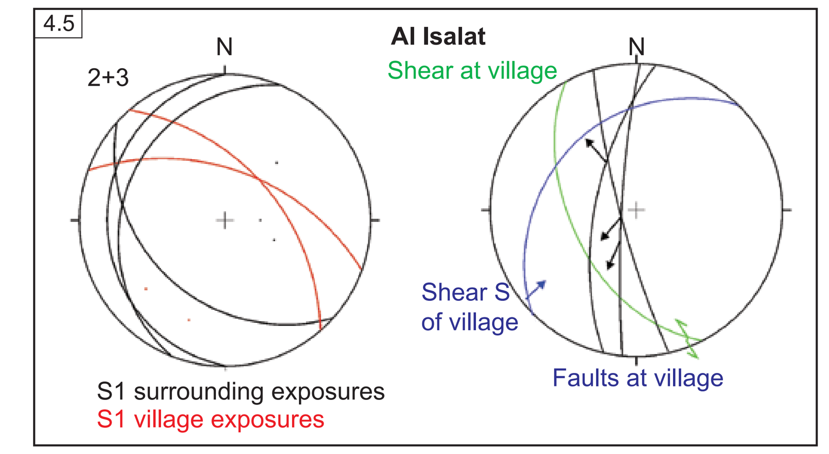
4.2: Steep axial surface tight isoclinal fold near Al Isalat. White marks the boundary of Sid'r chert and Nayid Limestone.



4.3: Syn-cleavage fold in Sid'r (variegated) and Nayid (lower left) Formations. Note that fold vergence is opposite of the general trend.

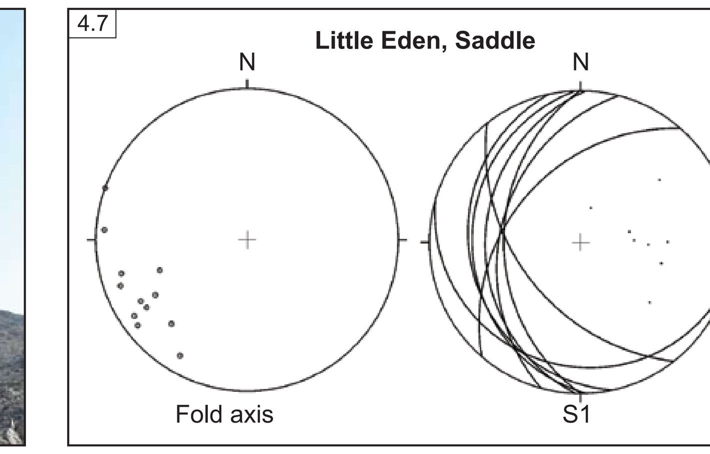


4.4: Explanatory cross section of the fold and structures at Al Isalat. Original isoclinal upright fold (F1 is covered on the external side by Matbat Formation of the Middle Hamrat Duru (purple line). Further north this nappe boundary cuts into the eastern limb (stippled). This fold is refolded by syn-cleavage F2 fold with flat axial surface. Note that this axial surface is titled to the east due to later movements. The whole structure is cut by the Semail boundary (red, figured on 4.1). Note the late nature of this boundary.

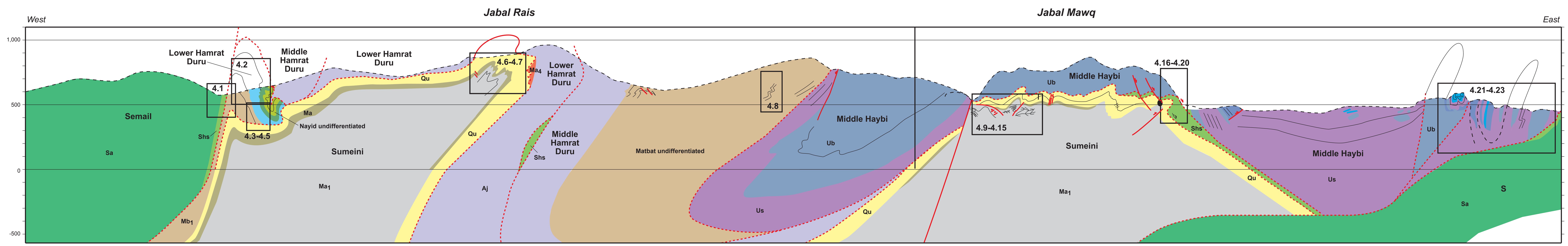


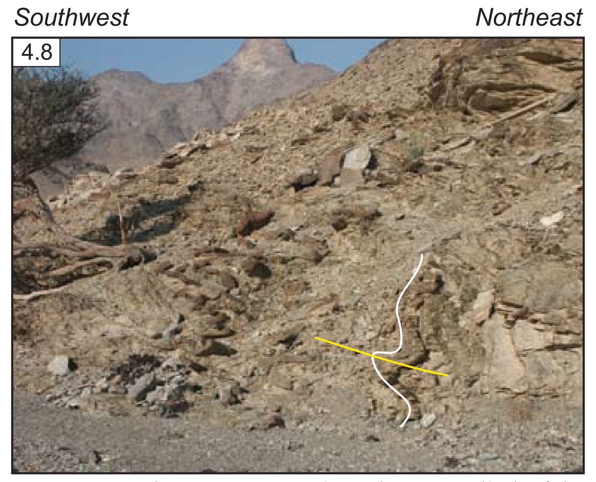
4.5: Stereoplot of exposures at Al Isalat. Left: cleavage planes measured around the village (black); and in the village (exposure 4.3, red). Note that cleavage dips either SW or (possibly locally) NE, as at exposure 4.3 Right: Faults and shear zones measured near Al Isalat. Green: boundary fault of 4.1. Blue: another boundary fault S of village. Black steep normal faults at village.

4.6: Jabal Rais saddle. Tight isoclinal fold in the Sumeini Unit. Note that axis is practically parallel to plane of picture.

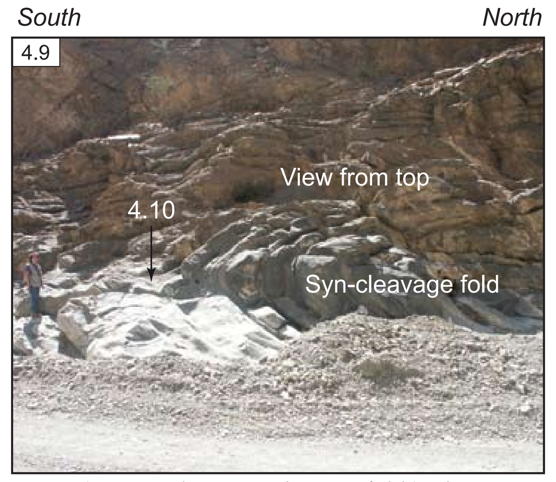


4.7: Stereoplot of measurements near saddle of Jabal Rais. Left: fold axes as dots. Note the main western trend of axial directions, which departs from the general NW-SE trend. right: cleavage planes near the saddle of Jabal Ries Jabal Ries eastern slope. Overturned Hamrat Duru unit on the eastern limb of the antiform.



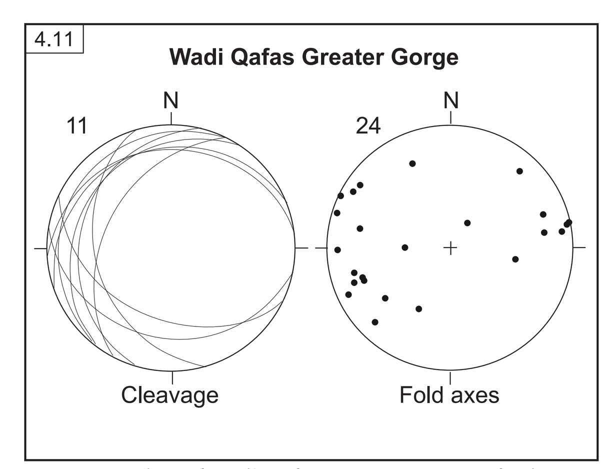


4.8: Overturned Hamrat Duru unit on the eastern limb of the main Jabal Rais antiform.



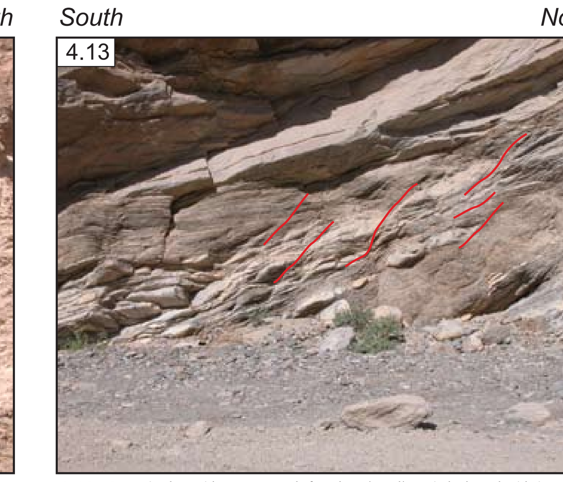
4.9: Major recumbent syn-cleavage fold in the greater Qafas Gorge. Axial surface is sub-horizontal. Note geologist (left side) for scale.

4.10: Layer-parallel shear; map view from fold limb in 4.9. Pencil marks cryptic cleavage related to shear.

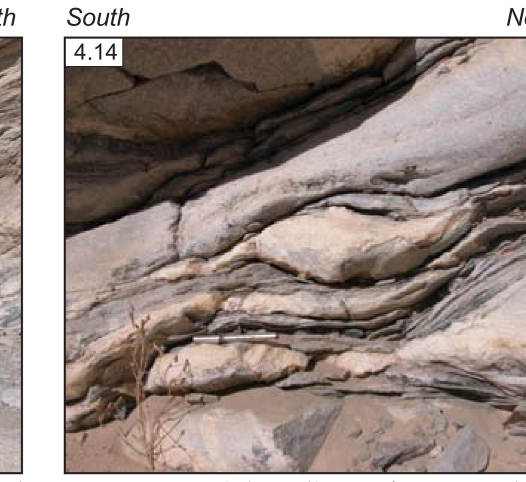


4.11: Stereoplots of Wadi Qafas Greater Gorge. Left: cleavage planes as traces. Note that flat cleavage appears to be folded around a NW dipping flat axis (red, constructed axis). Right: fold axes as dots. Note general E-W axial trend.

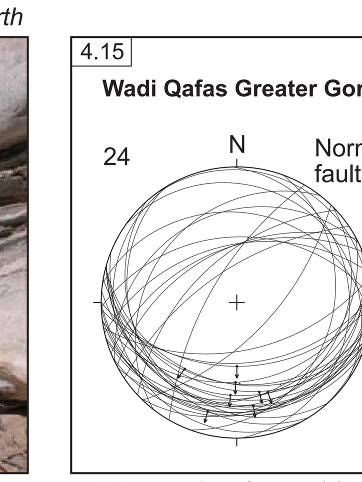
4.12: Major low angle normal fault cutting across the top of "Sumeini" succession in the greater Qafas Gorge. White marks layering.



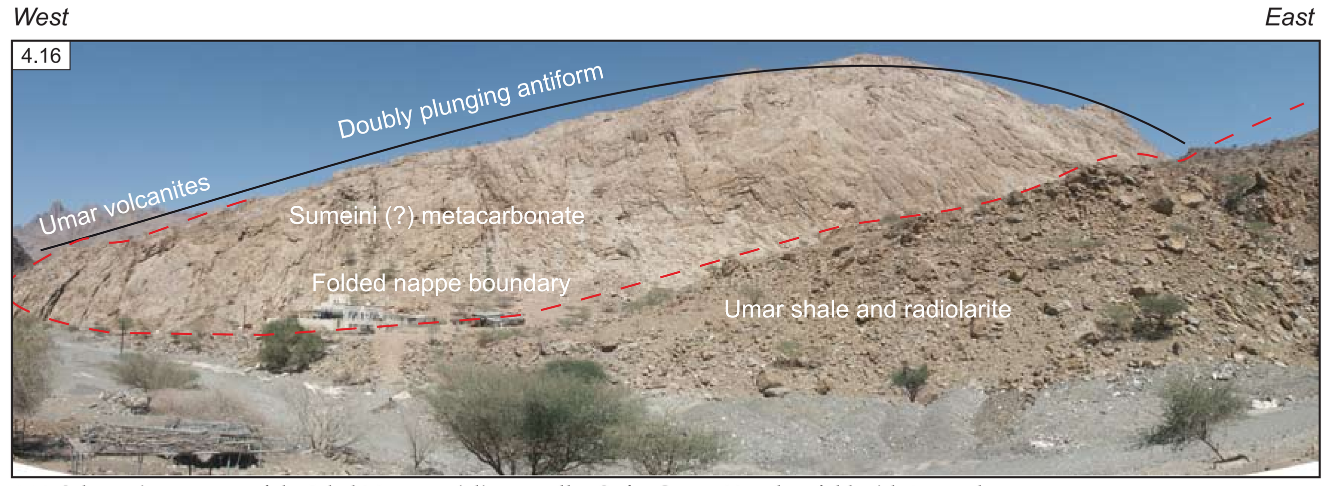
4.13: Semi-ductile normal faults (red) with backtilting and drag.



4.14: Asymmetric boundinage of more completent layers. Shear is top down, to the south.



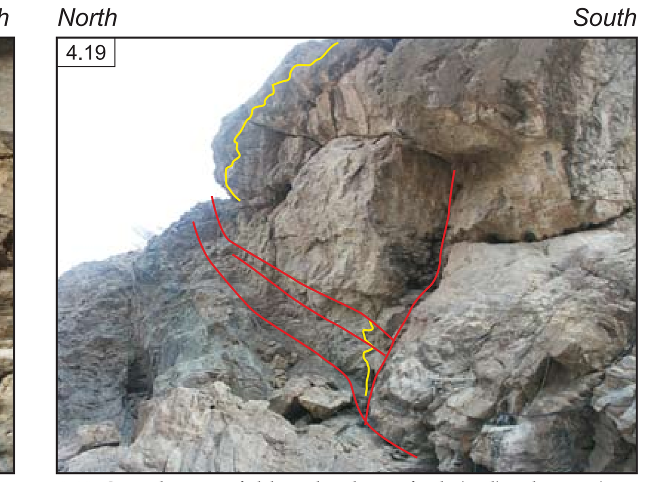
4.15: Stereoplot of normal faults as traces in greater Qafas Gorge. Note main N-S extension resulting from conjugate fault planes.



4.16: Schematic structure of the Jabal Mawq anticline, smaller Qafas Gorge. Note late fold with 4 way closure.

4.17: Flat isoclinal fold in marble in Smaller Qafas Gorge. Layering marked in white. Note red cherts and clasts of different color subject to ductile shear.

4.18: Shear indicator (delta clast) in clastic marble. Opposite shear indicators also exist.

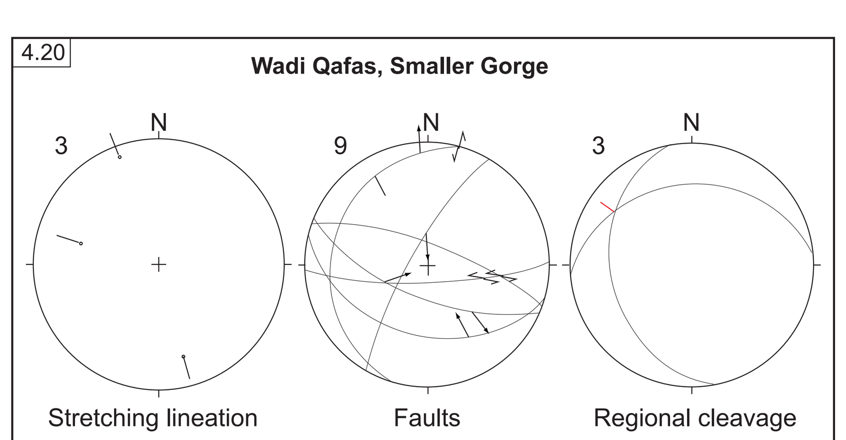


4.19: Syn-cleavage fold cut by thrust fault (red) at hot spring. A strike slip fault is also marked. Yellow line marks marker bed.

LEGEND

Hamrat Duru Group		
Nayid Formation	Na_2	Massive limestone breccia with calcareous matrix (Nayid Limestone sstr.)
Sid'r Formation	Si_1	Massive brown radiolarite and silicified limestone
Guweyza Formation	Gw_1	Oolitic limestone
Matbat Formation	Mb_4	Intrusions (sills and dikes) in the Matbat Formation
	Mb_1	Brown, grey thin limestone beds in shale (with filaments)
Al Jil Formation	Aj	Al Jil Formation, undifferentiated

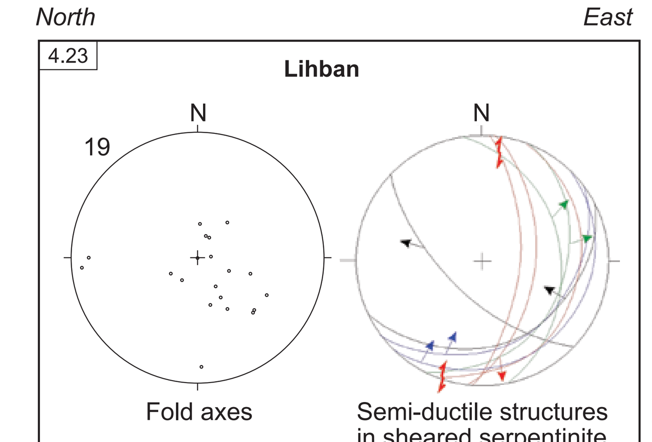
Semail Ophiolite	
Sa	Ophiolite (undifferentiated)
Shs	Sheared serpentinite
Umar Group	
Us	Red, green shale
Uc	Varicoloured radiolarian chert
Ub	Basaltic pillow lavas
Sumeini Group	
Qu	Qumayrah Formation
Ma	LImestone breccia (Mayhah Formation?)
Ma_1	Grey, micritic limestone (Mayhah Formation?)



4.20: Measurements in Wadi Qafas, Smaller Gorge. Left: stretching lineations. Center: Brittle faults as traces. Note E-W left lateral faults as last structures. Several (mostly top norterly) thrusts preceed this faulting event. Right: cleavage (not parallel to bedding). Note that cleavage appears to be folded, like at Greater Gorge.

4.21: Lhiban-Qafas road; Khorija road junction. Steep axis folds. Note sinuous pattern of layers in radiolarite photographed from above.

4.22: Lhiban. Northern border of the Hawasina Window. Note reversed tectonic position of the Semail and hawasina nappes (Haybi on top of Semail Unit).



4.23: Measurements near Lhiban. Left: fold axes as dots measured in exposure 4.21. Note the general steep axis of folds. Right: ductile shear indicators in an exposure near nappe boundary of 4.22. Shear planes (mostly C surfaces) marked as traces; shear directions (arrows) constructed after S/C relationships. Note several generations of shear (with different colors).

ENCLOSURE 4

STRUCTURAL EVOLUTION OF THE HAWASINA WINDOW, OMAN MOUNTAINS

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