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One line on the map: A review of the geological history of the Semail Thrust, Oman-UAE mountains

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ABSTRACT

The Semail Thrust in the Oman-UAE mountains is mapped along the base of the Semail Ophiolite, a 10–15 km thick sequence of Cenomanian oceanic crust and upper mantle emplaced from NE to SW onto the previously passive, Mid-Permian to Cenomanian continental margin of Oman. The juxtaposition of the Semail ophiolite with a range of different rock types sourced from different depths suggest a complex tectonic history for this major fault and shear zone. Here we summarize previous work and present an overview of the tectonic history of the fault. The Semail Thrust is mapped along the base of the ophiolite as a single line on the geological map, yet it covers a variety of structural features spanning depths of 40–45 km to the surface, and a time scale from ~96 Ma (or earlier) to Eocene time. The structural evolution of the Semail Thrust includes (a) the roof fault or ductile shear zone of an exhumed oceanic subduction zone (granulites, amphibolites and greenschists of the metamorphic sole), (b) a deep mantle ductile shear zone (Banded Ultramafic Unit), (c) a brittle fault above a foreland-directed fold-thrust belt, (d) an out-of-sequence brittle fault exhuming a higher ophiolite thrust sheet above deeper level lower crust granulites (e.g. Bani Hamid, UAE), (e) a late out-of-sequence thrust truncating underlying structural units (e.g. Hawasina Window), (f) a passive roof fault beneath exhuming HP rocks (e.g. 'Semail Thrust' below the Muscat peridotite, above the Ruwi mélange and high-pressure rocks of northern Saih Hatat), and (g) a reactivated normal fault bounding rising footwall culminations, notably of the Jebel Akhdar, Jebel Nakhl, and Saih Hatat anticlines. Different stages in the evolution of the Semail Thrust can be mapped out and interpreted from different regions along the Oman Mountains.

1. Introduction

The Semail (Oman) ophiolite is the largest-exposed obducted thrust sheet of oceanic crust and upper mantle emplaced onto a continental margin on Earth (Reinhardt, 1969; Glennie et al., 1973, 1974; Coleman and Hopson, 1981; Lippard et al., 1986; Searle and Cox, 1999; Searle, 2007, 2019; Ambrose and Searle, 2019). It is exposed along the length of the northern Oman – United Arab Emirates (UAE) mountains, which are more than 700 km in length and up to 150 km wide (Fig. 1). The ophiolite structurally overlies a thick sequence of older shelf carbonates (Mid-Permian to Cenomanian age), which are exposed in three major culminations: the Musandam peninsula in the far north, the Jebel Akhdar – Jebel Nakhl anticline in the central mountains (Figs. 2a and 3), and the Saih Hatat fold culmination in the central eastern mountains (Fig. 2b). The Semail ophiolite, together with underlying thrust sheets of the distal Haybi complex and the more proximal Hawasina complex, has been folded around the giant Jebel Akhdar and Saih Hatat anticlines.

The tectonic stratigraphy of the Semail ophiolite sequence is well-studied, and provides significant information regarding the formation and obduction of the ophiolite onto the former passive margin. The ophiolite itself comprises a complete section of upper mantle peridotites (harzburgites, dunites), Moho Transition zone (layered peridotites and gabbros with late wehrlite intrusions), lower crustal gabbros, sheeted dykes, and upper crust pillow lavas with interbedded radiolarian cherts (Fig. 4). In several localities along the base of the ophiolite thrust sheet, a narrow metamorphic sole is preserved that comprises a top-to-bottom

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sequence of garnet + clinopyroxene amphibolites metamorphosed to upper amphibolite or granulite-facies, garnet-free hornblende + plagioclase amphibolites, epidote amphibolites, and greenschist-facies meta-volcanics and meta-sediments showing an inverted and highly condensed pressure-temperature range (Searle and Malpas, 1980, 1982; Ghent and Stout, 1981; Hacker and Mosenfelder, 1996; Hacker and Gnos, 1997; Ishikawa et al., 2005; Cowan et al., 2014; Rioux et al., 2016; Soret et al., 2017, 2019; Garber et al., 2020; Ambrose et al., 2021). Peak PT conditions of the granulite-amphibolite facies rocks in the uppermost part of the metamorphic sole correspond to structural depths of 30–40 km (Gnos, 1998; Searle and Cox, 2001; Cowan et al., 2014; Soret et al., 2017, 2019; Ambrose et al., 2021). Structurally beneath the metamorphic sole is a series of thrust sheets including the Haybi Complex comprising distal sedimentary and volcanic rocks, Late Triassic alkali basalt and limestone seamounts (Oman Exotics), and mélanges. Structurally beneath the ophiolite and the Haybi Complex is the Hawasina complex, a series of 4–7 thrust sheets of basin to shelf slope sediments that restore to a position between the Mesozoic shelf margin and the Semail ophiolite (Cooper, 1987, 1988; Cooper et al., 2014).

The term 'Semail Thrust' is classically applied to the major detachment above which the entire ophiolite was emplaced from the Tethyan oceanic realm from NE to SW onto the previously passive continental margin of Arabia. However, the modern expression of the Semail Thrust juxtaposes the base of the ophiolite with a wide variety of rocks, including the preserved metamorphic sole, lower-grade Haybi complex mélange units, and Hawasina complex Tethyan oceanic sediments, and the unmetamorphosed shelf carbonates around the Jebel Akhdar and Saih Hatat tectonic windows. Restoration of the allochthonous rocks in the Oman Mountains shows that the same time-equivalent Permian to Cenomanian rocks occur in each structural unit, but range in facies from continental shelf to slope (Sumeini complex), proximal basin (Hamrat Duru Group), distal basin (upper Hawasina thrust sheets), trench (Haybi complex) including Triassic alkali volcanic rocks, Oman Exotic seamounts and deep-sea radiolarian cherts (Glennie et al., 1973, 1974; Searle, 2007, 2019; Cooper et al., 2014).

In the northern mountains, the Semail ophiolite rests directly on a 1 km thick unit of unique, strongly folded, high-temperature granulite facies rocks in the Bani Hamid thrust sheet (Searle et al., 2014, 2015). These rocks differ in several ways from the metamorphic sole, record significantly lower metamorphic pressures (6–7 kbar) than the sole rocks (10–14 kbar), and are interpreted as exhumed deep crustal rocks along the NE margin of the Arabian plate. Southeast of Muscat, the Semail ophiolite also directly overlies high-pressure metamorphic rocks including carpholite-bearing meta-sediments, blueschists and eclogite facies rocks (Goffé et al., 1988; El-Shazli et al., 1990, 2001; Searle et al., 1994, 2004; Miller et al., 2002; Agard et al., 2010). Thus, the map trace of the 'Semail Thrust' includes many different structural and metamorphic episodes occurring at different times and different depths, which are the focus of this paper.

We will first describe the Semail ophiolite complex and discuss its

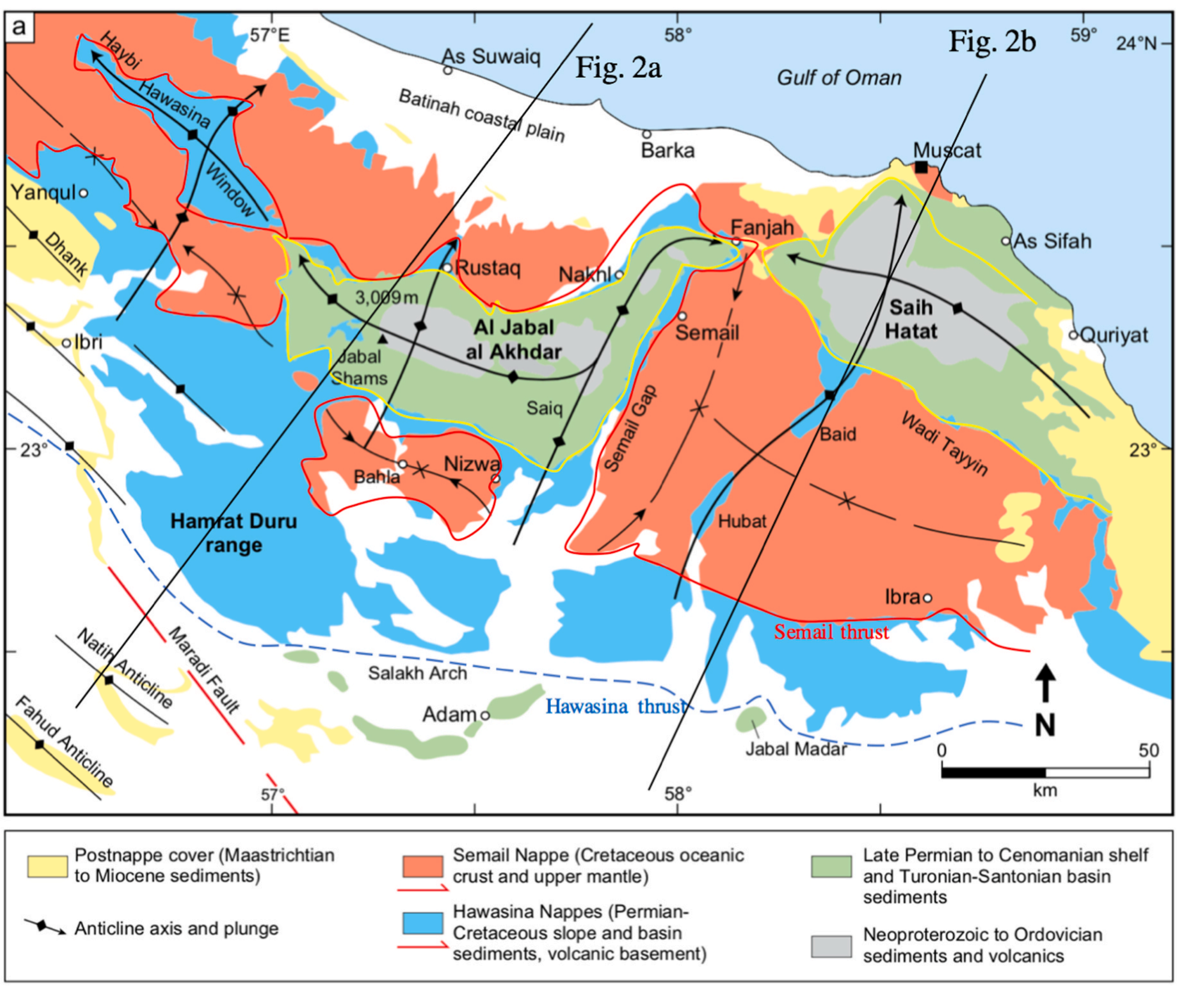

Fig. 1. Geological map of the Jebel Akhdar and Saih Hatat culminations in the central part of the Oman Mountains, showing key geological features. Red line is the Semail Thrust (*sensu stricto*). Dashed blue line is the SW limit of the Hawasina thrust sheet. Yellow lines are the low-angle normal faults surrounding the shelf carbonate inliers (or windows) of Jebel Akhdar and Saih Hatat. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

origin and tectonic setting. We then use the stratigraphic, structural, metamorphic and geochronological data to interpret the evolution of the Semail Thrust. The evolutionary sequence starts with the earliest evidence for subduction initiation and exhumation of the metamorphic sole, evolving through a thin-skinned foreland directed thrust belt, to the roof fault of an exhuming HP eclogite-blueschist zone, and later reactivation as normal faults formed during compressional formation of deeper culminations such as the Jebel Akhdar and Saih Hatat anticlines.

2. Origin and tectonic setting of the semail ophiolite

Early models for the formation of the Semail ophiolite proposed that it was formed at a typical mid-ocean ridge (MOR: Reinhardt, 1969; Hopson et al., 1981; Boudier and Coleman, 1981; Nicolas and Boudier, 2015; Nicolas and Boudier, 2017, 2015, 2017; Boudier and Nicolas, 2018), possibly a fast-spreading ridge comparable to the East Pacific Rise (Nicolas and Boudier, 2015, 2017). Three major factors argue against this MOR model, in favour of a supra-subduction zone (SSZ) model. Firstly, the geochemistry of both the lower Geotimes and overlying Lasail and Alley volcanic units is consistent with formation in a subduction zone setting, including boninitic magmatic rocks in the Alley-Lasail unit pillow lavas, as well primitive lenses with subduction-related geochemical signatures within the lower Geotimes unit (Pearce et al., 1981; Alabaster et al., 1982; Lippard et al., 1986; Pearce, 2008; MacLeod et al., 2013; Kusano et al., 2014; Belgrano and Diamond, 2019). Boninites are high-Mg and Si andesites, and are not found along any known mid-ocean ridge, only in arc, or fore-arc regions. The geochemical progression from the Geotimes to Lasail and Alley units is also similar to the evolution of magmatism in the Izu-Bonin-Mariana

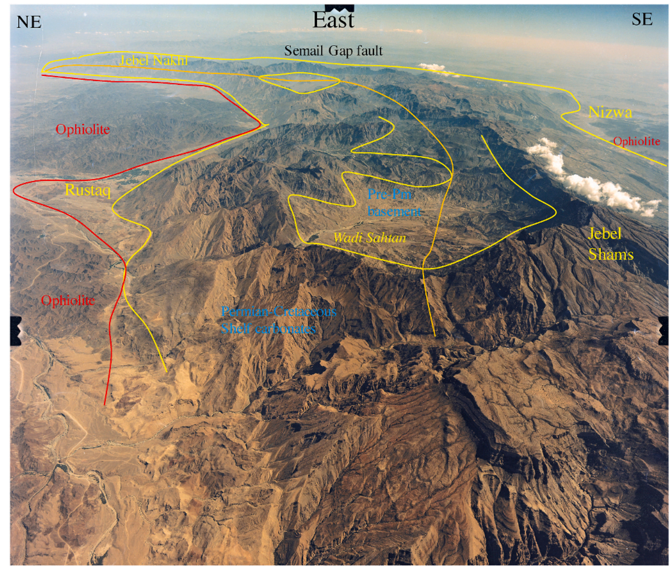

Fig. 3. Aerial view of the giant Jebel Akhdar – Jebel Nakhl anticline, view towards the southeast, showing the anticline axis curving through 90° from WNW-ESE in Jebel Akhdar to NNE-SSW along Jebel Nakhl. The Semail Thrust fault in red, reactivated as the low-angle normal fault bounding the top of the shelf carbonates, shown in yellow. Photo courtesy of Petroleum Development (Oman) Ltd. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

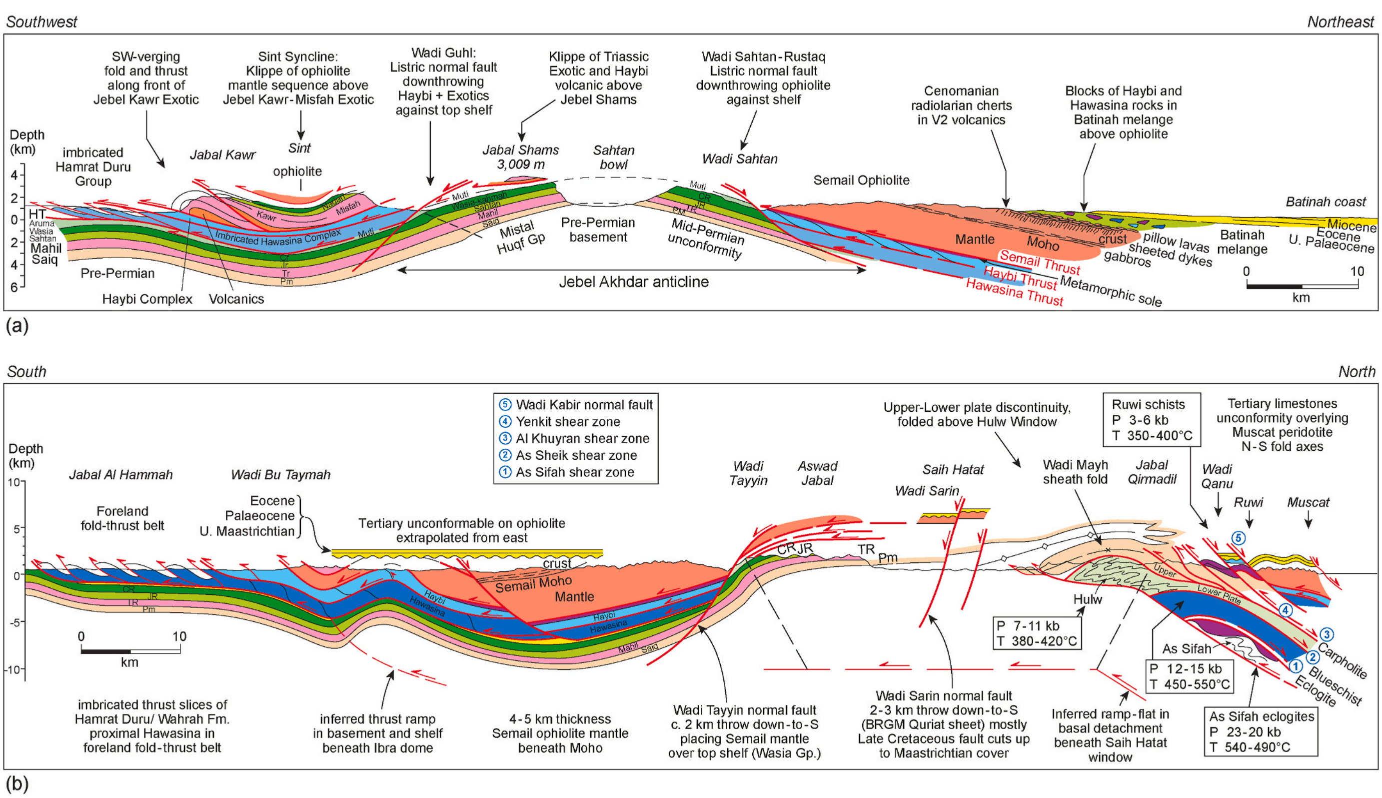

Fig. 2. (a) Cross section of the Jebel Akhdar massif showing the anticlinal structure in the shelf carbonates with overlying Hawasina, Haybi, and Semail ophiolite thrust sheets folded around the culmination, after Searle (2007). Note the low-angle normal faults bounding the north and south margins of the shelf carbonates. Note the sub-division of the Permian, Triassic, Jurassic and Cretaceous components of the shelf carbonates that are not shown on Fig. 1. (b) Cross-section of the Saih Hatat culmination showing folded allochthonous thrust sheets (Hawasina, Haybi, Semail ophiolite) folded over the shelf carbonates. The Muscat peridotite overlies a wide high-pressure zone including the Ruwi mélange, Wadi Mayh sheath folds, Hulw blueschists, and As Sifah eclogite units, each bounded by normal sense ductile shear zones or normal faults, indicative of exhumation of footwall rocks to the SE. The southern margin of Saih Hatat is a low-angle normal fault along the top of the shelf carbonates, reactivating the Semail Thrust.

(IBM) forearc, which has been attributed to subduction initiation, although there appear to be Semail *vs.* IBM differences between the mantle source and slab component (Reagan and Pearce, 2017; Belgrano and Diamond, 2019).

Secondly, the lithologies now forming the metamorphic sole are dissimilar to rocks expected along a mid-ocean ridge. In particular, if subduction initiation occurred along the ridge axis, the protolith of the metamorphic sole would be expected to have a composition similar to the ophiolite lavas. Instead, mafic rocks exposed in the sole are interpreted as metamorphosed tholeiitic to highly alkaline basalts of the Triassic-Jurassic Haybi complex based on trace-element data; these occur in association with meta-cherts and meta-limestones that also have suitable protoliths in the Haybi complex (Searle and Malpas, 1980, 1982; Searle and Cox, 1999, 2001). Highly alkaline peridotites (alkali wehrlite, jacupirangite) and gabbros in the Haybi complex represent deeper roots of Triassic and Jurassic off-axis, within-plate ocean island volcanoes that erupted alkali basalt and nephelinite lavas (Searle et al., 1980, 1982; Searle 1984), though these are only observed in the sole in the Wadi Ham region of UAE (Searle and Malpas, 1980).

Thirdly, in the MOR model, the metamorphic sole can only reach peak metamorphism after formation of the ophiolite crust (Searle and Malpas, 1980, 1982; Lippard et al., 1986; Searle and Cox, 1999, 2001; Rioux et al., 2016, 2021a). High-precision U–Pb zircon TIMS dating has demonstrated that the ophiolite crust formed between 96.1 and 95.0 Ma (Rioux et al., 2012, 2013, 2016, 2021). Additional U–Pb zircon TIMS geochronology, summarised in Fig. 5, from the highest-grade

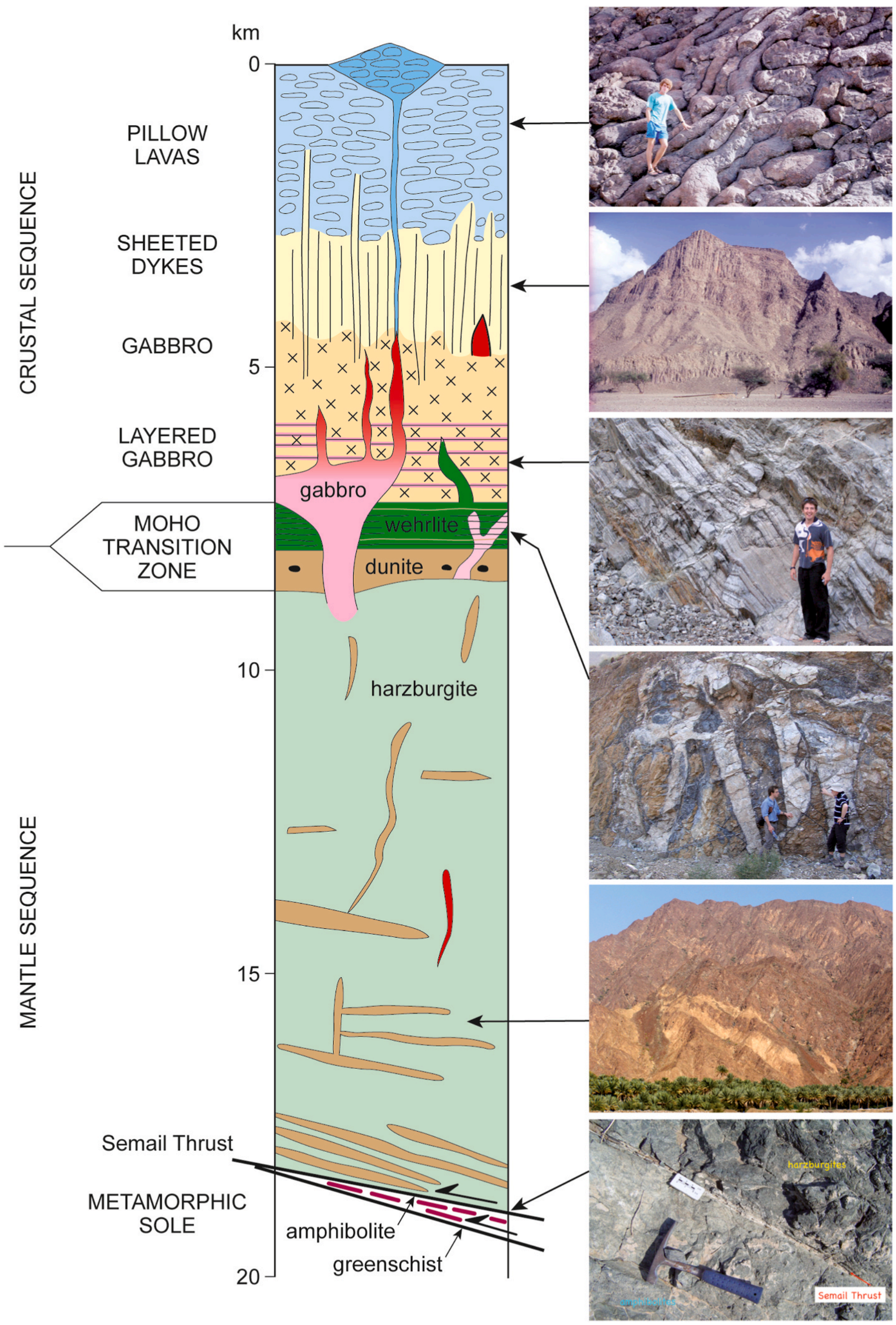

Fig. 4. Generalised section through the entire upper mantle and crust section of the Semail ophiolite, after Searle et al. (2014). The original Semail Thrust along the base of the mantle sequence is the initial obduction-related thrust fault.

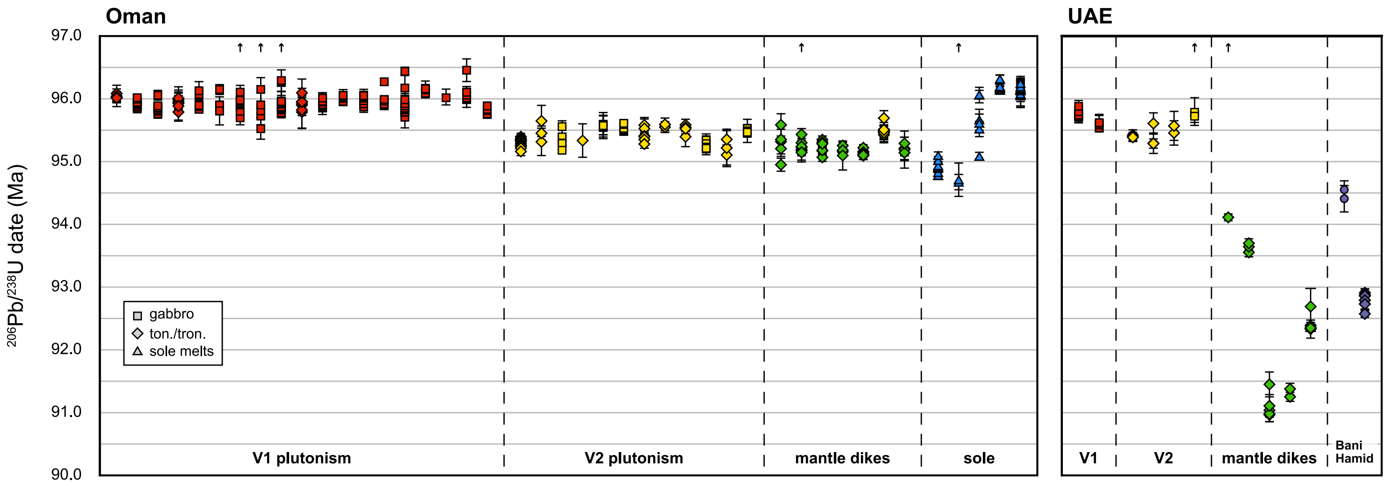

Fig. 5. Summary of high-precision U–Pb zircon dates from our previous work (Rioux et al., 2012, 2013, 2016, 2021; Searle et al., 2015). The data provide a large, internally consistent dataset that precisely dates the different magmatic and metamorphic events within the ophiolite. Each datum is the date from a single zircon grain or grain fragment (±2s), and vertical clusters of dates are from a single sample. Samples within each division are arranged from south to north. Dates from the Oman sole exposures are from four leucocratic pods (tight clusters) and a single garnet amphibolite. Small arrows at the top of the figure indicate that the sample contains one or more xenocrystic zircon grain(s) that plot off-scale.

amphibolites and leucocratic pods has now shown that the metamorphic sole reached peak metamorphic conditions at ~96.2–94.8 Ma, synchronous with or slightly predating formation of the ophiolite crustal sequence (see Rioux et al., 2016, 2021a,b, for all geochronology details) and strongly favouring a subduction zone setting. These data are supported by recently published zircon and monazite ages of ~98–94 Ma and a Lu–Hf garnet–whole rock isochron date of 93.0 ± 0.5 Ma from a lower-grade metasediment from the metamorphic sole at Wadi Tayyin; older detrital zircon dates in the same sample (~105–106 Ma) preclude metamorphism prior to that time (Garber et al., 2020). In contrast, Guilmette and Smit (2018) published older Lu–Hf garnet-whole rock isochron dates of ~104–103 Ma from garnet amphibolites from the Wadi Tayyin and Sumeini sole localities, raising the possibility that sole metamorphism more significantly predated formation of the ophiolite crust. Work is ongoing to further test these older dates and understand the offset between the Lu–Hf and U–Pb dates from these sole localities, but if accurate, the older Lu–Hf dates only further support a SSZ model for ophiolite formation. $^{40}Ar/^{39}Ar$ cooling ages of 95.7–92.6 Ma record the timing of cooling through the hornblende closure temperature (550-500 °C) during exhumation following peak metamorphism in the sole rocks (Hacker, 1994; Hacker et al., 1996).

3. The extended tectonic history of the Semail Thrust

3.1. Subduction initiation – metamorphic sole

Given the evidence that the ophiolite formed in a subduction zone setting, the metamorphic sole is thought to represent an accreted piece of the relict subducted slab, potentially recording the conditions of subduction initiation (see also Stern, 2004; Agard et al., 2010). The full metamorphic sole sequence is seen sporadically along the base of the Semail ophiolite in the Oman and UAE mountains, with many exposures exhibiting only a portion of the sequence. In the most complete sole exposures, an inverted sequence of garnet-clinopyroxene amphibolites or granulites (cpx + grt + amph + pl), amphibolite (amph + pl ± grt ± ep), and meta-sedimentary and meta-volcanic greenschist facies rocks occur along the base of the mantle sequence peridotites (Searle and Malpas, 1980, 1982; Ghent and Stout, 1981; Hacker and Mosenfelder, 1996; Hacker et al., 1996; Gnos, 1998; Searle and Cox, 1999, 2001; Rioux et al., 2016, 2021a; Soret et al., 2017, 2019; Ambrose et al., 2018, 2020; Garber et al., 2020). Mineral abbreviations are after Whitney and Evans (2010). Heat for metamorphism could have come from several sources, including conductive heating from the mantle wedge above, as well as shear heating along the Semail Thrust. The thermal contributions from either mechanism are as yet unknown; on the one hand the synchronous timing of partial melting in the metamorphic sole and ophiolite crystallization (Rioux et al., 2016; 2021a) suggests a significant contribution from conductive heating of the cooling ophiolite (see also Hacker, 1994). On the other hand, shear heating of granulite facies garnet- and clinopyroxene-dominated metabasalts adjacent to overlying high-temperature peridotite may have been significant, given the high material strength of both lithologies (Agard et al., 2010; Mako and Caddick, 2018), although all lithologies were probably hydrated at peak conditions (Searle and Malpas, 1980; Ghent and Stout, 1981; Cowan et al., 2014; Ambrose et al., 2018). Regardless of their origin, temperatures were sufficiently high (800-900 °C) to melt both mafic and meta-sedimentary source rocks in the downgoing slab resulting in intrusion of small degree granitoid dykes into the mantle sequence above (Cox et al., 1999; Searle et al., 2014; Rollinson, 2015; Haase et al., 2015; Rioux et al., 2021b). These high temperatures also fostered widespread hydrous melting and pervasive ductile deformation within the metamorphic sole, suggesting that shear heating was modulated by rock weakening, and was not the only heat source.

Protoliths of the metamorphic sole in Oman are various rock types of the underlying Haybi complex thrust sheet including tholeiitic and alkali basalts of Triassic to Early Cretaceous age, deep sea manganiferous (piemontite-bearing) cherts, carbonates, and uncommon pelites. Their composition and textural expression show that they are not subducted equivalents of the Semail ophiolite lithologies, as would be required in the MOR model for ophiolite formation. PT conditions in the high-grade metamorphic sole range from 700 to 900 °C and 10–14 kbar, corresponding to depths of 30–45 km for lithostatic pressures (Cowan et al., 2014; Soret et al., 2017, 2019; Ambrose et al., 2018, 2021). This depth exceeds the thickness of the preserved ophiolite in the Oman Mountains (~15 km maximum thickness), and so some sort of subduction system is required in order to generate the recorded pressures of metamorphism, and then to bring the material from depths far beneath the ophiolite, back up to its base.

As outlined above, U–Pb zircon ages from amphibolites and leucocratic pods from the upper parts of the metamorphic sole in Oman record zircon crystallization at 96.2–94.8 Ma (Rioux et al., 2016; 2021a; Guilmette and Smit, 2018), precisely overlapping with the U–Pb zircon ages from the ophiolite crust (96.1–95.0 Ma; Rioux et al., 2012; 2013, 2021a). The geochronology data strongly suggest that old, upper crustal oceanic rocks were subducted at the same time that the crustal sequence was forming above during the Cenomanian, conforming with the SSZ origin of the ophiolite.

Given the apparent depth of formation of the metamorphic sole (30–45 km) below and the maximum thickness of the overlying ophiolite (ca 15 km) above, the 'Semail Thrust' contact between the granulite-amphibolite facies rocks of the sole and the peridotites has to be a normal fault or ductile shear zone, active during the exhumation of the deeper metamorphic sole along the footwall (Fig. 5a). Exhumation occurred either by return ductile flow along the same subduction zone (Searle and Cox, 1999, 2001; Cowan et al., 2014), or by slab flattening (Ambrose et al., 2021). If slab flattening did occur, there should be a geographic trend to the distribution of sole PT conditions; the highest PT conditions representing the most deeply buried part of the sole would be expected in the hinterland regions of the mountains (e.g. Masafi, UAE, Hawasina Window, Wadi Tayyin in Oman), and the lower grade greenschist facies rocks only in the foreland (SW) parts of the mountain belt (e.g. Sumeini, Asjudi, Jebel Qumayrah). In fact, all regions show a very similar distribution of metamorphic conditions in the sole. Therefore, we prefer the model of return ductile 'flow' exhumation, back along the subduction channel.

3.2. Oceanic subduction exhumation

The 'Semail Thrust' between metamorphic sole amphibolites below and peridotites above is typically a sharp contact with little or no interfingering of lithologies. The base of the ophiolite is a strongly banded series of harzburgites (sometimes with ~5% clinopyroxene in addition to olivine and orthopyroxene), and dunites, termed the Banded Ultramafic unit (BUU; Searle and Malpas, 1980). Mylonitised peridotites in the BUU also contain hornblende, possibly as a result of fluids driven off the subducted slab (Ambrose et al., 2018). Hornblende occurs both in the matrix and as rims around enstatite crystals. Deformation temperatures of 850–650 °C have been inferred for the base of the ophiolite, similar to temperatures in the upper part of the metamorphic sole (Ambrose et al., 2018; Prigent et al., 2018). It is not possible to obtain pressure estimates from the peridotites, so it is unclear whether the BUU was exhumed as a part of the sole or whether it is part of the mantle preserved within the ophiolite itself. If it was the former, a major ductile shear zone should be expected above the BUU, separating deeper mantle rocks (hornblende-bearing lherzolites) from the shallower mantle part of the ophiolite (dunites, harzburgites); however, no such structure has been observed. Either way, the BUU represents a deeply exhumed part of the mantle and the upper contact of the exhuming subduction channel, where strain localisation occurred along the amphibolite-peridotite interface (Fig. 6a and b). Assuming the sole exhumed by return flow up the subduction channel, the contact has a normal sense of shear with uplift of footwall granulite-amphibolite facies relative to hanging-wall peridotite, but in a wholly compressional subduction zone tectonic setting.

3.3. Brittle thrusting

Following subduction initiation and formation of the metamorphic sole at depth, the sole rocks accreted to the base of the BUU and the ophiolite mantle sequence. The intact regions of the metamorphic sole show a smooth inverted metamorphic field gradient, but in numerous places along the base, a brittle top-to-southwest thrust fault has placed these sole rocks over relatively unmetamorphosed sedimentary and volcanic rocks of the Haybi thrust sheet (Fig. 6b). This later brittle phase of the Semail Thrust has juxtaposed mantle peridotites against unmetamorphosed Haybi and Hawasina complex rocks, partly to entirely omitting metamorphic sole rocks from the section. Deep ductile shearing progressed through time to shallower brittle thrust faulting during exhumation. Faulting in general propagated in-sequence towards the foreland with time placing more distal, outboard units structurally above more proximal units. Thus, the earliest thrusts were the deep, ductile shear zones placing the ophiolite sequence above the metamorphic sole (Fig. 6a), followed by the Haybi and Hawasina complex thrust sheets that carried the ophiolite above. There is evidence of some out-of-sequence motion along the Semail Thrust during this emplacement, notably from the Hawasina Window, where the ophiolite rests on a wide variety of rocks from the Haybi complex, Hawasina thrust sheets, Sumeini culminations and even directly on the shelf carbonates (Fig. 7; Searle, 1985, 2007; Searle and Cooper, 1986).

These allochthonous rocks – the Semail ophiolite, Haybi and Hawasina thrust sheets – were emplaced as thin-skinned thrust sheets across a minimum of 150 km of the Mesozoic shelf margin (Searle, 1985, 2007; Cooper, 1988). This is the present distance between the foreland position of the Hawasina thrust sheet along the SW, and the NE extent of Arabian continental crust exposed in the Saih Hatat culmination SE of Muscat (Fig. 1). Internal folding and thrusting within the foreland fold-thrust belt, both in the foreland (Cooper, 1987, 1988), and within tectonic windows through the ophiolite (Searle and Cooper, 1986) suggest that additional shortening must be added to this distance.

Restoration of the Hawasina and Haybi complex thrust sheets provides a minimum width of the preserved part of the Tethyan ocean between the Semail thrust and the continental margin. Cooper (1988) and Searle et al. (2004) suggested around 450 km of shortening across the Hawasina and Haybi thrust sheets. At fast plate convergence rates, such as the present-day India-Asia convergence (~50 mm/year), approximately 9 m.y. would be required to accommodate this shortening. The time scale for emplacement of the Semail, Haybi and Hawasina thrust sheets across the Oman continental margin is approximately 15 m.y, between ~95 Ma, the age of subduction initiation, and the 81-77 Ma continental subduction recorded in the As Sifah eclogite (see section 3.5; Warren et al., 2005; Garber et al., 2021).

3.4. Out-of-sequence thrusting – Bani Hamid

The Bani Hamid thrust sheet in the northern part of the Oman – UAE mountains shows a unique low-pressure granulite-facies sequence of meta-carbonates (with diopside, andradite garnet, wollastonite, scapolite), and two-pyroxene quartzites (with hornblende, cordierite, sapphirine), with uncommon bands of amphibolite (with hornblende, clinopyroxene, plagioclase), that are recumbently folded and completely surrounded by mantle sequence peridotites of the Semail ophiolite (Searle et al., 2014, 2015). U–Pb zircon and titanite dating suggests a protracted metamorphic history of at least 5 m.y. from 94.55 ± 0.14 Ma to 89.8 ± 1.5 Ma (Searle et al., 2015). Although these rocks are structurally beneath the peridotites, they are dissimilar to the metamorphic sole rocks seen elsewhere in Oman and UAE. Instead, they are interpreted either as lower crust equivalents of the Haybi complex rocks (Oman Exotic limestones, Haybi volcanic rocks and radiolarian cherts), or as lower crust granulites from the Arabian plate margin that were thrust up and cut through the overlying thin-skinned ophiolite thrust (Fig. 8). Folding and thrusting of granulite-facies deep crust over structurally higher, already emplaced ophiolite mantle sequence occurred by out-of-sequence thrusting along the Bani Hamid thrust that forms the western bound of the exposure. The eastern contact of the granulite facies rocks with overlying mantle peridotite, also mapped as the 'Semail Thrust', is a sharp fault and has a normal sense geometry, downthrowing ophiolite mantle rocks to the east against granulites along the footwall (Searle et al., 2015).

The upper contact of the Semail ophiolite offshore UAE and northern Oman has recently been imaged using seismic (multichannel reflection and wide-angle refraction), gravity, magnetic and bathymetric data (Ali et al., 2020; Pilia et al., 2021). The contact — the NE-dipping Fujairah normal fault — separates ophiolite crustal rocks to the SW from a deep Cenozoic basin overlying in situ Gulf of Oman to the NE (Fig. 9) showing that the Semail ophiolite is completely detached and not rooted in the Gulf of Oman crust. The Fujairah normal fault may have been active

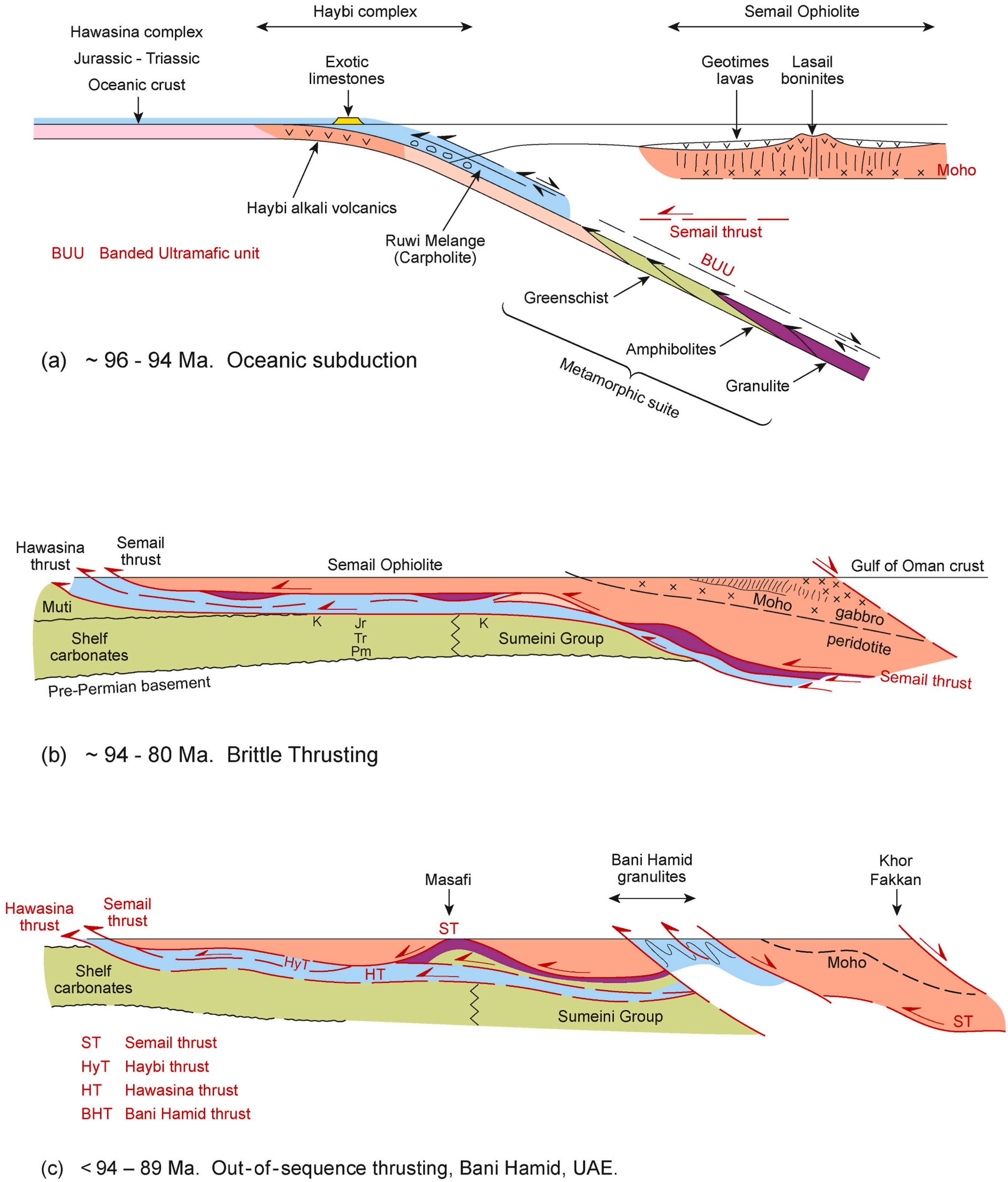

Fig. 6. Cross-sections across the Oman Mountains showing the evolution of features mapped as the 'Semail Thrust'. (a) Oceanic subduction zone at ~96-95 Ma showing the depths and positions of the granulite, amphibolite and greenschist facies metamorphic sole relative to the preserved 15 km thickness of the Semail ophiolite. Section is across the Muscat – Ruwi area of the Central Oman Mountains. (b) The Semail Thrust evolved from a deep ductile shear zone to a brittle thrust fault, carrying the Semail ophiolite at least 150 km over the underlying Haybi and Hawasina complex thrust sheets. These allochthonous thrust sheets overlie authochthonous Permian to Cenomanian shelf carbonates at this stage. (c) Following emplacement of the thrust sheets the Semail ophiolite was folded and repeated by out-of-sequence duplication along the Bani Hamid Thrust. Section is across the UAE part of the Semail ophiolite.

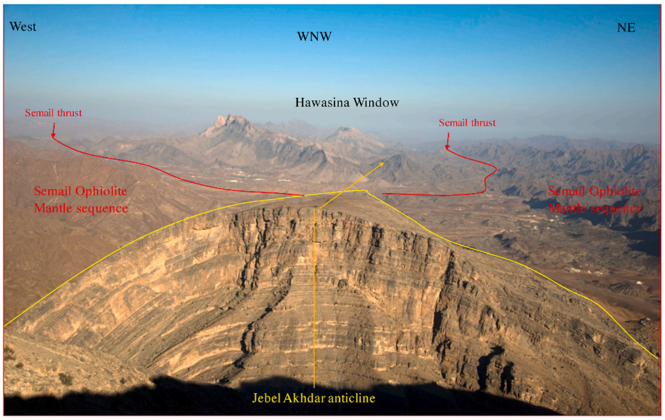

Fig. 7. Photo of the nose of Jebel Akhdar showing the anticline axis plunging WNW beneath the Hawasina Window. Note the Semail ophiolite resting directly on top of shelf carbonates on either side of the fold. Photo courtesy of Janos Urai.

during SW-directed thrusting of the Bani Hamid deep crust granulite rocks into the Semail ophiolite. The Fujairah fault was active from the Late Cretaceous time of obduction, and continued throughout the Cenozoic.

3.5. *Continental subduction; passive roof fault of exhumed eclogites-blueschists*

A zone of high-pressure, low-temperature rocks including eclogites (As Sifah unit), retrogressed blueschists (Hulw unit), a stack of carpholite-bearing meta-sedimentary rocks, and a prominent mélange (Ruwi mélange), crops out in the southeastern part of the Oman mountains, structurally beneath the Muscat part of the ophiolite, extending along the northern margin of the Saih Hatat culmination (Fig. 2b; Fig. 10). An additional large swath of metamorphosed shelf carbonates beneath the Muscat ophiolite (Yenkit, Yiti, Wadi Mayh units) includes Fe–Mg carpholite assemblages with chloritoid, pyrophyllite, sudoite and kaolinite that record pressures up to 9–11 kbar, and temperatures of only 320-280 °C (Goffé et al., 1988; Yamato et al., 2007; Agard et al., 2010). The Ruwi mélange includes lawsonite-bearing metabasalt blocks within a carpholite-bearing mudstone matrix (El-Shazli et al., 1990; 1995). It crops out immediately beneath the Muscat peridotite and is thought be a higher-pressure lithologic equivalent of the Haybi complex mélange (Searle et al., 2004; Searle, 2007). All these carpholite-bearing meta-sedimentary rocks record a similar range of PT conditions, suggesting the stacking of unsubductable carbonate-dominated, continental crustal rocks at depths of 30–35 km during choking of the subduction zone.

At deeper structural levels a zone of retrogressed blueschists occurs within the Hulw Window, and at deeper levels still, the As Sifah eclogites, exposed along the coast, have high-pressure minerals glaucophane, omphacite, garnet, phengite, chloritoid and epidote in both mafic and felsic protoliths. The As Sifah eclogites have PT conditions of 20–25 kbar and 490-540 °C (Searle et al., 1994, 2004; Warren and Waters, 2006; Yamato et al., 2007; Massonne et al., 2013), indicating depths of subduction to over ~80 km. The timing of HP metamorphism is given by a U–Pb zircon age from the structurally deepest mafic eclogite exposed at As Sifah beach of 79.1 ± 0.3 Ma (Warren et al., 2003), as well as garnet Sm–Nd ages from mafic and felsic eclogites that span 81–77 Ma (Garber et al., 2021). These Campanian dates are approximately 15 m.y. after formation of the Semail ophiolite crustal sequence and the metamorphic sole (Rioux et al., 2016).

During the period from 95 to 80 Ma, the ophiolite and underlying Haybi and Hawasina complex thrust sheets were emplaced >150 km SW across the shelf carbonates and Arabian basement, as discussed earlier. At ca 80 Ma the leading margin of the Arabian continental crust was dragged down the NE-dipping subduction zone to depths of ca. 80–100

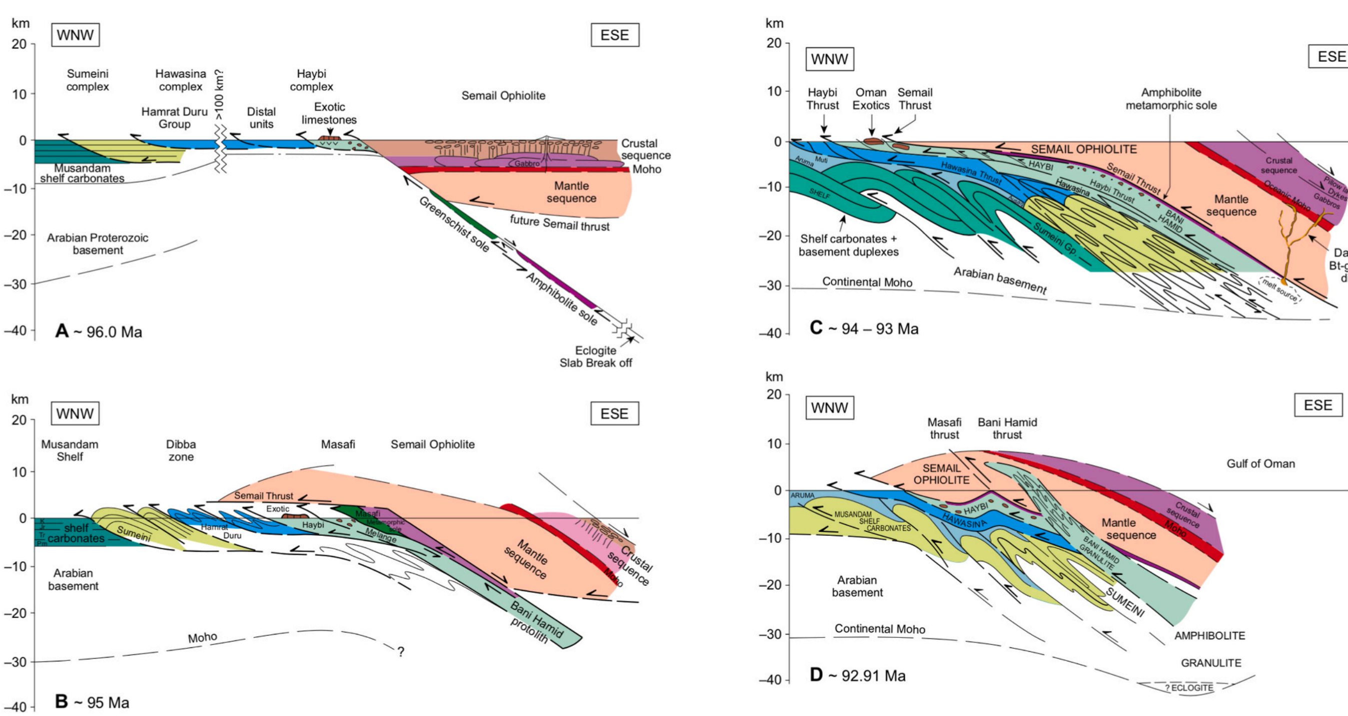

Fig. 8. Cross-sections across the UAE part of the north Oman Mountains, after Searle et al. (2015), showing four stages in the evolution of the Semail Thrust carrying the Semail ophiolite thrust sheet. (a) initiation of the Semail ophiolite with accretion of the metamorphic sole to base of the ophiolite. (b) exhumation from a deep, ductile shear zone to shallow brittle thrust emplacing the ophiolite over underlying Haybi and Hawasina thrust sheets over the autochthonous shelf carbonates. (c) final emplacement of the Semail ophiolite, which eventually travelled across ca. 150 km of the shelf margin. (d) Out-of-sequence thrusting along the Bani Hamid Thrust repeating the ophiolite section.

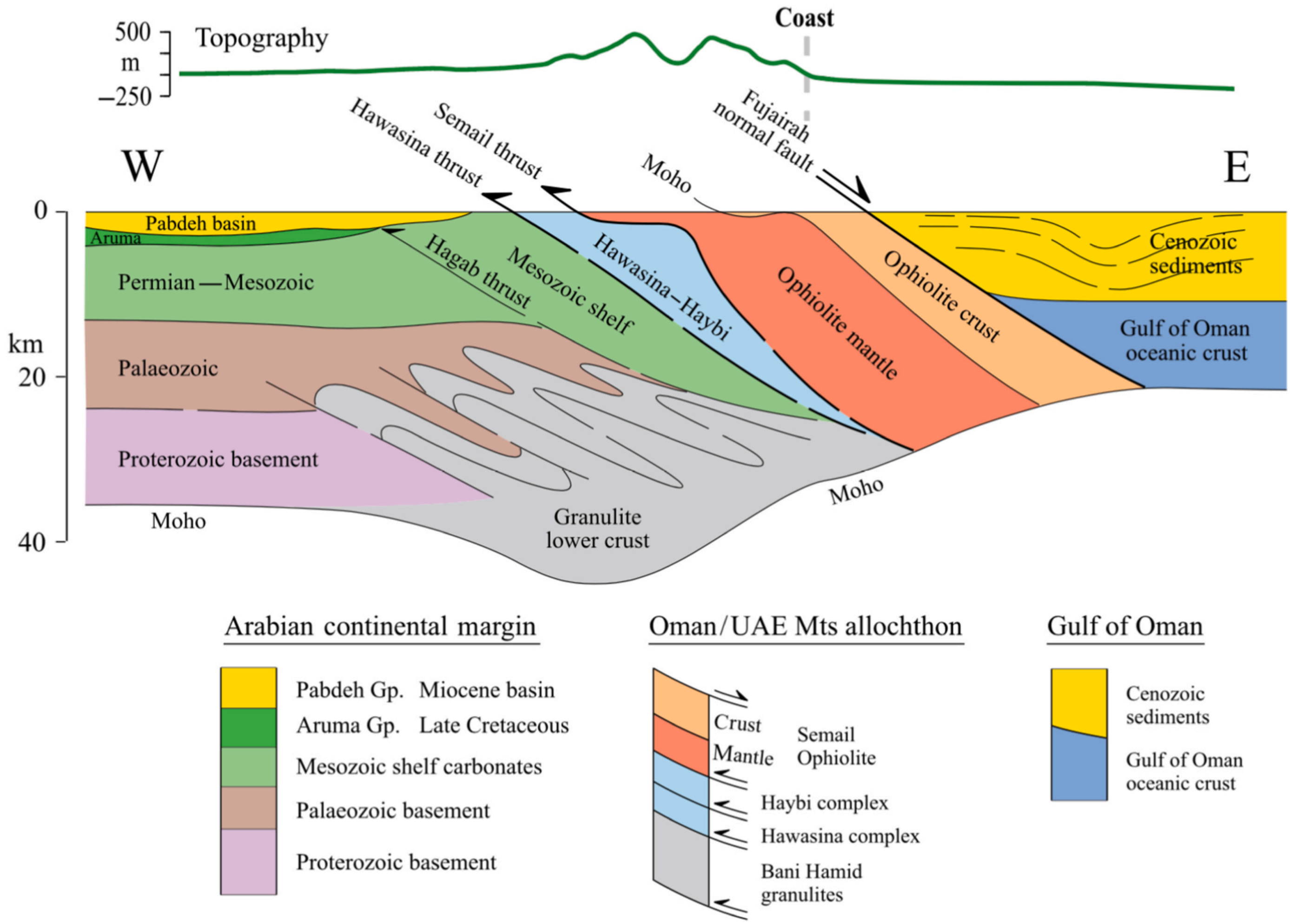

Fig. 9. Simplified section across the UAE part of the north Oman Mountains, after Ali et al. (2020), showing structural interpretation of surface geology combined with deep seismic profiles. The Semail Thrust structurally overlies the allochthonous Haybi and Hawasina thrust sheets. The eastern margin of the ophiolite is a ENE-dipping normal fault detaching the ophiolite from the in situ Gulf of Oman crust. The lower crust is interpreted as folded and thickened granulite facies rocks as exposed in the Bani Hamid thrust sheet.

km (20–25 kbar). Protoliths of the mafic eclogites were thought to be Saiq-1 Fm alkali volcanics that are exposed in the unmetamorphosed shelf carbonate sequence in the southern part of Saih Hatat, because they are the only mafic volcanic rocks exposed in the shelf carbonate sequence (Searle et al., 2004). New data from the felsic HP eclogites suggest that both mafic and felsic metavolcanics have Early Permian protoliths (Garber et al., 2021), and may possibly be related to the Permian-Carboniferous Al-Khlata Fm (Heward and Penny, 2014). The deformed quartz-rich schists at As Sifah might be metamorphosed equivalents of the Ordovician Amdeh Fm, the only quartz-rich sediments in the autochthonous part of the Oman margin. Following peak metamorphism of the As Sifah eclogites, the HP rocks were exhumed along several ductile shear zones towards the SSW, with each shear zone showing a downward increase in PT conditions (Searle et al., 2004; Hansman et al., 2021). The most significant jump in pressure occurs above the As Sifah eclogites; the structurally overlying Hulw blueschist unit never reached the high pressures experienced by the As Sifah rocks (20–25 kbar), and all overlying rocks (Yenkit, Yiti, Wadi Mayh units; Searle et al., 2004; Yamato et al., 2007; Agard et al., 2010) record stacking up of shelf carbonate rocks at similar depths of ~30 km (8–11 kbar). The uppermost thrust sheet is the Muscat peridotite, part of the Semail ophiolite exposed along the northern flank of the giant Saih Hatat anticline (Fig. 2b). Here, the 'Semail Thrust' beneath the Muscat ophiolite forms the passive roof fault of all the HP rocks beneath it. SW-directed thrusts between the HP units were reactivated as NE-dipping normal faults during exhumation of the HP units (Searle et al., 1994; Searle, 2007; Agard et al., 2010).

Porkolab et al. (2021) proposed that the extrusion of subducted crust beneath ophiolites triggered far-travelled ophiolite thrust sheets, such as that seen in Oman. However, in Oman the ophiolite thrusting initiation was 15 m.y. prior to continental subduction, and the ophiolite was thrust at least 150 km across the continental margin before continental subduction and formation of eclogites at As Sifah. It is therefore not possible that continental subduction and extrusion triggered ophiolite thrusting.

3.6. 'Semail Thrust' as a reactivated normal fault

The final stages of motion along the 'Semail Thrust' occurred during the culmination of the large-scale anticlines of Jebel Akhdar – Jebel Nakhl – Saih Hatat (Fig. 1). The deep level thrusts that were responsible for the uplift initiated in the basement and ramped up towards the SW along the frontal folds of the Salakh arch and Adam jebels (Figs. 1 and 2). The contact between the Semail ophiolite and the underlying shelf carbonates is commonly mapped as the 'Semail Thrust', but actually has a geometry reflecting reactivation as a low-angle normal fault, as is further described below. Two models have emerged concerning the uplift of these large-scale culminations that would have differing implications for the history of the 'Semail Thrust'. Model One proposes that

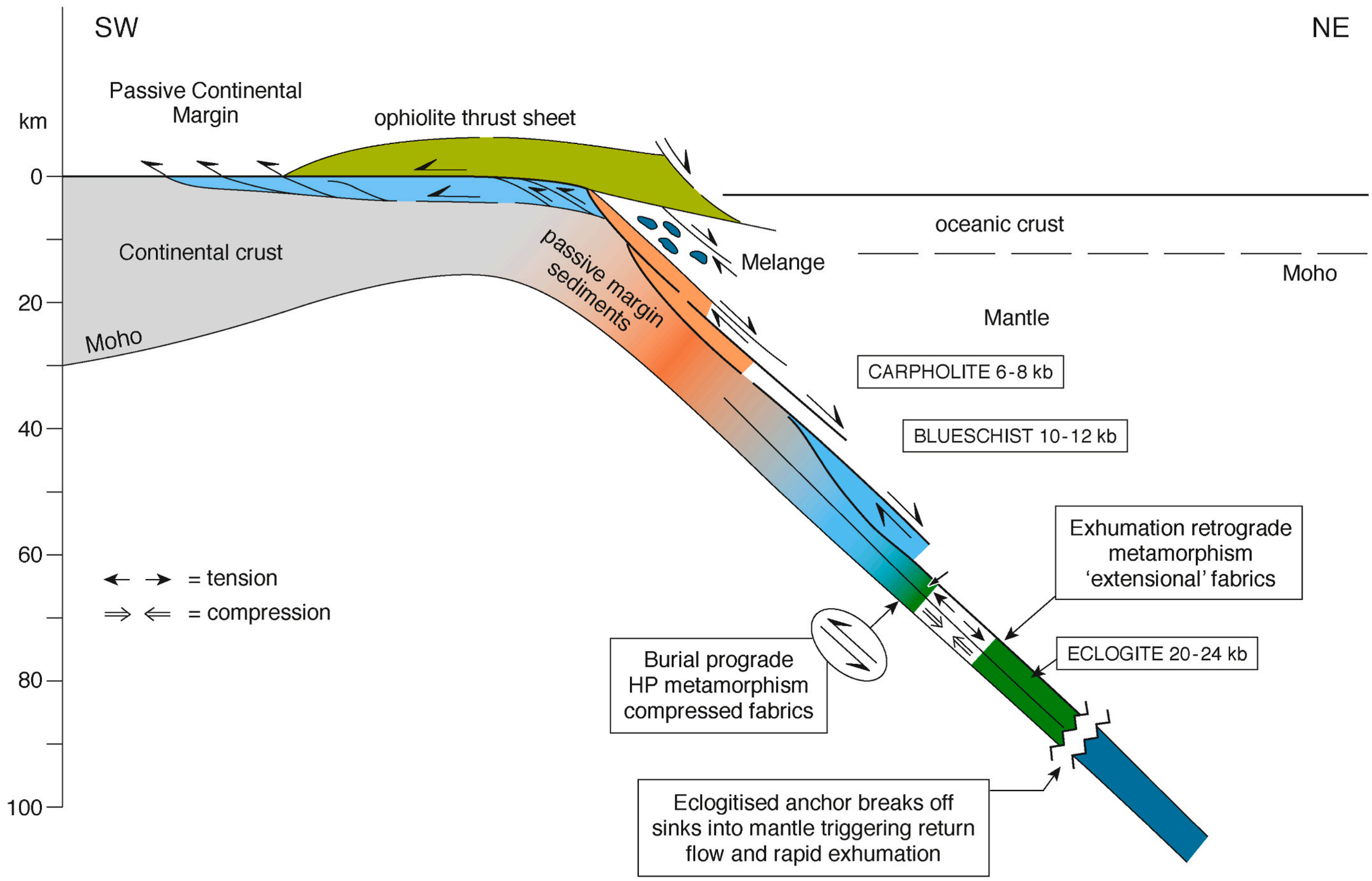

Fig. 10. Simplified section across the Muscat – As Sifah part of the north central Oman Mountains, showing a reconstruction of the HP rocks of As Sifah eclogites, Hulw blueschists, and Ruwi mélange units, using pressures to constrain depth. The Muscat ophiolite was continuous with the main Semail ophiolite at this stage at ca 79 Ma, the timing of peak eclogite facies metamorphism. Note the ‘extensional’ fabrics related to exhumation of footwall rocks along each thrust sheet. The Semail Thrust forms a passive roof fault above the Ruwi mélange.

most of the folding-related uplift occurred during the latest part of the Late Cretaceous thrusting event, with renewed compression-related uplift following the Paleocene-Eocene shallow marine carbonate deposition (Mount et al., 1998; Searle, 2007). Model Two relates the uplift to late Eocene – Oligocene extensional tectonics during orogenic collapse (Hansman et al., 2017; Grobe et al., 2018, 2019; Mattern and Scharf, 2018; Scharf et al., 2019). These models are further discussed in the following sections.

3.6.1. ‘Semail Thrust’ around Jebel Akhdar

The Semail ophiolite rests directly on top of the shelf carbonates along a low-angle normal fault in most localities around Jebel Akhdar (Fig. 11). The Haybi and Hawasina thrust sheets that underlie the Semail ophiolite appear to be considerably reduced, or missing in these sections, but they have been down-faulted and cut from the section around the flanks (Fig. 2a). Kinematic indicators in the Late Cenomanian-Turonian Muti Fm. shales along the top of the Cretaceous shelf carbonates show extensional fabrics consistent with uplift of footwall rocks. These extensional cleavages are also folded around the domes of Jebel Akhdar and Jebel Nakhl. The ophiolite and underlying Haybi and Hawasina thrust sheets were originally thrust across the shelf carbonates prior to the anticlinal folding of the Jebel Akhdar and Jebel Nakhl structures (Fig. 2a). The Semail Thrust was therefore reactivated by compressional uplift of the footwall shelf carbonates, and not to any crustal extension, or orogenic collapse. Normal faulting preferentially occurred along the top of the shelf carbonates and along the base of the ophiolite. The Semail thrust, Haybi thrust and base Hawasina thrust were all reactivated as normal faults during compressional uplift of

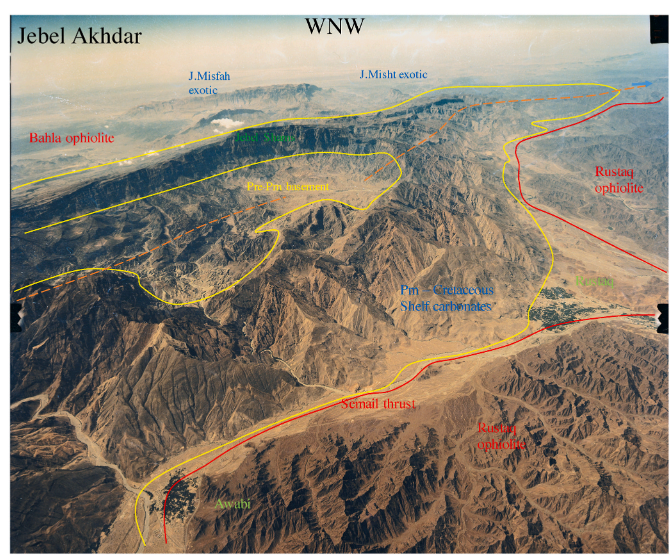

Fig. 11. Aerial photo of the giant Jebel Akhdar dome, view towards the WNW showing the Semail Thrust (red) folded over the anticline, and reactivated as a low-angle normal fault (yellow) during compressional uplift of Jebel Akhdar. Photo courtesy of Petroleum Development (Oman) Ltd. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

footwall shelf carbonates.

3.6.2. Semail Gap fault

The contact between the Semail ophiolite and the Jebel Nakhl shelf carbonates is a sharp contact running along the Semail Gap, a 70 km long NNE-SSW aligned topographic feature (Fig. 12). The contact has been interpreted as (a) an east-dipping normal fault above a lateral ramp during Late Cretaceous thrusting (Mount et al., 1998; Searle, 2007), or (b) a dextral strike-slip or transtensional fault, formed as a result of gravitational collapse (Mattern and Scharf, 2018; Scharf et al., 2019) during the late Eocene (Hansman et al., 2017; Grobe et al., 2018). No strike-slip offsets occur in the geology along the northern part of the Semail Gap in the Jebel Nakhl – Fanjah region, so there is no evidence for any strike-slip faulting. Indeed, the major NNE-trending anticlinal axis of Jebel Nakhl swings around to E-W trending in the Fanjah saddle area (Coffield, 1990). Bedding dips steeply away from the anticline axis on both the west and east sides of Jebel Nakhl, and curves around the 90° bend in the northern part of the Semail Gap. The 90° swing in alignment of the major anticlinal axes of Jebel Akhdar and Jebel Nakhl is best explained as the result of a classic dome and basin fold interference pattern (Ramsay and Huber, 1987). Maximum compressive stress in Oman during the Late Cretaceous was NE-SW with the obduction of the ophiolite and underlying thrust sheets, but a contemporary, or later WNW-ESE compression resulted in the NNE-SSW alignment of the Jebel Nakhl anticline axis (Searle, 2007). The cause of this secondary WNW-ESE compression remains unknown.

3.6.3. 'Semail Thrust' around Saih Hatat

The northern margin of the Saih Hatat culmination exhibits a spectacular listric fault geometry showing a variety of different lithologies along the hanging-wall, including serpentinized peridotites and HP Ruwi mélange, unconformably overlain by Maastrichtian (Simsima Fm.) and Paleocene-Eocene limestones (Jafnayn, Seeb Fms). Well-bedded and folded shelf carbonates are exposed in the high mountains along the footwall, although the upper stratigraphic units have been excised by a significant fault. This fault has been mapped as the 'Semail Thrust', and has also been termed the 'Frontal Range fault' (Hanna, 1990; Mattern and Scharf, 2018). This name is, however, inappropriate because the fault lies along the hinterland margin of the culmination, not the frontal part, and actually wraps all around the shelf carbonates (Fig. 1). Several authors have related the fault to extension during gravitational collapse (Mann et al., 1990; Mattern and Scharf, 2018). 'Collapse' implies a lowering of surface elevation, normal faulting and thinning of the crust. However, we favour an alternative explanation whereby uplift of the

Fig. 12. Aerial view of the Semail ophiolite, taken above Semail village, looking west towards the Jebel Nakhl, showing the shelf carbonates in distance. The contact is the Semail Gap fault, interpreted as a normal fault dropping ophiolite rocks down to the east overlying a lateral ramp, formed during compressional uplift and culmination of the Jebel Akhdar anticline.

footwall (shelf carbonates of Jebel Akhdar and Saih Hatat) occurs along the normal faults when the hangingwall (allochtonous Hawasina, Haybi and Semail ophiolite thrust sheets) remains static. These normal faults were active during compressional uplift of the Saih Hatat shelf carbonates, similar to features observed throughout the entire Jebel Akhdar and Saih Hatat regions. These normal faults do not require lithospheric-scale extension, or orogenic collapse, at all; they merely relate to late-stage uplift and culmination of deeper, later thrust sheets. In this scenario, the hanging-wall of the normal fault remained relatively static, as the footwall rocks rose due to compressional thrust culmination.

Based on inferred stress directions from faults cutting the ophiolite and younger units, Fournier et al. (2006) proposed two stages of ENE-WSW extension, one during Late Cretaceous to Early Eocene, the second post-Eocene, followed by NNE-SSW extension, and finally by early Miocene-Pliocene inversion and compression. These multiple apparent 'phases' of extension may more simply reflect the compressional uplift of lower footwall rocks as described above. Post-Eocene extension in northern Oman is also difficult to reconcile with large-scale post-Eocene compressional folds along the Qurum – Muscat region north of Saih Hatat and Oligocene-Miocene uplift of the Oman Mountains. Based on offshore seismic reflection data and onshore structural data, Levell et al. (2021) provide compelling evidence for a deep hinterland basin above, to the NE of the trailing edge of the ophiolite that contains ca 5 km of Late Cretaceous deep-sea sediments. This hinterland basin is coeval with the Aruma foreland basin SW of the mountains. A prominent phase of Late Eocene – Oligocene east-west compressional folding (north-south fold axes) of Paleogene shallow marine carbonates around Qurum – Bandar Jissah region also includes folding and doming of the Muscat ophiolite. A second major phase of compression occurred in the Pliocene, and it is very likely that the compressional uplift of the Oman Mountains continues to this day. Major upper crustal extension is seen only in the distal part of the Gulf of Oman where a spectacular 60 km long, low-angle fault, down-throws the hinterland basin toward the Makran trench (Levell et al., 2021).

4. Summary

The Semail Thrust is commonly shown as a single line on geologic maps along the base of the ~15 km thick Semail ophiolite, an intact thrust sheet of upper mantle and oceanic crust emplaced onto the Arabian continental margin during the Late Cretaceous. However, this single line on the map includes a wide range of structures in time and space, imparted by a wide array of processes. A combination of structural mapping together with stratigraphic and geochronological constraints enables a detailed evolution of the Semail Thrust over time and space. The first increment of the Semail Thrust started as an early ductile shear zone along which exhumed, subduction-related garnet- and clinopyroxene-bearing amphibolites, garnet-free amphibolites, and greenschists were accreted to the base of the ophiolite during exhumation immediately following initial subduction. This was immediately followed by exhumation of the metamorphic sole, and welding of the sole rocks along the base of the ophiolite. Exhumation progressed in time and space to brittle thin-skinned thrusting of the ophiolite over allochthonous distal (Haybi complex) and proximal (Hawasina complex) Tethyan oceanic rocks. Late stage out-of-sequence brittle thrusting along the Semail Thrust is apparent from the Bani Hamid thrust sheet in UAE, where two large ophiolite thrust sheets are separated by a 1 km thick thrust sheet of highly folded and sheared lower crust Late Cretaceous granulites.

During the period from 96 to 80 Ma the Semail Thrust was the compressional fault along which the Semail ophiolite was emplaced over the continental margin. At ~80-79 Ma the leading margin of the continental crust in the NE part of the mountains was subducted to depths of around 80–100 km as the As Sifah eclogites attained peak HP metamorphism. The Semail Thrust beneath the Muscat part of the Semail ophiolite then acted as a passive roof fault beneath which the entire HP sequence of NE Oman was exhumed to the SW following NE-dipping subduction of the former continental passive margin. The HP rocks include the structurally deepest level eclogites at As Sifah, the intermediate Hulw blueschsists, the carpholite-bearing meta-sediments and lawsonite-bearing meta-basalts of the Ruwi mélange, and underlying shelf carbonate units, also containing carpholite (Wadi Mayh, Yenkit, Yiti, Al Khuyran units). Widespread regional 'extensional' top-to-NNE ductile shear S–C fabrics and other kinematic indicators relate to SSW-extrusion of footwall HP rocks in a wholly compressional environment (Searle et al., 1994, 2004; Agard et al., 2010; Yamato et al., 2007; Garber et al., 2021), not to any SW-directed subduction (Gregory et al., 1998; Gray et al., 2000, 2004; Miller et al., 2002; Goscombe et al., 2020), or to crustal extension related to orogenic collapse (Mattern and Scharf, 2018; Scharf et al., 2019).

The final motion along the Semail Thrust was reactivation of the initial thrust fault by low-angle normal faulting during compressional culmination of deep-level Jebel Akhdar and Saih Hatat domes. These very large-scale domes affect all rocks from pre-Permian basement up through Permian – Mesozoic shelf carbonates, as well as all the overlying Late Cretaceous allochthonous thrust sheets, including the Semail ophiolite. These normal faults encircle both culminations, but do not relate to any net extension. Instead, they relate to compressional folding and uplift of footwall shelf carbonates beneath a static or passive roof fault, in a similar manner to the low-angle normal faults beneath the hanging walls of compressional core complexes (Searle and Lamont, 2019).

The Semail Thrust is thus a complex structural feature, varying with depth and time, belying its simple expression of a single line on most geologic maps. Interpretation of the detailed structural maps, combined with metamorphic, thermobarometric, and geochronological data, reveals a time-resolved evolution of the complete emplacement history of the Semail ophiolite, the late-stage subduction and exhumation of the continental margin, and to mountain building processes along the Oman Mountains.

Author statement

All authors participated in field work and write-up.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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