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Tectonics of the Musandam Peninsula and northern Oman Mountains: From ophiolite obduction to continental collision

Michael P. Searle, Alan G. Cherry, Mohammed Y. Ali and David J.W. Cooper

ABSTRACT

The tectonics of the Musandam Peninsula in northern Oman shows a transition between the Late Cretaceous ophiolite emplacement related tectonics recorded along the Oman Mountains and Dibba Zone to the SE and the Late Cenozoic continent-continent collision tectonics along the Zagros Mountains in Iran to the northwest. Three stages in the continental collision process have been recognized. Stage one involves the emplacement of the Semail Ophiolite from NE to SW onto the Mid-Permian–Mesozoic passive continental margin of Arabia. The Semail Ophiolite shows a lower ocean ridge axis suite of gabbros, tonalites, trondhjemites and lavas (Geotimes V1 unit) dated by U-Pb zircon between 96.4–95.4 Ma overlain by a post-ridge suite including island-arc related volcanics including boninites formed between 95.4–94.7 Ma (Lasail, V2 unit). The ophiolite obduction process began at 96 Ma with subduction of Triassic–Jurassic oceanic crust to depths of > 40 km to form the amphibolite/granulite facies metamorphic sole along an ENE-dipping subduction zone. U-Pb ages of partial melts in the sole amphibolites (95.6–94.5 Ma) overlap precisely in age with the ophiolite crustal sequence, implying that subduction was occurring at the same time as the ophiolite was forming. The ophiolite, together with the underlying Haybi and Hawasina thrust sheets, were thrust southwest on top of the Permian–Mesozoic shelf carbonate sequence during the Late Cenomanian–Campanian. Subduction ended as unsubductable cherts and limestones (Oman Exotics) jammed at depths of 25–30 km. The Bani Hamid quartzites and calc-silicates associated with amphibolites derived from alkali basalt show high-temperature granulite facies mineral assemblages and represent lower crust material exhumed by late-stage out-of-sequence thrusting.

Ophiolite obduction ended at ca. 70 Ma (Maastrichtian) with deposition of shallow-marine limestones transgressing all underlying thrust sheets. Stable shallow-marine conditions followed for at least 30 million years (from 65–35 Ma) along the WSW and ENE flanks of the mountain belt. Stage two occurred during the Late Oligocene–Early Miocene when a second phase of compression occurred in Musandam as the Arabian Plate began to collide with the Iran-western Makran continental margin. The Middle Permian to Cenomanian shelf carbonates, up to 4 km thick, together with pre-Permian basement rocks were thrust westwards along the Hagab Thrust for a minimum of 15 km. Early Miocene out-of-sequence thrusts cut through the shelf carbonates and overlying Pabdeh foreland basin in the subsurface offshore Ras al Khaimah and Musandam. This phase of crustal compression followed deposition of the Eocene Dammam and Oligocene Asmari formations in the United Arab Emirates (UAE), but ended by the mid-Miocene as thrust tip lines are all truncated along a regional unconformity at the base of the Upper Miocene Mishan Formation. The Oligocene–Early Miocene culmination of Musandam and late Cenozoic folding along the UAE foreland marks the initiation of the collision of Arabia with Central Iran in the Strait of Hormuz region. Stage three involved collision of Arabia and the Central Iran Plate during the Pliocene, with ca. 50 km of NE-SW shortening across the Zagros Fold Belt. Related deformation in the Musandam Peninsula is largely limited to north and eastward tilting of the peninsula to create a deeply indented coastline of drowned valleys (rias).

INTRODUCTION

The Musandam Peninsula at the northern end of the Oman Mountains marks a transition zone between the Upper Cretaceous ophiolite obduction tectonics recorded in the Oman Mountains to the southeast with the Upper Cenozoic continental collision tectonics as seen along the Zagros Mountains in southern Iran to the northwest (Figures 1 to 3). A vast thrust sheet of Cenomanian oceanic crust and upper mantle rock, the Semail Ophiolite, forms much of the Oman Mountains (Reinhardt, 1969; Coleman, 1981; Lippard et al., 1986; Nicolas, 1989). The Semail Ophiolite, together with its underlying thrust sheets of distal ocean trench and seamount (Haybi Complex), proximal to distal oceanic sedimentary rocks (Hawasina Complex) and shelf margin-slope facies rocks (Sumeini Group) was thrust onto the previously passive continental margin of Arabia during the Late Cretaceous

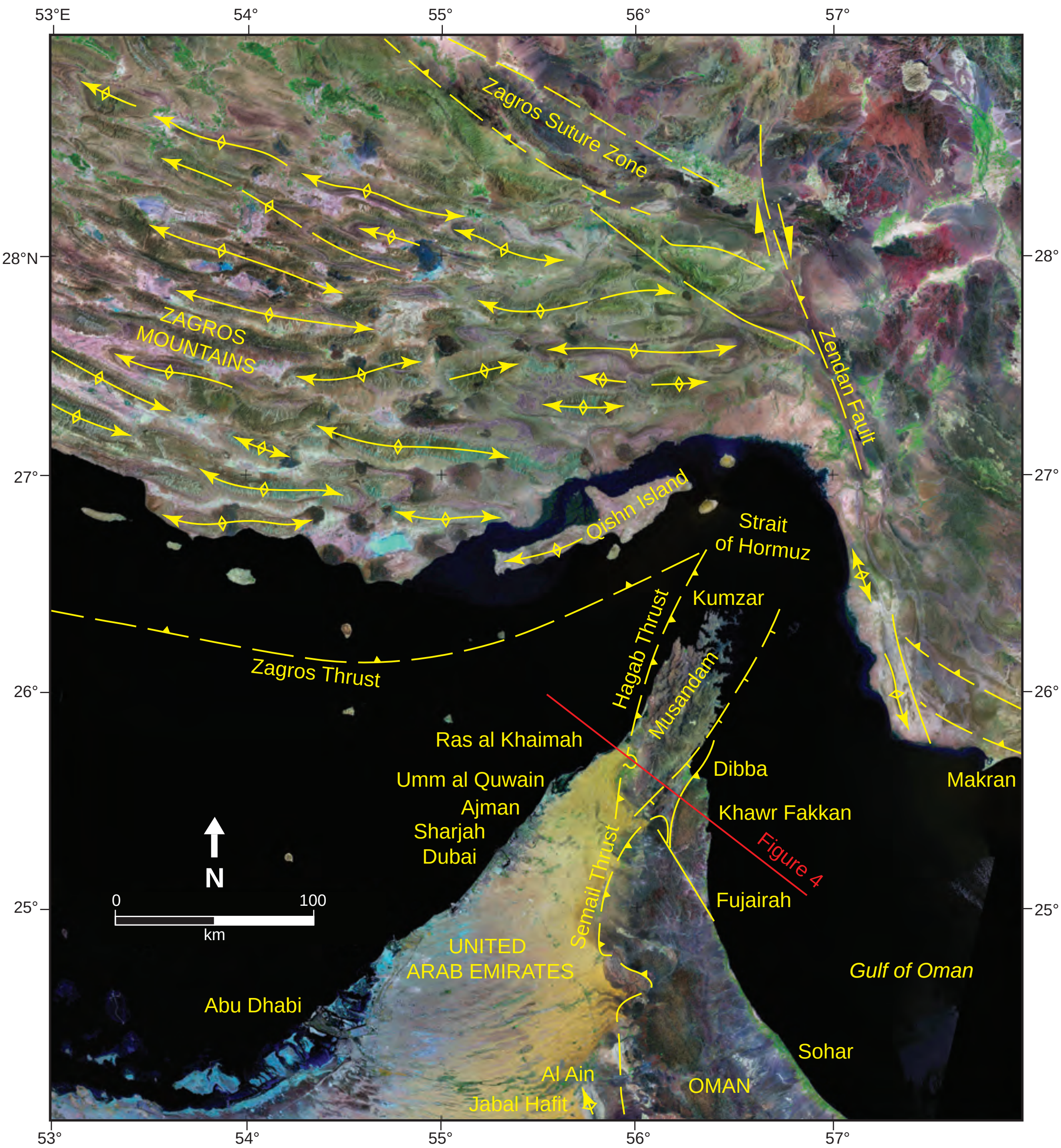

Figure 1: Landsat image of the northern Oman Mountains, Musandam Peninsula, Strait of Hormuz, the southern Zagros Mountains and Arabian Gulf region. Major anticline axes in the Zagros are shown; circular dark-coloured areas are Proterozoic Hormuz salt domes.

(Glennie et al., 1973, 1974; Searle, 1985, 2007; Cooper, 1988; Robertson and Searle, 1990; Rabu et al., 1993; Searle and Cox, 1999; Cooper et al., 2012). After ophiolite obduction, the mountain belt subsided and was the site of shallow-marine passive margin carbonate sedimentation lasting ca. 35 Myr from Maastrichtian to end-Eocene (Nolan et al., 1990; Fournier et al., 2006). Shallow-marine sedimentation persisted southwest of the mountains throughout the Oligocene (Asmari Formation) and Miocene (Fars Formation). A second major period of crustal shortening, folding and thrusting started in the early Oligocene and continued intermittently into the Miocene (Searle and Ali, 2009). Large-scale folding created the large antiformal structures of Jabal al-Akhdar and Saih Hatat in Oman (Mount et

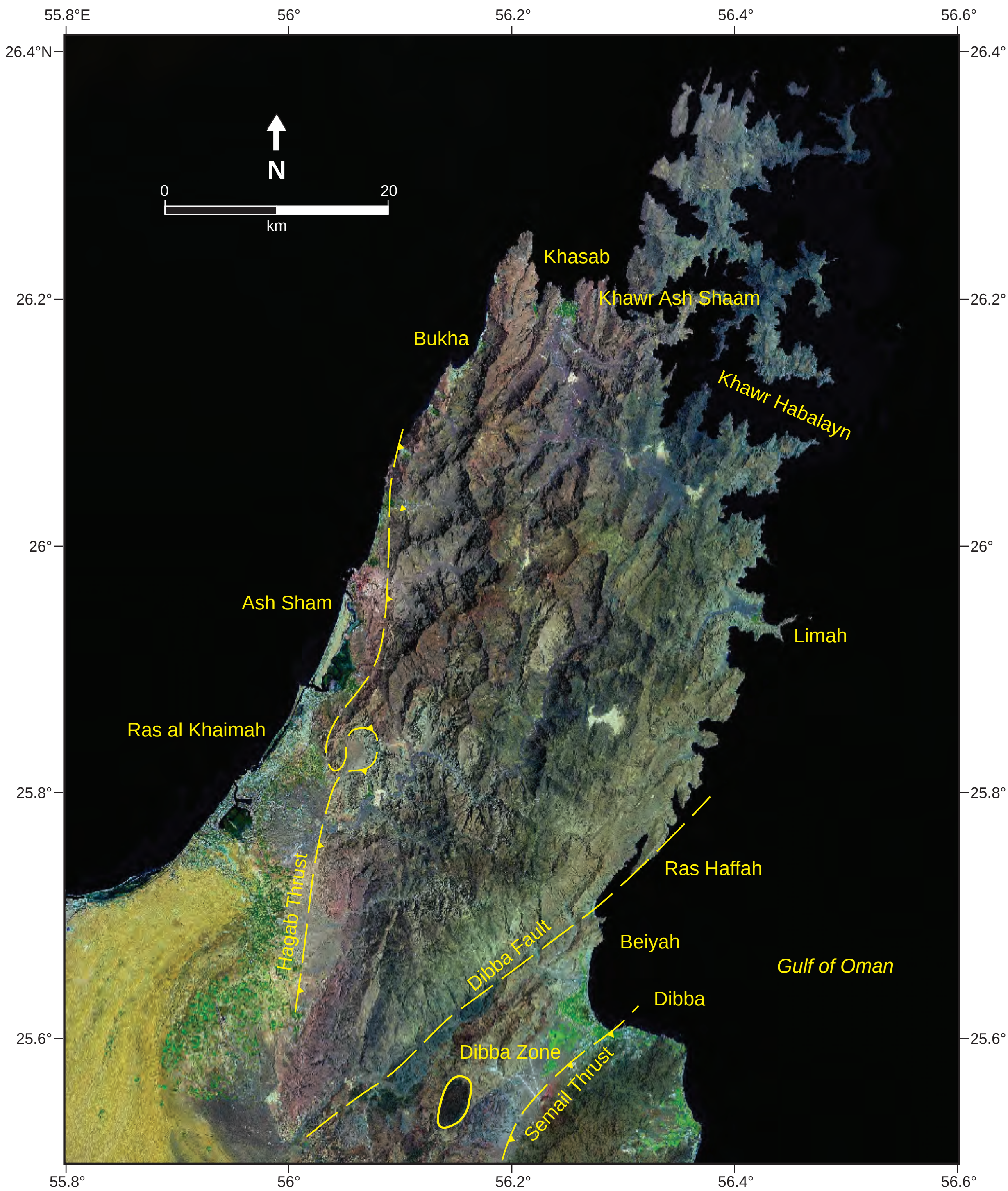

Figure 2: Landsat image of the Musandam Peninsula showing major faults, the Hagab Thrust, Dibba normal fault and Semail Thrust.

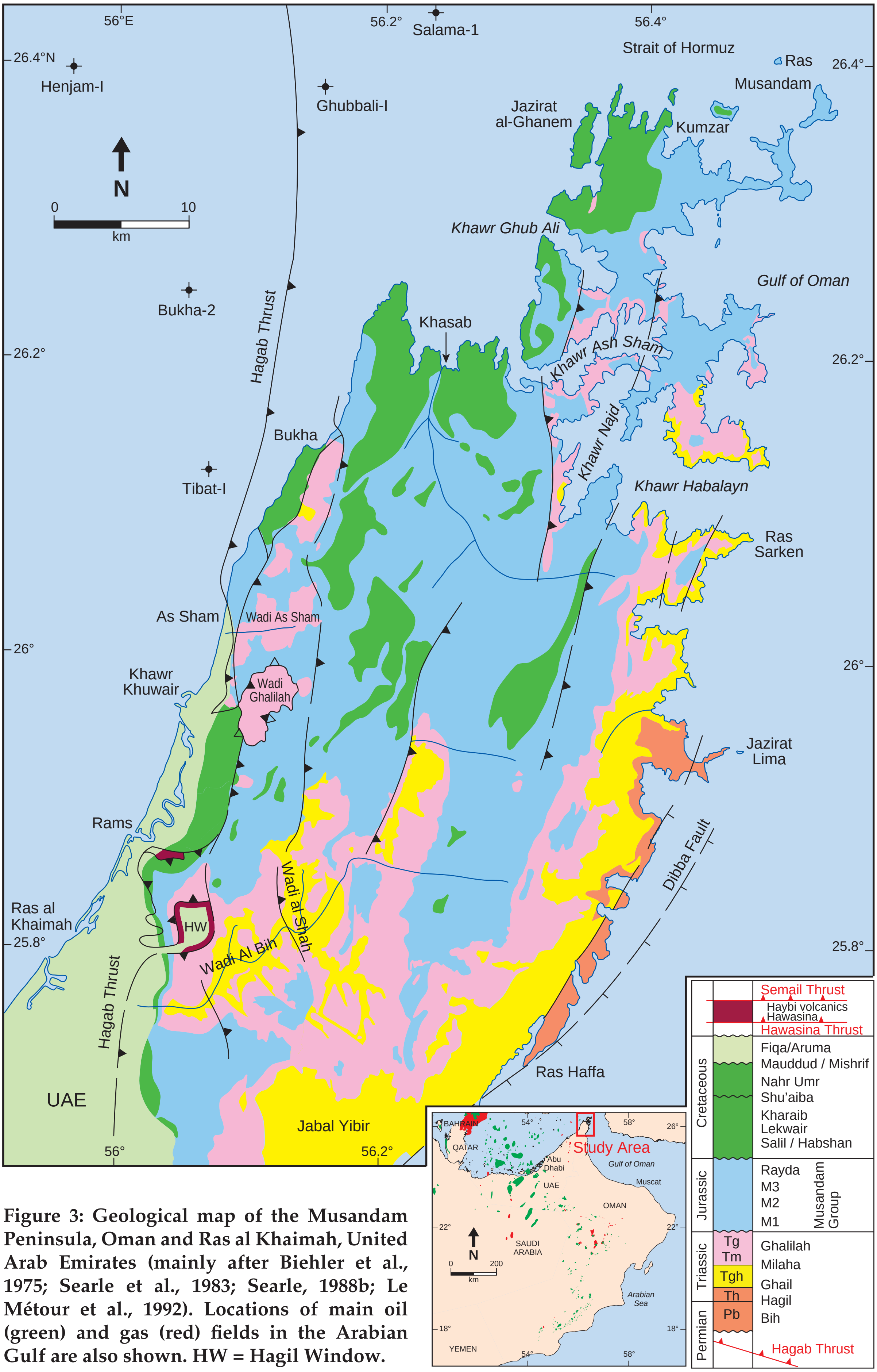

Figure 3: Geological map of the Musandam Peninsula, Oman and Ras al Khaimah, United Arab Emirates (mainly after Biehler et al., 1975; Searle et al., 1983; Searle, 1988b; Le Métour et al., 1992). Locations of main oil (green) and gas (red) fields in the Arabian Gulf are also shown. HW = Hagil Window.

al., 1998; Al-Lazki et al., 2002; Filbrandt et al., 2006) and numerous Cenozoic folds along the western flank of the mountains in Oman and UAE (Glennie et al., 1973, 1974; Searle, 2007; Searle and Ali, 2009).

In the Musandam Peninsula a third large-scale culmination of the Permian–Cretaceous shelf carbonate sequence with a major crustal-scale thrust, the Hagab Thrust, repeats the entire shelf plus pre-Permian basement units at depth (Searle et al., 1983; Searle, 1988b; Dunne et al., 1990). A composite cross-section from the Gulf of Oman to the Arabian Gulf, across the northern part of the Semail Ophiolite and Dibba Zone and across the Musandam Peninsula, is shown in Figure 4. Searle (1988b) determined a minimum 15 km of westward translation along the Hagab Thrust during the mid-Cenozoic from balanced and restored cross-sections. In this paper we describe the main structural units across the northern Oman Mountains from the Semail Ophiolite, Metamorphic sole, Cenozoic thrust sheet, the Dibba Zone thrust sheets (Hawasina and Haybi complexes) and the Musandam shelf carbonates. We summarise the key seismic and well data from offshore Ras al Khaimah, Umm al Quwain (UAE) and Omani Musandam around the Strait of Hormuz syntaxis (Figure 5). Finally we present a crustal-scale section across the Musandam-Dibba Zone and northern part of the Semail Ophiolite and propose a tectonic sequence of events that span the entire Late Cretaceous ophiolite obduction event up to the Oligocene–Miocene culmination of Musandam and the beginning of Arabia-Central Iran continental collision.

SEISMIC CONSTRAINTS ON THE DEEP STRUCTURE

Seismic reflection profiles and exploratory well data show that the rifted passive margin sequence (Middle Permian to Cenomanian, Middle Cretaceous) is ca. 4 km thick, the Upper Cretaceous Aruma foreland basin thickens northeastward to a maximum thickness of about 4 km along the western margin of the mountains (Warburton et al., 1990; Boote et al., 1990; Loosveld et al., 1996; Johnson et al., 2005; Ali et al., 2013), and that the Paleogene Pabdeh foreland in the northern Emirates and west of Musandam is ca. 3 km thick (Ricateau and Riche, 1980). Backstripping of well sections reveal that initial rifting occurred during the Mid Permian at ca. 260 Ma, and continued through to the Jurassic, with a transition from extension to compression during the Late Cretaceous, concomitant with formation and emplacement of the Semail Ophiolite (Ali et al., 2013). Backstrip curves also reveal an increase in tectonic subsidence during the Late Cenozoic, concomitant with collision of Arabia with Central Iran and the beginning of the Zagros Orogeny.

Four deep seismic profiles, two along the strike of the mountains and two across the strike were acquired in the UAE by WesternGeco (2005) for the Ministry of Energy, UAE (Figure 6). Two of these lines cross the mountains, one (D4 line) from Umm al Quwain across the southern tip of the shelf carbonates, Dibba Zone and northern ophiolite to Ras Dadnah, the other (D1 line) from Ajman to Dhaid across the ophiolite and the Bani Hamid thrust sheet to south of Khawr Fakkan (Roure et al., 2006; Tarapoanca et al., 2010; Naville et al., 2010). The other two lines are aligned NNE-SSW, one along the foreland west of the mountain front (D3 line), the other runs along the Masafi corridor south into the ophiolite. The Moho was imaged at a depth of 45–47 km, dipping gently to the east towards the continental margin. The greater depth beneath the continental margin is thought to have been due to the stacking-up of deep crustal granulite facies rocks similar to those exposed in the Bani Hamid thrust sheet. Despite the difficulties of penetrating the ophiolite, some structural detail has been determined with thrust repetitions of the 3.8–4 km thick shelf carbonate units. Tarapoanca et al. (2010) proposed less than 40 km of shortening for the shelf carbonate repetitions along D1 and D4 lines.

An aeromagnetic survey carried out by Fugro Airborne Surveys also confirmed that the ophiolite thickens from west to east, tapering to 4 km thick beneath Khawr Fakkan, and that a thin sheet of mantle harzburgites extends west to the Jabal Faiyah region, the westernmost exposures of ophiolite (Batty et al., 2004). The eastern limit of the ophiolite was found to be about 10 km offshore in the Gulf of Oman, east of Khawr Fakkan, and this is an abrupt break, interpreted as a steep normal fault. The ophiolite has a strong magnetic signature compared to the sedimentary sequences beneath. Both the magnetic and the seismic data confirm the field mapping that shows the ophiolite extending

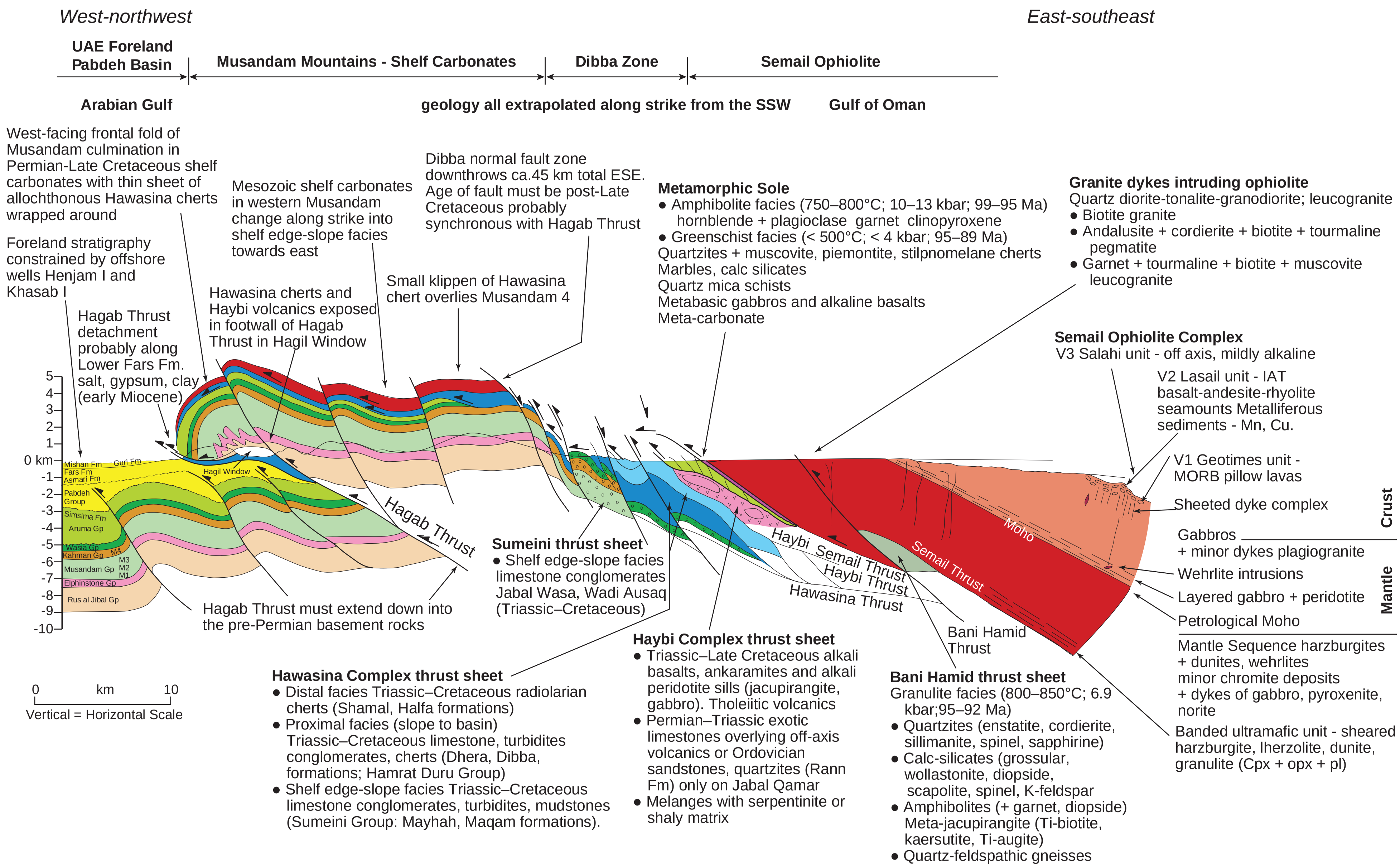

Figure 4: Composite geological cross-section across the northern part of the Semail Ophiolite, the Bani Hamid thrust sheet, the Dibba Zone and Musandam shelf carbonates.

Figure 5: Photo of the Musandam Peninsula taken from the Space Shuttle, Arabian Gulf on the left, Gulf of Oman on the right.

west of the main mountain front to the Jabal Fayiah region (Figure 6). The aeromagnetic data also shows that the depth to the crystalline basement ranges from 6.5 km to 9.7 km (Batty et al., 2004).

Industry seismic data also shows a thick Upper Cretaceous foreland basin west of the mountain front, the Aruma foredeep, that initiated during the Cenomanian (ca. 95 Ma) and attained its maximum relief during the Turonian ca. 93.5–89.3 Ma (Patton and O'Connor, 1988). The onset of ophiolite obduction and loading of the thrust sheets caused the abrupt collapse of the shelf margin during the Cenomanian and initiation of the foreland flexural basin. The entire ophiolite obduction process occurred beneath sea level. Rare laterite horizons exist above the ophiolite in Oman showing that the obduction process may have just breached sea level in places. The foreland basin and the peripheral bulge (Lekhwair bulge) migrated westward during this time and is recorded by the thickness and numerous intra-formational unconformities in the Aruma sedimentary fill, comprising the Muti, Fiqa and Juweiza Formations (Robertson, 1987; Warburton et al., 1990; Boote et al., 1990; Ali and Watts, 2009). In the UAE and west of Musandam a second, later foredeep, the Pabdeh Basin developed in front of the Oligocene–Early Miocene Musandam culmination (Ricateau and Riche, 1980; Searle, 1988b; Dunne et al., 1990). Along the strike of the mountains, the Upper Cretaceous Aruma foredeep shallows towards the north, whereas the mid-Cenozoic Pabdeh foredeep shallows to the south from in front of the Musandam culmination. The Pabdeh foreland basin continues to the northwest along the Arabian Gulf where it thickens as a result of loading of the Zagros hinterland. Both the Upper Cretaceous (Aruma) and Cenozoic (Pabdeh) foreland basins are characterised by a negative Bouguer gravity anomaly parallel to positive gravity highs over the ophiolite (Ravaut et al., 1997; Ali et al., 2014). Another negative Bouguer anomaly runs along the Sohar Basin, offshore in the Gulf Oman bounded by the Dibba Fault to the northwest (Ravaut et al., 1998).

STAGE 1: LATE CRETACEOUS OPHIOLITE EMPLACEMENT

Semail Ophiolite

The Semail Ophiolite of Oman is thought to represent a slice of oceanic crust and upper mantle formed at a fast-spreading ridge. The ridge has been compared to a mid-ocean ridge similar to the East Pacific Rise or a back-arc spreading centre above an active subduction zone. The Semail Ophiolite consists of ca. 7–8 km thickness of oceanic crust and at least 15 km thickness of upper mantle peridotites, dominantly depleted mantle harzburgites and dunites (Figure 7; Reinhardt, 1969; Glennie et al., 1974; Manghani and Coleman, 1981; Lippard et al., 1986; Searle and Cox, 1999; Nicolas et al., 1988). The crustal section is composed of 'MORB-related' axial volcanics, mainly pillow lavas (Geotimes unit or V1 unit) dated by U-Pb zircon between 96.4–95.4 Ma overlain by a sequence of pillow lavas (Lasail

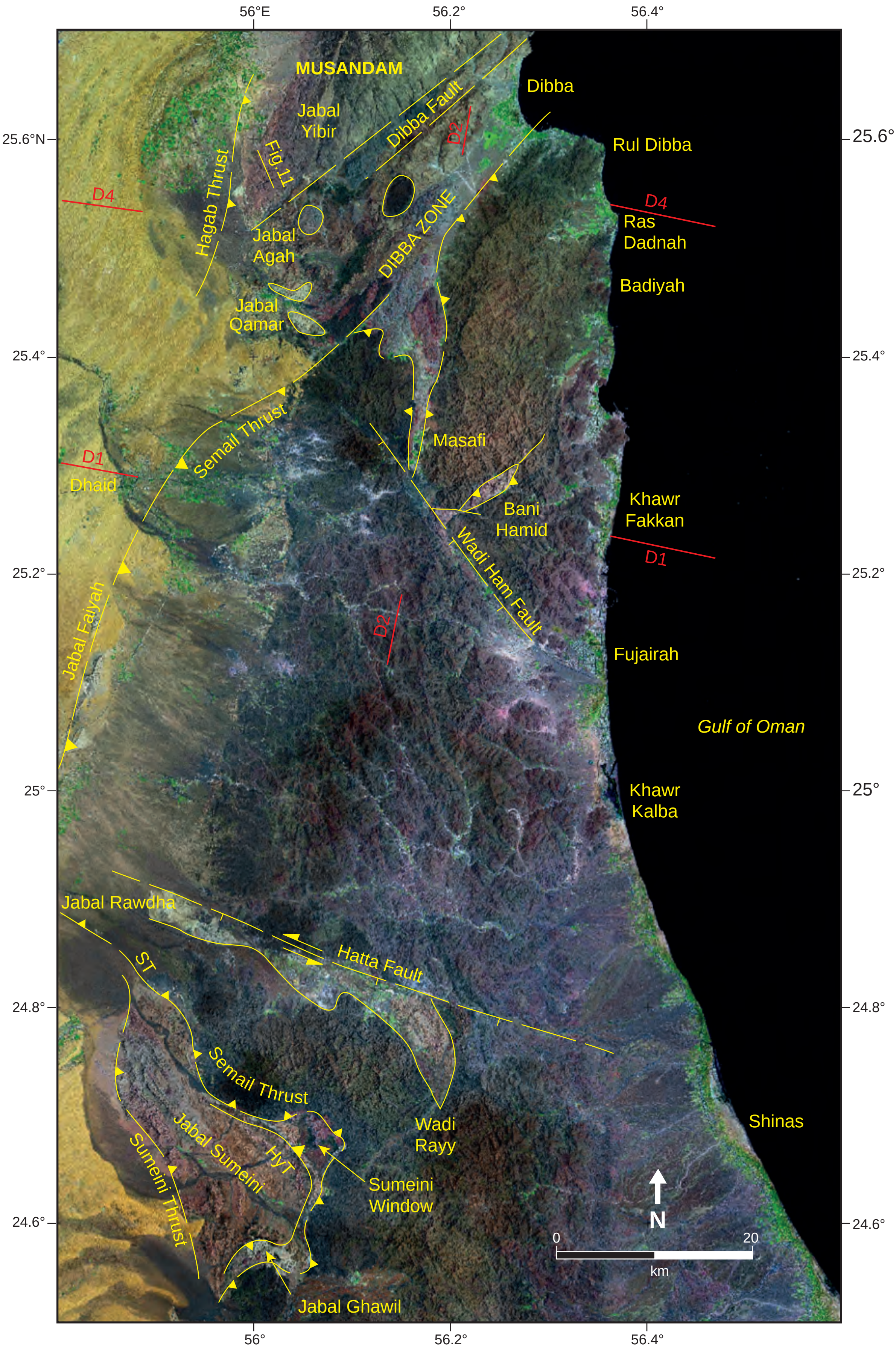

Figure 6: Landsat photo of the northern part of the Semail Ophiolite in Oman and UAE, showing the Sumeini Window, the Bani Hamid Thrust sheet, and the Dibba Zone. Locations of the D1, D2 and D4 seismic profiles and cross-section of Figure 11 are also shown. ST = Semail Thrust, HyT = Haybi Thrust.

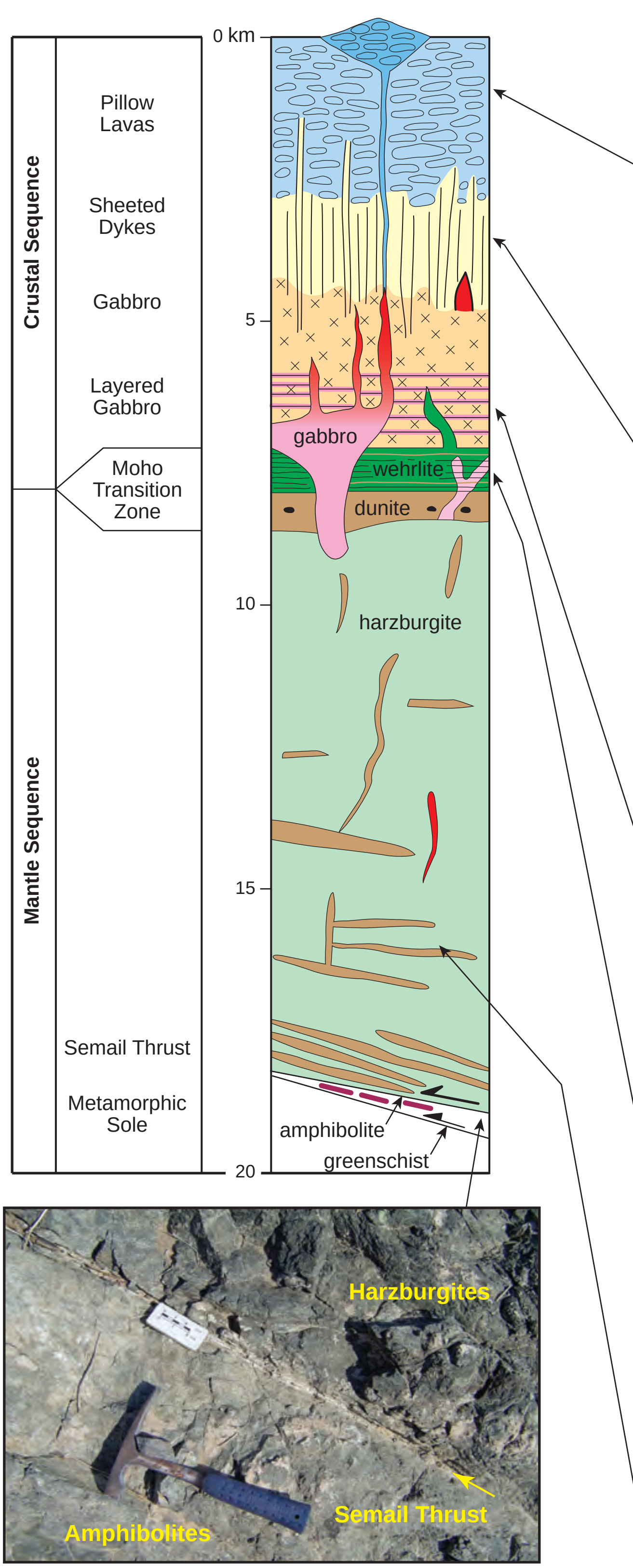

Figure 7: Composite profile through the Semail Ophiolite showing major lithological units in the mantle (harzburgite, dunite), the Moho Transition Zone and crustal (wehrlite intrusions, layered gabbros, sheeted dykes, pillow lavas) sequences.

unit) that are depleted arc tholeiites and boninites, volcanic rocks that only form above subduction zones (Pearce et al., 1981; MacLeod et al., 2013). A post-ridge suite of gabbros, trondhjemites and island-arc related volcanics including boninites formed between 95.4–94.7 Ma (Tilton et al., 1981; Warren et al., 2005; Styles et al., 2006; Rioux et al., 2012). Several authors have proposed a Mid-Ocean Ridge (MOR) model for generation of the Oman lavas (Nicolas, 1989; Boudier et al., 1988; Godard et al., 2006). Pearce et al. (1981) and Alabaster et al. (1982) used immobile trace element (e.g. Ti, Zr, Y, Nb) data to demonstrate that the upper lavas (Lasail unit) had compositions much more similar to immature island arc lavas and boninites (high-Mg andesites) rather than MORB. MacLeod et al. (2013) showed that all the lavas, including the so-called 'MORB-like' Geotimes unit were much closer in composition to supra-subduction zone magmas, particularly back-arc basin or fore-arc basalts.

The basaltic lavas are fed by a series of sheeted dykes that root into the upper gabbros and can be mapped as the feeders for the lower pillow lavas. The sheeted dykes show 100% crustal extension, at a ridge axis. The gabbroic lower crust represents a dynamic magma chamber beneath a spreading ridge, continually feeding magma up to the dykes and pillow lavas above and continually replenished by mantle derived melts from below. Olivine + clinopyroxene + plagioclase gabbros show gravity settling cumulate textures in the lower layered gabbros and layering (sometimes inter-layered with peridotites) suggests a cyclic nature to magma generation. The more primitive magmas are represented by gabbro norites (olivine + orthopyroxene + clinopyroxene). Late wehrlite (olivine + clinopyroxene) intrusions cut the layered gabbros and are thought to be the plutonic relatives of the late arc magmatism. The upper gabbros show large horizontal sill complexes that feed magma away from an axial magma 'mush' zone. High-level intrusives include scattered plagiogranites or trondhjemites (plagioclase + hornblende + quartz ± biotite), the final fractionation phase of the melting process. These plagiogranites form in the roof zone of the magma chamber where volatiles are concentrated and they contain < 1% zircon, a mineral that can be used for U-Pb dating of ophiolites. Tilton et al. (1981), Warren et al. (2005), and Rioux et al. (2012) published U-Pb zircon ages of 95.07–95.41 Ma from the Oman plagiogranites and gabbros, interpreted as dating the formation of the ophiolite crustal sequence.

The transition from the crust to the mantle is marked by the Moho, or the 'Moho Transition Zone', a zone that separates the ultramafic mantle peridotites from the plagioclase-bearing crustal rocks. In Oman the Moho can rarely be an abrupt contact but it is more usually a zone of layered peridotites and gabbros (Boudier and Nicolas, 1995). The Moho separates high-temperature solid-state flow fabrics in the mantle below from magmatic flow fabrics in the gabbros above. The boundary between the tectonized harzburgites and the cumulate gabbro-peridotites is referred to as the 'petrological Moho', whereas the 'seismic Moho' is the upper boundary where ultramafic peridotites give way to a mafic lower crust. In the UAE the Moho Transition Zone shows a complex sequence of dunites intruded by wehrlite, pyroxenite and troctolite cut by late gabbros (Bithnah facies gabbros) (Styles et al., 2006; Goodenough et al., 2010). The Moho Transition Zone is well exposed around Ras Dadnah where layered gabbros are cut by dark brown weathering wehrlite intrusions. Layering gradually dies out up-structural section towards more isotropic high-level gabbros. Abundant dolerite dykes cut the high-level gabbros and in the Khawr Fakkan block trend NNW-SSE. The sheeted dykes and pillow lavas are only exposed in the far south of the UAE part of the mountains, but occur throughout northern Oman (Pearce et al., 1981; Lippard et al., 1986).

Metamorphic Sole beneath the Semail Ophiolite

The metamorphic sole to the ophiolite shows a narrow thrust slice of hornblende + plagioclase ± garnet ± clinopyroxene amphibolites in places containing small relic pods of garnet + clinopyroxene granulite, amphibolites without garnet and pyroxene, epidote amphibolites and greenschist facies meta-sediments. Together these record an inverted and highly condensed PT gradient and showing intense mylonitic fabrics (Searle and Malpas, 1980, 1982; Ghent and Stout, 1981; Gnos, 1998; Searle and Cox, 2002; Cowan et al., 2014). During initial NE-dipping oceanic subduction amphibolites with small enclaves of garnet + clinopyroxene granulites were formed at P-T conditions of 770–900°C and 11–15 kbar (Searle and Malpas, 1982; Gnos, 1998; Searle and Cox, 2002; Cowan et al., 2014). Pressures indicate that metamorphism occurred at depths (35–40 km) far greater than can be accounted for by the preserved thickness of the ophiolite (ca. 15–20 km). U-Pb zircon ages from the metamorphic sole

(94.48–94.90 Ma; Warren et al., 2005; Rioux et al., 2013) show that peak PT conditions (ca. 850°C, 10–12 kbar) occurred within 0.1–0.25 Myr of formation of the crustal part of the ophiolite. The synchroneity of the formation of the ophiolite crustal sequence with the amphibolite-granulite metamorphic sole can only imply that the ophiolite formed above a NE-dipping subduction zone and not at a mid-ocean ridge. Although almost all amphibolites are meta-basaltic rocks, Gnos (1998) described one meta-pelitic sample containing kyanite. It is possible that some variably banded amphibolites may have a more tuffaceous volcano-sedimentary protolith.

Greenschist facies lithologies include meta-cherts, piemontite quartzites, calc-silicates, and occasional meta-volcanics. Pelites are generally absent making any quantitative PT calculations very difficult. In the northern Oman Mountains the metamorphic sole is widely exposed along the base of the ophiolite and is imbricated in with other components of the Haybi Complex in the thrust sheet immediately beneath the peridotite. In places in the Dibba Zone, blocks of amphibolites, greenschists, exotic limestones and cherts are enclosed in a serpentinite matrix mélange (Kub Mélange; Searle et al., 1983; Searle, 1988a; Robertson et al., 1990a). Large-scale folding of the ophiolite has resulted in exposure of the amphibolite sole along the Masafi corridor.

The Bani Hamid Thrust slice represents a unique 1.2 km thick thrust sheet of HT granulites that have been thrust into the harzburgite-dunite section of the mantle sequence in the northern Oman Mountains. These rocks, discussed in the next section, are completely different from the usual sub-ophiolite metamorphic sole rocks and might be representative of lower crust metamorphism at deeper levels of the crust in northern Oman and UAE (Gnos and Kurz, 1994; Gnos, 1998; Cherry, 2013). Another major difference in the sub-ophiolite geology of the northernmost Khawr Fakkan Ophiolite block is the occurrence of numerous S-type granite dykes, ranging from cordierite + andalusite + biotite monzogranite to garnet + tourmaline + biotite leucogranite intruding the mantle sequence and Moho Transition Zone (Briqueu et al., 1991; Peters and Kamber, 1994; Gnos and Nicolas, 1996; Cox et al., 1999; Searle and Cox, 1999, 2002).

Bani Hamid Granulites

Lithologies from the Bani Hamid high-temperature granulites include two-pyroxene (± cordierite ± sillimanite) quartzites, diopside + garnet + tremolite + scapolite calc-silicates and hornblende + plagioclase (± garnet ± clinopyroxene) amphibolites with localised partial melting, intruded by hornblende pegmatites (Gnos and Kurz, 1994; Gnos, 1998; Searle and Cox, 1999; Cherry, 2013). Figure 8 shows a simplified metamorphic tectonic 'stratigraphy' through the Bani Hamid granulites with lower quartzite unit with less common marble bands, and an upper marble and calc-silicate unit containing bands of amphibolite, and Mn-rich quartzites with pods of diopsidites. The Bani Hamid Thrust slice is

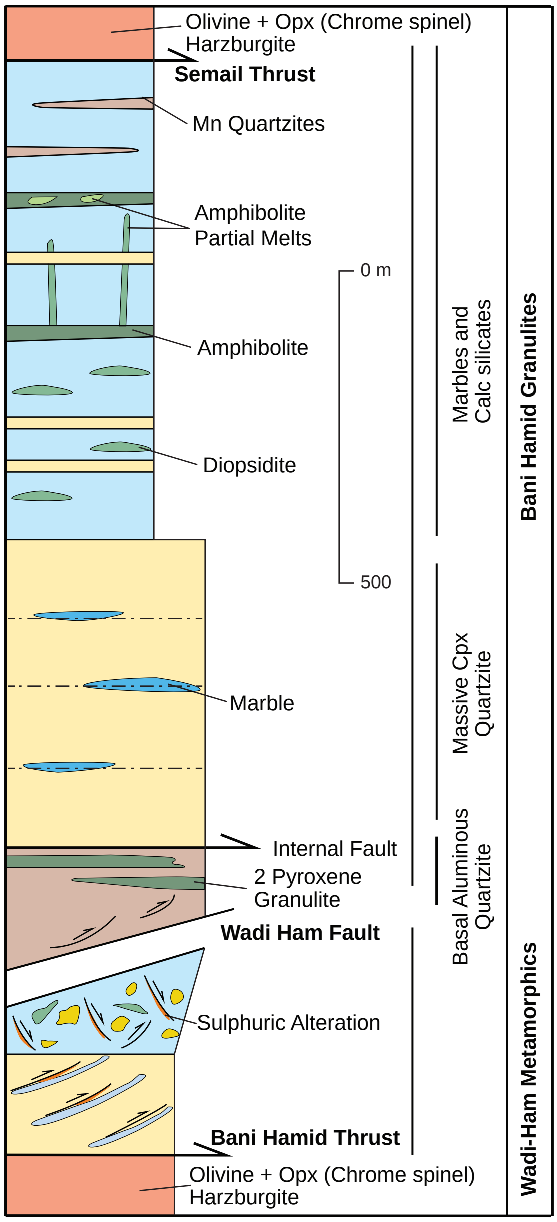

Figure 8: Simplified metamorphic-structural profile through the Bani Hamid granulites and Wadi Ham metamorphic rocks (after Cherry, 2013; Cherry et al., 2014).

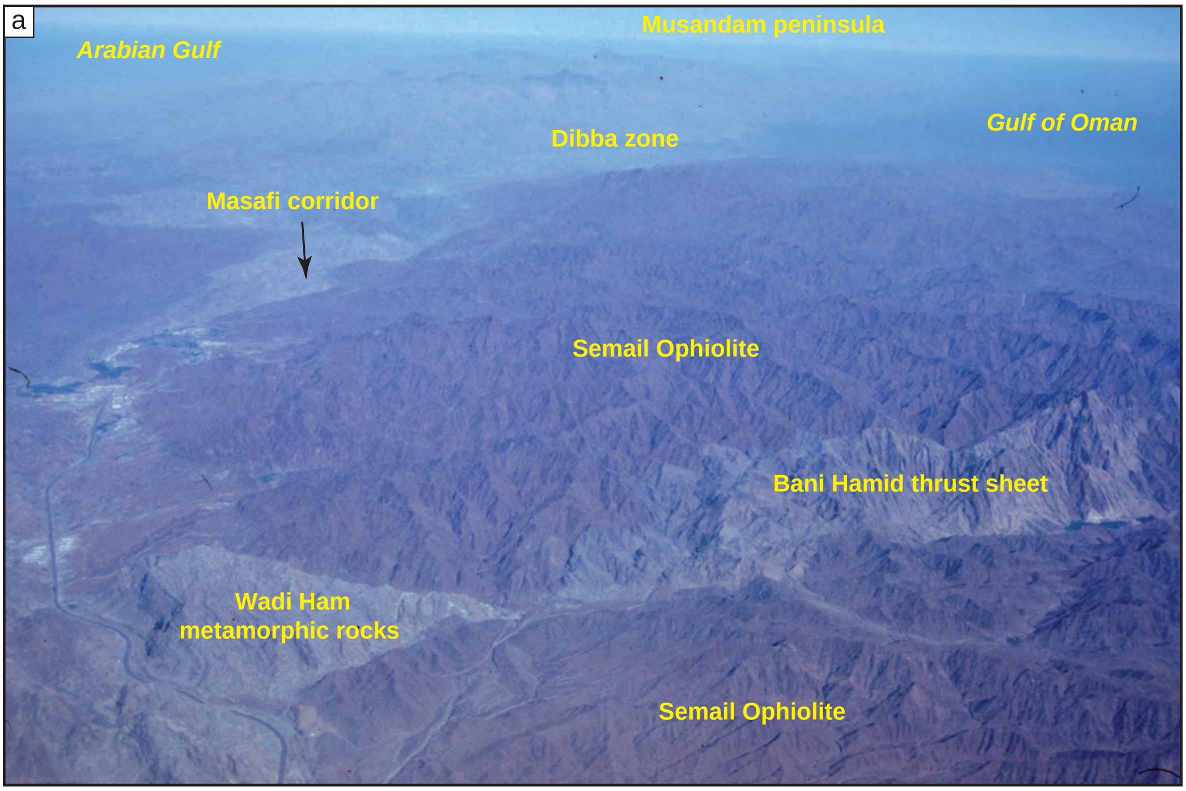

Figure 9: Photos of the Bani Hamid thrust sheet. (a) Aerial photo of the Bani Hamid thrust sheet (pale coloured rocks), Wadi Ham Fault (bottom left), Masafi corridor (left) and Dibba Zone in the distance.

Figure 9: (b) Semail Thrust with dark brown harzburgites of the ophiolite thrust over pale calc-silicates of the Bani Hamid thrust sheet.

surrounded by peridotites (Figure 9a) and the Semail Thrust (Figure 9b) has been duplicated but uplift along the later, out-of-sequence Bani Hamid Thrust that places granulites over the lower peridotite unit. Clinopyroxene (Ca-Mg) quartzites (Figure 9c) also contain quartz, andradite garnet and sphene, whereas more aluminous quartzites contain quartz + ilmeno-haematite + spinel + cordierite + orthopyroxene (enstatite) + kyanite + biotite + chlorite.

Gnos and Kurz (1994) discovered sapphirine-quartz and sapphirine-corundum assemblages indicative of ultra-high temperature conditions. The sapphirine-corundum assemblage is confined to one Al-rich layer in Wadi Madhah. Calc-silicates typically contain wollastonite, scapolite, andraditic garnet and diopside (Figure 9d). Although most granulites are anhydrous assemblages, wollastonite forms at high temperatures through fluid infiltration and the presence of diopsidites and some hydrous phases does indicate high-temperature fluid infiltration. Deformation is intense throughout

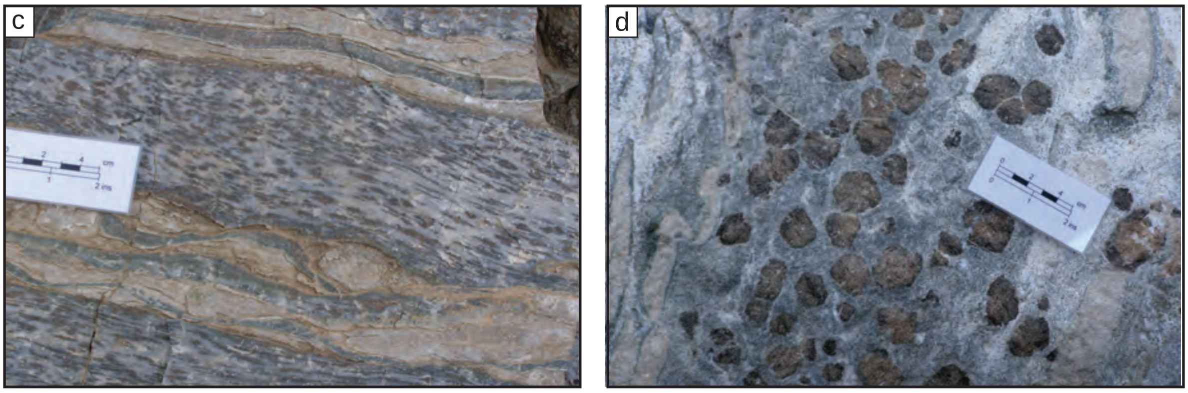

Figure 9: (c) Clinopyroxene quartzites with a marble band in the middle. (d) Euhedral andradite garnets in calc-silicate.

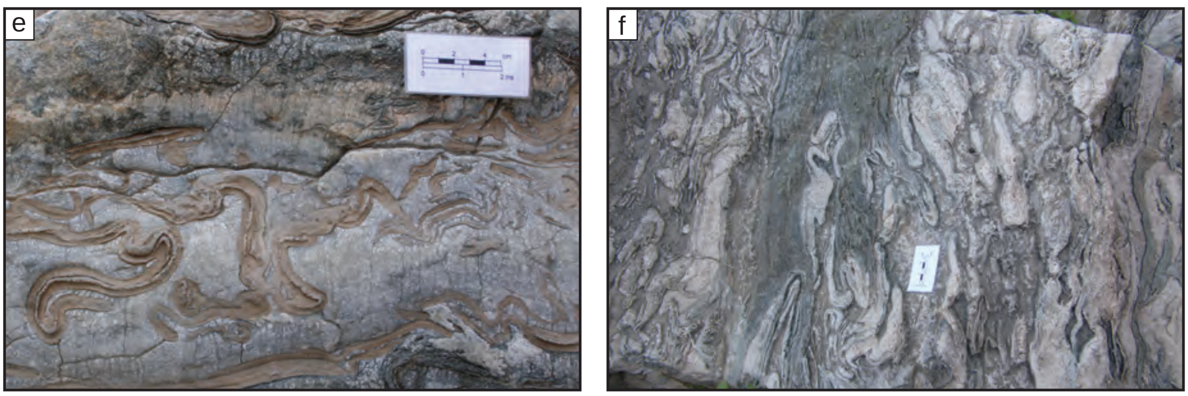

Figure 9: (e) Ductile folding in incompetent marbles. (f) Extreme ductile folding and shearing in Bani Hamid calc-silicates and marble.

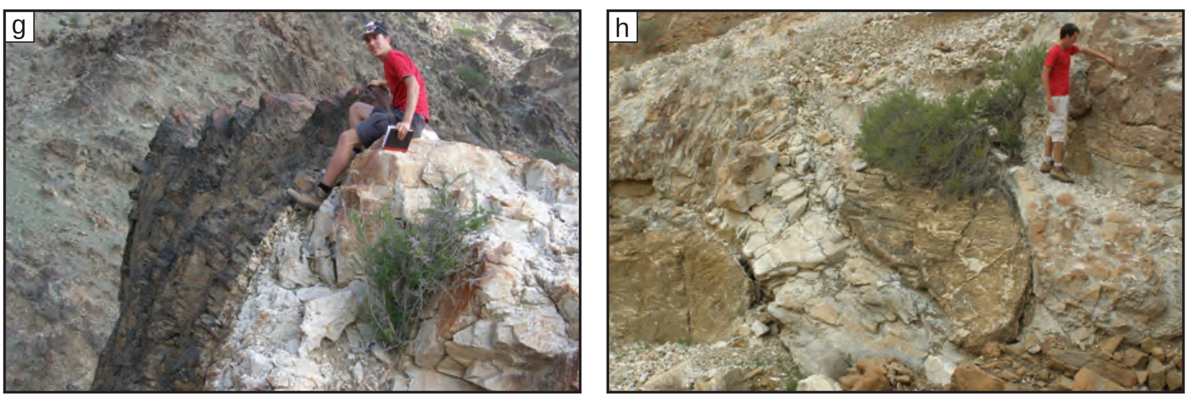

Figure 9: (g) Leucogranite dyke intruding amphibolites, Bani Hamid. (h) Leucogranite dykes intruding Moho Transition Zone, Ras Dadnah, east coast of UAE.

with the incompetent marble units exhibiting totally ductile folding and shearing (Figures 9e and 9f). Metabasites contain hornblende + plagioclase as well as both orthopyroxene and clinopyroxene in the granulite facies. Petrology and thermobarometry of the Bani Hamid granulites show an anticlockwise isobaric high-temperature cooling path (Searle and Cox, 1999; Cherry et al., 2014), suggesting that the heat source must have been from the overlying hot mantle sequence during the early stages of ophiolite obduction, but probably after the formation of the sub-ophiolite amphibolite sole.

The Bani Hamid granulites are highly deformed and are isoclinally folded at all scales. A minimum of 130 km shortening is recorded by restoration of the major folds only. The west-directed breaching out-of-sequence Bani Hamid Thrust shows a minimum 30 km offset from simple restoration of the Semail Thrust pinning point. These granulite facies rocks represent metamorphosed cherts and calcareous turbidites probably derived from the distal Haybi Complex (Cherry et al., 2014). Protoliths most likely include the Oman Exotic limestones (marbles and calc-silicates), cherts (meta-quartzites) and alkali basalts (amphibolites). Cherry et al. (2014) showed that the lithologies of the Bani Hamid granulites correlate closely with the Haybi Complex, and not with the more proximal Hamrat Duru Group (limestone turbidites and cherts) or Sumeini Group (shelf margin limestones) thrust sheet lithologies. The base of the Jabal Qamar south exotic limestone in the Dibba Zone shows an unusual Ordovician quartz-rich sandstone, siltstone and shale sequence (Rann Formation; Fortey et al., 2011), which could be regarded as a possible protolith for some of the Bani Hamid granulites. A tectonic 'stratigraphic' profile through the Haybi Complex rocks in the Dibba Zone that we regard as the most likely protolith for the Bani Hamid granulites is shown in Figure 10.

Gnos and Kurz (1994) suggested PT conditions of 800–850°C and 6.5–9 kbar for the sapphirine-bearing assemblages. Equilibrium pseudosection (phase diagram) modelling in the system NCKF-MASHTO using THERMOCALC gives a peak PT estimate of metamorphism of 876 ± 31°C and 6.9 ± 0.3 kbar (Cherry, 2013; Cherry et al., 2014). Temperatures are similar to or slightly higher than the amphibolite metamorphic sole, but pressures are considerably lower, equivalent to depths beneath an ophiolite hanging-wall of 20–25 km. The (ultra-) high temperatures are interpreted to result from a heat source from the overlying hot mantle rocks. Field constraints show that the Bani Hamid rocks were intensely deformed, isoclinally folded and ductile sheared as a result of stacking up at granulite facies depth. Pressures indicate that this folding and stacking up occurred at lower middle crustal depths. The quartzite, marble and calc-silicate rocks were far too buoyant to be able to subduct, unlike the sub-ophiolite amphibolites, and hence were jammed up during the death throws of the Cretaceous subduction zone. U-Pb zircon dating of a felsic pod within amphibolite constrains the age of peak granulite metamorphism in Bani Hamid at 92.43 ± 0.15 Ma (Styles et al., 2006). The timing of the Bani Hamid granulite facies metamorphism marked the ending of

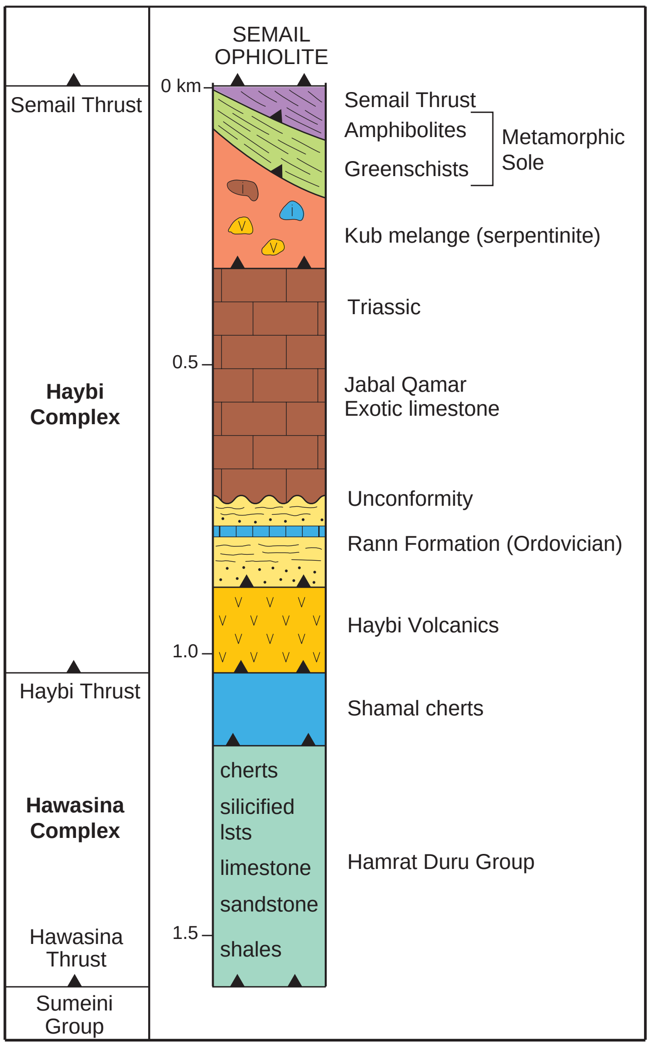

Figure 10: Composite structural-stratigraphic profile through the Haybi Complex, and distal Hawasina Complex rocks of the Dibba Zone, the likely protolith rocks for the Bani Hamid granulites.

subduction beneath the ophiolite, and is completely distinct temporally and spatially from the As Sifah UHP (ultra-high pressure) eclogites in the Oman Mountains southeast of Muscat that occurred at 79.6 ± 1.1 Ma (Warren et al., 2005), 12 million years after 'peak' Bani Hamid granulite metamorphism.

Granite Dykes Intruding the Khawr Fakkan Ophiolite

A few uncommon granitic dykes intrude the Bani Hamid granulites (Figure 9g) but far more numerous granitic dykes intrude the ophiolite sequence in the Khawr Fakkan block (Figure 9h). Whereas in the Oman part of the ophiolite, most of the acid dykes are leucocratic trondhjemites or plagiogranites, the final products of fractional crystallization of the tholeiitic ophiolite, in the UAE part these constitute only a minor part. A few granitic dykes cutting the ophiolite both in Oman and UAE are biotite granites that are geochemically distinct from the trondhjemites. These have been interpreted as late-stage melts derived from a sedimentary source beneath the ophiolite, rather than derived from partial melting of a basaltic protolith within the ophiolite (Lippard et al., 1986; Pearce, 1989). Most granitic dykes in the Khawr Fakkan block are S-type crustal melt granites ranging from peraluminous hornblende-biotite monzogranite through quartz diorite-tonalite-granodiorite to garnet-tourmaline leucogranite (Peters and Kamber, 1994; Gnos and Kurz, 1994; Cox et al., 1999). The least evolved granitoids (diorites) could be related to an ophiolitic source but the petrology, geochemistry and Pb isotopic data show that the leucocratic granites have a high degree of crustal contamination, and many have an entirely sedimentary source. Granitic rocks have negative E_{Nd} values and intermediate to high $^{87}Sr/^{86}Sr$ ratios characteristic of crustal melt granites, contrasting completely with the Semail Ophiolite (Cox et al., 1999). The Ras Dibba andalusite-cordierite monzogranites have the highest E_{Nd} values and the most mantle-like $^{87}Sr/^{86}Sr$ ratios, whereas the Wadi Hulw bin Sulayman garnet-tourmaline leucogranites have low E_{Nd} values and high initial $^{87}Sr/^{86}Sr$ ratios. Based on Sr and Nd isotope data, Cox et al. (1999) suggested that the source was likely to be more quartzo-feldspathic psammitic gneisses rather than meta-pelite.

The leucogranites have a wide range in composition and contain varying amounts of andalusite, cordierite, tourmaline, Mn-rich spessartine garnet, biotite, secondary muscovite, lepidolite and topaz (Searle and Cox, 1999; Cox et al., 1999). Secondary minerals include epidote, clinozoisite, chlorite, prehnite and pumpellyite. The S-type leucogranites are most likely derived from a pelitic or shaly psammitic source. Since the dykes intrude the mantle sequence and layered gabbros, and frequently contain xenoliths of the ophiolitic mantle within, the granites must have been formed and intruded after the ophiolite was obducted, at least after the earliest phase of mantle thrusting. Searle and Cox (1999) suggested that the protolith for the leucogranites could have been Bani Hamid type rocks; however this seems unlikely as the majority of lithologies in Bani Hamid are quartzites and carbonates with a minor component of alkali basalt, all of which are unsuitable protoliths. The source of the leucogranite melts remains unresolved, since there is a distinct lack of suitable pelite in the Haybi Complex, the metamorphic sole, in the Bani Hamid thrust sheet or in the more distal Hawasina Group lithologies. The shelf carbonates and Sumeini Group are not a suitable source for granite melting.

There are thick (100 m+) shale sequences in the Hamrat Duru Group in the northern Oman Mountain exposures (Jabal Qumayrah to Jabal Sumeini) and further south. They span the Lower–Middle Triassic (beneath the Carnian–Norian cherts of the upper Al Jil/Zulla Formation) to the Middle–Upper Jurassic beneath the Guwayza limestones. They also contain other thinner cherts, siliceous mudstones, thin silicified limestones and minor volcanics. Similar sequences are not seen in the more basinal Hamrat Duru elements of the Dibba Zone (the 'Dhera' Formation) because the sole thrust is mostly in the Guwayza Formation and the Triassic–Middle Jurassic substrate is not generally preserved (although there are thin slices of Upper Triassic cherts; Cooper, 1990). However, shales and cherts of inferred Triassic age are preserved at the base of thrust sheets of more proximal Hamrat Duru Group successions (the 'Dibba' Formation) which suggests the thick shale sequences that characterise much of the continental rise sedimentation of the North Oman sector of the Hawasina Ocean extended to the Dibba Zone, between the limestone-rich debris apron of the Sumeini Group and proximal Hamrat Duru Group and the more distal Shamal cherts. These shaly lower Hamrat Duru units could then have been subducted while the more rigid overlying Guwayza-Nayid sediments were detached, imbricated and thrust beneath the leading edge of the ophiolite.

Dibba Zone – Haybi and Hawasina Complexes

The Dibba Zone is a structurally extremely complex zone separating the Musandam shelf carbonates to the north from the Semail Ophiolite to the south (Figure 6). It consists of a series of WSW-verging thrust sheets of Hamrat Duru Group (Dibba and Dhera formations) and distal Hawasina Complex (Shamal Formation) thrust sheets structurally overlain by the more distal Haybi Complex thrust sheets, including the Jabal Qamar Exotics, the Kub Mélange, and imbricated thrust sheets of greenschist and amphibolite facies metamorphic sole rocks (Figure 11; Allemann and Peters, 1972; Searle, 1988a; Robertson et al., 1990a; Styles et al., 2006). Since the early field studies, many key localities in the Dibba Zone have been destroyed through construction development. The entire thrust stack has been affected by folding that exposes inliers of the structurally deepest Sumeini Group rocks, for example in Jabal Agah (Figure 6). A restoration of the thrust sheets in the Dibba Zone where the original passive margin – Tethyan basin architecture can be seen is shown in Figure 12. It is not known precisely how far offshore the attenuated continental crust extended during the Mesozoic, but the occurrence of mildly alkaline basalts in the distal Hawasina and Haybi complexes suggests that the Shamal cherts

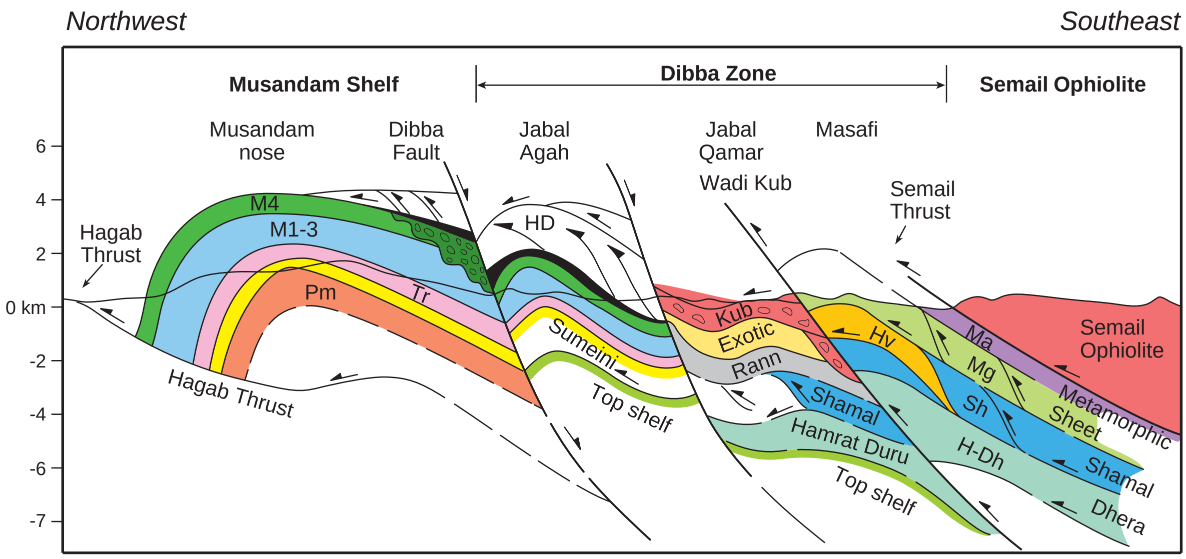

Figure 11: Simplified geological cross-section of the Dibba Zone showing major thrust sheets underlying the Semail Ophiolite (after Searle, 1988a).

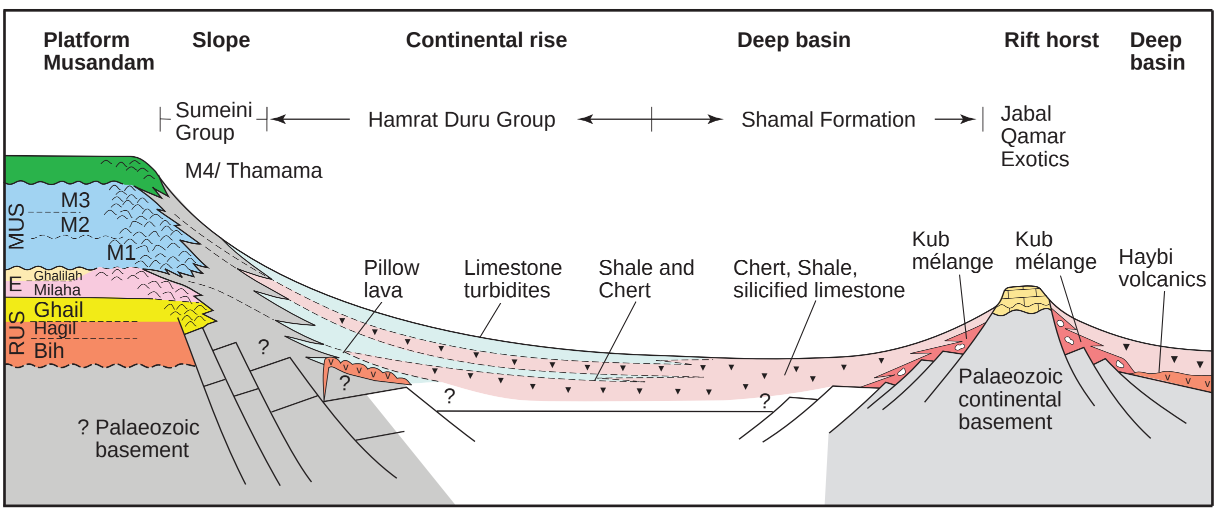

Figure 12: Restoration of the thrust sheets in the Musandam-Dibba Zone area showing a palinspastic reconstruction of the shelf-slope-basin profile (modified from Searle et al., 1983).

MUS = Musandam Group
E = Elphinstone Group
RUS = Rus Al Jibal Group

and Haybi Complex were underlain by a mainly alkali basalt substrate. Robertson et al. (1990a, b) describe Upper Cretaceous volcanic rocks intruding the Hamrat Duru Group in the Dibba Zone and the Hatta Zone further south, again suggesting an alkali basaltic oceanic substrate.

The Triassic Jabal Qamar south exotic limestone is underlain by the Ordovician Rann Formation (Fortey et al., 2011), the only Exotic in the Oman Mountains to be underlain by such continental rocks. Whereas most Exotic limestones are ocean island guyots overlying a Triassic alkali volcanic substrate (Searle and Graham, 1982; Pillevuit et al., 1997), Jabal Qamar appears to be a similar Late Triassic ocean island carbonate seamount but lying above a rifted piece of Arabian continental crust. Most of the Rann Formation outcrops mapped by Searle (1988a) and Robertson et al. (1990a) have now been quarried away, but a detailed biostratigraphic study by Fortey et al. (2011) confirms that the faunas are dominantly Middle and Late Ordovician. Extensive outcrops of volcanics in the Haybi and Hawasina thrust sheets in Oman mapped by Searle et al. (1980, 1983), Maury et al. (2003) and Chauvet et al. (2009) are mainly alkali basalts, ankaramites and trachytes occasionally intruded by alkali peridotite and pyroxenite sills. These volcanics are dominantly Middle Permian (Maury et al., 2003; Chauvet et al., 2009) to Late Triassic (K-Ar ages ca. 233–200 ± 8 Ma), but are also Middle Jurassic (K-Ar ages ca. 162–129 ± 6 Ma) and Late Cretaceous (K-Ar ages ca. 96–92 ± 4 Ma). They are probably related to passive margin rifting (Searle et al., 1980; Lippard and Rex, 1982) rather than to plume magmatism.

Restoration of thrust sheets beneath the Semail Ophiolite complex in the Oman Mountains show at least 400 km of shortening in the proximal (Sumeini Complex), slope and basin (Hawasina Complex) and distal trench (Haybi Complex) sedimentary rocks structurally beneath the ophiolite (Cooper, 1988, 1990; Béchennec et al., 1990). Lithologies along the northwestern margin of the Dibba Zone along Wadi Batha Mahani indicate that shelf carbonates pass across strike to slope facies carbonates with numerous intra-formational unconformities and slope conglomerates. The northern margin of the Dibba Zone was the location of the Cretaceous shelf edge that collapsed during the Cenomanian–Turonian times and was subsequently cut by NNE-aligned, ESE throwing normal faults during the Oligocene–Early Miocene culmination of the Musandam shelf carbonates and their pre-Permian basement. The Dibba Fault is a major normal fault down-throwing to the ESE that bounds the SE margin of the Musandam shelf carbonates along Wadi Batha Mahi. The fault is hinged with the amount of throw increasing dramatically to the NNE, from almost nothing at the SW limit of Musandam to more than 4 km at Dibba.

Musandam Shelf Carbonates

The Musandam Mountains in the far north of Oman show a complete Middle Permian (Hudson, 1960; Glennie et al., 1974) or Upper Permian (Maurer et al., 2009) to Cenomanian shelf carbonate sequence (Figure 13) with a sedimentary history similar to the equivalent rocks exposed in the Jabal Al-Akhdar and Saih Hatat culminations of Oman. An important regional Mid-Permian unconformity is common throughout the Oman Mountains and marks initial continental break-up and the beginning of the Oman sector of the Neo-Tethyan Ocean (Blendinger et al., 1990; Lee, 1990; Sharland et al., 2001, 2004). Above the unconformity thick dolomites of the Bih (Upper Permian–Lower Triassic), Hagil and Ghail (Lower, Middle Triassic) formations in Musandam (Styles et al., 2006; Maurer et al., 2008; Clarkson et al., 2013) are equivalent to the Permian Saiq and Lower Triassic Mahil formations in Al Jabal Al-Akhdar (Hudson, 1960; Glennie et al., 1974; Le Métour et al., 1992; Koehrer et al., 2010). The Bih Formation dolomites are the time-equivalent to the highly productive hydrocarbon-bearing Khuff Formation in interior Oman, which hold a significant quantity of natural gas reserves (Sharland et al., 2004; Koehrer et al., 2012). The Bih Formation carbonates formed in a shallow-water, tidal-flat environment, probably very similar to offshore Abu Dhabi today (Maurer et al., 2009). The Triassic Milaha Formation grades from open-shelf, bioclastic *Megalodon*-rich limestones in the north of Musandam to outer shelf skeletal and peloidal lime sand shoals and coral-algal reefs along the southern margin of Musandam (Searle et al., 1983). This is interpreted as the timing of development of a distinct shelf edge facies and coincides with establishment of deeper marine sedimentation in the proximal Hamrat Duru Group (Cooper, 1988, 1990; Blechschmidt et al., 2004). The Late Triassic Jabal Wasa facies in Oman is a reefal carbonate containing abundant corals, sponges, encrusting algae and foraminifera. Similar facies rocks also occur along the southern margin of the Musandam.

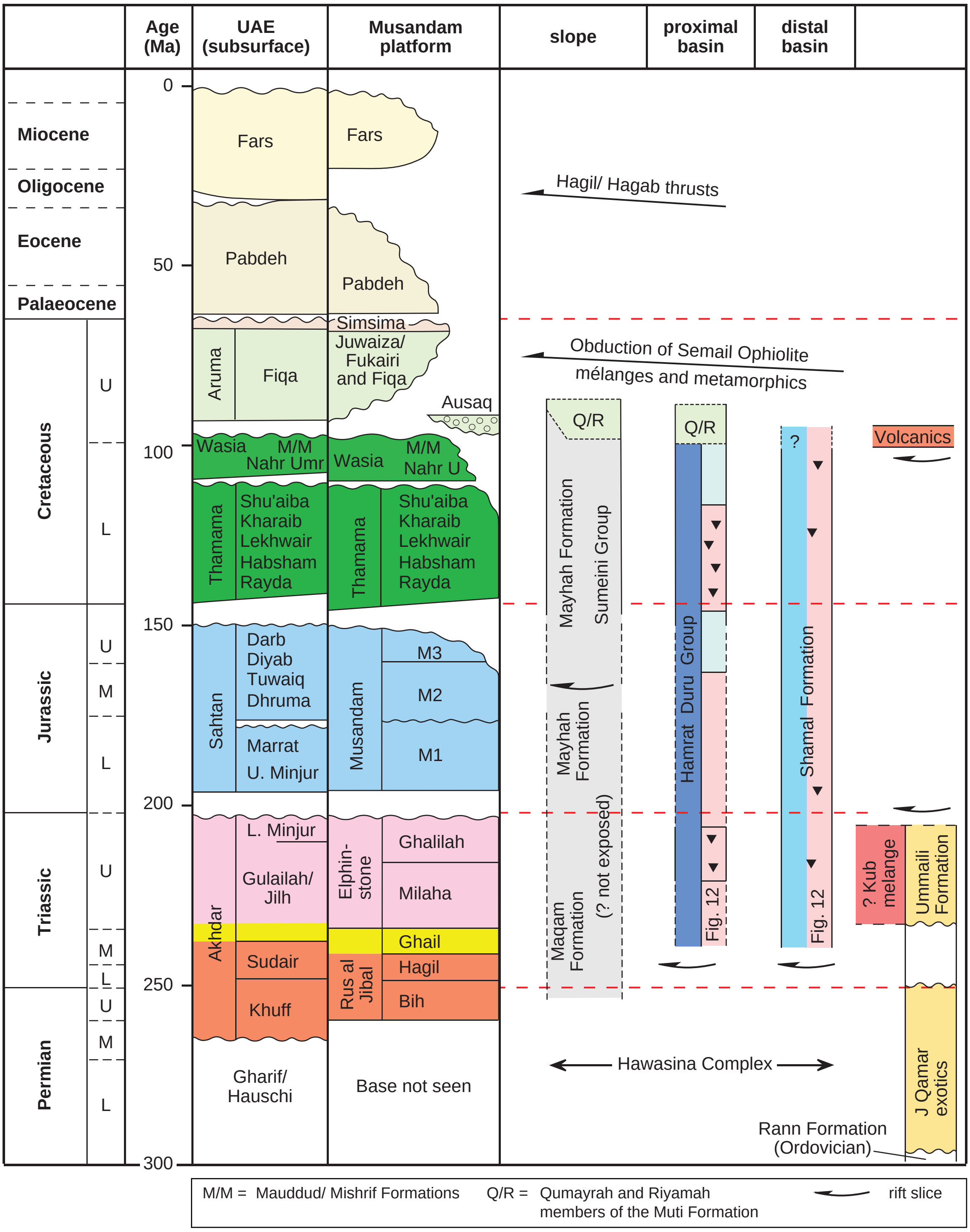

Figure 13: Stratigraphy of the Musandam and UAE foreland and allochthonous Sumeini Group, Hawasina and Haybi complexes, and Semail Ophiolite in the northern Oman Mountains (after Glennie et al., 1973, 1974; Nairn and Alsharhan, 1997; Searle, 2007).

A major eustatic drop in sea level at the end of the Triassic is evident from an erosional unconformity above which orangy-brown ferruginous sandstones and oolitic limestones with bivalves, gastropods, brachiopods and ostracods (Ghalilah Formation; Figure 14a) were deposited in northern Musandam. The Ghalilah sandstone horizon thins dramatically to the southeast, towards the shelf margin where there is abundant evidence for sub-aerial exposure. A deepening of the offshore basin at this time is reflected in the deposition of chert horizons in the upper Al Jil/Zulla and Halfa formations in Oman and the Shamal cherts in the Dibba Zone. Sandstone progradation into the proximal basin is reflected in the deposition of quartzose sandstones in the Sumeini Group slope deposits in the northern Oman Mountains (upper Triassic 'F'-member of the Maqam Formation, Watts and Garrison, 1986; Watts, 1987, 1990).

The Jurassic was a long, stable period of shallow-marine passive margin sedimentation with limestone deposition across the Arabian platform shelf. The Musandam Group is ca. 1,500 m thick and exposed throughout the Musandam Peninsula (Figures 14b, c, d). Musandam units 1, 2 and 3 are Jurassic and are time-equivalent rocks to the Sahtan Group in Jabal Al-Akhdar (Glennie et al., 1974; Ricateau and Riche, 1980; Rabu et al., 1993). Muddy, tidal-flat shoaling-upward sequences contain abundant fossils including gastropods, bivalves (*Lithiotis* sp.), corals and stromatoporoids. Facies changes gradually towards the SE, towards the shelf margin, along the Dibba Zone where well-bedded shelf carbonates grade into coarser grained deposits, slope facies carbonates and slope mudstones of the Mayhah Formation (Sumeini Group). At Ras Musandam, syn-sedimentary listric normal faults have boulder-size mega-breccias associated with shelf margin faulting. The uppermost Jurassic–Lower Cretaceous in the Musandam Peninsula is marked by a prominent band of thin-bedded, pelagic lime mudstones and cherts (Rayda Formation; Figure 14b, c) that marks the base of Musandam unit 4.

The latest Jurassic–early Cretaceous sequence (Figure 14d) is represented by the Musandam unit 4 of Glennie et al. (1974) and Biehler et al. (1975) and is equivalent to the Thamama Group in sub-surface Oman and the Kahmah Group in Al Jabal Al-Akhdar. Musandam unit 4, Thamama Group and equivalents are part of megasequence AP8 (*sensu* Sharland et al., 2001), which starts in the Tithonian. This is also confirmed by recent studies (e.g. Droste, 2013; Razin et al., 2013) in sub-surface Oman and UAE (Strohmenger et al., 2006). It comprises five formations, from the base the Rayda, Salil/Habshan, Lekhwair, Kharaib and Shu'aiba. The group is ca. 600 m thick along the western edge of the Musandam Mountains, but just 140 m thick along their southern edge at Batha Mahani (Styles et al., 2006). The Musandam unit 4/Thamama Group is overlain unconformably by the Aptian–Cenomanian Nahr Umr, and Mauddud/Mishrif formations that together comprise the Wasia Group. The Shu'aiba Formation and the Mauddud/Mishrif formations (equivalent to the Natih Formation) are the main hydrocarbon reservoirs in interior Oman (Hillgärtner et al., 2003; Homewood et al., 2008). Muddy carbonates with abundant benthic foraminifera (*Orbitolina* sp.) represent a major rise in sea level in the latest Aptian (Nahr Umr Formation). Shale deposits of the Nahr Umr Formation are widespread on the Arabian Plate following the late Aptian lowstand and form a major seal over the important Lower Cretaceous reservoirs in the UAE (van Buchem et al., 2002, 2010; Pierson et al., 2010). Stable carbonate shelf sedimentation ended abruptly in the Cenomanian, with the collapse and drowning of the continental margin ahead of emplacement of the Semail Ophiolite and its underlying Tethyan oceanic deeper water thrust sheets.

Along the Musandam shelf edge, large-scale olistostromes and debris flows lie above an unconformity that cuts progressively down-stratigraphic section to the SE along Wadi Batha Mahani (Searle et al., 1983; Styles et al., 2006). This unconformity cuts down to the top of the Jurassic having scoured out at least 600 m thickness of Lower Cretaceous. Numerous intra-formational unconformities along the southeastern margin of Musandam (Figure 14e) also record a prominent slope facing ESE. The shelf margin collapsed catastrophically in the late Cenomanian–Turonian with even larger debris flows (Ausaq conglomerates). These olistostromes and breccias are also exposed in Wadi Dhayah beneath the Hagab Thrust (Figures 14f, g). Along the east coast of Musandam these slope facies conglomerates and limestones are abruptly truncated by the steep, east-dipping Dibba normal fault (Figure 14h). West of the mountain front the Aruma Group is the flexural foredeep of the foreland basin that initiated with loading of the thrust sheets during the Turonian–Campanian (Robertson, 1987; Patton and O'Connor, 1988). In the Oman Mountains, the Muti conglomerates unconformably overlie the Cenomanian–?lowermost Turonian shelf carbonates reflecting the final collapse of the Mesozoic shelf. In the interior, the thick Upper Cretaceous Aruma Basin is infilled with the Fiqa shales and Juweiza Formation shales and conglomerates as seen in all wells SW of the mountain front in Oman and UAE. These shales and conglomerates are probably equivalent to the 'Fukairi beds' of Hudson et al. (1954a) that are exposed along the western side of the Musandam Mountains in the Hagil Window area (Figure 14f). In the Rams-Dhayah area of Ras al Khaimah, these conglomerates lie stratigraphically above the Upper Albian–Middle Cenomanian Mauddud/Mishrif formations which mark the top of the shelf carbonates.

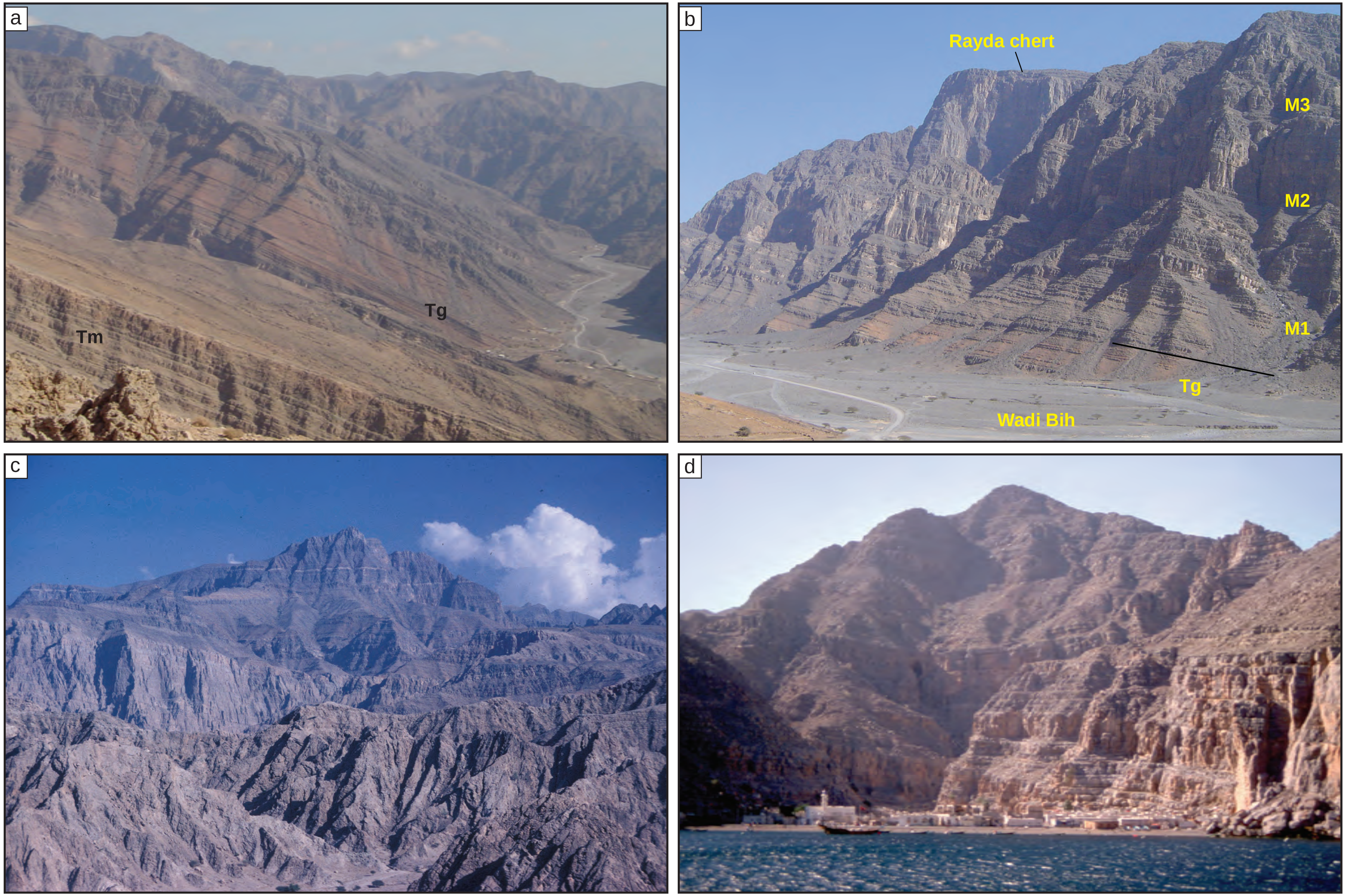

Figure 14: Photos, Musandam shelf carbonates. (a) Triassic Milaha (Tm) and Ghalilah (Tg) Formations, Wadi Bih. (b) Jurassic Musandam Group limestones and overlying Rayda cherts, Wadi Bih. (c) Jabal Hagab, Musandam Group limestones in central Musandam. (d) Jurassic Musandam Group limestones on cliffs above Kumzar village, north coast of Musandam.

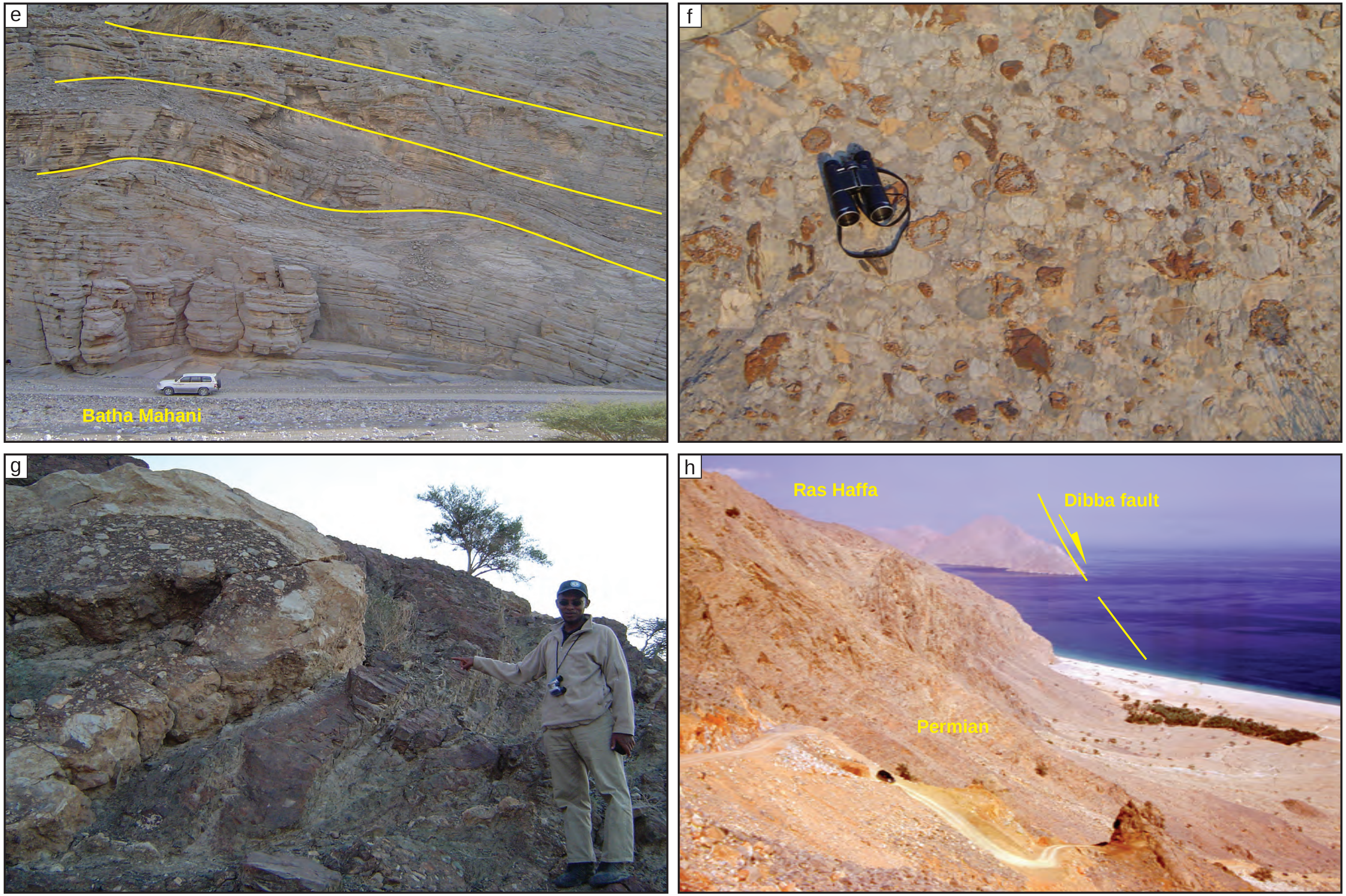

Figure 14: (e) Intra-formational unconformities in the shelf slope facies limestones, Batha Mahani, Dibba Zone. (f) Cenomanian slope facies conglomerates (Ausaq conglomerates) Wadi Dhayah, Ras al Khaimah. (g) Cenomanian–Turonian slope facies conglomerates folded beneath the Hagab Thrust, Dhayah, Ras al Khaimah. (h) Permian Bih Formation dolomites along the southeast coast of Musandam south of Ras Haffa. The Dibba normal fault lies immediately offshore extending south onshore along the southern margin of Musandam shelf carbonates.

TECTONIC MODEL FOR LATE CRETACEOUS OPHIOLITE OBDUCTION AND EMPLACEMENT

We propose a tectonic model for the obduction history of the Semail Ophiolite in the northern Oman Mountains based on mapping, structural, metamorphic and thermo-barometric constraints, combined with U-Pb geochronology. Timing constraints for the ophiolite, metamorphic sole, Bani Hamid granulites and granitic dykes are shown in Figure 15. Although the obduction history is a continuum it can best be illustrated in four 'stages' illustrated in Figures 16a to 16d.

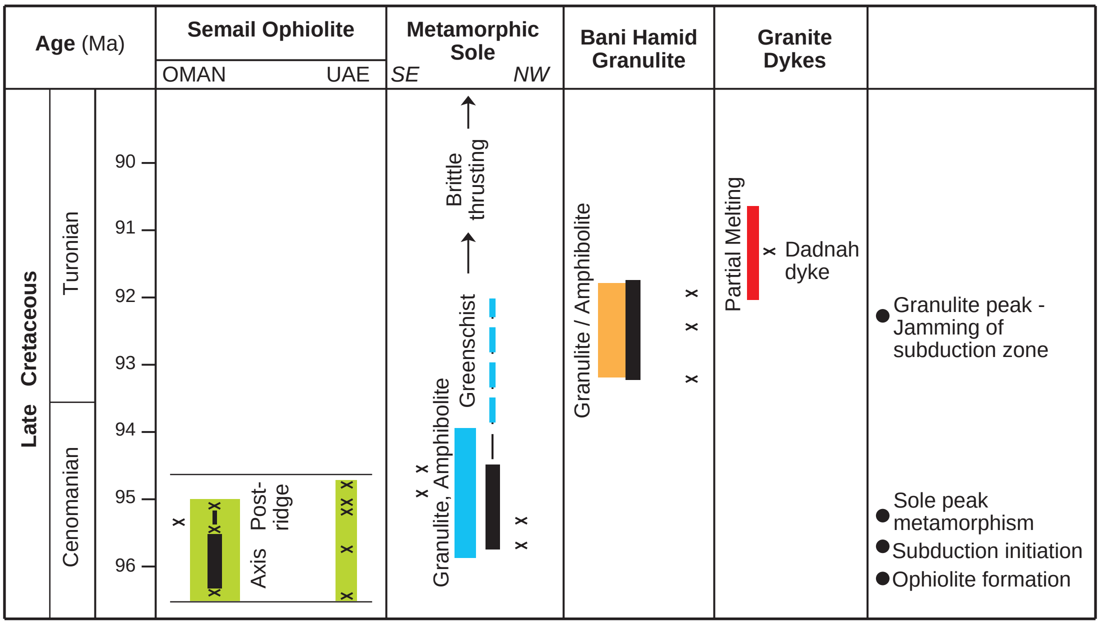

Figure 15: Time chart for the Cenomanian–Turonian period of the Late Cretaceous showing all precise U-Pb zircon age constraints (see text for sources of data).

(a) Formation of the Ophiolite and Subduction of the Metamorphic Sole

U-Pb zircon dating shows that the ophiolite crustal sequence gabbros and trondhjemites crystallised at 96.4–95.3 Ma (Tilton et al., 1981; Warren et al., 2005; Styles et al., 2006; Rioux et al., 2012) overlapping synchronously with U-Pb zircon ages from the amphibolite sole at 94.90–94.48 Ma (Warren et al., 2005; Styles et al., 2006; Rioux et al., 2013). The 'normal' metamorphic sole comprising the amphibolites with granulite enclaves, formed in an exhumed subduction channel from depths as much as ca. 40 km and were accreted onto the base of the ophiolite mantle sequence peridotites during the initial obduction event (Searle and Malpas, 1980, 1982; Gnos, 1998; Cowan et al., 2014). These data strongly suggest that subduction zone amphibolite-granulite metamorphism at depths of ca. 40 km was occurring in the mantle beneath the ophiolite at the same time as the ophiolite crustal gabbros and trondhjemites were crystallising (Figure 16a).

(b) Exhumation of the Metamorphic Sole and Initiation of Obduction

The sole amphibolite-granulites were exhumed from 35-40 km depth up to higher levels and successively had thrust slices of epidote amphibolites and greenschists accreted to their base (Figure 16b). The exhumation of the sole rocks was extremely rapid as deduced from almost synchronous $^{40}Ar/^{39}Ar$ cooling ages of hornblende at 93.5 Ma and muscovite and biotite ages of 92.4–89.2 Ma (Hacker, 1994; Hacker et al., 1996). The inverted metamorphic gradient in the metamorphic sole clearly shows that the heat source for metamorphism lay in the overlying Mantle Sequence harzburgites and dunites. As the rocks in the subduction channel exhumed as the metamorphic rocks were returned to the surface, ductile shearing and isoclinal folding gave way to brittle thrusting and high-level imbrication as seen in the Dibba Zone and along the Masafi corridor. The metamorphic sole is now only seen in various tectonic windows (e.g. Sumeini, Asjudi, Hawasina windows) along the western margin of the Oman Mountains (Searle, 1985, 1988a, 2007; Searle and Cooper, 1986; Cowan et al., 2014).

(c) Jamming of the Subduction Zone; Granulite Facies Metamorphism

As the ophiolite obduction process continued the Haybi Complex thrust sheet was progressively underthrust beneath the ophiolite with its accreted metamorphic sole (Figure 16c). These predominately carbonate and quartzite rocks were unable to subduct more than mid- or lower crustal depths due to buoyancy and were therefore jammed against the subduction zone. Continued compression led to isoclinal folding at all scales in the Bani Hamid granulites (Cherry et al., 2014). Restoration of the large-scale folds show a minimum of 130 km internal shortening, and the west-directed breaching out-of-sequence Bani Hamid Thrust shows more than 30 km offset. At higher structural levels, the metamorphic sole, Haybi Complex and Hawasina Complex thrust sheets were imbricated and subsequently folded across the Dibba Zone (Searle, 1988a). Deep seismic profiles (Tarapoanca et al., 2010) show that the Sumeini Group shelf-slope carbonates, the easterly extension of the Permian–Cenomanian shelf sequence was stacked up at depth beneath the ophiolite.

(d) Out-of-sequence Thrusting and Exhumation of Bani Hamid Granulites

The final stage in the evolution of the Bani Hamid granulites involved late-stage west-vergent out-of-sequence thrusting along the Bani Hamid Thrust (Figure 16d). This late thrust effectively doubles the thickness of the overlying Semail Ophiolite mantle sequence and thrusts a more outboard complete ophiolite unit onto a more inboard mantle sequence unit. The Bani Hamid Thrust is therefore a later structure cutting through, or breaching, the overlying Semail Ophiolite, and the upper thrust is a structurally deeper part of the original Semail Thrust, carried passively piggy-back fashion along the Bani Hamid Thrust.

At some stage between 'peak' granulite metamorphism (Figure 16c) and out-of-sequence thrust culmination (Figure 16d), localised crustal melting resulted in production of small-scale tonalitic to leucogranitic melts. These small granitic dykes have common biotite, and variable amounts of garnet, tourmaline, andalusite, muscovite and cordierite (Peters and Kamber, 1994; Cox et al., 1999). These minimum melt peraluminous crustal melt granites require a muscovite- or biotite-rich psammitic or pelitic source. This presents a problem, since none of the Bani Hamid granulite lithologies are suitable source rocks. We propose a pelitic component of the Haybi Complex, or possibly the Hamrat Duru Group could be buried beneath the eastern UAE part of the mountains, beneath the region where the granitic dykes now occur (eastern Khawr Fakkan block, Ras Dadnah area). Clearly more work is required to determine the precise sources of these enigmatic leucogranitic dykes.

(e) Subduction of the Continental Margin and Eclogite Facies Metamorphism

Evidence for this final stage in the ophiolite obduction history comes only from the eastern Oman Mountains around Muscat-Ruwi area and the As Sifah eclogites (e.g. Searle et al., 1994, 2004; Agard et al., 2010). Here, at the deepest structural levels of the eastern part of the mountains, Permian basaltic sills intruded into Saiq Formation carbonates at the lower levels of the shelf carbonate sequence have been subducted to depths of nearly 100 km beneath the Muscat peridotite (the eastern part of the Semail Ophiolite). U-Pb ages (TIMS) of zircon inclusions in garnet from the As Sifah eclogites are 79.1 ± 0.3 Ma (Warren et al., 2003), 15 million years younger than the age of the ophiolite and the age of the sub-ophiolite metamorphic sole (Figure 15).

Between 95 Ma and 79 Ma the entire Oman Mountains allochthon was assembled by progressive thrust stacking of more distal units over more proximal units (Haybi Complex over Hawasina Complex over Sumeini Group and shelf-margin carbonates). Shortening of some 300–400 km is recorded by restoring these thrust sheets (Cooper, 1988). NE-vergent folds and top-to-NNE shear sense indicators

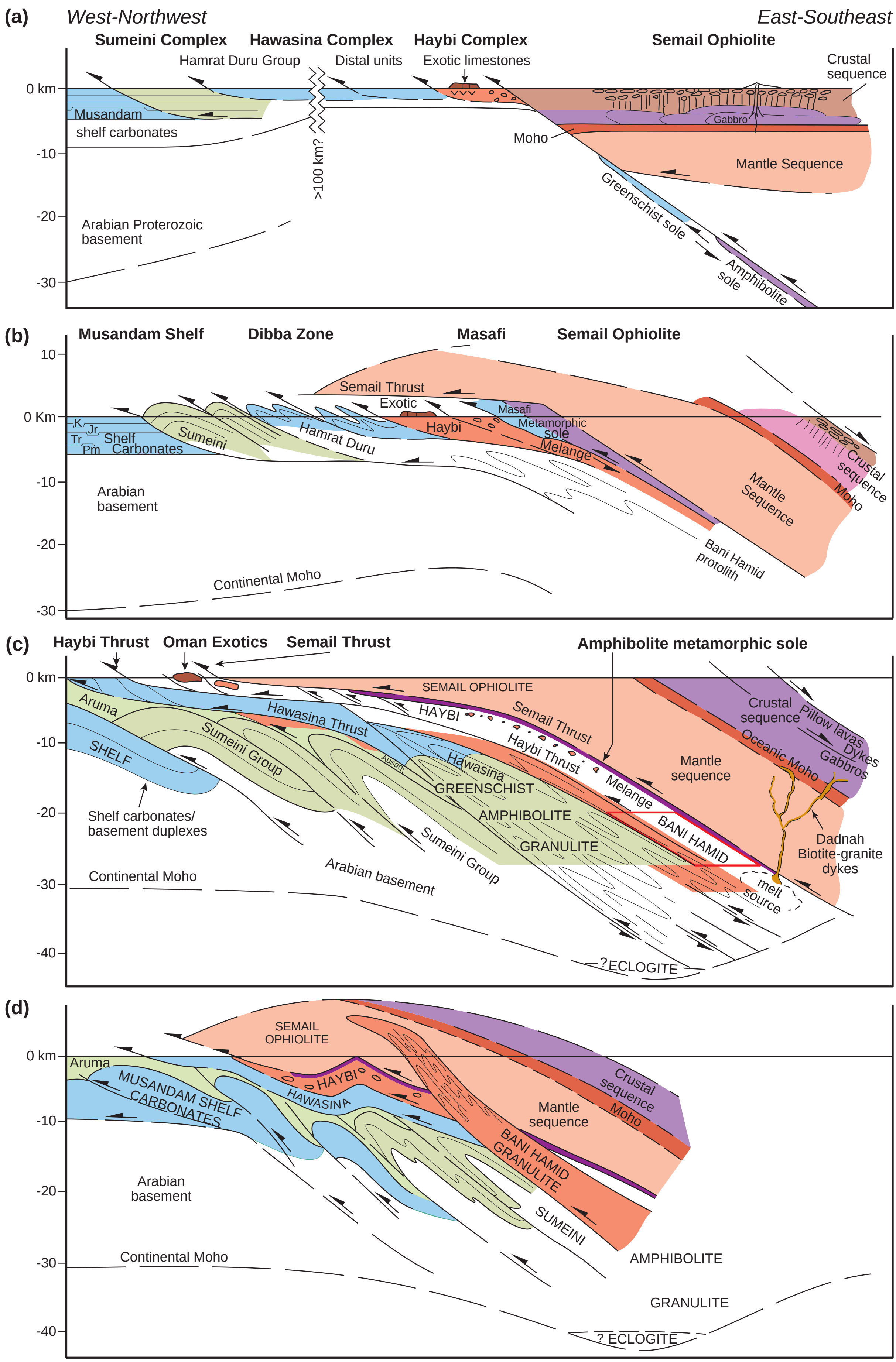

Figure 16: *See facing page for caption.*

throughout the eclogite-blueschist zone are interpreted as representing relative extension during exhumation of the footwall high-pressure (HP) rocks in a subduction channel (Searle et al., 2004; Agard et al., 2010). Exhumation of the footwall HP rocks was accompanied by NE-dipping normal faults that progressively place lower pressure rocks above higher-pressure rocks. Structurally higher units around Muscat-Ruwi contain lawsonite in meta-basalts and carpholite, pyrophyllite, sudoite and kaolinite in meta-sediments (7–10 kbar; 27–39 km depth; Goffé et al., 1988; Agard et al., 2010). Structurally lower garnet- glaucophane/crossite blueschists were metamorphosed at 12–15 kbar (equivalent to 47–58 km depth). The lowest unit, the As Sifah eclogites contain the assemblage: garnet + clinopyroxene + glaucophane + phengite and was metamorphosed at 20–23 kbar (78–90 km depth; Searle et al., 2004; Massonne et al., 2013).

Whereas in the northern Oman Mountains the subduction process terminated in the Turonian with high-temperature stacking of distal Tethyan sediments (Bani Hamid granulites), in the eastern mountains subduction continued until the Campanian with high-pressure stacking of the Permian dolomites-limestones with their basaltic-eclogite pods (As Sifah eclogites).

STAGES 2 AND 3: OLIGOCENE–MIOCENE CULMINATION AND CONTINENTAL COLLISION

Following ophiolite obduction, passive margin sedimentation was re-established in the Maastrichtian with the deposition of widespread shallow-marine gastropod and rudist-rich limestones of the Simsima Formation (Skelton et al., 1990; Searle and Ali, 2009). A period of erosion at the start of the Cenozoic is attributed to isostatic rebound (Nolan et al., 1990) before the onset of the development of a second foreland basin, the Pabdeh Basin, along the western side of the northern Oman Mountains and Musandam Peninsula and northwards into Iran. Tarapoanca et al. (2010) used 'Thrustpack' to model broadly continuous deformation throughout the Palaeogene. However, this scenario seems unlikely because of the very stable conditions shown by the fossiliferous shallow-water carbonates deposited throughout this period lasting ca. 40 Myr along the entire Oman Mountains (Fournier et al., 2006; Searle and Ali, 2009). It is possible that the Upper Cretaceous thrust sequence seen along the Oman Mountains did last beyond the Maastrichtian in a few cases. For example in Jabal Sumeini (Figure 1; Searle and Ali, 2009, their figure 7) the youngest thrust along the western margin of the mountains cuts up into the Maastrichtian and Palaeocene neoautocthonous succession.

Figure 16 (see facing page): (a) Initial tectonic setting of the Semail Ophiolite during its formation in the Late Cenomanian (96–95 Ma) showing depth and position of the Metamorphic sole amphibolites with granulite enclaves forming in a NE-dipping subduction zone beneath the ophiolite.

(b) Cenomanian/Turonian boundary (94–93 Ma). The Metamorphic sole has exhumed to higher structural levels and accreted onto the base of the Semail Ophiolite. The ophiolite has obducted onto the margin together with underlying thrust sheets of Haybi Complex and Hawasina Complex rocks. Thrusting has progressed by deep subduction-related ductile shearing to more brittle fold-thrust structures as seen in the Dibba Zone.

(c) Turonian (93–92 Ma). This is the timing of peak granulite facies metamorphism in the Bani Hamid rocks. Unsubductable cherts, limestones and calc-silicates were jammed at mid- to lower crust depths, isoclinally folded and shortened beneath the ophiolite. Deep-level thrusting in the Sumeini Group shelf margin rocks is seen in seismic profiles and was initiated at depth beneath the western part of the ophiolite in the UAE.

(d) Late Turonian (91–90 Ma). Final exhumation of the Bani Hamid granulites along the breaching out-of-sequence Bani Hamid thrust occurred in the middle of the ophiolite. Stacked-up Haybi, Hawasina and Sumeini Group rocks thickened the Oman continental margin. Thin-skinned thrusting continued on from Turonian into Coniacian–Santonian times as the Oman Mountain fold-thrust belt developed. By this time all granulites, amphibolites and greenschists had been exhumed to high structural levels.

The Cenozoic jabals along the western foreland in northern Oman and UAE also show extensive folding of Palaeocene–Eocene rocks (Searle and Ali, 2009; Warrak, 2010). In the deep crustal seismic lines D1 and D4 several west-vergent thrusts also cut up into the Pabdeh Formation implying continuing crustal shortening after ophiolite obduction including during sedimentation of the Late Oligocene–Early Miocene Asmari Group (Tarapoanca et al., 2010). Seismic data shows that several anticlines formed during Early Miocene Fars Formation sedimentation, synchronously with subsidence in the outer zones (Tarapoanca et al., 2010). One anomalous feature on the seismic interpretation of Tarapoanca et al. (2010) is the large-scale east-vergent backthrust along the Fujairah coast, extending east into the Gulf of Oman. There is no surface geological evidence for this backthrust and industry seismic data offshore UAE shows only pre-Middle Miocene folding, with no evidence for an east-verging thrust-fold belt in the Gulf of Oman.

Hagil Window and Ras Al Khaimah Offshore

The Hagab Thrust is the major west-vergent thrust that places the entire Middle Permian–Cenomanian shelf carbonate sequence exposed in the Musandam Mountains together with its unexposed pre-Middle Permian basement rocks westward over the stable Arabian platform (Figure 4). Seismic sections in the UAE foreland (Dunne et al., 1990; Tarapoanca et al., 2010) and in the Arabian Gulf offshore Ras al Khaimah (Ricateau and Riche, 1980) show several west-vergent thrust structures of which the Hagab Thrust is the largest. It is well exposed around the Hagil Window in Ras al Khaimah (Figure 17; Biehler et al., 1975; Searle et al., 1983; Searle, 1988b). The footwall of the Hagab Thrust shows a complex thrust sheet that includes Jurassic–Lower Cretaceous radiolarian cherts, Haybi alkali basalts including a rare alkaline ultramafic intrusion, identical to those in the Haybi Complex in Oman (Searle, 1984). The hanging-wall shows a large-scale west-vergent fold that affects the entire Permian–Cenomanian shelf carbonate sequence.

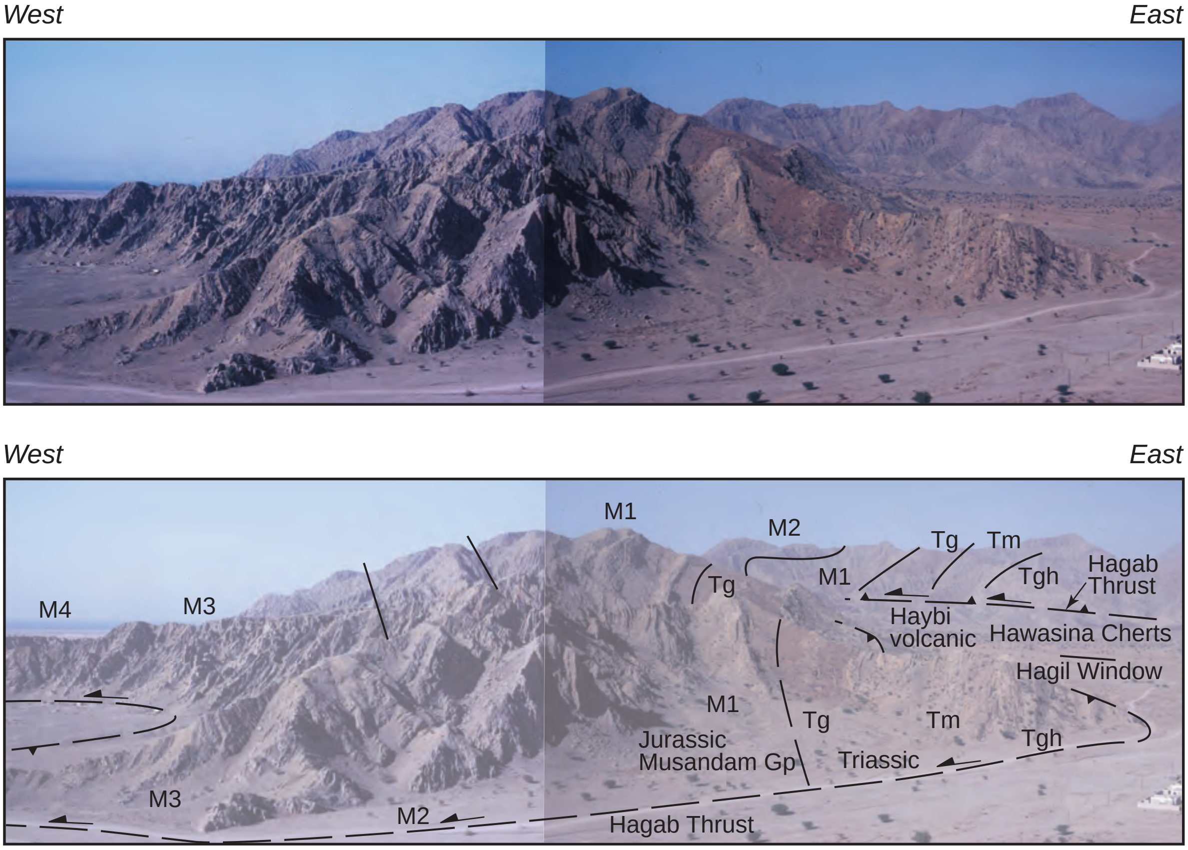

Figure 17: Panorama of the Wadi Hagil section showing the frontal fold of the Musandam, the Hagab Thrust and Hagil Window, Ras al Khaimah.

The subsurface structural configuration along the unexposed western leading edge of the deformed thrust front belt that flanks the Musandam Peninsula is less well understood. However, determining the subsurface structures of this area is of great interest for hydrocarbon exploration as several oil and gas condensate fields, such as West Bukha, Bukha, Saleh, Tibat, occur along this trend. Recently, an exploration drilling programme was completed on the western side of the Hagil Window where the main target was composed of uplifted Mesozoic shelf carbonates. The main structures within these fields are assumed to be anticlines over tilted fault blocks and reverse faults with deep basement detachments.

Along the east margin of the Hagil Window, Permian Bih Formation dolomites are thrust over the Haybi Complex rocks. The Bih, Hagil and Ghail Formation dolomites strike north into the Wadi Shah region where a band of intense folding and minor thrust faulting extends north to the Wadi Rahabah and Wadi Ghalilah region, where it merges with splays off the Hagab Thrust. North of the Hagil Window the footwall of the Hagab Thrust shows a complete Lower–middle Cretaceous section in the Rams quarry area between Wadi Dhayah and Wadi Ghalilah (Hudson et al., 1954b; Hudson and Chatton, 1959). Here the Shu'aiba, Nahr Umr and Mauddud formations are well exposed along the western flank of the mountains. Overlying the Cenomanian Mauddud Formation is a thin layer of grey marl with Late Turonian–Santonian planktonic foraminifera (Ilam shales) and then a highly distinctive limestone breccia marking the final collapse of the shelf as the thrust sheets were emplaced above (Figures 14f, g).

The west-vergent Hagab Thrust is seen on offshore seismic profiles extending at least as the Ghubbali-1 Well. A structurally higher thrust, the Bukha Thrust is well exposed around Bukha village on the west coast of Musandam (Figure 18a). Onland, this thrust has been mapped towards the south linking with the Wadi Shah Thrust along the northeast margin of the Hagil Window (Figures 18b, c and d). South of Bukha village it places Upper Triassic Ghalilah Formation over Jurassic Musandam Group rocks. The throw increases to the south and along Wadi Shah it places Permian Bih and Triassic Hagil Formation dolomites over Jurassic Musandam Group rocks. Further east in the central part of the Musandam, two further thrust faults have been mapped, one cutting across Khawr Najd and Khawr Ash Sham placing Ghalilah Formation over Musandam Group (Figures 18e and 18f), the second running south of Khawr Habalayn placing Jurassic Musandam Group units 1 and 2 over Lower Cretaceous Musandam unit 4 rocks (Figure 3). Neither of these thrusts have a large offset, but both extend through the whole shelf carbonate sequence into the pre-Permian basement.

Well sections in UAE record a second major flexural foreland basin, the Palaeocene–Eocene Pabdeh Basin that developed in front of the Hagab Thrust as a result of loading of the Musandam thrust sheet. Balanced and restored cross-sections show that a minimum of 15 km of westward translation occurred along the Hagab Thrust (Searle, 1988b; Dunne et al., 1990). Offshore Ras al Khaimah and Omani Musandam, industry seismic data image several major east-dipping, west-verging thrust faults that cut through Upper Cretaceous Fiqa Formation and Palaeogene Pabdeh Formation rocks in the footwall (Figure 19). Thrust tip lines terminate beneath the Upper Miocene Lower Fars Formation and are abruptly truncated at the base of the Mishan Formation (Upper Miocene) marls (Ricateau and Riche, 1980; Michaelis and Pauken, 1990; Jahani et al., 2009). These structural relationships confirm that the culmination of the Musandam shelf carbonates and movement along the Hagab Thrust was a mid-Cenozoic event spanning Oligocene–Early Miocene. Several exploration wells drilled offshore Omani Musandam reached the top shelf carbonates (Henjam, Bukha, Ghubbali, Salama wells). Seismic and well data show that the Henjam and Bukha wells were on the stable folded foreland beneath the Hagab Thrust, whereas the top-shelf carbonates in the Ghubbali and Salama wells are much shallower, because they drilled into the toe of the Hagab Thrust (Figure 20). The Hagab Thrust therefore must lie between the sites of the Bukha and Ghubbali wells, offshore Musandam.

East of the Musandam Peninsula seismic data offshore Fujairah (UAE) show complex faulting and deep down-warped troughs infilled with Eocene, Oligocene and Lower Miocene sediments. An abrupt unconformity at the base of the Mid-Miocene truncates all earlier strata, above which Mid-Miocene, Pliocene and younger sediments are flat-lying, dipping gently and thickening towards the east. This Mid-Miocene unconformity is similar to that west of the Musandam Peninsula and strongly suggests that culmination of the Musandam shelf carbonates ended at this time. In the Gulf

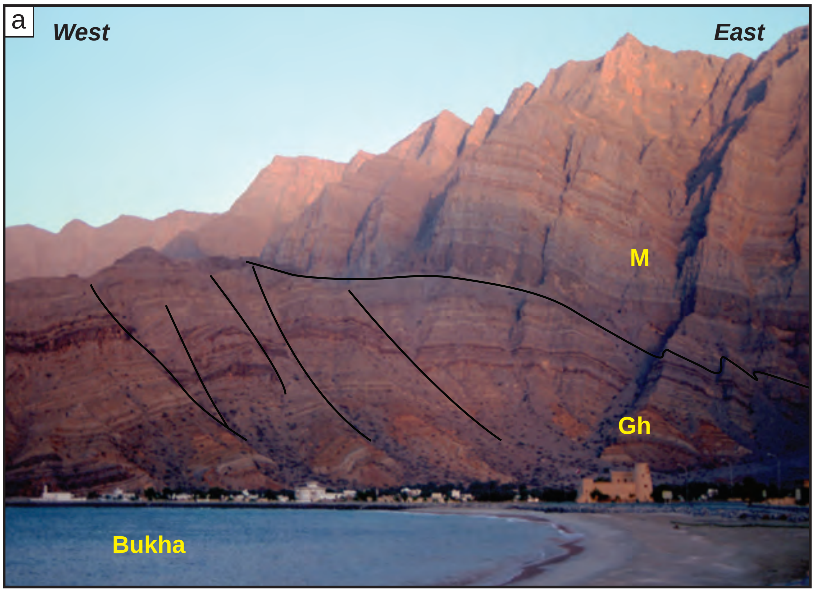

Figure 18: Photos, Musandam structures. (a) Bukha Thrust, structurally higher than the Hagab Thrust running along the northwestern shore of Musandam.

Figure 18: (b) A minor thrust associated with the hanging-wall of the Hagab Thrust.

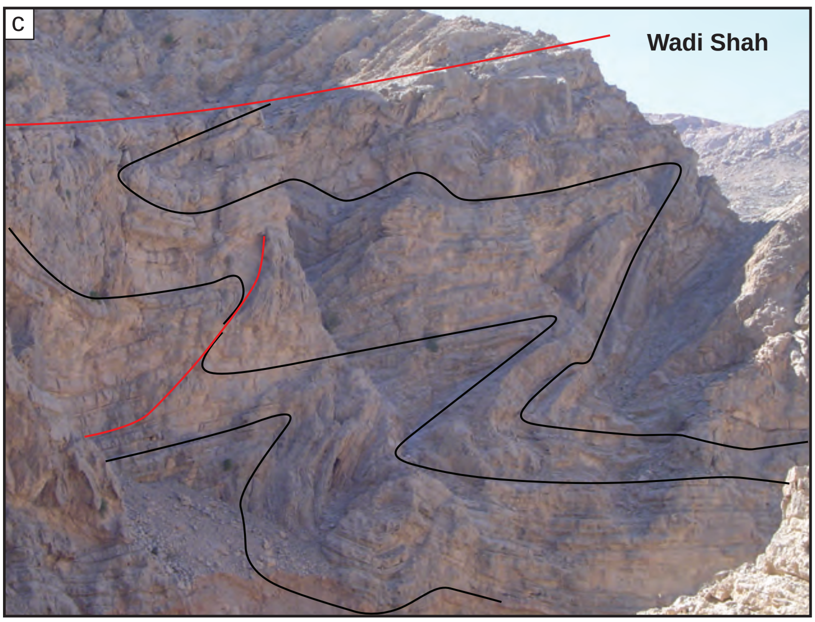

Figure 18: (c) Folding above the Bukha-Wadi Shah Thrust, northeast of the Hagil Window.

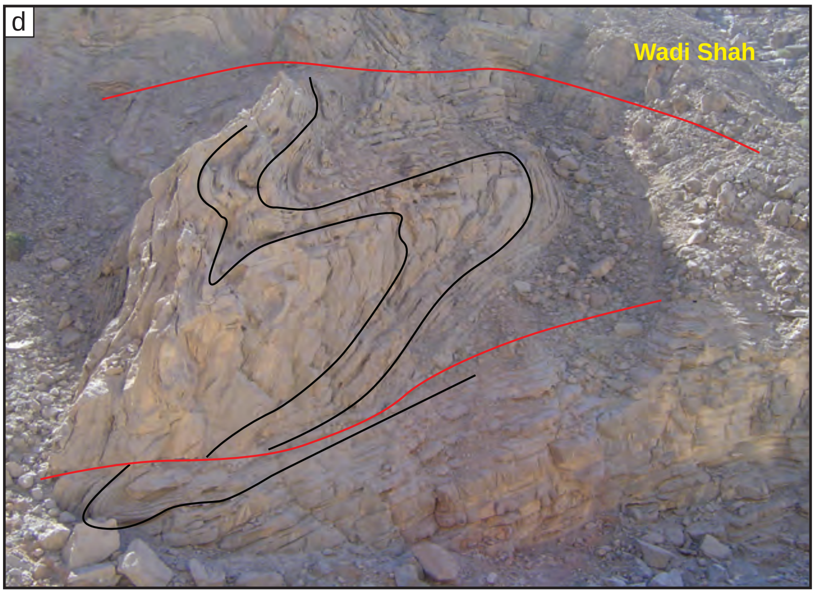

Figure 18: (d) Isoclinal folding and thrusting associated with the Bukha-Wadi Shah Thrust, northeast of the Hagil Window.

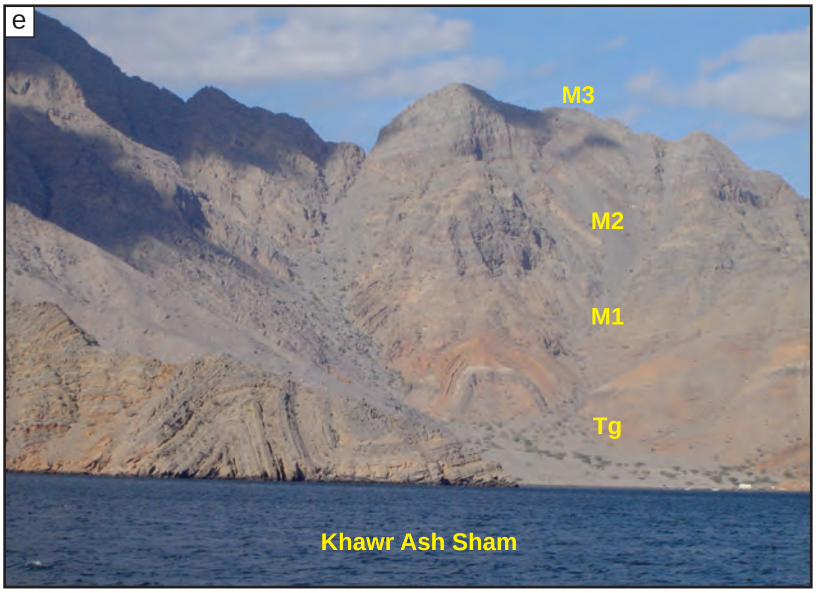

Figure 18: (e) Tight, upright folding in the Upper Triassic Ghalilah and Lower Jurassic Musandam unit 1 formations, Khawr Ash Sham, east of Khasab.

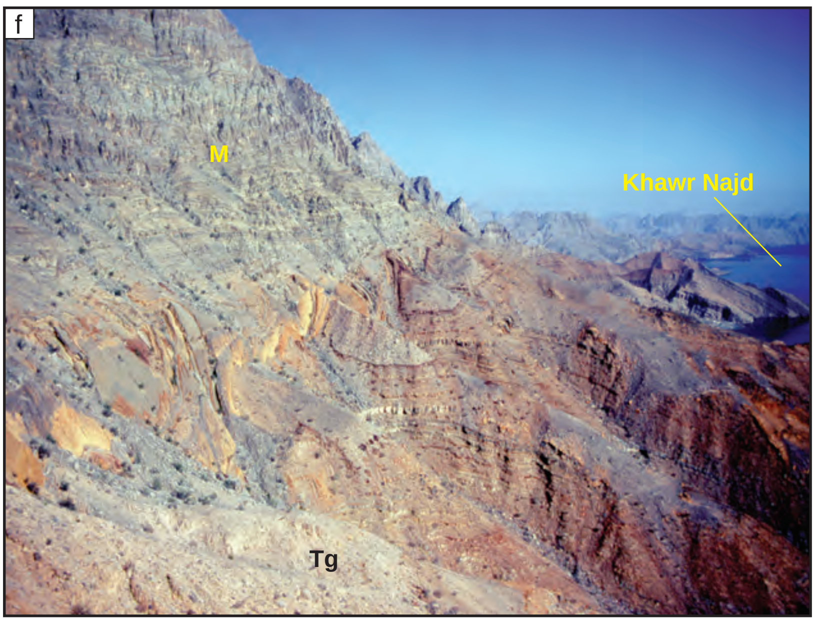

Figure 18: (f) Khawr Najd Thrust placing Upper Triassic Ghalilah Formation (right) over Musandam units 2–3, Khawr Najd, east fjords of Musandam.

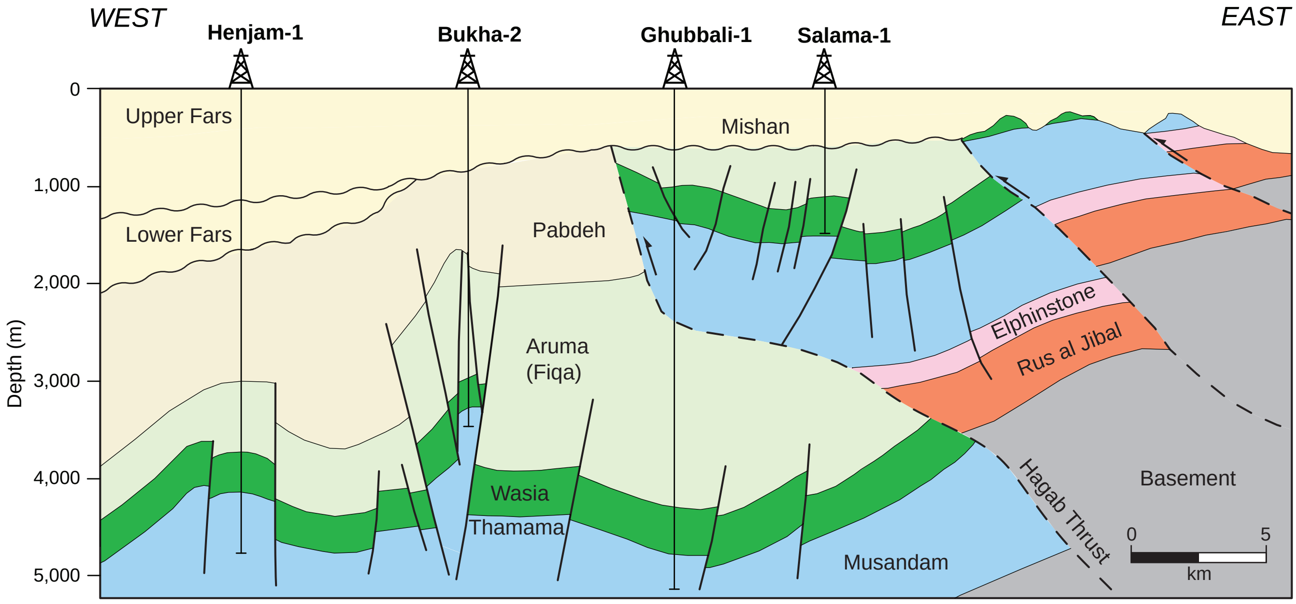

Figure 19: Simplified section showing depth conversion from two-way travel time and stratigraphic thicknesses linking the offshore Henjam, Bukha, Ghubbali and Salama wells based on offshore seismic and well data.

of Oman compressional folding is apparent during the Early Miocene but there is little or no evidence of compression in the younger sedimentary sequence above the Mid-Miocene unconformity. The two separate tectonic stages are also apparent from diagenetic studies. In the Musandam Peninsula, a large-scale fluid system with migration of hot brines has been inferred along Cenozoic reverse faults (Breesch et al., 2011). These brines were sourced from deeper rocks and are restricted to the footwall of the Hagab Thrust.

Strait of Hormuz Syntaxis

The 90 degree orogenic bend in thrust strike between the east-west striking southeastern Zagros Mountains and the north-south striking Musandam Mountains is termed the Strait of Hormuz syntaxis (Searle, 1988b). It marks the point where the Musandam promontory of the Arabian Plate is beginning to embed into the Iranian terrains of the Eurasian Plate. GPS velocities show that the Musandam is presently moving at about 25 mm/year towards the NNE (Talebian and Jackson, 2004). All structures in the Musandam Peninsula plunge gently to the north and have been traced on seismic profiles to extend as far as the Oman-Iran boundary in the Strait of Hormuz. In Iran the Zagros periclinal folds extend east as far as Qishn Island (Figure 1). Although being the eastern extremity of the Zagros, fold axes on Qishn Island do not all parallel the Zagros trend. Folds trend E-W (Salakh Anticline), NE-SW (Ramkan Anticline) and NW-SE (Laft Anticline) converge to form a complex structure in the central part of the island (Nissen et al., 2007). We interpret this pattern to reflect the indenting Musandam Peninsula to the south of the Strait of Hormuz syntaxis.

The active southern boundary of the Zagros Mountains, the Zagros Thrust is interpreted to lie immediately south of Qishn Island. This Pliocene–Recent NE-dipping thrust fault intersects the northern extension of the east-dipping Hagab Thrust at a point ca. 30 km north of Kumzar in Oman, SE of the eastern tip of Qishn Island in Iran. The Strait of Hormuz syntaxis separates the dominantly Palaeogene tectonic regime in the Musandam Peninsula with the mainly Neogene tectonic regime in the Zagros Mountains.

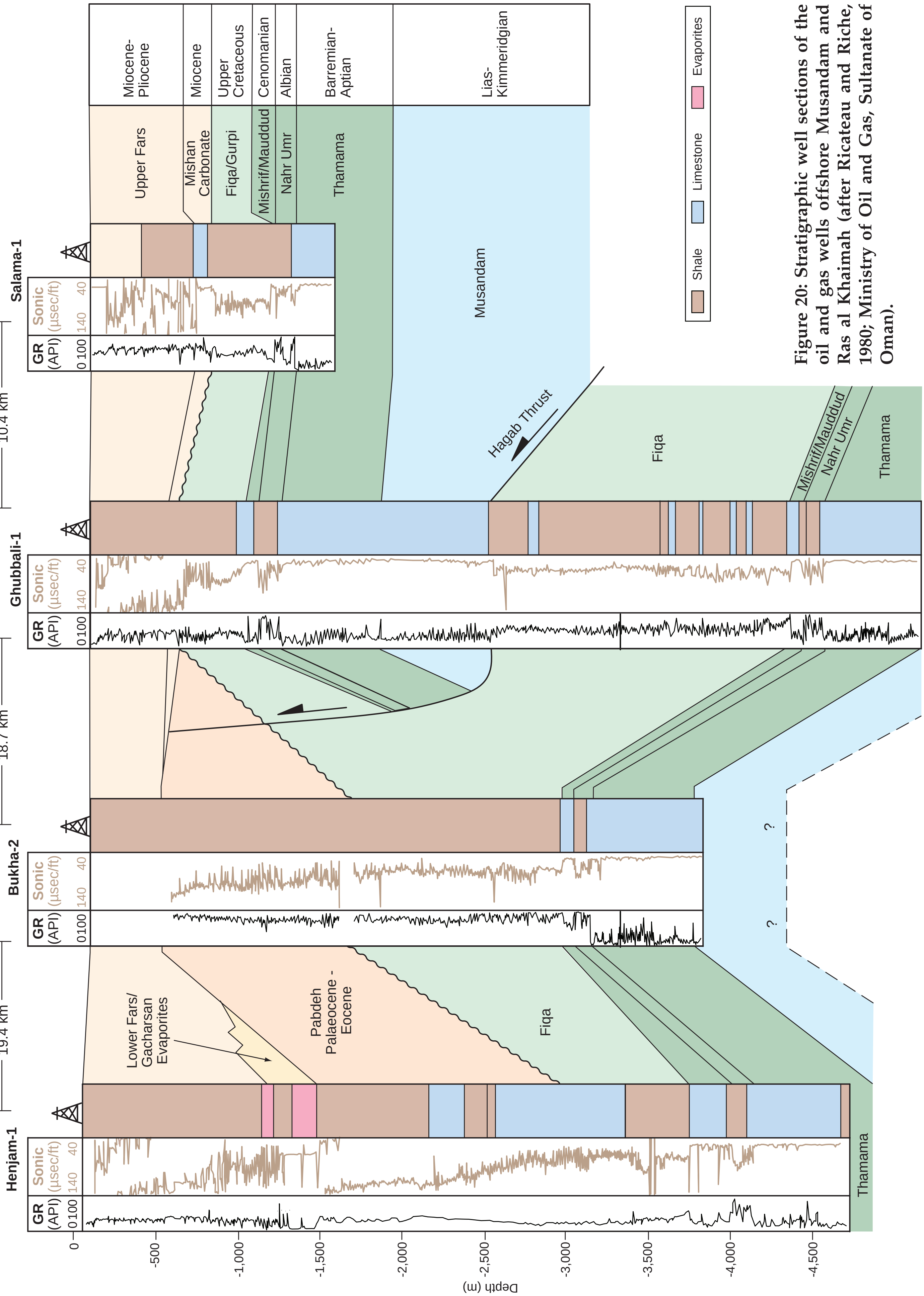

Figure 20: Stratigraphic well sections of the oil and gas wells offshore Musandam and Ras al Khaimah (after Ricateau and Riche, 1980; Ministry of Oil and Gas, Sultanate of Oman).

TECTONIC MODEL FOR CULMINATION OF MUSANDAM AND ARABIA-IRAN COLLISION

Abundant geological and geochronological data show that ophiolite obduction along the Oman Mountains spanned the Late Cretaceous from Cenomanian to Maastrichtian. There seems little doubt from seismic and field evidence that culmination of the Musandam and motion along the Hagab Thrust was an early Miocene event. The Musandam Peninsula now separates relict Tethyan oceanic crust in the Gulf of Oman to the east, presently subducting northwards beneath the Makran accretionary prism, from continental crust in the Arabian Gulf to the west. During the Middle Miocene the Arabian Plate separated from Africa with the first oceanic crust, recorded by magnetic anomalies, forming in the axial zone of the Red Sea along the southwestern margin of Arabia (Le Pichon and Gaulier, 1988). Collision of Arabia with Central Iran-Turkey and closing of the Bitlis-Zagros Suture along the northeastern margin also occurred about this time (Hempton, 1987; Blanc et al., 2003; McQuarrie, 2004; Mouthereau et al., 2012; McQuarrie and van Hinsbergen, 2013). Continental collision along the Zagros Suture was preceded by a phase of Late Cretaceous–?Palaeocene ophiolite obduction with poorly preserved ophiolites exposed for example at Neyriz and Kermanshah, ophiolitic mélanges and blueschists (Agard et al., 2006, 2011).

The Zagros Mountains in Iran shows spectacular folding of a ca. 8–10 km thick package of Phanerozoic sedimentary rocks overlying a ca. 2–4 km thick Ediacaran–Cambrian salt (Hormuz-Ara salt) which provided the low-strength horizon for the basal detachment (Stephenson et al., 2007). This thick salt has mobilised and intruded to form many surface-piercing salt domes throughout the Zagros. Crustal shortening estimates from restoring balanced sections show ca. 85–50 km of Late Cenozoic shortening in upper crustal rocks (McQuarrie, 2004; Sherkati et al., 2005; Jahani et al., 2009; Verges et al., 2011; Mouthereau et al., 2012). Balancing constraints suggest that a similar length of lower crust (Proterozoic basement of Arabia) must have underthrust the Sanadaj-Sirjan Zone of Central Iran, northeast of the Zagros Suture. Deformation progressed from NE to SW and the active southern boundary of the Zagros is immediately offshore the Iranian coast. Present-day maximum horizontal stress (S_{Hmax}) inferred from earthquake focal mechanisms and borehole measurements as well as present-day GPS is approximately oriented NE-SW.

The Zagros style of folding extends east to the region north of the Strait of Hormuz syntaxis, and may terminate at the Zendan Fault (Figure 1). This fault was thought to be a dextral strike-slip fault accommodating the northward indentation of the Musandam but recent work has shown that it is a low-angle NE-dipping thrust fault (Molinaro et al., 2004). The Zendan Fault also clearly does not align with the steeper, east-dipping Dibba normal fault. The Zendan Fault marks a major difference in structural style. To the west in the Zagros there are large-scale periclinal and box-folds, detaching at 8–10 km depth, numerous salt domes and strong seismicity. To the east, the folds are long and narrow detaching at ca. 6 km depth, there are no salt domes and decreased level of seismicity (Molinaro et al., 2004). The volcanic arc in Baluchistan and Makran also extends west as far as the longitude of the Zendan Fault suggesting that the Zendan Fault may mark the boundary between continent-continent collision to the west (Zagros) and oceanic subduction beneath the active continental margin to the east (Makran).

CONCLUSIONS

Most of the structures along the Oman Mountains were formed as a direct result of the obduction of the vast Semail Ophiolite thrust sheet with underlying Tethyan oceanic thrust sheets from NE to SW onto the previously passive Permian–Mesozoic shelf carbonates of the Arabian platform. Metamorphic rocks beneath the ophiolite record both Cenomanian oceanic subduction during initial ophiolite detachment (granulite-amphibolite-greenschist metamorphic sole) and early Turonian Bani Hamid granulite facies rocks jamming of the subduction zone. In the Musandam peninsula the first affects of the Arabia-Central Iran continental collision are seen in the thick-skinned thrust repetition of the entire Permian–Mesozoic shelf sequence with thrusts extending into the basement.

The Semail Ophiolite is a ca. 15 km thick thrust sheet of Cenomanian oceanic crust and upper mantle that has been emplaced from NE to SW onto the previously passive continental margin of Arabia during the Late Cretaceous. The ophiolite shows an early ocean ridge axis suite of gabbros, tonalites, trondhjemites and pillow lavas (Geotimes, V1 unit) dated by U-Pb zircon between 96.4–95.4 Ma followed by a later post-ridge suite of gabbros, trondhjemites and island-arc related volcanics including boninites formed between 95.4–94.7 Ma (Lasail, V2 unit). Tonalitic partial melts in the metamorphic sole amphibolites-granulites formed at PT conditions of 770–900°C and 11–15 kbar (Cowan et al., 2014), equivalent to 35–40 km beneath oceanic crust and formed at 95.6–94.5 Ma. These ages overlap precisely in age with the ophiolite crustal sequence implying that subduction of the sole was happening at depths of > 35–40 km at the same time as the ophiolite was forming. The ophiolite thus formed in a supra-subduction zone tectonic setting and not at a mid-ocean ridge.

During the Turonian (ca. 93–92 Ma) the attempted subduction of Oman Exotic seamounts and associated cherts resulted in isoclinal folding and stacking of these granulite facies units (Bani Hamid thrust sheet) at PT conditions of 876 ± 31°C, 6.9 ± 0.3 kbar, and depths of 20–25 km (Cherry et al., 2014). Following exhumation and accretion of the metamorphic sole to the base of the ophiolite, and exhumation of the Bani Hamid granulites in the UAE-Madhah region, thrusting progressed from deep, ductile shearing to shallow, foreland-propagating thin-skinned thrusting with more distal units thrust over more proximal units. Restoration of the thrust sheets shows that more than 300–400 km of shortening occurred in the Sumeini (shelf margin), Hawasina Complex (proximal Tethyan ocean sediments), Haybi Complex (distal oceanic sediments, Oman Exotic seamounts and alkali basaltic substrate) trench mélange, between the stable shelf and the Semail Ophiolite. Towards the ending of the obduction history, the passive margin itself was dragged into the subduction zone. Permian basaltic sills within the base of the shelf sequence were subducted to depths of > 78–90 km in the As Sifah region of Oman, formed at PT conditions of 500–540°C, 21–23 kbar in the eclogite facies. Since the shelf carbonates are far too buoyant to be able to subduct, the entire subduction zone finally jammed, the eclogitic slab broke off and the As Sifah unit (Permian carbonates with eclogitised basaltic sills) exhumed rapidly due to buoyancy forces. The entire ophiolite obduction process lasted 23 Myr from Cenomanian to Early Maastrichtian times and occurred beneath sea level.

Following ophiolite obduction, stable, shallow-marine conditions resumed lasting from Late Maastrichtian to Early Oligocene. As the Arabian Plate began to collide with Central Iran, the first effects of this collision are seen in the Musandam Peninsula with development of the Hagab Thrust in the Late Oligocene and thick-skinned thrusting of the entire basement, Permian–Mesozoic shelf carbonate sequence and overlying Late Cretaceous Aruma foreland basin and associated thrust sheets, as well as the neo-autochthonous Palaeogene marine limestones. Offshore seismic sections both in the Arabian Gulf and Gulf of Oman show a prominent Upper Miocene unconformity that truncates folds and thrusts beneath. The Musandam phase of mountain building thus started in Late Oligocene and ended in Middle Miocene time.

Collision of Arabia and Central Iran and closure of the Zagros Suture Zone occurred at 27–20 Ma with between ca 80–200 km of upper crustal shortening in the Zagros Fold Belt. An equivalent width of Arabian Plate lower crust (Proterozoic basement) must have been underthrust northward beneath Central Iran. In UAE and Oman shortening is far less during this time, with gentle but large-scale, whale-back periclinal and box-folds seen throughout the western foreland region of the Oman Mountains. The Strait of Hormuz syntaxis between Ras Musandam and Qishm Island thus separates the tectonics of the Late Cretaceous ocean-continent collision and ophiolite obduction along the Oman Mountains from the full continent-continent collision along the Zagros ranges to the northwest.

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ABOUT THE AUTHORS

Michael P. Searle *is a Lecturer in the Department of Earth Sciences, Oxford University, United Kingdom, and is a Senior Research Fellow at Worcester College, Oxford. He obtained his PhD in 1980 working on structures and metamorphism beneath the Semail Ophiolite in northern Oman. Since then he has worked along the length of the Oman Mountains from the Musandam to Masirah Island and the Batain coast. Michael has also worked over 25 years along the Himalayan and Karakoram Ranges in Pakistan, India, Nepal, Bhutan and Sikkim as well as in Tibet, Burma, Thailand and Vietnam. His research integrates field mapping, structural geology, metamorphic and igneous geology, and geochronology with the aim of unraveling the large-scale evolution of mountain belts.*

mikes@earth.ox.ac.uk

Alan G. Cherry *obtained a First class degree in Earth Sciences from Oxford University (UK) in 2013. His MRes thesis was entitled "Structural and Metamorphic evolution of lower crust granulites in the northern Oman/UAE Mountains". This won the BP prize for the highest mark in the class. He presently works for Statoil in Bergen, Norway as a Graduate Geologist performing near field exploration in the northern North Sea.*

alan.cherry@icloud.com

Mohammed Y. Ali *has a BSc in Exploration Geology from Cardiff University, an MSc in Geophysics from Birmingham University, a Postgraduate Certificate in Education from UWCN, and a PhD in Marine Geophysics from Oxford University, UK. His current research projects are focused on exploration geophysics in the areas of passive seismic, seismic stratigraphy and reservoir characterization and modelling. Other research interests include basin analysis, crustal studies, and the structure of passive margins. Mohammed joined the Petroleum Institute in 2003 and currently he is an Associate Professor of Geophysics. He is a fellow of the Geological Society of London and a member of the SEG, EAGE and AGU.*

mali@pi.ac.ae

David J.W. Cooper *is an independent Consultant Geologist working out of the UK. He obtained a BA in Geology from Oxford University (1982) and a PhD from Edinburgh University in the sedimentology of the Hamrat Duru Group in Oman (1986). This was followed by a NERC research fellowship at Leicester University working on the sedimentology and structure of the Neo-Tethyan continental margin and deepwater sediments in Ladakh, NW India. He has recently returned to geological research after a diverse career working for the UK tax authorities.*

djwcooper@gmail.com

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