Structural architecture of a thin-skinned imbricate fan: Evidence from Mesozoic deepwater sediments in the Jabal Wahrah area of the central Oman Mountains

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ABSTRACT

In the central Oman Mountains, Mesozoic deepwater off-margin sediments of the Hawasina Complex were emplaced from the northeast onto the Oman continental margin during the Late Cretaceous obduction of the Semail Ophiolite. Detailed field mapping and structural investigation have shown that, in the area studied, margin-ward detachment of continental rise sediments (Hamrat Duru Group) created two major thrust units in the face of the advancing ophiolite and subduction zone wedge of sediments from more distal parts of the Hawasina Ocean.

The upper unit is preserved in jabals Wahrah and Hurah as a wedge-shaped sheet, restoring to at least 60 km perpendicular to the line of emplacement but only about 500 m thick at its maximum. Its thinner leading edge (Jabal Wahrah) comprises a classic thin-skinned imbricate fan which is divided into five laterally continuous structural zones with finer-grained structures that are influenced by local stratigraphical variations in its Early Jurassic to Early Cretaceous section. The rear part of the thrust sheet (Jabal Hurah) behaved more rigidly, reflecting a thicker and more competent sedimentary sequence spanning the Early Triassic to ?mid Cretaceous. With the exception of a major duplex along its trailing edge, significant internal thrusts are rare and shortening is mostly accommodated by asymmetrical folding. This wedge was emplaced over the trailing edge of a lower thrust unit (Hammat Shulayshil), which formed through forward propagation of the Hawasina sole thrust and which was also deformed primarily through SW-directed folding with limited internal imbrication even after a translation during emplacement of at least 150 km.

A second stage of thrusting after the main emplacement phase is linked to renewed locking of the lowest thrust planes in the imbricated Hawasina sediment wedge ahead of the Semail Ophiolite and late-stage motion transferring to higher structural levels closer to the ophiolite as movement of the latter gradually ceased. This resulted in out-of-sequence re-thrusting of higher thrust sheets over lower sheets along existing thrust planes. This was accompanied by the local rotation of parts of the Jabal Wahrah imbricate fan as an effect of the heterogeneous composition of the overlying thrust units, in particular the out-of-sequence emplacement of a mountain-sized thrust block of intra-oceanic reef limestone (Jabal Kawr) over the Hamrat Duru Group immediately to the east.

A third phase of compression then folded and locally thrusted this re-thrust stack. The timing of this phase is not well constrained. It may represent the final effects of the Campanian emplacement; alternatively it may be tentatively linked to limited lateral motion (gravity sliding) of the thrust stack along the flanks of the Al Jabal al-Akhdar anticline during its main growth phase in the Oligocene.

INTRODUCTION

The Oman Mountains (Figure 1a) record the evolution and subsequent destruction of part of the south Neo-Tethyan passive margin. Unlike many other Alpine and Himalayan areas, the destruction of the margin has not ended with continent-continent collision and a fragment of Neo-Tethys remains between Oman and Pakistan, under which subduction continues (White and Ross, 1979; Kopp et al., 2000). Instead, during the Late Cretaceous, a slab of Neo-Tethyan oceanic crust about 500 km long, the Semail Ophiolite, was obducted onto the Arabian continental margin together with various structural units that represent deep-water sediments of the “Hawasina Ocean”, that part of Neo-Tethys which lay to the northeast of the Oman margin.
Figure 1: Geology of the Oman Mountains.
(a) Geological map of the central Oman Mountains, modified from Glennie et al. (1974), Lippard et al. (1986) and Béchennec et al. (1992).
(b) Geological cross section through the southern central Oman Mountains modified from Glennie et al. (1974), Searle (1985) and Cooper (1990). Symbols as in Figure 1(a).
(c) Simplified reconstruction of the Mesozoic Oman Tethyan continental margin in the central Oman Mountains showing the main tectonic units and distal-proximal stacking: shelf/slope (Sumeini Group)/continental rise (Hamrat Duru Group: proximal Hamrat ad Duru, distal J Wahrah/J Hurah)/distal basin with offshore platforms (Al Aridh/Kawr/Umar groups). Modified from Bernoulli and Weissett (1987); Béchennec et al. (1990), Cooper (1990) and Blechschmidt et al. (2004).
The Tethyan sequences in the central Oman Mountains (Figures 1b and 1c) can be divided into six main components. The autochthonous units comprise (1) pre-Permian basement unconformably overlain by (2) Hajar Supergroup - Permian to mid-Cretaceous shelf carbonates. The allochthonous units comprise (3) Sumeini Group - primarily continental slope deposits, (4) Hawasina Complex - deep-ocean sediments, split into continental rise sediments derived from the Oman margin (Hamrat Duru Group), sediments deposited on and from an intra-oceanic carbonate platform ridge (Kawr and Al Aridh groups) and the most distal abyssal plain sediments (Umar Group), (5) mélanges and metamorphic rocks below the Semail Ophiolite, and (6) the Semail Ophiolite. Both autochthonous and allochthonous units include elements of the Aruma Group - sediments related to the emplacement of the Semail Ophiolite (Glennie et al., 1973, 1974; Cooper, 1987, 1990; Béchennec et al., 1988, 1990; Rabu et al., 1993; Blechschmidt et al., 2004). Searle and Malpas (1980, 1982) defined the Haybi Complex as a thrust-bound structural unit beneath the Semail Ophiolite comprising distal ocean (Umar Basin) sediments and volcanics that were imbricated in the trench ahead of the advancing ophiolite and which are now preserved as thrust slices, and sedimentary and tectonic mélanges.

The allochthonous components were thrust towards the southwest onto the adjacent Arabian platform, with the Hamrat Duru Group sediments bulldozed in front of, and partly overridden by the Semail Ophiolite. Margin proximal sediments are thus now located at least 150 km from their original place of deposition (Figures 1b and 1c; Cooper, 1988, 1990; Warburton et al., 1990). Within this wider structural context, Jabal Wahrah represents an imbricate fan of comparatively distal Hamrat Duru Group limestones, shales and cherts lying to the southwest of the leading edge of the ophiolite in the central part of the Oman Mountains.

JABAL WAHRAH AREA - OVERVIEW

The Jabal Wahrah area (Figures 1a, 2 and 3) is located on the interior side of the central Oman Mountains to the east of the town of Ibri. The structure of Jabal Wahrah is intimately related to the adjacent areas of Jabal Hurah in the northeast and Hammat Shulayshil to the southwest.
Jabal Wahrah (Figures 2 and 3) covers an area of approximately 35 km x 11 km. It forms a range of laterally continuous linear ridges with a predominant NW-directed strike trending 310°, but with areas where this trend changes to about 340°. Jabal Wahrah is cut by two major wadis, Wadi Manqas and Wadi al Rafesh. A combination of stratigraphical and structural features has enabled the identification of five broad structural zones (Figure 3), arranged in bands parallel to the strike of the range which are recognised by their effect on the landscape.

Jabal Hurah lies directly to the northeast of Jabal Wahrah. The land becomes increasingly high towards the northeast, reaching 1,000 m where a ridge of exotic limestones, cherts and breccias of the Al Aridh Formation is thrust over the Hamrat Duru Group immediately to the south of Wadi al Hijr, which follows the sole thrust of the Semail Ophiolite. The eastern side of the area is bounded by Wadi Al Ayn, then the massive Jabal Kawr exotic limestone (Kawr Group), measuring 35 km x 17 km, which has been thrust over the Hamrat Duru Group sediments, and which represents a fragment of an Oman Neo-Tethyan intra-oceanic carbonate platform (Glennie et al., 1974; Béchennec et al., 1990; Pillevuit et al., 1997).

Hammat Shulayshil lies to the southwest of Jabal Wahrah, from which it is separated by Wadi Lusayl (Figure 2). It forms the northwestern extension of the Hamrat ad Duru range, a major imbricate fan of Hamrat Duru Group rocks which has been described by Warburton et al. (1986, 1990) and Cooper (1988).
STRATIGRAPHY OF THE HAMRAT DURU GROUP IN THE JABAL WAHRAH AREA

The original tectono-stratigraphy set up by Glennie et al. (1974) identified three separate sedimentary sequences which they named the Hamrat Duru Group, Wahrah Formation and Al Ayn Formation, from sections in the Hamrat ad Duru, Jabal Wahrah and Wadi Al Ayn (Jabal Hurah) areas respectively. Subsequent workers have modified this and proposed a number of parallel schemes in which these units are all included in a broader Hamrat Duru Group, representing an evolving deep-water system of clastic and carbonate fans with sediments originating from the adjacent Oman Mesozoic passive continental margin, punctuated by chert-rich intervals of reduced clastic input and increased radiolarian productivity (Minoux and Janjou, 1986, 1992; Cooper 1987; Béchennec et al., 1988, 1990; Bernoulli et al., 1990; Béchennec et al., 1992; Blechschmidt et al., 2004). The framework used here follows the stratigraphy set out in the Oman geological maps for the Jabal Wahrah area (Minoux and Janjou, 1986; Béchennec et al., 1992), modified by Blechschmidt et al. (2004). The Hamrat Duru Group is divided into the Al Jil, Marbat, Guwayza and Sid’r formations (the Sid’r Formation as used here thus includes much of the Nayid Formation of Glennie et al., 1974, and Cooper, 1987). The lateral equivalent of the chert-rich Sid’r Formation in Jabal Wahrah is the Wahrah Formation.

Figure 4 compares sections through the Hamrat Duru Group in the different structural zones of Jabal Wahrah, Hammat Shulayshil, and Jabal Hurah. The most complete sections of the Hamrat Duru Group are found in Jabal Hurah, where it spans the Early Triassic (?Olenekian) to Early Cretaceous (Barremian – Early Aptian) (Glennie et al., 1974; Bernoulli and Weisset, 1987; Cooper, 1987; Bernoulli et al., 1990; De Wever et al., 1990; Blechschmidt et al., 2004). Lower stratigraphical levels are missing from the exposed successions in Jabal Wahrah and Hammat Shulayshil, which span the Early Jurassic to Early Cretaceous (Glennie et al., 1974; Béchennec et al., 1992; Blechschmidt et al., 2004). Most limestone and sandstone beds show well-developed graded Bouma (1962) turbidite structures, with bed bases starting at the T\textsubscript{a} to T\textsubscript{c} division and fining upwards to T\textsubscript{d/e}, and individual beds separated by shale. Shale-rich sequences are usually poorly exposed and stratigraphical thicknesses may be affected by tectonic thickening and internal thrusting.

Stratigraphy of Jabal Wahrah

The Jabal Wahrah succession is largely limited to the Guwayza and the Wahrah formations, although locally the upper Marbat and Aruma Group may be present (John Hurst, written communication, 2009). While the Guwayza Formation and, to a lesser extent, the Variegated Mudstone Member of the Wahrah Formation show significant lateral variation, the upper Chert Member of the Wahrah Formation is consistent across the area. Similarly, distinctive sediment packets can be correlated between thrust slices and, where appropriate, larger structural units. The base of the upper Chert Member forms a distinctive regional boundary throughout Jabal Wahrah.

The Guwayza Formation (Lower Jurassic – Bathonian, Blechschmidt et al., 2004) comprises a sequence of oolitic limestone turbidites that are characteristic of the formation and its temporal equivalents along the length of the Oman Mountains (Glennie et al., 1974; Cooper, 1987; 1990; Watts, 1990; Blechschmidt et al., 2004). It is up to 310 m thick in Jabal Wahrah, and shows significant variation, in particular between the different structural zones. The lowest exposures are of at least 90 m of characteristically dark grey, poorly-exposed, generally fine-grained decimetre-bedded oolitic limestone turbidites interbedded with purple shale. This sequence is seen in Zone 1 only in the northwest of Jabal Wahrah, in Zone 2 and in the southwestern imbricates of Zone 3. Its abrupt absence from Zone 1 in the southeast part of Jabal Wahrah suggests a tectonic rather than sedimentary origin with the sole thrust climbing to a higher level within the sedimentary sequence.

This passes up into a shale-rich sequence containing rare centimetre-bedded silicified limestones, marls and metre-bedded limestone turbidites. This unit reaches 200 m in Zone 1, where it contains a distinctive sequence 30–50 m thick of poorly-exposed fine-grained oolitic limestone turbidites, lime mudstones, marls and shales. These are not developed to any significant extent in the other structural zones. This shale-rich sequence is 60–90 m thick in zones 2 and 3 and probably over 100 m thick in Zone 4.
The upper limestone unit of the Guwayza Formation is thicker and coarser-grained in Zone 1, where it is characterised by 30–50 m of light brown-grey, fine-grained limestone and lime mudstone turbidites interbedded with shale, arranged in a broad thinning and fining upwards sequence. A similar, but finer-grained sequence is seen in Zone 2. In Zone 3, the unit starts additionally with a 20 m interval of redeposited lime mudstones. There is a marked lateral variation in Zone 4 where a shale-rich succession 100 m thick shows a gradual increase in the frequency and thickness of limestone beds arranged in fining-upwards packets on a 5 m scale which, as a whole, form a mega-coarsening upwards sequence.

Figure 4: Measured stratigraphical sections through the Hamrat Duru Group in the northwestern Hamrat ad Duru (Hammat Shulayshil), J. Wahrah showing variation between the different structural zones, and J. Hurah (composite section). Basalts (not shown in these sections) occur in outcrops at the base of the Al Jil Formation to the east of the area investigated (Minoux and Janjou 1986). Stratigraphical nomenclature follows that of Béchennec et al. (1986, 1990). The stratigraphy of Jabal Wahrah follows the modification of Blechschmidt et al. (2004). Dating is mainly from Blechschmidt et al. (2004) with additional information from Cooper (1986), Béchennec et al. (1990) and Bernoulli et al. (1990).
The Wahrah Formation is at least 125 m thick and is divided into two members, a lower Variegated Mudstone Member and an upper Chert Member (Béchennec et al., 1992; Blechschmidt et al., 2004).

The base of the Variegated Mudstone Member has been dated by Blechschmidt et al. (2004) as ?Bathonian – Kimmeridgian, with a Bathonian – Lower Bajocian date from the upper part of the Guwayza Formation. This stratigraphical boundary, as defined by Blechschmidt et al. (2004), is thus significantly earlier than that between the Guwayza Formation and the Sid’r Formation in other areas of the Hamrat Duru Group, including Hammat Shulayshil, where the base of the Sid’r Formation cherts is typically Late Jurassic (Kimmeridgian – Tithonian) This is consistent with dates published by Glennie et al. (1974), Cooper (1986), Minoux and Janjou (1986), Béchennec et al. (1990) and Blechschmidt et al. (2004) for the base of the overlying red cherts of the Chert Member.

The Variegated Mudstone Member in zones 1 and 2 is composed 15–25 m of lime mudstones and chalky lime mudstones and marls showing varying degrees of silicification. The sequence in zones 3 and 4 becomes significantly more silicified to the northeast, where this member is represented by 15 m of light grey, green and pale purple bedded cherts with shale partings.

The overlying Chert Member (Tithonian to Barremian – Early Aptian; Blechschmidt et al. 2004) comprises uniform brick-red radiolarian cherts, silicified and chertified marls and lime mudstones interbedded with brick-red shales. The transition from the Variegated Mudstone Member is abrupt. An interval up to 25 m thick, of greener shales, cherts, and dark and mid-grey partly silicified fine-grained limestone turbidites, is seen after 40–50 m. These are overlain by purple and orange weathering cherts, highly silicified marls and shales, which appear to be equivalent to the Upper Limestone Member of the Wahrah Formation as defined by Glennie et al. (1974).

Stratigraphy of Jabal Hurah

The Hamrat Duru Group in Jabal Hurah, lying to the northeast of Jabal Wahrah, comprises a sequence exceeding 500 m thick of shales, limestone and sandstone turbidites, silicified limestones and cherts of Early Triassic to ?Early Cretaceous age (Glennie et al., 1974; Bernoulli and Weissert, 1987; Cooper, 1987; Béchennec et al., 1992; Blechschmidt et al. 2004).

The lowest stratigraphical unit seen in thrust slices in the Jabal Hurah area comprises the Lower Member of the Al Jil Formation, represented by up to 40 m of grey and green shales and fine-grained limestone turbidites. It is synonymous with the Zulla Formation Unit 1 (Cooper, 1987), Turbiditic Limestone and Shales (Bernoulli et al., 1990) and Limestone and Shale Member (Blechschmidt et al., 2004). The base, where seen, is tectonic. This passes up through 10 m of fine-grained green graded quartz-rich turbiditic sandstones, siltstones and shales into a sequence up to 60 m thick of green and purple radiolarian cherts with shale partings and thin silicified limestones. Together, these comprise the Upper Member of the Al Jil Formation, synonymous with the Zulla Formation units 2 and 3 (Cooper, 1987), and the Sandstone and Shale Member and Chert Member (Bernoulli et al., 1990; Blechschmidt et al., 2004).

This is succeeded by the Lower Member of the Marbat Formation, about 35 m of thin-bedded fine-grained limestone turbidites, lime mudstones and shales. The limestones contain abundant fragments of the filamentous bivalve Halobia. This is synonymous with the Zulla Formation Unit 4 (Cooper, 1987) and the Halobia Limestone Member (Bernoulli et al., 1990; Blechschmidt et al., 2004). The Upper Member of the Marbat Formation comprises two units of purple shales about 40 m and 30 m thick respectively containing rare, thin-bedded quartz arenites which sandwich 100 m of fine and medium-grained graded quartz-arenite turbidites arranged in both coarsening-upwards and fining-upwards sequences. This unit is synonymous with the Guwayza Sandstone Formation (Cooper, 1987), the Al Ayn Formation (Glennie et al., 1974; Bernoulli et al., 1990) and the Al Ayn Formation and Tawi Sadh Member of the Guwayza Formation (Blechschmidt et al., 2004).

The overlying Guwayza Formation comprises about 50 m of purple and green shale with rare oolitic limestone turbidites, which pass up into a sequence of decimetre-bedded oolitic limestone turbidites with chert nodules that grade upwards into silicified lime mudstones, with shale partings. This unit is about 40 m thick, but there is significant lateral variation and sections in the southern part of Jabal
Hurah are finer-grained and consist mainly of silicified lime mudstones. This is overlain by up to 100 m of very fine grained to lime mudstone turbidites interbedded with shale. The top is always tectonic. Minoux and Janjou (1986) and Béchennec et al. (1992) include these sequences in the Sid’r Formation.

**Stratigraphy of Hammat Shulayshil**

The Hamrat Duru Group in Hammat Shulayshil, lying to the southwest of Jabal Wahrah, is represented by approximately 420 m of fine-grained oolitic limestone turbidites, shales and silicified lime mudstones of the Hamrat Duru Group (Figure 4). Blechschmidt et al. (2004) indicate a late Early Jurassic (Toarcian) to Late Jurassic (Kimmeridgian) age for the succession in this area.

The lowest exposed stratigraphy comprises up to 40 m of purple and green shale assigned to the Guwayza Formation (Tawi Sadh Member of Blechschmidt et al., 2004). This always has a tectonic base. It passes up into about 330 m of poorly exposed 10 to 50 cm-bedded medium- and fine-grained oolitic limestone turbidites arranged in poorly-defined packets up to 20 m thick, interbedded with creamy-purple shale and marls. There is a prominent 20 m thick band of silicified limestones and lime mudstones 50 m from the base.

This passes over a few metres into the Lower Member of the Sid’r Formation (the Sid’r Formation of Glennie et al., 1974 and Cooper, 1987). This comprises 120 m of silicified and chertified white, cream and light purple graded silty lime mudstones bedded on a 5 to 15 cm scale with purple shale partings. This in turn passes upwards into the Upper Member of the Sid’r Formation (the Nayid Formation of Glennie et al., 1974 and Cooper, 1987). The lower 10 m comprises very fine-grained 10 to 20 cm bedded limestone turbidites with shale partings, before the introduction of 20 to 40 cm bedded fine-grained graded limestone turbidites. This is overlain by poorly exposed siliceous graded lime silt and mudstones with shale partings and rarer fine and medium-grained limestone turbidites. This member is over 50 m thick.

The Hamrat Duru Group sediments are locally seen to be thrust over Fiqa Formation shales and cherts along the southwestern side of Hammat Shulayshil. Slithers of Fiqa sediments have also been incorporated within the Hamrat Duru Group units (John Hurst, written communication, 2009).

**STRUCTURE OF JABAL WAHRAH**

Figure 3 shows a structural map of Jabal Wahrah and Figure 5 illustrates cross-sections running from northeast to southwest across the strike of Jabal Wahrah. Five broadly parallel structural zones are identified that run northwest-southeast, based on their differing structural and sedimentological patterns and boundary relationships. The zones become less differentiated in northwest Jabal Wahrah.

**Structural Zone 1**

This forms the southwestern part of the Wahrah imbricate fan. The leading edge of the imbricate fan is thrust over the underlying Hamrat ad Duru imbricate fan immediately to the northeast of Hammat Shulayshil in an area mostly covered by wadi gravels. Local bedding trends suggest the thrust dips approximately 50° to the northeast.

The main exposure of Zone 1 lies to the northeast of Wadi Lusayl. It is characterised by parallel ridges comprising limestones of the middle and upper part of the Guwayza Formation and cherts of the Wahrah Formation. The low ground separating the ridges comprises the shale-rich lower parts of the Guwayza Formation. Individual thrust slices can be traced laterally for over 20 km. Bedding in thrust slices becomes progressively steeper to the northeast, where it is overturned and steeply SW-dipping.

In the northwest of Jabal Wahrah, to the north and west of Wadi Manqas, Zone 1 is just over 8 km wide and individual imbricates are 500 m to 800 m apart (X-S1 in Figure 5). They are locally internally folded, and folds are tight and vertical to NE-facing with axial planes parallel to, or steeply oblique to the strike line of thrusting. Large folds, with wavelengths on a 100+ m scale, are sometimes seen to fold thrust planes. Smaller folds, with wavelengths on a scale of tens of metres, usually have axial
Figure 5: Cross sections through the Jabal Wahrah area. Sections X-S1 to X-S4 run from northwest to southeast. See Figures 2 and 3 for locations. The sections are constrained by the surface geology and the subsurface detail is projected.
planes that plunge very steeply, typically between 40° to 80° and are arranged en-echelon at a low angle to strike of imbricates. Folding becomes more open towards the southwest leading edge of the Wahrah imbricate fan.

The zone narrows towards the southeast, where imbricates in the higher structural levels are overturned, dip 80° to 60° to the southwest, and become more closely spaced with increased smaller-scale internal thrusting and folding. Some imbricates that are present in the northwest die out to the southwest as their thrusts tip out in the cores of folds. While there is clearly significant lateral variation in stratigraphy, the abrupt change in the detailed stratigraphy of the Guwayza Formation, suggests that the trailing edge of Zone 1 has been overridden to a significant but unquantified extent by the overlying Zone 2.

**Structural Zone 2**

This part of the Wahrah imbricate fan lies to the northeast of, and structurally above Zone 1. Zone 2 is about 2.5 km wide in the northwest, but tapers over its 24 km length towards the southeast where it is less than 500 m wide near Wadi al Rafesh.

In general, the pattern of imbrication in Zone 2 is similar to that seen in Zone 1. Individual imbricates are laterally continuous and form parallel ridges (Figure 6a). In the northwest of Jabal Wahrah, imbricates

![Figure 6: Photographs of the Jabal Wahrah area. See Figure 2 for locations.](a) Jabal Wahrah: view across structural Zone 2 looking west, showing multiple SW-dipping, overturned imbricates of the upper Guwayza Fm limestones (cream) and Wahrah Fm cherts (brick-red). Foreground comprises dark limestones of the lowest stratigraphical level of the Guweyza Fm of structural Zone 3. Higher ground in the distance is structural Zone 1 with Tertiary limestones of Jabal Kawas on the far skyline. Note the fault off-set of the foreground thrust. (b) Jabal Wahrah: structural Zone 3 looking west across Wadi al Rafesh, showing very tight upright to SW-facing folded Guwayza Fm (grey), Lower Member of the Wahrah Fm (creamy brown) and Upper Member of the Wahrah Fm (brick-red). Foreground limestone ridge has been thrust out-of-sequence over the folded units. See Figure 8 for a geological map of this area. See facing page for continuation.
Figure 6 (continued): (c) Jabal Wahrah: structural Zone 4 looking northwest with Wadi al Rafesh in the middle distance. Brick-red cherts in the middle ground form the core of a SW-facing syncline with the corresponding anticline to the right. The twin peaks on the rear skyline are folded shales and limestones of the Guwayza Fm in a folded thrust contact with the foreground cherts. See Figure 8 for a geological map of this area.
are more widely spaced and associated with vertical to SW-facing steeply-plunging folds oblique to the line of thrusting which, locally, also fold thrusts. Imbricates become more compressed towards central and southwestern Jabal Wahrah where they form regularly-spaced linear ridges with bedding almost invariably over-turned and SW-dipping. Exposures of the highest structural levels near the boundary with Zone 3 are limited to the uppermost parts of the Guwayza Formation and the Wahrah Formation and show more extensive folding and smaller-scale thrust slicing within the Wahrah cherts.

Imbricates in zones 1 and 2 are aligned parallel to each other in the northwest and southeast of the range, but are oblique in the central section. The pivot point is marked by folding on the south side of the Wadi Manqas tributary (Figure 7). At point A in Figure 7, two stacked imbricates at the top of Zone 1 have been refolded by two SW-plunging anticline-syncline pairs. To the northeast, at point B in Figure 7, two over-steepened NE-facing anticlines, separated by a syncline, plunge at about 40° to the northeast away from a 500 m wide zone where folded and thrusted limestones of the lowest part of the Guwayza Formation are exposed. The strike of these imbricates is rotated up to 15° clockwise from 130° (which remains the strike of the Zone 1 imbricates) to 145°. The effect is to create a ‘dog-leg’ in strike of the lower Zone 2 imbricates.

Figure 7: Geological map of the area of Jabal Wahrah southeast of Wadi Manqas, showing the folding of thrusts and lateral cutting out towards the SE of imbricates in structural Zone 2. See Figures 2 and 3 for location and X-S2 in Figure 5 for a cross section. The photograph in Figure 6(a) looks over structural Zone 2 in the east of the area shown. (A) SE-plunging folded imbricates in structural Zone 1. (B) NW-plunging folded imbricates in structural Zone 2. (C) oblique cut-off of structural Zone 2 imbricates as they are thrust over structural Zone 1. (D) fault bounded rotated imbricates in structural Zone 2. See text for discussion.
The product of this folding and rotation in the overlying Zone 2 imbricates is the relationship shown in Figure 7 at point C, in which the lower imbricates of Zone 2 are successively cut out against the roof thrust of Zone 1. This geometry, together with the folding of thrusts in the upper Zone 1 imbricates, indicates at least part of the emplacement of Zone 2 was oblique to Zone 1, with increasing displacement towards the southeast, where the leading imbricates of Zone 2 have now been removed by erosion. This is illustrated in Figure 5 by the successive disappearance of imbricates in Zone 2 between cross section X-S2, X-S3 and X-S4.

Structural Zone 2 imbricates become parallel again with those of Zone 1 at the southeastern end of Jabal Wahrah. These changes in orientation are not smooth curves, but take place in two brittle fault zones (Figure 7, each side of point D). Here faults are developed in conjugate sets at a high angle to the prevailing strike of the imbricates. They can be traced for a few metres to over 500 m and lateral displacements can reach 100 m. Faults are predominately strike-slip and are locally associated with parasitic folds that have vertically plunging hinges. These faults clearly post-date the main imbrication event as they cut and off-set thrusts and truncate thrust-related folds.

Structural Zone 3

This zone lies to the northeast and structurally above Zone 2. It is up to 3 km wide in the centre of the range, tapering slightly to the northeast, where it becomes low-weathering and poorly exposed, and also to the southeast of Wadi al Rafesh, where it narrows to 2 km.

Whereas zones 1 and 2 are classic imbricate stacks, the large-scale structure of Zone 3 is of a tightly folded sedimentary sequence that, from southwest to northeast, forms a kilometre-scale SW-facing syncline-anticline pair. This pattern is blurred by numerous second-order folds that have been sliced-up by thrusts. The major syncline forms a wide, low valley of Wahrah Formation red cherts that runs northwestwards along the centre of the zone’s outcrop area. The overturned limb on the northeast side of this major syncline is subject to parasitic folding, in particular in the southeast, and cut by small-displacement thrusts which become increasingly significant to the northwest as the hanging wall cuts down through the stratigraphical section.

The right-way-up trailing limb of the anticline has been sliced into a series of steeply NE-dipping imbricates that are themselves tightly folded internally with vertical to steeply NE-dipping axial planes. 100 m-scale folds are accompanied by parasitic chevron folding, best-developed in the more competent silicified limestones and cherts of the Variegated Mudstone Member. Thrusting becomes increasingly important towards the trailing edge of Zone 3, in particular in the central part of Jabal Wahrah, although displacements are comparatively small and some thrusts are laterally discontinuous on a kilometre-scale with movement accommodated between thrusts by relay zones (Figure 8, point B). This appears to reflect, at least in part, a change in the sedimentology and the thinning of the more competent limestones in the upper part of the Guwayza Formation, transitional to the sedimentary sequence in Zone 4 (Figure 4).

East of Wadi al Rafesh, this tightly folded zone is about 1 km wide (Figure 6b). Folds plunge to the east and the grain of these structures and the immediately overlying imbricates are successively truncated by out-of-sequence thrusting in the overlying part of the imbricate fan (Figure 8, point D). This geometry is discussed in more detail in relation to Zone 4.

Structural Zone 4

This element of the Wahrah imbricate fan lies to the northeast of and structurally above Zone 3. It is about 18 km long and 3 km wide at its maximum point. The differentiation between zones 3 and 4 is less significant to the northwest, where the structural boundary is marked by imbricates that become thicker and stratigraphical sections more complete.

Structural Zone 4 is characterised by laterally extensive imbricates that generally dip to the northeast at a lower angle to those seen elsewhere of Jabal Wahrah, with dips of 50° to 60° typical. Imbricates also show large-scale laterally persistent folding, mainly along the northern edge of the range near Bat.
See facing page for Figure 8 caption.
village and around Wadi al Rafesh (Figure 8 point A, cross section 1-1’, X-S3 in Figure 5, photograph Figure 6c). Here, a lower imbricate with a restored length of not less than 2 km is folded into a series of tight SW-facing folds on a 100–200 m scale. The folds plunge gently to the northwest. The overlying imbricate, which has a restored width of at least 2.7 km is folded around these underlying folds, with numerous 50–100 m scale parasitic folds. A similar arrangement is seen 6 km to the southeast, where the upper folded thrust sheet of the Wadi al Rafesh structure forms the lower folded imbricate, around which the next structurally higher imbricate is also folded in a broad anticline-syncline pair (X-S4 in Figure 5).

Just southeast of Wadi al Rafesh, the folding in the lower imbricate of the Wadi al Rafesh structure is associated with out-of-sequence thrusting, originating in the core of a SW-facing anticline with displacement increasing to the southeast (Figure 8, point C, cross sections 2-2’ and 3-3’). Successively lower stratigraphical elements are thrust obliquely across underlying Zone 3, truncating both folds and thrusts. The Zone 3 rocks in the footwall of the secondary thrust at this location are not only tightly folded, as seen across the central part of Jabal Wahrah, but these folds plunge to the southeast so that the roof thrust is at a significantly lower structural level. The effect of the increased displacement to the southeast is the rotation of the Zone 4 thrust sheets to the east of Wadi al Rafesh. These strike 150°, compared with a strike of about 135° of the Zone 3 structures, which is similar in magnitude to the rotation seen in Zone 2.

**Structural Zone 5**

This forms a series of poorly-exposed rounded rubbly hills to the northeast of Zone 4. They are formed from pink-purple shales and fine-grained oolitic limestones which are similar to those of the Guwayza Formation of Zone 4. The overlying silicified micrites and radiolarian cherts of the Wahrah Formation are not, however, present. This zone is up to 22 km long and 3 km wide.

For most of its width, Zone 5 is an essentially flat-lying sedimentary sequence that has been shortened by some 60% by close-spaced imbricate slicing and associated SW-facing folding. Bedding dips 50° to 60° to the northeast within imbricates. The boundary with Zone 4 is not exposed, but sedimentological evidence suggests it is not a major structural line. There is a sedimentological contact with the Jabal Hurah area to the northeast, where folds become NE-facing and beds dip predominantly to the southwest.

**STRUCTURE OF HAMMAT SHULAYSHIL AND JABAL HURAH**

The structural evolution of the Jabal Wahrah imbricate fan needs to be considered in the context of the structure of the adjacent areas. Figure 9 shows cross sections through the northern part of the Hamrat ad Duru (Hammat Shulayshil), and Jabal Hurah.

**Structure of Hammat Shulayshil (X-S5)**

Hammat Shulayshil is the northern end of the Hamrat ad Duru range, and is part of a large imbricate fan of Hamrat Duru Group sediments, the structure of which has been described by Cooper (1988) and Warburton et al. (1990). Hammat Shulayshil is a series of NW-trending ridges 8.5 km wide which rise 300 m above the surrounding wadi gravels (Figure 10a). The structural style, shown in Figure 9 X-S5 is of a series of ½–2 km-scale SW-facing folds with smaller scale upright to SW-facing chevron folding in
the more competent units, in particular the Sid’r Formation cherts. While some major folds are cut by thrusts, thrusting is generally low-displacement, slicing thin imbricates through the Sid’r Formation, in particular towards the trailing edge of the exposed area of the Hamrat Duru imbricate fan.

The southwest end of the cross section in Wadi Aswad contains isolated exposures of Hamrat Duru Group lithologies, mainly Sid’r Formation, and autochthonous foredeep sediments of the Fiqa Formation. Although poorly exposed, this arrangement is interpreted as late-emplacement involvement of the foredeep sediments in thrusting, similar to that observed by Warburton et al. (1990) in the subsurface to the southeast. This area is also along strike from the northeast limb of a broad post-emplacement anticline that runs NW-SE through the centre of the Hamrat ad Duru and locally exposes the Fiqa Formation through windows in the Hamrat Duru sole thrust. This folding is also developed in the Maastrichtian to Eocene sediments to the west of the Hamrat ad Duru.

The trailing edge of the imbricate fan is overthrust by the Jabal Wahrah imbricate fan. The contact is buried by wadi gravels on the southern side of Wadi Lusayl, but it appears to be oblique, up to about 15°, to the strike of the Hamrat ad Duru fold axes and thrusts. Geometrical relationships indicate that folds and thrusts along the trailing edge of the Hamrat Duru imbricate fan have been truncated by the Jabal Wahrah sole thrust so the Wahrah imbricate fan sediments are locally in thrust contact with lower Sid’r Formation cherts and oolitic limestones of the Guwayza Formation.

Figure 9: Cross sections through Hammat Shulayshil (X-S5) and Jabal Hurah (X-S6). Figure 5 shows the linking section X-S4 through Jabal Wahrah, although there is a 2 km offset. The sections are constrained by the surface geology and the subsurface detail is projected.

The trailing edge of the imbricate fan is overthrust by the Jabal Wahrah imbricate fan. The contact is buried by wadi gravels on the southern side of Wadi Lusayl, but it appears to be oblique, up to about 15°, to the strike of the Hamrat ad Duru fold axes and thrusts. Geometrical relationships indicate that folds and thrusts along the trailing edge of the Hamrat Duru imbricate fan have been truncated by the Jabal Wahrah sole thrust so the Wahrah imbricate fan sediments are locally in thrust contact with lower Sid’r Formation cherts and oolitic limestones of the Guwayza Formation.
Structure of Jabal Hurah (X-S6)

As noted by Minoux and Janjou (1986), the dominant structural style across most of the Jabal Hurah is of a single thrust sheet, in which large-scale imbrication is mostly absent. This sheet is internally folded on a NW-SE axis into an open syncline-anticline pair with a 12 km wavelength. Mid-scale folding varies from open to tight, either SW-facing or irregular 100 m to 1 km scale box folds. Folds on a 10–100 m scale are typically tight, with chevron folding developed in bedded limestone-shale sequences.

At the southwest edge of Jabal Hurah, this thrust sheet is stratigraphically contiguous with Zone 5 in Jabal Wahrah. Here Marbat Formation sandstones dip to the southeast under the overlying Guwayza Formation, associated with NE-directed folding and, locally, backthrusting.

The northeast margin of the Jabal Hurah structural unit is marked by a major thrust which puts deep-water sediments and exotic limestones of the Al Aridh and Kawr groups at Wadi al Hijr over the Hamrat Duru Group sediments. The angle of contact is approximately 45°. The Hamrat Duru Group immediately beneath this thrust comprises an upper thrust sheet of highly folded and imbricated NE-dipping cherts of the upper Al Jil Formation and limestone turbidites and shales of the lower Marbat Formation. The stratigraphical units above this are missing. This upper thrust sheet, which restores to at least 20 km wide, has been thrust over the main Jabal Hurah thrust sheet. It becomes broader to the southeast and a 3-km-wide klippe is preserved along Wadi Al Ayn, in the core of a broad syncline. This syncline plunges gently to the southeast beneath the Jabal Kawr Exotic.

Both of these Hurah thrust sheets have been overridden by the Al Aridh and Kawr group thrust sheet. Klippes of the Al Aridh Group are found in five discontinuous NW-trending bands across the width of Jabal Hurah, in thrust contact with various stratigraphical levels of the Hamrat Duru Group. They are now preserved in the cores of post-emplacement synclines. One typical outcrop (Figure 10b) forms an exposure 1,800 m x 500 m and is formed from exotic limestone blocks up to 300 m long lying on broken red cherts and shales which overlie pillow lavas. This is thrust over sandstones and shales of the Marbat Formation. This structural pile has been refolded and cut by two SW-directed thrusts which places the Marbat Formation over the northeast margin of the Al Aridh Group and duplicates the structural Al Aridh-Hamrat Duru group sequence.

The Al Aridh sole thrust cuts progressively down-section. From northeast to southwest, Al Aridh rocks are in thrust contact first with the upper, and then the lower thrust sheet, where they are first in thrust contact with the Guwayza Formation, but they lie over Marbat Formation sandstones in the southwestern part of Jabal Hurah. This relationship is not considered sedimentological. The Al Aridh sediments do not form large sheets at specific stratigraphic levels, nor are finer grained lateral equivalents seen in elsewhere the Hamrat Duru succession, which might be expected if they had been deposited in situ.

TERTIARY STRUCTURES

Apart from the folding in Hammat Shulayshil referred to above, direct evidence of Tertiary folding in jabals Wahrah and Hurah is limited. Large areas of post-Hawasina emplacement limestones are found in jabals Jifrah and Wa’bah, 5–10 km to the west of Jabal Wahrah. Localised small exposures of Maastrichtian limestones lie unconformably over the folded and thrust Hawasina sediments and are themselves overlain unconformably by Eocene limestones of the Umm Er Radhuma Formation. These are deformed into large wavelength, open doubly-plunging, SW-facing asymmetrical box folds arranged en-echelon. Southwest limbs are locally overturned. The central axis of Jabal Wahrah is broadly along strike from the main anticline through Jabal Wa’bah, and the southern edge of Jabal Wahrah along Wadi Lusayl can be correlated with a syncline east of the town of Ibri. The impact is limited to a gentle down warping. Similarly, the long-wavelength warping on Jabal Hurah may also be a Tertiary structure. In the frontal thrust zone of Jabal Wa’bah and further north where sections are more complete, J. Hurst (written communication, 2009) has noted syn-sedimentary growth and failure of carbonate platforms during Eocene to Oligocene time. This was localised along thrusts which peel out of the underlying Hawasina, indicating that there was local reactivation of certain thrusts, probably linked to regional elevation during this period.
Figure 10: Photographs of Hammat Shulayshil and Jabal Hurah areas.
(a) Hammat Shulayshil, looking 060° towards Jabal Wahrah (hills on horizon). Foreground shows NE-dipping rubbly ridges of oolitic limestones of the Guwayza Formation (Gw) then silicified limestones of the Sid’r Formation, Lower Member (SL). Low grey-weathering band in the middle distance comprises a syncline of limestones and shales of the Upper Member of the Sid’r Formation (SU), with folded and thrust Sid’r Formation beyond.
(b) Central Jabal Hurah looking north. White limestones and less well exposed cherts and volcanics of the Al Aridh Group, thrust (T2) over sandstones and shales of the lower Hurah thrust sheet of Marbat Formation and then folded and re-thrust (T3) to form an isolated, topographically low klippe. The mountain on the right side of the skyline is the NW-plunging end of Jabal Akhdar shelf carbonates (Hajar Supergroup).
DISCUSSION

Figure 11 illustrates a proposed sequence of thrusting and nappe emplacement for the Jabal Wahrah area of the central Oman Mountains. Multiple phases of folding and thrusting are identified, although the absence of syn-tectonic sedimentation across the area makes it difficult to determine unequivocally the precise temporal relationships.

Initial Configuration and the Onset of Subduction (Figure 11a)

In recent years, a range of significantly different models have been proposed to explain not only the obduction of the Semail Ophiolite and Hawasina Complex, but also the pattern of deformation and metamorphism recorded in the autochthonous basement and sedimentary cover of the Oman margin. There is an increasing metamorphic grade from very mild along the southwest edge of Al Jabal al-Akhdar to blueschists and eclogites in Saih Hatat, southeast of Muscat, and a pervasive top-to-the-northeast sense of shear throughout the autochthon of these areas. There remain fundamental differences in the interpretations of isotope ages, their reliability and the effects of retrograde overprinting, derived from metamorphic rocks following their exhumation. In each case, the models invoke the creation of the Semail Ophiolite at about 95 Ma followed very quickly by the development of a NE-dipping Neo-Tethyan subduction zone with the Semail Ophiolite comprising the hanging wall. This is the “traditional model”, for example from Coleman (1981) to Searle (2007). Breton et al. (2004, 2005) have argued for a second northeast-directed intra-continental subduction zone that developed at about 90 Ma close to, but inboard from the edge of the Cretaceous carbonate platform creating a “North Muscat micro-plate”. Conversely, Gregory et al. (1998), Gray et al. (2000, 2004) and Grey and Gregory (2003) have also posited the existence of a “North Muscat micro-plate” but suggested there was, instead, an early southwest-directed subduction zone inboard from, but close to the edge of the Oman carbonate platform, active between about 130 and 110 Ma.

The structures in allochthonous Hawasina sediments in the Jabal Wahrah area of the central Oman Mountains preserve evidence of their emplacement as a sediment wedge ahead of, and beneath the leading edge of the Semail Ophiolite, but offer few insights into the wider question of the existence, timing and polarity of any intra-continental subduction zone.

The onset of the obduction of the Semail Ophiolite started in the Cenomanian, soon after its creation (Tilton et al., 1981; Hacker et al., 1996; Warren et al., 2005), with NE-directed subduction of the distal Hawasina Ocean. Initial imbrication started with stacking of what is now the Haybi Complex (Searle and Malpas, 1980) along and beneath the leading edge of the ophiolite. The Umur, Kawr and Al Aridh sediments, including the 400 square km Jabal Kawr oceanic platform and smaller fragments now represented by Jabal Misht and Jabal al `Alan collapsed and were detached and dismembered (Glennie et al., 1974; Minjoux and Janjou, 1986; Béchennec et al., 1988). As subduction continued, the Hawasina sole thrust propagated towards the Oman continental margin and décollement proceeded along a basal detachment in the Early Triassic (and locally Permian) Al Jil Formation. The more margin-proximal Hamrat Duru Group sediments were in part overridden and accreted to the base of the ophiolite, but partly imbricated and bulldozed ahead of the ophiolite (Cooper, 1988). The creation of the main thrust sheets stacking of the Hamrat ad Duru and Jabal Wahrah/Jabal Hurah imbricate fans is related to this phase.

Emplacement of the Semail Ophiolite on to the Arabian continental margin was accompanied by a westward advancing foredeep (Glennie et al., 1974; Lippard et al., 1986; Robertson, 1987; Patton and O’Connor 1988). Warburton et al. (1990) have suggested that the peripheral bulge was essentially static, possibly reflecting the impact of deeper crustal structure, and pre-existing basement faults also impacted on the development of Cretaceous and Tertiary structures in the Oman Mountains (Boote et al., 1990; Hanna, 1990; Mann et al., 1990). Obduction of the ophiolite and Hawasina nappes onto the submerged continental margin probably started in the Santonian (Breton et al., 2004) and was completed by the Late Campanian – Early Maastrichtian, when the sediments of the Qahlah Formation were deposited unconformably over the allochthonous units.
The earliest preserved detachment of the Hamrat Duru Group is the upper thrust sheet of Jabal Hurah. This comprises Al Jil and Marbat units, and higher stratigraphical units are missing. While this implies an earlier and higher-level detachment during the emplacement process, the location of these units is unknown. The upper Hurah thrust sheet was emplaced as a large, mainly folded unit with subordinate thrust development over more margin-proximal Hamrat Duru sediments of the lower Wahrah-Hurah thrust sheet.

The Hawasina sole thrust then propagated to detach the lower Wahrah-Hurah thrust sheet. The thicker (500+ m) stratigraphy of Jabal Hurah resisted imbrication, and shortening occurred through folding. The sole thrust cut up section to exclude the Al Jil and Marbat formations from the leading edge of Jabal Wahrah, resulting in a thinner sedimentary sequence and the development of the Jabal Wahrah imbricate fan. Imbricates were stacked successively, and the imbrication of successive thrust slices led to the rotation and oversteepening of the thrust stack. Within this, individual thrust slices can be traced laterally for up to 30 km yet they are only 250–400 m thick, reflecting the lateral continuity and homogeneity of the sedimentary sequences and an even force applied by the advancing ophiolite during emplacement.

Shortening across Jabal Wahrah (zones 1 to 4) is a minimum of 170% and the restored width is at least 30 km. A similar degree of shortening is seen in the lower Jabal Hurah thrust sheet. The restored width is about 29 km. Thus the wedge-shaped Jabal Wahrah-Hurah thrust sheet had a minimum width of about 60 km across strike. It could be significantly wider, depending on the volume of Wahrah-Hurah sediments in the sub-surface and in the trailing edge extension beneath the Muqniyat ophiolite block to the northeast. Similarly, parts of this sedimentary pile may have become detached during the transport of the thrust sheets across the proximal parts of the Hawasina Ocean to their current position on the continental margin.

The thicker, limestone-rich succession of Hammat Shulayshil militated against large-scale imbrication in the northwestern Hamrat ad Duru. Palinspastic reconstructions (Figure 1c, Glennie et al., 1974; Bernoulli and Weissert, 1987; Béchennec et al., 1988, 1990; Cooper, 1990, Blechschmidt et al., 2004) place the sequences represented by Jabal Wahrah as the distal equivalents to those of the Hamrat ad Duru. The significantly different detailed stratigraphies indicate that the thrust stack carried on the Wahrah sole thrust must have travelled some distance over what is now Hamrat ad Duru thrust stack before the sole thrust propagated margin-wards into the latter to detach and begin emplacement of the Hamrat ad Duru imbricate fan.

Reactivation of the T1 Al Aridh sole thrust resulted in further motion in the Al Aridh and Kawr group thrust units, including the giant Jabal Kawr exotic limestone immediately to the east of Wadi Al Ayn. They were emplaced to the southwest over the previously imbricated and folded upper and lower Hurah thrust sheets and truncated T1 structures in the underlying Hamrat Duru Group rocks. As a result, the Al Aridh Formation lies on the Guwayza and ?Sid’r formations in central northeast Jabal Hurah, and on the stratigraphically lower Marbat Formation further to the southwest. Structural
styles suggest that this phase is also represented by localised NE-directed back-thrusting of Marbat sandstones over the Guwayza Formation.

In Jabal Wahrah, further compression, folding and out-of-sequence thrusting resulted in the asymmetrical clockwise rotation seen in both zones 2 and 4. In both cases, displacement increased to the southeast along the thrust boundary with the underlying structural zone, creating the oblique relationship with the underlying structural zone. The wider overturning of thrusts and folding of thrusts in Jabal Wahrah may also have been accentuated during this phase.

Figure 11: Schematic structural evolution of the Jabal Wahrah area.

a) commencement of thrusting: imbrication and subduction of the distal Hawasina sediments showing locations of the main thrusts. The scale is highly schematic.

b) formation of upper imbricate of Hamrat Duru Group lithologies in the Jabal Hurah area as part of the initial piggy-back imbrication of the Hawasina ocean sediments.

c) out-of-sequence thrusting emplaces upper Hawasina lithologies (Al Aridh Formation) over Jabal Hurah/Hamrat Duru Group imbricates, truncating existing folds and thrusts.

d) final configuration following (i) late compressional phase with folding, thrusting and local back-thrusting of the Hamrat Duru/upper Hawasina nappe pile and (ii) Tertiary folding, the effects of which are comparatively minor in this area. In the absence of published seismic or borehole information, subsurface projections, including the northwest extension of the Hamrat Duru dome, are schematic and based on data in Boote et al. (1990), Warburton et al. (1990) and Al Lazki et al. (2002).
The clockwise rotation of imbricates in zones 2 and 4 mirrors the thrust front of the overlying out-of-sequence Al Aridh and Jabal Kawr thrust sheets (Figures 1 and 3). This phase of the evolution of Jabal Wahrarah imbricate fan indicates renewed compression, which increased in intensity to the southeast. The geometry suggests that these are related and that the asymmetrical compression in Jabal Wahrarah reflected the later-stage emplacement of the upper Hawasina thrust sheets and, in particular, the giant Jabal Kawr Exotic to the east over the Wahrarah imbricate fan.

**Late-stage Refolding and Thrusting: T3 (Figure 11d)**

Further shortening in the Jabal Hurah area resulted in the refolding of the second phase T2 Al Aridh-Hamrat Duru Group thrust stack into tight SW-facing folds, with the structurally higher Al Aridh sediments now preserved in synclines. This folding is also associated with a minor thrust phase which locally imbricated the Al Aridh-Hamrat Duru stack.

**Origin of T2 and T3 Phase Re-thrusting**

Multistage emplacement structures, in which out-of-sequence movement on structurally higher thrusts post-dates structurally lower thrusts, have been recognised in a variety of locations in the Hawasina Complex allochthon of the Oman Mountains (Graham, 1980; Minoux and Janjou, 1986; Searle and Cooper, 1986; Barrette, 1987; Barrette and Calon, 1987; Cooper, 1988, 1990; Béchennec et al., 1990; Warburton et al., 1990; Gregory et al., 1998). Béchennec et al. (1990) proposed three main emplacement phases within the Hawasina allochthon; (i) in-sequence stacking of the Hawasina sediments in the Hawasina Ocean ahead of the Semail Ophiolite, (ii) out-of-sequence stacking in which lower structural units are overridden by higher structural units, and (iii) late obduction NE-directed folding. This picture was then locally modified by phases of Tertiary deformation. The first Tertiary phase occurred during the Early Palaeocene and represented by an unconformity between the post-obduction Maastrichtian Simsima Formation and the Late Eocene Umm er Radhuma Formation, while the second phase comprises a mid Tertiary event. In the central Oman Mountains sector, this is most clearly displayed in folding of the Palaeocene to Oligocene (Tertiary) sediment pile along the western mountain front, into large-scale en echelon west-verging folds.

In the Jabal Wahrarah area, these stages are reflected in (i) the initial imbrication of the Hamrat ad Duru imbricate fan, the joint Wahrarah-Hurah thrust sheet, and the Al Aridh and Kawr Group units, then (ii) the oblique relationship from re-thrusting of the Wahrarah sole thrust at Hammat Shulayshil, and the re-thrusting and folding of the Al Aridh and Kawr groups over the Jabal Hurah part of the Wahrarah-Hurah thrust sheet. While NE-facing folds are seen in both the Hamrat ad Duru and Jabal Wahrarah, they are attributed to oversteepening and overturning of imbricates during normal in-sequence thrusting and they do not record a separate late stage event.

It is proposed that the T2 and T3 structures primarily reflect thrust dynamics in the later stages of obduction of the Semail Ophiolite, when motion ceased on the lowermost thrust planes (base Hamrat ad Duru imbricate fan) at the leading edge of the Hawasina wedge. This had been bulldozed ahead of the ophiolite and lay up to 30–40 km to the southeast of the edge of the ophiolite itself (Cooper, 1988). Thus, as the forces driving the SW-directed motion of the Semail Ophiolite reduced towards the end of the obduction phase, they may have been no longer intense enough to carry the whole wedge before the ophiolite, resulting in out-of-sequence thrusting higher up the structural stack closer to the leading edge of the ophiolite.

An origin of the re-thrusting linked to the uplift of the adjacent Al Jabal al-Akhdar area is unlikely. It is clear that, during the later Campanian and Maastrichtian, the Saih Hatat area to the southeast of Muscat, was subject to rapid uplift, exhumation and erosion down as far as the pre-Permian sediments that underlie the Mesozoic shelf carbonate sequence (Nolan et al., 1990). However, Nolan et al. (1990) also demonstrated by analysis of the adjacent Maastrichtian and Tertiary sediments, that the amount of uplift further to the west was much reduced. While the Al Jabal al-Akhdar area formed a positive feature during the Maastrichtian, recorded to the north of the Jabal Wahrarah area by the presence of thin spherulitic ironstones and laterites (Qahlah Formation), it was low and the growth of the Al Jabal al-Akhdar anticline occurred during the Oligocene–Early Miocene, evidenced by the unroofing signature...
form clasts in surrounding sedimentary sequences (Nolan et al., 1990) and apatite fission track data (Mount et al., 1998). Indeed, much of the Maastrichtian period limestone sequence to the northwest of Jabal Wahrah (Qahlah and Simsima formations) records a gradual deepening (Le Métour et al., 1991).

Thus, while gravity-driven movement may have played a part in the last stage of emplacement of the Semail Ophiolite in particular in the eastern part of the Oman Mountains (Lippard et al., 1986; Gregory et al., 1998) this process was probably significantly less important in the Jabal Wahrah sector where Late Cretaceous uplift along the margin at the end of ophiolite obduction was much smaller.

A later Oligocene – Miocene phase of re-thrusting linked to uplift of the Al Jabal al-Akhdar anticline is also discounted as an origin of the T2 and, probably T3 structures, for reasons that are primarily negative. Figures 1a and 1b show how the Hawasina sediments are now absent, or restricted to a narrow, structurally thin band between the autochthonous shelf sediments of Al Jabal al-Akhdar and the Semail Ophiolite, whereas gravity and seismic modelling suggests the Hawasina sediments on the northeast coastal side of Al Jabal al-Akhdar reach a thickness of at least 2 km while they vary on the southwest side from 2–3 km (Al-Lazki et al., 2002) to upwards of 4–5 km (Warburton et al., 1990). This geometry has been interpreted as the product of gravity-driven listric normal faults around the edge of the growing Al Jabal al-Akhdar culmination (Hanna, 1990; Mann et al., 1990; Searle, 2007) as the Hawasina nappes and Semail Ophiolite decoupled from the rising anticline. Hanna, (1990) and Mann et al. (1990) considered the large-scale folds in the pre-Oligocene post-emplacement Tertiary sedimentary cover and their Hawasina substrate in the Ibri area as the compressional products of a predominantly extensional regime created in response to uplift of the central Oman Mountains axis. They attributed at least some of the Tertiary folding in the Ibri area to folding around the lateral tips of reactivated Late Cretaceous thrusts as well as pre-existing basement faults. However, Boote et al. (1990) and Warburton et al. (1990) concluded from seismic investigations that any such late-stage or post-emplacement gravity sliding did not reach as far as the leading edge of the allochthonous wedge.

The projected Tertiary displacement on these thrusts is small, and insufficient to accommodate the displacement on the out-of-sequence thrusting seen between the Hamrat ad Duru and Wahrah imbricate fans, and the higher level out-of-sequence thrusts between the Hamrat ad Duru and the Al Aridh-Kawr groups. They are unlikely to be related to this event. This is reinforced by the absence of Tertiary (Eocene and earlier) sediments caught up in the folding and re-thrusting in the Jabal Hurah and Jabal Kawr area, which might have been expected if there had been significant lateral translation following the main phase of uplift of Al Jabal al-Akhdar at the end of a period of mainly shallow-water sedimentation in the area of what are now the Oman Mountains.

The broad warping of Jabal Hurah and Jabal Wahrah along a NW-SE axis is consistent with this phase of Tertiary tectonics, and at least some of the T3 structures may date from this period, driven by minor motion of the Semail Ophiolite (Muqniyat block) immediately to the north of Jabal Hurah resulting from uplift of the Al Jabal al-Akhdar anticline to its northeast, but the absence of Tertiary rocks preserved in this area makes it impossible to determine accurately if other structures have a Tertiary origin or component.

**CONCLUSIONS**

While the emplacement of the Semail Ophiolite and structurally underlying Hawasina thrust sheets was primarily a SW-directed event, with in-sequence detachment and imbrication of successively more margin-proximal units ahead of the advancing ophiolite, detailed investigation yields a more complex picture of multiple stages of imbrication, folding and out-of-sequence thrusting. In the central Oman Mountains, thrust propagation through the continental rise sediments of the Hamrat Duru Group created in two mega-thrust units, represented by the Jabal Hurah-Jabal Wahrah and the Hamrat ad Duru (Hammat Shulayshil) sedimentary sequences.

The Jabal Hurah-Jabal Wahrah thrust sheet was wedge-shaped and the Jurassic and Cretaceous sediments along its leading edge were closely imbricated in a fan structure (Jabal Wahrah) that can be divided into five structural zones. The main, thicker body of the wedge, represented by Jabal Hurah, was folded, but not imbricated to any material extent. An upper thrust sheet, preserved...
along its northern trailing edge, shows increased folding and thrust development truncating fold limbs. The underlying Hamrat ad Duru thrust sheets behaved comparatively coherently during their emplacement onto the Oman margin. Its northern section was comparatively gently folded, with subordinate internal thrusting during its lateral translation of at least 150 km from its original position in the Hawasina Ocean.

A second phase of thrusting reactivated the main detachment horizons between the various structural units, resulting in the development of out-of-sequence relationships as higher structural thrust sheets moved over lower thrust sheets. This is tentatively linked to the successive locking of lower thrust planes in the Hawasina wedge that was bulldozed ahead of the Semail Ophiolite during the final phase of ophiolite emplacement in the Campanian. Local structures in the Jabal Wahrah area that are oblique to the original direction of nappe transport are linked to the late-stage out-of-sequence movement of the huge Jabal Kawr exotic limestone over the lower Hawasina thrust sheets immediately to the east.

A third phase of refolding with localised thrust development cannot be accurately dated. It is linked either to the closing stages of the second phase compression; alternatively it relates to local SW-directed gravity-driven compression related to the main phase of growth of the Al Jabal al-Akhdar antcline in the Oligocene.

ACKNOWLEDGMENTS

This work builds on work previously funded by the Natural Environment Research Council and Amoco Petroleum. I am grateful to Mike Searle for his encouragement and helpful discussions, and to Deborah Rees for her assistance in the field and technical support. John Hurst and an anonymous reviewer are thanked for their helpful reviews that greatly improved the manuscript. I would like to thank the Editors of GeoArabia and the design staff, whose assistance is appreciated. I am indebted to Nestor “Niño” Buhay IV for the final design and drafting of the figures.

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Manuscript received September 13, 2009

Revised May 22, 2010

Accepted June 27, 2010

Press version proofread by author December 4, 2010