Structural and tectonic evolution of the Jabal Sumeini –
Al Ain – Buraimi region, northern Oman and
eastern United Arab Emirates

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ABSTRACT

Four main Late Cretaceous and Tertiary phases of crustal shortening and thrust-related deformation are recognised in the northern Oman Mountains, each phase ending with a regional unconformity throughout the Oman Mountains and the UAE foreland. The earliest is the major thrust emplacement of the Semail Ophiolite, and underlying Haybi, Hawasina and Sumeini duplexes from NE to SW onto the depressed northeastern continental margin of the Arabian Plate during the Cenomanian to Campanian-early Maastrichtian (D1). A prominent widespread unconformity that places Maastrichtian Qahlah Formation laterite, sandstones and conglomerates and Simsima Formation rudist - Acteonellid gastropod limestones over all underlying allochthonous units is recognised throughout the Oman Mountains. SW-verging folds and thrusts in Triassic to Cretaceous carbonate slope facies rocks exposed in Jabal Sumeini (Sumeini Group and Hamrat Duru Group) have been emplaced over uppermost Cretaceous Juweiza Formation conglomerates at the highest level of the Aruma foreland basin. These Sumeini D1 structures are abruptly truncated by an unconformity, above which are Middle Maastrichtian beds showing up to 95% ‘death assemblage’ rudists and gastropods just below the Cretaceous – Tertiary boundary (top of Simsima Formation). A second deformation event (D2) affected the Simsima Formation and underlying Sumeini Group, Hamrat Duru complex and Semail Ophiolite rocks. This phase shows gentle folding about NW-SE fold axes (e.g. Jabal Rawdah), along a similar trend to the Late Cretaceous D1 event. This trend is also parallel to a regional set of NW-SE aligned fractures in the UAE foreland. A major angular unconformity occurs beneath the Upper Palaeocene – Eocene shallow-marine limestones (Umm Er Radhuma, Rus and Dammam formations). Many foreland jabals in eastern Abu Dhabi (Jabals Qatar, Malaqet, Mundasa) show gentle post-Eocene folding formed during the third stage of crustal shortening (D3). The large pericline of Jabal Hafit is a double-plunging, east-verging box fold that formed after deposition of the Oligocene Asmari Formation limestones and Miocene Fars Formation gypsum and clays, the youngest beds affected by the fold. This Late Miocene – Pliocene phase of crustal shortening (D4) is the youngest phase of deformation in the eastern Al Ain-Buraimi region.

INTRODUCTION

The northern Oman Mountains (Figure 1) expose a stack of thrust sheets emplaced from the Tethyan oceanic domain, from northeast to southwest onto the Arabian continental margin during the Late Cretaceous (Figure 2; Glennie et al., 1973, 1974; Lippard et al., 1986). These thrust sheets include (1) the Semail Ophiolite complex, an up to 8–15 km thick Cenomanian oceanic crust and upper mantle, (2) Haybi thrust sheet comprising Upper Permian to Cenomanian distal oceanic sediments, alkaline volcanics and oceanic seamounts, (3) Hawasina Complex, comprising a number of thin thrust sheets of oceanic sediments ranging from proximal (Hamrat Duru Group) to distal (Hálfa and Haliw formations), and (4) Sumeini complex consisting of proximal carbonate slope facies rocks. The Haybi, Hawasina and Sumeini complexes are time-equivalent units to the Middle Permian to Cenomanian autochthonous shelf carbonates exposed around Al Jabal al Akhdar and the Musandam Peninsula (Glennie et al., 1973, 1974; Searle et al., 1983, 2004; Searle, 1988a, b, 2007; Bernoulli and Weissart, 1987; Robertson and Searle, 1990; Blechschmidt et al., 2004). Mapping in Oman by the BRGM group, Béchennec et al. (1990) and Rabu et al. (1993) reinterpreted the distal Haybi complex rocks and defined two stratigraphic groups, the upper Umar Group (Aqil Formation sedimentary rocks and Sinni
Figure 1: (a) Landsat photo of the northern Oman Mountains, Jabal Sumeini and UAE foreland. (b) Geological map of the northern Oman Mountains (after Glennie et al., 1975, and Searle, 2007). (c) Simplified geological map of the UAE foreland. Black lines show the location of the seismic profile and well locality.
Recent deposits
Miocene (Fars Formation)
Oligocene (Asmari Formation)
Eocene (Dammam and Rus Formations)
Maastrichtian (Simsima and Qahlah Fm)
Semail Ophiolite
Haybi and Hawasina thrust sheets
Sumeini Group
Semail Ophiolite - A separate subsurface thin thrust sheet of mantle sequence (Batty et al., 2004)
Folds
Reverse/Thrust fault
Formation volcanics) and the lower Kawr Group (shallow-marine limestones of the Oman Exotics with their volcanic substrate, the Misfah Formation). These stratigraphically defined rock units are within the Haybi complex (Searle and Malpas, 1980, 1982) – a structural definition that includes rocks bounded below by the Haybi thrust and above by the Semail thrust (Figure 2). Whereas the Semail and Haybi thrusts are present everywhere along the Oman Mountains, the Kawr Group limestone exotics are restricted to certain areas, mainly in the Jabal al Akhdar region of Oman.

The Late Cretaceous phase of thrusting accompanied the closure of an ocean at least 400–450 km wide (Searle and Cooper, 1986; Cooper, 1988) and lasted ca. 27 My from 95–68 Ma (Tilton et al., 1981; Warren et al., 2003, 2005; Searle et al., 2004; Searle, 2007). Minimum convergence rates were of the order of 17 mm/year (Searle et al., 2004). The Semail Ophiolite was formed above a NE-dipping subduction zone at 95.3 ± 0.2 Ma (Tilton et al., 1981; Warren et al., 2005), of similar age as the formation of amphibolite facies metamorphic sole rocks (Hacker, 1994; Hacker et al., 1996) at pressures of 10–12 kbar (equivalent to depths of 39-45 km) and temperatures of up to 950°C (Searle and Malpas, 1980;
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Ghent and Stout, 1981; Gnos, 1998; Searle and Cox, 1999, 2002). Thrusting propagated from the NE towards the SW with time, from the Semail to Haybi to Hawasina thrusts. Many of these thrusts were locally reactivated during the later phases of deformation as normal faults or backthrusts.

The Sumeini Window (Figure 1) provides some of the best exposures of the metamorphic sole and the structures along the base of the Semail Ophiolite thrust sheet in Oman (Searle 1980; Searle and Malpas, 1980, 1982). The foreland region near Al Ain, and in particular the Jabal Sumeini region in northern Oman, show excellent exposures of the entire allochthon as well as the neo-autochthonous Maastrichtian – Tertiary limestones that enable us to define the major stages of deformation and crustal shortening. In addition to detailed field mapping, stratigraphic and structural analyses (Searle, 1980; Watts, 1987; Cooper, 1988, 1990; Searle et al., 1990; BRGM, 1993, Al Buraymi, Mahdah, Al Sumayni and Jabal Ar’Rawdah sheets), a recent high-resolution airborne magnetic and gamma-ray spectral survey has been flown by Fugro Airborne Surveys (Batty et al., 2004). This work has enabled constraints on the subsurface and the deep structure beneath the mountains to be integrated into tectonic models. Also, deep seismic surveys across the United Arab Emirates (UAE) carried out by WesternGeco in 2005 have enabled interpretation of further structural constraints from the subsurface (Roure et al., 2006).

Gravity and magnetic data from the UAE foreland, together with seismic interpretation have managed to constrain sub-surface structures, particularly the ophiolite front and the westward extent of the Hawasina thrust sheet (Ali et al., 2008). In this paper we report structural field observations along the foreland jabels in the eastern Emirates from Wadi Hatta south to Jabal Hafit, and also from Jabal Sumeini and the Sumeini Window regions of northern Oman. We integrate surface field mapping and cross-sections with sub-surface data from seismic reflection profile, well and gravity data. In addition, the Fugro airborne magnetic survey and the WesternGeco deep seismic data were incorporated into this study. We use all these data to constrain the timing of deformation and the structural geometry of the fold-thrust belt.

MAASTRICHTIAN – TERTIARY STRATIGRAPHY

The Maastrichtian – Tertiary neo-autochthonous sedimentary rocks unconformably overlie all of the Upper Cretaceous thrust sheets (U-1) along both flanks of the Oman Mountains (Figure 3). The same Maastrichtian unconformity is seen in the subsurface southwest of the mountains, and all the way along the southeast coast of Oman. In several places a thin laterite horizon indicates a tropical climate with high rainfall, and shows that the Oman Mountains thrust stack had just emerged above sea level. From Maastrichtian time onwards the proto-Oman Mountains were progressively transgressed by the Qahlah Formation fluviatile to shallow-marine conglomerates and clastic sediments and the Simsima Formation shallow-marine limestones.

The base of the neo-autochthon is marked by the Qahlah Formation comprising reddish siltstones and conglomerates that contain pebbles of ophiolite, passing upward to more sandstone-type lithologies (Figure 3). An abrupt transition to shallow-marine limestones is marked at the base of the Simsima Formation by numerous rudists (lower ‘Durania’ facies; upper ‘Dictyoptychus’ facies’; Skelton et al., 1990) and large Acteonellid gastropods forming a death assemblage (e.g. at Jabal Sumeini). Skelton et al. (1990) described detailed stratigraphy through this sequence with the oldest rudist limestones at Qarn Murrah assigned a lowermost Maastrichtian, or even Upper Campanian age. Planktonic foraminifera also suggest that the Simsima Formation may extend down to the Upper Campanian (Abdelghany, 2003). The Simsima Formation passes from a basal rudist-rich inshore facies to a more open-shelf facies of orbitoid foraminiferal packstones to wackestones. The upward-deepening transgressive trend during the Maastrichtian can be explained by isostatic subsidence caused by the weight of the ophiolite. The regressive phase at the end of the Maastrichtian corresponds to a global eustatic fall in sea level (Haq et al., 1987).

Above the Simsima Formation a low-angle unconformity (U-2) marks another phase of uplift and gentle folding prior to the deposition of the Muthaymimah Formation, a fine-grained, creamy white pelagic limestone with abundant planktonic foraminifera (Skelton et al., 1990). This unconformity is marked by a slight angular discordance of bedding and a basal conglomerate. In the UAE foreland, SW
Figure 3: Late Cretaceous and Tertiary stratigraphy of the UAE-north Oman foreland along the SW flank of the Oman Mountains, after Nolan et al. (1990), and the northeast flank, after Fournier et al. (2006). U1 to U4 refer to the four major unconformities that define the age of each phase of deformation.
of the mountains the Palaeocene Umm Er Radhuma Formation marly limestones, Lower Eocene Rus Formation anhydrite and dolomitized limestones, and Middle – Upper Eocene Dammam Formation limestones form a continuous sedimentary sequence indicating stable shallow-marine conditions persisted up to the Oligocene. West of Musandam the Pabdeh Formation marks a deepening foredeep that developed in front of the Hagab thrust culmination (Searle, 1988b). Along the foreland jabels near Al Ain the Palaeocene Muthaymimah Formation unconformably overlaps the Maastrichtian Simsima Formation with a slight angular discordance. In eastern Oman ENE- to NE-directed extension culminated with deepening of the Abat Basin (Mann et al., 1990; Fournier et al., 2006).

The Eocene – Oligocene boundary is marked by a third regional unconformity (U-3) separating the Dammam Formation from the Oligocene Asmari limestones (Cherif and El Deeb, 1984). In the UAE foreland a fourth unconformity (U-4) above the Asmari limestones is overlain by the Fars Formation anhydrites, marking the emergence of the region prior to buckling and fracture formation associated with the main Zagros collision event. Along the Batinah coast of Oman thin Miocene limestones (Sawadi Formation) mark the final marine deposits prior to emergence of the NE flank of the Oman Mountains (Mann et al., 1990; Nolan et al., 1990).

STRUCTURE OF THE SUMEINI WINDOW

The Sumeini Window (Figures 1 and 4) cuts through the base of the Semail Ophiolite thrust sheet that shows a complete section through the amphibolite and greenschist facies rocks of the metamorphic sole in Oman (Searle, 1980, 1985; Searle and Malpas, 1980, 1982). Garnet and clinopyroxene amphibolites are attached to the base of the ophiolite along the Semail thrust in several localities (Figure 5a). Above the Semail thrust the Banded Ultramafic Unit shows high-temperature shear fabrics superimposed upon harzburgites, lherzolites and dunites along the base of the ophiolite (Figure 5b). These emplacement-related shear fabrics have been superimposed upon earlier Cenomanian mantle convection flow fabrics. Beneath the amphibolites a range of greenschist facies assemblages (Figure 5c) are present including piemontite-bearing quartzites, marbles with pods of quartz, and rare crossite-bearing meta-basalts. These units are imbricated by a series of east-dipping thrust faults forming a duplex immediately beneath the ophiolite.

The metamorphic sole shows an inverted pressure and temperature gradient with highly sheared and telescoped metamorphic isograds. P-T conditions of the garnet + clinopyroxene amphibolites immediately beneath the Semail thrust are 870–840°C and 11.9–11.3 kbar (Searle and Cox, 2002) indicating depths of burial of around 44–46 km. The depth of amphibolite facies metamorphism is far greater than the exposed thickness of the Semail Ophiolite so the metamorphism is interpreted as subduction zone metamorphism with the heat derived from the overlying mantle sequence peridotites (Searle and Maplas, 1980, 1982; Searle and Cox, 1999, 2002). Within a few meters of the Semail thrust, partial melting within the amphibolites has resulted in small wispy zones of tonalitic melts formed from hornblende dehydration melting at temperatures above 750°C and pressures of 5.6 ± 0.6 kbar (Searle and Cox, 2002). P-T conditions of the Sumeini Window amphibolites are similar to those from Wadi Tayyin (Hacker and Mosenfelder 1996) and the Asjudi and Hawasina Windows in Oman (Searle and Malpas, 1980, 1982) and the Masafi area in UAE (Gnos, 1998). In the Bani Hamid Window in Madhah-Al Fujairah granulate facies meta-carbonates and meta-quartzites with enstatite-bearing metabasalts immediately beneath the Semail thrust have similar pressures but even higher temperatures (864 ± 15°C; 14.7 ± 2.8 kbar, Searle and Cox, 2002).

Beneath the metamorphic sole rocks a series of alkaline volcanic rocks including ankaramites, alkali basalts, trachytes and rare nephelinites (Searle et al., 1980) have Late Triassic, Jurassic and Early Cretaceous ages. Highly alkaline sills of alkali peridotite (jacupirangite, wehrlite) and alkaline gabbro intrude the volcanic sequence (Searle, 1984). The highly alkaline geochemistry of these Haybi Volcanic rocks show that the rocks immediately beneath the ophiolite, and the protoliths of the metamorphic sole, are clearly very different from the ophiolite lavas and gabbros, both in composition and age. Protoliths of the metamorphic sole rocks are clearly older Triassic, Jurassic and Cretaceous oceanic crust with their sedimentary cover, and are clearly not equivalent to the Semail Ophiolite (e.g. Boudier et al., 1988).
Figure 4: (a) Geological map, and (b) cross-section of the Sumeini Window, after Searle (1980). See Figure 1 for location.
The Haybi Volcanic Group and the metamorphic sole have been stacked along a series of imbricate thrust faults above a major regional thrust called the Haybi thrust (Searle et al., 1980; Searle and Malpas, 1980, 1982). This Haybi thrust sheet always lies structurally beneath the Semail Ophiolite and above the Hawasina complex rocks (Figure 4), as originally defined (Searle and Malpas, 1980, 1982). Mapping by the BRGM group and Béchennec et al. (1990) reinterpreted the distal Haybi complex rocks and defined two stratigraphic groups, the upper Umar Group (Aqil Formation sedimentary rocks and Sinni Formation volcanics) and the lower Kawr Group (shallow-marine limestones of the Oman Exotics and their volcanic substrate, the Misfah Formation). These units, notably the Misfah-type exotics, do not occur north of Al Jabal al Akhdar or in the Sumeini region and the original definitions and structural nomenclature are retained here (Searle et al., 1980; Lippard et al., 1986). Middle Permian basalts associated with the break-up and rifting of the Arabian continental margin, occur in the Saiq Formation at the base of the shelf carbonate sequence (Maury et al., 2003), in the proximal Hamrat Duru slope (Al Jil Formation) and in the distal Haybi complex (Searle et al., 1980) where they are associated with Upper Permian exotic limestones (Searle and Graham, 1982; Pillevuit et al., 1997).

Figure 5: Field photos of the Sumeini Window; red lines are thrust faults. (a) Sharp contact of the Semail thrust showing harzburgites thrust over garnet amphibolite. (b) Banded Ultramafic Unit along the base of the Semail Ophiolite, showing emplacement-related shear fabrics in light colored dunites and dark colored harzburgites overlying garnet and clinopyroxene-bearing amphibolites; northern margin of the Sumeini Window (approximate width of view 200 metres). (c) Imbricated metamorphic sole rocks along base of the Semail Ophiolite. Greenschist facies marbles, quartzites, uncommon crossite-bearing metabasalts and rare pelites beneath the garnet-clinoproxene amphibolites in the metamorphic sole; Wadi Shuwayhah, Sumeini Window.
STRUCTURE OF JABAL SUMEINI

Jabal Sumeini (Figures 1, 6 and 7) comprises three main thrust sheets composed of Upper Permian to Lower Cretaceous Sumeini Group shelf – proximal slope facies carbonates and the Upper Cretaceous Qumayrah facies of the Muti Formation, which marks the beginning of flexural foreland basin subsidence. The Sumeini Group comprises Upper Permian and Triassic Maqam Formation and
Jurassic – Lower Cretaceous Mayhah Formation (Glennie et al., 1973, 1974; Watts and Garrison, 1986; Watts, 1987, 1990). Thin-bedded limestones are interbedded with shales and prominent horizons of conglomerates and mega-breccias. Sumeini Group rocks are time-equivalent to the true shelf facies carbonates inboard, and the Hamrat Duru Group rocks adjacent but outboard.

The northern mountain range of Khatma Al-Atash is composed of Hamrat Duru Group slope facies turbidites, sandstones, limestones and shales. The Hawasina Thrust runs along Wadi Mayhah and emplaced Hamrat Duru rocks southwestwards over Sumeini Group rocks. Whereas the Sumeini Group rocks show large-scale SW-verging folding and thrusting, the Hamrat Duru Group on Khatma Al-Atash is more strongly deformed with tight to isoclinal folds and steep cleavage. The northeastern flank of Khatma Al-Atash is a steep normal fault down-throwing the Semail Ophiolite to the NE (Figure 7).

All folds and thrusts are truncated by the Maastrichtian unconformity at the base of the Qahlah and Simsima Formation indicating that folding and thrust culmination of Jabal Sumeini must have been a Late Cretaceous event. Only the westernmost thrust beneath Jabal Wasa may have a tip line that extends up into the Maastrichtian Simsima Formation (Figure 7). Maastrichtian and Palaeogene rocks are exposed on the NW corner of Jabal Sumeini where they dip gently to the NW and are folded about NW–SE aligned fold axes (Figure 8a). The basal Simsima Formation shows a spectacular ‘death assemblage’ of Acteonellid gastropods (Figure 8b), occasionally also with rudist corals (Durania, Dicytyoptchus, and large Hippurites cornucopiae; Skelton et al., 1990; Figure 8c) and also with the giant benthic foraminifera Loftusia sp. These superbly preserved fossil sites may not be true death assemblages, but rather rolled gastropods, rudists and corals transported by wave action from a more open-marine site into local graveyards. Individual beds comprising almost 100% Acteonellid gastropods with rudists, are overlain by beds which show only 30–60% Acteonellids (Figure 8d).

Another unconformity above the Simsima Formation is somewhat irregular with Palaeogene slope carbonates of the Malaqet and Mundassa formations (Muthaymimah Group) lying above with a slight angular discordance. The contact marks an erosional emergence at the Cretaceous – Tertiary

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**Figure 7: Cross-sections of Jabal Sumeini, (see Figure 6 for locations and abbreviations).**
(K-T) boundary, possibly associated with a renewed compressional phase, followed by rapid drowning to a carbonate slope facies. The entire sequence shows a general eastward onlap towards the emergent mountains (Skelton et al., 1990). During the Palaeocene, rapid subsidence west of the mountains (Muthaynimah Formation) and east of the mountains (Jafnayn, Seeb formations) produced slope facies carbonate fans (Nolan et al., 1990). No Tertiary rocks are exposed along the main ranges of the northern Oman Mountains east of Jabal Sumeini, so it remains uncertain whether the mountains were emergent during the Palaeogene or whether they formed a positive topographic feature but were submerged.

Figure 8: Field photos of Jabal Sumeini.
(a) Maastrichtian neoautochthonous sedimentary rocks of Qahlah and Simsima Formations unconformably overlying imbricated Hamrat Duru complex limestones and turbidites, Khatm al Atash, northwest corner of Jabal Sumeini.
(b) Acteonellid gastropods at the base of the Simsima Formation, Khatm al Atash.
(c) Acteonellid gastropods with hippuritids and other broken rudists, gastropods, corals and stromatoporoids (Durania facies of Skelton et al., 1990).
(d) Beds of almost 100% Acteonellid gastropods with rudists along the base of the Simsima formation overlain by beds with fewer gastropods and occasional corals; Khatm al Atash.
Jabal Rawdah is a linear mountain range aligned parallel to the WNW-ESE Wadi Hatta fault (Figures 1 and 9). Robertson et al. (1990) interpreted the fault as an approximately 50-km-long right-lateral continental margin transform fault that influenced passive margin sedimentation, off-axis volcanism prior to ophiolite formation and developed into an oblique lateral ramp during Late Cretaceous ophiolite emplacement. The eastern end of the Wadi Hatta zone (Jabal Quimah) shows large folds with NW-SE trending axes and structurally higher thrust sheets folded around lower, later ones. Seismic data indicates a major component (>5 km) of down-to-north throw across the Hatta zone (Dunne et al., 1990). The Wadi Hatta fault cuts the entire ophiolite sequence, as well as the Sumeini, Hawasina and Haybi complex rocks, but is clearly truncated by the Maastrichtian unconformity (Figure 9a, b, c).

Figure 9: (a) Geological map, and (b) cross-section of Jabal Rawdah; see Figure 1 for location. (c) Three stages in the tectonic evolution of the Jabal Rawdah region.
On Jabal Rawdah, steeply-dipping, thin-bedded Sumeini Group carbonates and Hawasina thin-bedded limestones and cherts (Figure 10a) are overlain by harzburgites and dunites of the Semail Ophiolite along the Semail Thrust. These rocks have been folded by a SW-vergent recumbent fold (Figures 9c and 10b) and subsequently cut by east-west aligned normal faults that bound each flank of Jabal Rawdah (Figure 10a). All these rocks have been truncated by a shallow-dipping unconformity, above which are reddish conglomerates and sandstones of the Qahlah Formation and overlying Middle Maastrichtian shallow-marine rudist-gastropod bearing limestones of the Simsima Formation. The Maastrichtian sequence on Jabal Rawdah thins to the southeast from 90 m at the western end to <30 m at the southeastern end (Skelton et al., 1990).

The Simsima Formation and all underlying rocks on Jabal Rawdah have been gently folded with NW-SE aligned axes that plunge around 20° NW. At least two main phases of deformation are apparent here, one Late Cretaceous, and the second post-Maastrichtian (Figure 9c). During the Late Cretaceous the Semail Ophiolite was thrust over the Haybi, Hawasina and Sumeini thrust sheets. This phase of deformation was followed by recumbent SW-verging folding of all thrust sheets before uplift, erosion and planation occurred beneath the mid-Maastrichtian unconformity. Deposition of the Simsima Formation was followed by gentle folding along a similar trend to the Late Cretaceous event, indicating a reactivation of the NE-SW maximum compressive stress field. The basal Muthaymimah unconformity above the Simsima is irregular, but cuts down to the east, indicating higher topography to the northwest (Figure 10b). Since the regional facies pattern shows onlap to the east (Skelton et al., 1990) it is likely that the basal Muthaymimah unconformity was an irregular surface with small-scale basins in between emergent mountains.

FORELAND JABALS IN NORTH OMAN – UAE

Several Tertiary jabals northeast of Al-Ain show gentle folding about NNW-SSE fold axes. Folding affects both the Semail Ophiolite and the neo-autochthonous Maastrichtian and Palaeogene cover. Stratigraphic studies show that a major unconformity cuts out the Palaeocene succession on Jabal Auha and Jabal Huwayyah (Figure 1), where Middle Eocene Damman Formation overlies Maastrichtian Simsima Formation (Noweir and Alsharhan, 2000), whereas on Jabal Hafit (Figure 1) a full succession of Eocene – Miocene stratigraphy is exposed (Noweir, 2000). Fold style in the foreland jabals is one of fault-propagation folds, frequently with box fold geometries, above a major regional detachment.

A seismic profile running east of Al Ain shows the Hawasina thrust sheet roughly 1–2 km thick emplaced within the Upper Cretaceous Fiqa foredeep shales above a relatively flat and undisturbed top shelf datum (Ali et al., 2008). Several shallow west-vergent thrusts have been mapped beneath the Al Jaww Plain from shallow seismic studies (Woodward, 1993). The tip of the Hawasina thrust sheet lies immediately east of Buraimi and the NE flank of Jabal Hafit (Ali et al., 2008) (Figure 1b). The Maastrichtian and Tertiary cover rocks are gently folded about NNW-SSE aligned fold axes.

STRUCTURE OF JABAL HAFIT

Jabal Hafit is an anomalous periclinal fold structure, approximately 22 km long and 4 km wide, located 20 km west of the Oman Mountain front south of the cities of Al Ain and Buraimi (Figure 1). It is an asymmetric ENE-verging, doubly plunging anticline with a steep, even slightly overturned, east limb and a gentle dipping west limb (Figure 11). It has a rounded (non-angular) box-fold shape, similar to a fault-propagation fold with a minor east-vergent thrust (Tarabat thrust) along the eastern kink band set. The main Hafit anticline axis plunges NNW and a subsidiary anticline splays off to the northeast (Al-Ain anticline) with an asymmetric syncline (Rwaidhat syncline) separating the two anticline axes (Warrak, 1996; Noweir, 2000). The east-vergent Jabal Hafit fold is anomalous because its vergence is antithetic to the dominant WSW vergence of other folds and WSW transport of thrusts in the area.

The oldest rocks exposed in the core of the anticline are Lower Eocene Rus Formation limestones with successive Middle-Upper Eocene Dammam and Lower-Middle Oligocene Asmari Formation limestones above. The youngest rocks affected by the fold are the Miocene Fars Formation limestone and gypsum clays, although the dips in the Fars beds are not as steep as the Eocene-Oligocene rocks. A major unconformity cuts out the Upper Oligocene and this probably correlates with initiation of

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Figure 10: Field photos, Jabal Rawadh.
(a) Steeply dipping thin-bedded limestones with shales and cherts of the Al Jil Formation, proximal Hawasina complex, cut by east-west striking normal faults along both north and south flanks of Jabal Rawdah.
(b) Southern flank of Jabal Rawdah showing ophiolite Mantle sequence harzburgites thrust over Hawasina and Sumeini Group limestones, subsequently folded by a west-vergent recumbent fold. Semail Ophiolite, Hawasina and Sumeini Group rocks are all truncated by the Maastrichtian unconformity along the base of the Qahlah and Simsima formations. Bedding in the Qahlah Formation shows onlap with uplift to the west and deepening to the east. All these rocks were subsequently folded by a NW-SE aligned gentle anticline-syncline axis pair along Jabal Rawdah (approximate height of peak is 400 metres above desert floor).
folding of the Hafit Anticline. This age corresponds to the beginning of Arabia-Central Iran collision along the Zagros Suture in Iran, and the Hafit folding may be a far-field effect of the stress system imposed on the Arabian foreland at that time. Culmination of the Musandam Peninsula on the Hagab thrust occurred at this same time and Searle (1988b) suggested that this marked the first effects of the continent-continent collision to the north and northwest.

Boote et al. (1990) interpreted the structure beneath Jabal Hafit from seismic sections as two high-angle reverse faults that penetrate into the shelf carbonate sequence. Warrak (1996) interpreted the Hafit structure as a detachment fold above a basal detachment located in the Fiqa Formation, the base of the Upper Cretaceous foreland basin sequence. He also suggested that the anticline grew synchronously with sedimentation during Middle Eocene to Miocene time. However, detailed balanced cross-sections constructed by Noweir (2000) showed no onlap or thinning of Tertiary beds around the Hafit Anticline suggesting that the fold formed after the Miocene.

The tightness of the anticline on Jabal Hafit geometrically requires a detachment at depth, and balanced cross-sections suggest that this blind thrust detached either along the base of the Fiqa Formation or beneath the Cretaceous shelf carbonates (Shu’aiba, Nahr Umr, Natih formations; Noweir, 2000). We suggest that Jabal Hafit represents a backfolded anticline associated with a steep east-vergent thrust that developed along the dominant kink band set (Figure 11). The style of deformation is reminiscent of the rounded box-fold geometries of several Palmyra folds in Syria (Searle, 1994). The Jabal Hafit structure lies above a blind west-vergent thrust fault along the base of the Aruma Group at depth.

SUBSURFACE STRUCTURE OF FRONTAL FOLDBELT FROM GEOPHYSICAL DATA

**Jabal Hafit**

A seismic reflection profile (Profile 1 with total length of 24.8 km) that traverses Jabal Hafit with a NE-SW orientation was used to determine its subsurface structure (Figures 1 and 12). It was part of a large seismic survey acquired in the 1980s and reprocessed in 2007 for hydrocarbon exploration in the area. The good quality of the data allowed the interpretation of four main sequences: (1) Mesozoic Shelf Carbonates, (2) Foreland Basin, (3) Upper Cretaceous – Lower Tertiary and (4) Upper Tertiary.
Each sequence was delineated on the basis of its seismic character, reflector terminations (e.g., onlap) and structural style, including prominent reflectors, continuity and amplitude (e.g., Mitchum et al., 1977; Vail et al., 1977; Sheriff and Geldart, 1995).

The top of the Mesozoic Shelf Carbonates (Wasia Group) is laterally continuous with strong reflectors interpreted as the top of the Wasia Group. Internally the sequence exhibits high-amplitude, continuous to discontinuous reflectors. The seismic section suggests the presence of thrusts that cut through the shelf carbonates and overlying foreland basin sequence, as well as low-displacement normal faults that offset the top of the sequence. This pattern has been interpreted as a period of plate margin uplift caused by the development of a flexural bulge during the initial phases of emplacement of the allochthons.

The Upper Cretaceous Fiqa Formation (Aruma Group) forms most of the Foreland Basin Sequence infill deposits and thicken towards the east. The sequence displays internal seismic reflections that show variable-amplitude, discontinuous, low vertical spacing and a chaotic pattern. The Fiqa sequence gradually onlaps onto the underlying shelf margin sequence to the west, where it exhibits low-amplitude sub-parallel reflectors. The seismic section indicates the presence of a WSW-dipping high-angle thrust fault underlying the tight fold of Jabal Hafit (Figure 11). The thrust appears to detach within the lower part of the Fiqa sequence or along the top of the shelf carbonates. In addition, other thrust faults appear to extend down to the shelf carbonate sequence.

The Lower Tertiary (Pabdeh Group) and Upper Tertiary (Fars Group) Sequences are characterized by highly deformed concordant reflections over most of the length of the section. Internally the sequences display strong amplitude, continuous, parallel reflectors that can be mapped throughout the seismic section. The top of the Maastrichtian – Lower Tertiary sequence is disconformable with the Fiqa Formation and is characterized by prominent high-amplitude, continuous reflectors. This is interpreted to represent a post-obduction, shallow-marine transgression across the Oman Mountains. The sequences thicken to the west probably due to the tectonic thickening as a result of the growth of Jabal Hafit structure. In the centre of the profile the thickness of the Maastrichtian – Lower Tertiary sequence decreases dramatically and the Upper Tertiary sequence is totally absent, due to the post-Oligocene uplift which caused erosion of large parts of the mountain belt.

**Region to the West of Jabal Sumeini**

Figure 13 shows Seismic Reflection Profile 2 (total length of 37.4 km), which runs west of Jabal Sumeini with an orientation of NE-SW (Figure 1). It is used to determine the subsurface structure of the frontal fold belt and foreland basin west of Jabal Sumeini. The profile was part of large seismic survey acquired and processed in the 1980s for hydrocarbon exploration. The quality of seismic profile is poor due mainly to the geological complexity of the area. Nevertheless, well ties and the lateral continuity of seismic horizons allowed interpretation of the geometric features on the seismic profile.

The seismic stratigraphy along the profile has been subdivided into six main sequences: (1) Permian-Jurassic Shelf Carbonates, (2) Thamama-Wasia, (3) Aruma, (4) Pabdeh, (5) Fars and (6) Sumeini (Figure 13). The Thamama-Wasia and Aruma sequences are tied to well W1 (Figure 1). The other sequences were delineated on the basis of their seismic character, reflector terminations and reflection style including prominent reflectors, continuity and amplitude.

The top of Thamama-Wasia sequence is a prominent reflector that can be easily traced across the profile. The thickness of Aruma sequence increases gradually towards the NE, except around well W1 where the sequence has been partially eroded. Furthermore, the Pabdeh and Fars sequences are absent in the centre of the profile (around well W1) due to post-Oligocene uplift. However, the sequences thicken towards the NE and SW of the profile.

The southwestern limit of the assumed Sumeini allochthon lies at about CMP 670. The Sumeini Group rocks within this thrust sheet are overlain by a relatively thin cover of Aruma Group foreland basin sediments. The sequence can be traced from outcrops of the Sumeini Group in the NE. However, it becomes difficult to pick the wedge as it gradually pinches out at the boundary between the Upper and Lower Fiqa units.
Figure 12: (a) Uninterpreted seismic profile across Jabal Hafit (for location see Figure 1).
(b) Interpreted seismic profile showing series of thrust fault and high amplitude fold.
Structural Style of the Region to the West of Jabal Sumeini

Folding and thrusting dominate the structural style of the seismic section. The seismic profile supports the surface geology, which shows at least two major phases of deformation, a Late Cretaceous phase developed in the east resulting from the emplacement of the Oman Mountains thrust sheets, and a Tertiary deformation phase. In the Late Cretaceous (Aruna Group) and Early Tertiary (Pabdeh Group) foreland basin sequences, relatively high-angle thrusts are associated with a series of tight folds. Most of these thrusts appear to detach within the lower part of Aruma sequence as indicated by the series of imbricate thrusts along the front of Sumeini allochthonous wedge. However some thrusts may be related to faults that extend deeper and offset the carbonate platform.

The most prominent thrust cuts through the shelf carbonates causing large-scale uplift on the hanging wall of the thrust (>2 second TWT) and juxtaposition of shelf carbonates onto Aruma Group. Major subsidence is also observed on the southwestern side of the major thrust where the shelf carbonates are at ~3.6 second TWT. Significant subsidence is also seen on the NE of the uplift around CMP 636. In addition, the seismic section suggests the presence of low-displacement back thrusts that offset the top of Thamama-Wasia sequence but do not continue upward into the overlying Aruma sequence. The interpretation presented here for the carbonate platform is compatible with that presented by Dunne et al. (1990), Roure et al. (2005) and Ali et al. (2008).

Gravity Model of the region to the west of Jabal Sumeini

Gravity measurements were acquired in December 2007 at 64 stations along the Seismic Profile 2 (Figures 1 and 13) using a Scintrex CG5 gravimeter (Figure 14). The gravity stations were spaced approximately 1 km apart, but some variations in the sampling distance was required due to difficulties in accessing some areas. The gravity data were corrected for instrumental drift, earth tides, elevation, latitude and terrain. The drift was assumed to be linear between consecutive base-station readings and was subtracted from the observed value. The data were reduced to Bouguer anomaly using an average density of 2,670 kg/m$^3$. In addition, the regional gradient was removed by upward continuation of the gravity data to 20 km.

The gravity profiles were modelled using the 2.5-D GM-SYS program to verify the seismic interpretation and to determine deep structure of the area. The model was initially based on the interpreted seismic horizons and subsequently refined to reconcile the differences between the observed and computed gravity data. The densities assigned to the shelf carbonates and Tertiary rocks were based on available well data and density analyses of Ali et al. (2008), whereas the rocks of the Sumeini Group and basement were assigned a uniform density of 2,600 kg/m$^3$ and 2,800 kg/m$^3$, respectively (Manghani and Coleman, 1981).

The final subsurface model presented in Figure 14 displays a good match between the observed and calculated gravity anomalies, and the seismic interpretation. The folded and thrusted Sumeini nappe correlates with the gravity positive anomalies and the foredeep basin with a large negative anomaly. Furthermore, the model indicates that the central area of the profile is underlain by a major thrust fault that has been reactivated during the Late Tertiary causing basement uplift.

SUBSURFACE STRUCTURE OF THE SEMAIL OPHIOLITE

The Semail Ophiolite has a strong magnetic signature compared to the sedimentary and metamorphic sequences, enabling its lateral extent and thickness to be ascertained from airborne magnetic data. Ultramafic rocks have high degrees of magnetisation and susceptibilities much greater than felsic gabbros. Moreover, magnetic susceptibility of ophiolite increases with increased serpentinisation (Nazarova et al., 2000; Schmitt et al., 2007). The Semail Ophiolite thickness increases from west to east confirming the overall westward tapering wedge shape and the westward (or southwest) obduction-emplacement direction. The ophiolite reaches more than 3.5 km in thickness along the eastern margin, with the maximum thickness ~6-6.5 km along the east coast near the Oman-UAE border. Post-emplacement folding of the ophiolite has also resulted in thickness variations across strike. A separate
Figure 13: (a) Uninterpreted seismic profile west of Jabal Sumeini (for location see Figure 3).
(b) Interpreted seismic profile showing series of folds and a high-angle thrust fault.
Figure 14: (a) Observed and calculated residual gravity anomaly. (b) Gravity model.
thin thrust sheet of mantle sequence harzburgite has been detached from the main ophiolite and occurs in a discontinuous sheet from at least Jabal Faiyah south to Jabal Huwayyah (Batty et al., 2004). Around Jabal Faiyah this detached slice of ophiolite forms a broad anticline about 10 km across.

Gravity data across the Oman Mountains (Manghani and Coleman, 1981; Shelton, 1990; Ravaut et al., 1997) show that the Semai Ophiolite is detached from the Tethyan oceanic lithosphere beneath the Gulf of Oman. The eastern boundary of the ophiolite is abrupt, roughly beneath the coastline in Oman, and extends 6–10 km offshore in UAE (Batty et al., 2004). Northeast of Dibba it extends for up to 40 km offshore. Tertiary sedimentary rocks thicken dramatically to the northeast, offshore in the Gulf of Oman.

**STRUCTURAL CONSTRAINTS FROM REGIONAL SEISMIC PROFILES**

Shallow seismic profiles including 3-D surveys were used by Dunne et al. (1990) to interpret the sub-surface structure of the UAE foreland. Their profiles show westward tapering ‘thin-skinned’ thrust sheets of Hawasina complex and Semai Ophiolite thickening to the east. Thick-skinned thrusts cut the entire shelf carbonate and basement sequence beneath the Hawasina thrust, and show listric shape flattening into a basal detachment at about 10–12 km depth. Some of these steep reverse faults are sealed by the Aruma Group, but towards the north most faults extend tip lines up into the Fadheh Group showing that timing of slip extended up to the Eocene – Oligocene. In the northern UAE and west of the Musandam Peninsula these thrusts are sealed by the flat-lying Miocene Mishan Formation marls and clays (Michaelis and Pauken, 1990). West of Jabal Sumeini, average displacement of the Mesozoic shelf carbonates (and the laterally equivalent Sumeini Group) is 10 km, decreasing to 5 km west of the Dibba zone (Dunne et al., 1990). In the Musandam Peninsula westward translation on the Middle Tertiary Hagab thrust is >15 km (Searle et al., 1983; Searle, 1988a, b; Dunne et al., 1990).

Deep seismic imaging of the UAE carried out by WesternGeco (2005) has provided unique data on the deep structure of the Oman Mountains (Roure et al., 2006). Two west-east seismic lines were shot across the entire UAE, one roughly from Umm al Quwain across the southern part of the Dibba zone to the coast south of Dadnah (line D4), the other roughly from Ajman across the Saja’a field to Khor Fakkan (line D1). Two north-south lines were also shot, one along the foreland west of the mountain front (line D3) and one from Dibba south across the high mountains to the Oman border (line D2). The western part of these profiles in the foreland shows prominent bright reflections at 15.5 seconds TWT that are interpreted as the Moho at about 44–47 km depth beneath a layered lower crust. The Moho also dips to the east towards the coast to accommodate the wedge shaped Semai-Haybi-Hawasina thrust sheets that also thicken to the east (Roure et al., 2006). The geometry is consistent with southwest-directed thrust emplacement.

Both lines D1 and D4 show complex geometries of the Late Cretaceous thin-skinned Semai Ophiolite and underlying Haybi and Hawasina thrust sheets, but also deep, thick-skinned imbrication of the entire shelf carbonate sequence (Roure et al., 2006). The style and magnitude of thrusting that cuts down through the entire Permian – Mesozoic shelf sequence into the pre-Permian basement confirms both the interpretation of surface structures of the Musandam Peninsula and culmination along the Hagab thrust (Searle et al., 1983; Searle, 1988a, b) and the shallow seismic interpretation of Dunne et al. (1990). A later set of small-displacement thrusts affects the Palaeocene – Eocene Pabdeh Group foreland sediments, west of the mountain front. Both surface geology and shallow and deep seismic interpretation now confirm that at least two phases of thrusting occur in the northern Oman Mountains and foreland, one Late Cretaceous and one post-Eocene – Oligocene.

**SUMMARY OF THE TECTONIC EVOLUTION**

The major event along the northeast Arabian Plate margin was the obduction of the Semai Ophiolite and the underlying duplexes of the Haybi and Hawasina thrust sheets during the Late Cretaceous. U-Pb ages of zircons from plagiogranites show that the ophiolite crust formed in the Cenomanian at 95.3 ± 0.2 Ma (Tilton et al., 1981; Warren et al., 2005). Triassic – Jurassic basalts were subducted to depths of 37–45 km to form the garnet amphibolites of the metamorphic sole (Searle and Malpas, 1980,
Structural and tectonic evolution, Oman and UAE

During the Cenomanian–Turonian, the loading of the ophiolite caused the continental margin to flex downward (Glennie et al., 1974; Patton and O’Connor, 1988; Warburton et al., 1990). The Aruma flexural basin was infilled rapidly, initially by Muti Formation conglomerates and shales (Robertson, 1987), and later by deeper water shales of the Fiqa and Juweiza formations (Santonian–Campanian). The Hawasina, Haybi and Semail ophiolite thrust sheets were emplaced into, or on top of the Aruma basin. Ophiolite debris only appears in the uppermost Juweiza Formation foreland basin deposits (Glennie et al., 1974).

By Campanian time, when the allochthonous thrust sheets were emplaced across the northern continental margin, the Permian and deeper levels of the leading edge of the Arabian continental margin was dragged down the subduction zone to form eclogites in the As Sifah area of northeast Oman (e.g. Searle et al., 1994, 2003, 2004). A U-Pb zircon age of 78.95 ± 0.13 Ma (Warren et al., 2003, 2005) is interpreted as dating peak eclogite facies metamorphism. In northern Oman in the Bani Hamid area, granulite facies metamorphism occurred beneath the ophiolite at P-T conditions of 800–860°C and 10.5–14.7 kbar (Searle and Cox, 2002). These pressures are equivalent to depths of burial of 38–54 km depth. The Bani Hamid granulites are dominantly quartzites (containing enstatite, cordierite, sillimanite, spinel and sapphire), calc-silicates and meta-carbonates (containing garnet, diopside, scapolite, wollastonite, plagioclase) and rare basalts (garnet-diopside-hornblende amphibolites).

The Late Cretaceous thrusting event ended in the Late Campanian–Early Maastrichtian. A regional unconformity beneath the Maastrichtian Qahlah Formation and Simsima Formation truncates folds, thrusts and stratigraphy everywhere across the mountains and foreland. A second but minor phase of folding occurred across the Cretaceous–Tertiary (K-T) boundary with another regional unconformity beneath the Palaeocene–Eocene shallow water carbonates. In the eastern Oman Mountains, Fournier et al. (2006) documented two distinct phases of extension: (1) ENE-WSW extension during the Late Cretaceous to early Eocene, and (2) NNE and NW-oriented extension directions affecting Upper Eocene and Oligocene rocks, followed by compressional phases during the Early Miocene oriented E-W to NE-SW, and during the Pliocene oriented N-S to NNE-SSW.

The collision of Arabia with Central Iran along the Zagros Suture started in the Late Oligocene with indentation of the Musandam Peninsula and initiation of the Hagab thrust (Searle et al., 1983; Searle, 1988a,b). This collision may have resulted in far-field effects including the Miocene–Pliocene phase of folding that resulted in the foreland folds near Al Ain-Buraimi and Jabal Hafit.

Deep seismic reflection profiles (Roure et al., 2006) and airborne gravity and magnetic data (Batty et al., 2004) across the UAE-northern Oman Mountains show no trace of any supposed SW-dipping slab beneath the Oman Mountains as speculated by Gregory et al. (1998). All thrust sheets taper to the west and thicken to the east at depth as expected with SW-directed emplacement thrusting. We suggest that the thick crust beneath the coastal regions of UAE may be stacked slabs of granulite facies lower crustal rocks similar to those seen in the Bani Hamid thrust sheet (Searle and Cox, 2002). Thrusting progressed from deep subduction-related ductile shearing in the Cenomanian metamorphic sole, to a shallow fold-thrust belt in the foreland during the Turonian to Campanian. The leading edge of the lower Arabian Plate crust was dragged down the subduction zone and metamorphosed to high-pressure eclogite facies in the eastern mountains (As Sifah). In the northern mountains stacking of lower crust granulites (Bani Hamid) indicates lower pressures but higher temperatures. The deep thrust sheets imaged beneath the ophiolite on the east coast of Fujairah are interpreted as granulite-amphibolite facies thrust sheets, stacked up at depth in the hinterland.
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