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Research paper

Geochronological constraints on the metamorphic sole of the Semail ophiolite in the United Arab Emirates

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ABSTRACT

The Semail ophiolite of Oman and the United Arab Emirates (UAE) provides the best preserved large slice of oceanic lithosphere exposed on the continental crust, and offers unique opportunities to study processes of ocean crust formation, subduction initiation and obduction. Metamorphic rocks exposed in the eastern UAE have traditionally been interpreted as a metamorphic sole to the Semail ophiolite. However, there has been some debate over the possibility that the exposures contain components of older Arabian continental crust. To help answer this question, presented here are new zircon and rutile U-Pb geochronological data from various units of the metamorphic rocks. Zircon was absent in most samples. Those that yielded zircon and rutile provide dominant single age populations that are 95–93 Ma, partially overlapping with the known age of oceanic crust formation (96.5–94.5 Ma), and partially overlapping with cooling ages of the metamorphic rocks (95–90 Ma). The data are interpreted as dating high-grade metamorphism during subduction burial of the sediments into hot mantle lithosphere, and rapid cooling during their subsequent exhumation. A few discordant zircon ages, interpreted as late Neoproterozoic and younger, represent minor detrital input from the continent. No evidence is found in favour of the existence of older Arabian continental crust within the metamorphic rocks of the UAE.

1. Introduction

The obduction of oceanic lithosphere during plate convergence remains one of the enigmatic features of Earth's plate tectonic regime. Obduction allows the on-land study of the composition of the oceanic crust and upper mantle, and the processes by which crustal rocks are subducted to deep pressures and exhumed back to the surface. The Semail ophiolite (also known as the Oman-United Arab Emirates (UAE) ophiolite complex), is the largest and best preserved sliver of oceanic crust exposed on Earth's continental crust. It comprises a complete section from upper mantle harzburgite rocks, through to the uppermost pillow basalts (e.g., Searle and Cox, 1999; Goodenough et al., 2014b).

In the Hajar Mountains of the eastern United Arab Emirates (UAE), fault-bounded sequences of medium to high grade metamorphic rocks lie beneath and within tectonic slabs of the Semail ophiolite complex (Fig. 1). These have traditionally been termed "metamorphic sole" rocks, correlating to those seen in Oman (e.g., Searle and Malpas, 1980; Searle and Cox, 1999, 2002). However, there remains a possibility that some components of the metamorphic rocks exposed in the UAE might include remnants of much older regionally metamorphosed Arabian continental crust. In the metamorphic sole hypothesis, the rocks are presumed to be the metamorphosed equivalents of the late Cretaceous deep ocean and continental margin rocks that became caught between the Arabian margin and the obducted mass of the Semail ophiolite (Searle and Cox, 2002). However, this correlation is by no means obvious from field relationships.

In this study, we present new U-Pb geochronology from zircon and rutile obtained from quartzose meta-sedimentary rocks of the Bani Hamid and Masafi areas, in order to help constrain the origin and history of the metamorphic rocks of the UAE during ophiolite formation and obduction. In addition to constraining the age of metamorphism, this study was also aimed at obtaining detrital

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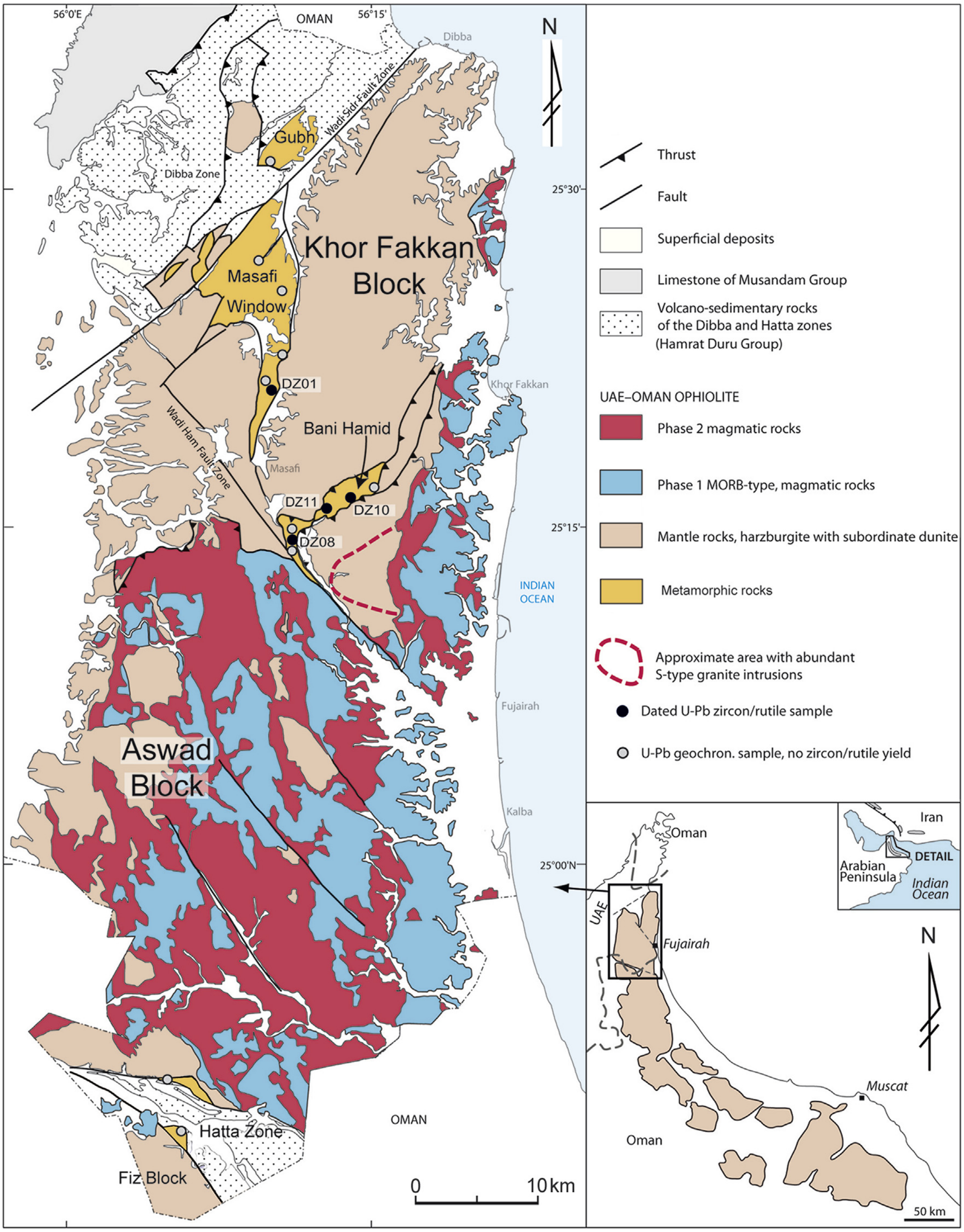

Figure 1. Simplified geological map of the Hajar Mountains in eastern UAE showing the location of samples collected, many of which did not yield zircon and/or rutile (modified after Goodenough et al., 2010). The successfully dated samples are marked in black. Inset shows location of the Semail ophiolite within the UAE.

zircon data from the metamorphic rocks in the UAE, in order to quantify the possible provenance and maximum depositional age of the original sediments. The data are used to constrain whether the metamorphic rocks contained elements of Arabian crust.

2. Geological setting

The Semail ophiolite complex is one of the Alpine ophiolites that formed during closure of the Neotethys Ocean, and that occur in isolated belts across Europe and Asia. The ophiolite complex extends over 500 km from the NE coast of Oman, to Dibba in the UAE (Fig. 1). Obduction of the ophiolite occurred in an arcuate, generally south-westwards direction onto the Arabian margin during the late Cretaceous. The Arabian continental margin at this time comprised Cryogenian crystalline basement, with a cover of Ediacaran volcanic and sedimentary rocks, and overlying Palaeozoic to Mesozoic rocks (Allen, 2007; Bowring et al., 2007; Thomas et al., 2015). The latter comprise platform carbonates of the Musandam Supergroup, and

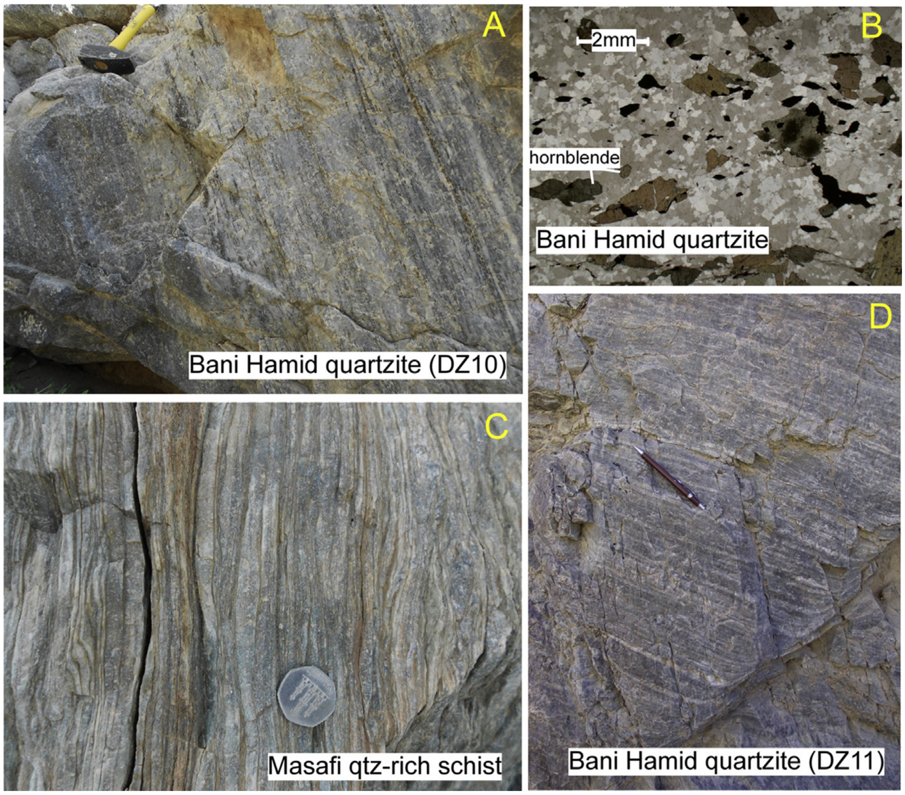

Figure 2. Field photographs (A, C, D) and photomicrograph (B) of typical Bani Hamid and Masafi quartzites.

passive margin continental slope and deep water volcano-sedimentary sequences of the Hamrat Duru Group (Styles et al., 2006; Thomas and Ellison, 2014).

The igneous rocks of the ophiolite in the UAE segment exhibit a complex history of magmatism (Goodenough et al., 2010, 2014b). A similar complexity has been reported in the main, Oman, section of the ophiolite (e.g. Tsuchiya et al., 2013). In short, magmatism occurred in two major phases. The first phase, characterized by typical ocean-crust rocks (layered gabbro, isotropic gabbro, sheeted dykes and basaltic pillow lavas) with MORB type geochemistry was generated at an oceanic spreading centre, while the second phase that comprises high-level gabbros, dolerites and wehrlites has island-arc type hydrous geochemistry and is interpreted to have been generated in a supra-subduction zone (SSZ) environment from the partial melting of a descending oceanic lithosphere slab. Magmatic ages relating to both phases overlap and range from ~96.5 to 94.5 Ma (Warren et al., 2005; Goodenough et al., 2010; Rioux et al., 2012, 2013). There has been some debate over the origin of obduction of the Semail ophiolite, whether it was initiated in a mid-ocean ridge setting (e.g. Boudier et al., 1985, 1988; Hacker, 1991, 1994), or in a supra-subduction zone (SSZ) setting. The latter is our preferred option, being supported by abundant evidence (e.g. Searle and Malpas, 1980; Pearce et al., 1981; Searle and Cox, 1999, 2002; Searle et al., 2003; Goodenough et al., 2010, 2014b; Cooper et al., 2014; Cowan et al., 2014).

Apart from the observed two-phase magmatic history of the ophiolite, a primary line of evidence for a SSZ setting is the nature of the metamorphic rocks. These are metamorphosed supracrustal rocks that record metamorphic conditions with much higher pressures than could have been imposed by the thickness of an overthrust ophiolite slab alone. They are traditionally referred to as the "metamorphic sole" to the ophiolite (e.g. Searle and Cox, 2002). Obduction of the ophiolite took place in the late Cretaceous (Glennie et al., 1973), very soon after initiation of the Phase 2 (SSZ) magmatism.

Metamorphic sole rocks crop out at various locations across the entire region of the Semail ophiolite complex and have been studied in detail by various workers. Searle and Cox (2002) provided a review of these findings and highlighted the key points: (1) an inverted metamorphic gradient occurs in the metamorphic rocks at the base of the ophiolite, (2) amphibolites containing garnet and clinopyroxene record temperatures of ~850 °C at 1.1–1.4 GPa, (3) partial melting forming small tonalitic pods occurred at these high temperatures, (4) thrust faults bound the upper and lower contacts of the metamorphic sole rocks, (5) heat for metamorphism must have been sourced from the overlying ophiolite mantle sequence, (6) greenschist facies meta-sediments were accreted to the base of the amphibolites at shallower depths during thrust emplacement, and (7) the final emplacement involved at least 250 km of thrusting south-westwards. Cowan et al. (2014) provided a detailed description of the metamorphic rocks at the base of the ophiolite in Oman. The metamorphic rocks exposed in eastern UAE of interest here are described in detail in Styles et al. (2006) and Thomas and Phillips (2014), and are briefly discussed in the next section.

2.1. Metamorphic rocks

The metamorphic rocks of the UAE outcrop in four areas, from north to south, these are the Ghub, Masafi, Bani Hamid and Hatta areas (Fig. 1). The Masafi area is the largest and covers an area of nearly 100 km^2. Both the Masafi and Ghub areas are dominated by pale grey to green, greenschist to lower amphibolite facies schistose metasedimentary and meta-volcanic rocks. The metamorphic rocks of the Bani Hamid area are much higher grade, up to granulite

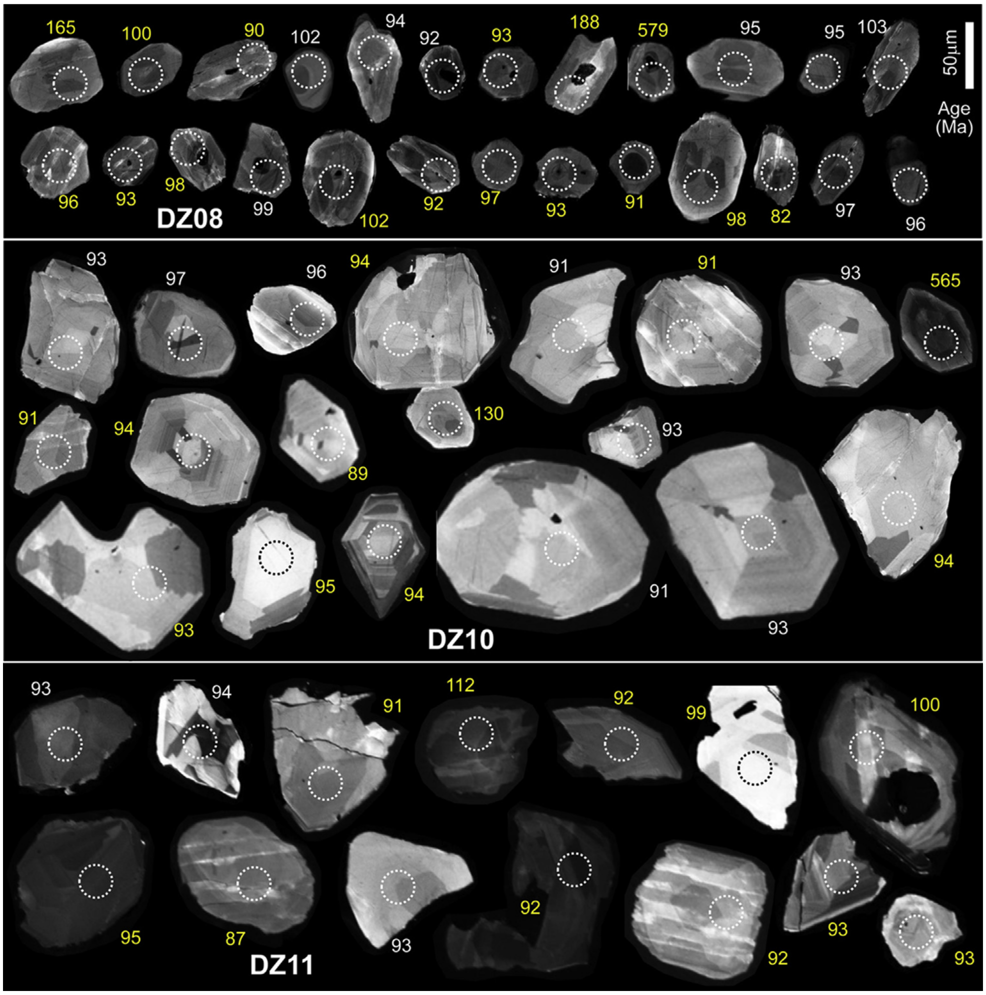

Figure 3. Cathodoluminescence images of representative zircons analysed in this study. Ellipses show common-lead corrected $^{206}Pb/^{238}U$ ages (white are >90% concordant, and yellow are >10% discordant).

facies. Further to the south in the Hatta area, greenschist to lower amphibolite facies metamorphic rocks occur as small fault-bound slivers at the tectonic margins of the Hatta Zone.

2.1.1. *Masafi-Ghub area*

The metamorphic rocks exposed in the Masafi and Ghub areas are divided into two lithostratigraphic divisions known as the Masafi-Ismah and Jebel Hakimah groups. The former comprises deformed greenschist to locally amphibolite facies, quartz-rich metasedimentary rocks (quartz-chlorite ± biotite ± garnet schists, metacherts; Fig. 2) with subordinate meta-carbonate and meta-volcanic rocks. The Jebel Hakimah Group underlies the Masafi-Ismah Group and comprises more weakly metamorphosed basaltic volcanic rocks, cherts and siliceous mudstones. The chemistry of the volcanic rocks in the Masafi-Ismah group is quite distinct from that of the underlying Jebal Hakimah Group and indicates that the meta-volcanic rocks that dominate the lower part of the Masafi-Ismah Group were erupted at a mid-ocean ridge (Styles et al., 2006). Both groups are subdivided into a number of north-south-trending formations, the boundaries between which are mainly tectonic, and marked by gently inclined brittle thrusts and/or high-angle brittle faults. The upper part of the Jebal Hakimah Group contains carbonatites that have given a U-Pb SHRIMP zircon date of 103 ± 1 Ma (Grantham et al., 2003), indicating that the group is no younger than late Cretaceous (Albian). These carbonatites were intruded at shallow depths into the ocean crust as hypabyssal intrusions, and were also extruded as pyroclastic rocks on the ocean floor, possibly in an ocean-island type setting (Grantham et al., 2003).

2.1.2. *Bani Hamid area*

The highest grade metamorphic rocks in the UAE and the Omani Madhah enclave are a sequence of upper amphibolite to granulite facies gneisses that crop out in the Bani Hamid area to the south of Masafi (Fig. 1), where they form very rugged mountains, and underlie a combined area of about 20 km^2. The structural upper and lower boundaries of the package of high-grade rocks are marked by moderate to high-angle, SE-dipping, NW-verging ductile thrusts. The polyphase Wadi Ham shear zone forms the western margin. The Bani Hamid Group (Styles et al., 2006) has been subdivided into four informal tectonostratigraphic units, each comprising differing proportions of layered and foliated to massive quartzites and quartz schists (Fig. 2), calc-silicate/marbles and amphibolites (Thomas and Phillips, 2014). The massive to banded, dark-green to black amphibolites are up to 100 m thick and comprise the mineral assemblage amphibole, plagioclase and clinopyroxene ± garnet. Although high-grade, few of the Bani Hamid rocks show significant partial melting and, where present, migmatisation has resulted in the formation of relatively thin veins and small pods of trondhjemitic leucosome in the amphibolites. Small melt pods have been dated by zircon U-Pb at 95.69 ± 0.25, 95.29 ± 0.21 and 92.43 ± 0.15 Ma (Styles et al., 2006).

2.1.3. Hatta area

Relatively small areas of greenschist to lower amphibolite rocks occur adjacent to the north and south bounding faults of the Hatta Zone in the southern UAE (Fig. 1). These comprise quartz schists and meta-cherts, mafic chlorite-actinolite schists with impure marbles and chlorite-epidote-rich calc-silicate rocks.

2.2. Intrusive felsic rocks

The ophiolite harzburgite nappe that structurally overlies the Bani Hamid metamorphic rocks is locally riddled by a complex array of sheets, dykes, small irregular intrusions and stockworks of white-weathering leucogranite. The largest of these form irregular, steep-sided dyke-like bodies up to several hundreds of metres in length, and in a few localities, also intrude the metamorphic rocks. Larger leucogranite bodies are in places composite, comprising two or more phases of intrusion with slightly differing grain size and mineralogy. Many possess a weak foliation parallel to their margins. The granites are meta- to peraluminous in composition, and are composed of quartz, K-feldspar, albite and biotite with minor muscovite, tourmaline, garnet and sillimanite. This composition is typical of S-type granites derived from the partial melting of a metamorphosed sedimentary protolith. The leucogranites possibly formed by the partial melting of the Bani Hamid metasedimentary rocks, with the resultant magma intruding upwards into the overlying ophiolite (see Rioux et al., 2013). A small peraluminous granite body within the uppermost harzburgite nappe in the UAE was dated at 93.22 ± 0.29 Ma (Styles et al., 2006).

2.3. Metamorphic evolution

The localised biotite-garnet assemblage within the metabasites of the Masafi-Ismah Group, coupled with the amphibole-rich nature of the meta-mafic igneous rocks, is consistent with the schistose rocks of the Masafi-Ismah Group having undergone greenschist to lower amphibolite facies metamorphism.

High-pressure conditions for the metamorphic rocks are compatible with the deep levels indicative of subduction zone burial. Pressure and temperature of those in the UAE have been estimated by various workers. In the Masafi area, Gnos (1998) determined temperatures of 800 ± 100 °C and pressures of 1.1 ± 0.2 GPa for garnet-diopside amphibolites. In the Bani Hamid area, Gnos and Kurz (1994) estimated peak conditions at 800 ± 50 °C and 0.65–0.9 GPa. Subsequently, Gnos (1998) and Cox (2000) determined temperatures of 800–860 °C and pressures of 1.05 ± 0.1 to 1.47 ± 0.3 GPa, and found these are uniform across this thrust slice. More recently, using petrogenetic grids combined with conventional thermobarometry, Searle and Cox (2002), determined conditions of ca. 850 °C at 1.0–1.5 GPa. An inferred anticlockwise P-T path is preferred by Searle and Cox (2002), compatible with a model whereby heating from the hot overlying ophiolite lithosphere increased the temperature of the sole rocks.

3. Samples

In addition to constraining the age of metamorphism of the high grade Bani Hamid rocks, an original aim of this project was also to obtain detrital zircon data from all four of the areas of metamorphic rocks in the UAE (see Fig. 1 for locations). This proved unsuccessful, as separation of twenty samples only yielded four with minerals useful for geochronology, and in these, zircon and rutile were present but not particularly abundant. The samples that did not yield zircon or rutile are not discussed further in this paper.

DZ01 is a quartz schist from the Masafi-Ismah area. Rutile from DZ01 is 50–100 um in size and anhedral. No zircon was recovered.

DZ08 is a coarse grey foliated quartzite from Unit 4 of the Bani Hamid Group. Zircon grains from DZ08 (see Fig. 3) are euhedral to subhedral, short stubby prisms, with crystal facets preserved in many cases. The grains are 50–150 μm long, with length/width ratios of 1–3. Zonation according to CL is weakly developed, occurring as sector zoning in many grains, and poorly and coarsely developed oscillatory zoning. Many grains are fractured. A few grains exhibit darker remnant cores. Rutile grains are 50–100 μm in size and anhedral.

DZ10 is a grey quartzite from Unit 2 of the Bani Hamid Group. Zircon grains are 50–300 μm long, with length/width ratios of 1–2. Zonation in CL is typically sector zoned, and/or with fir-tree zoning. A few embayments and unconformities between outer and inner zones occur in some grains, suggesting multiple age populations may exist. Grain shapes range from anhedral to euhedral, some are irregular, but many grains have preserved crystal facets. Rutile grains are 50–100 μm in size and anhedral to subhedral.

DZ11 is a layered grey quartzite from Unit 1 of the Bani Hamid Group. Zircon grains from DZ11 are 50–200 μm long, although often represent broken fragments, with estimated length/width ratios of 1–2. Zonation is weakly defined in most grains, and either looks disturbed, or is coarsely developed oscillatory or sector zonation. Grain shapes are generally anhedral to subhedral, and are poorly rounded, but also lack preserved crystal facets. Many grains are cracked or broken.

4. Methods

Samples were crushed and minerals were separated using standard techniques (Jaw-crushing, disc milling, sieving, Rogers table, heavy liquids, Frantz magnetic separation). Heavy minerals (rutile and zircon) were picked under alcohol and mounted in 1 inch epoxy resin mounts. Zircon was imaged for cathodoluminescence (CL) on a FEI600 scanning electronic microscope (SEM), and rutile was identified using back-scattered electrons (BSE) but not imaged.

U-Pb geochronology was conducted at the NERC Isotope Geosciences Laboratory (Nottingham) and utilised a Nu Attom single collector inductively coupled mass spectrometer (ICP-MS) coupled to a New Wave Research 193ss Nd:YAG laser ablation system, fitted with a large format cell. Methods for zircon follow those described previously in Spencer et al. (2015). Laser ablation parameters were 25 μm spots for zircon, and 35 μm for rutile, a fluence of 2.0–2.5 J/cm^2, an ablation time of 30 s, a repetition rate of 5 Hz, and a 10 s washout between ablations. A 60 s on-peak gas blank is taken before every 10 to 20 ablations. For rutile, methods are identical for zircon, except that ^{238}U is measured instead of ^{235}U, and sweep and dwell times are adjusted. For zircon, these were 100 sweeps per integration using dwell times of 200 μs for ^{202}Hg, ^{204}Hg, ^{208}Pb and ^{232}Th, 400 μs for ^{206}Pb, and 1000 μs for ^{207}Pb and ^{235}U (^{238}U is calculated using ^{235}U ×137.818 Hiess et al., 2012). For rutile, measurement includes 80 sweeps of the following dwell times 200 μs for ^{202}Hg, ^{204}Hg, ^{208}Pb, ^{232}Th and ^{238}U, 1000 μs for ^{206}Pb, and 2000 μs for ^{207}Pb.

Standard-sample bracketing is used for normalisation and correction of mass bias (of ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U ratios), utilising 91500 (Wiedenbeck et al., 1995) for zircon as a primary reference material, and Sugluk-4 (Bracciali et al., 2013) for rutile. Three to four primary reference material analyses between every 8–12 samples analyses. Secondary reference materials were run as unknowns, GJ-1 for zircon, and PCA-S207 for rutile. Data reduction uses the TRA software from Nu Instruments, and an excel spreadsheet for calculation of ratios and ages. Final age uncertainties include propagation of systematic uncertainties. Isoplot 3.75 (Ludwig, 2012) is used for plotting. No common lead correction is made to the initial ratios or ages. For zircon, high common lead contents are monitored using on-peak measurement of the ^{202}Hg/^{204}X ratio, and subtraction of the ^{204}Hg signal. High ^{204}Pb values can then be excluded from age calculations. Concordia plots of both zircon and rutile show data not corrected for common lead. Since both zircon and rutile contained substantial common lead, a ^{207}Pb based method (e.g. Chew et al., 2011) was used to correct the ^{206}Pb/^{238}U ages, which assumes concordance of all analyses. These ages are used for calculation of the final reported ages, and are shown in Fig. 4. The precision across the analytical sessions, based on reproducibility of the primary and secondary reference materials was 1.2–1.7% for zircon, and 2.3–3.7% for rutile. Accuracy, i.e. offset from accepted age, based on secondary reference materials is 0.4% and 2.2% for zircon and rutile respectively; 604.4 ± 1.8 Ma for GJ-1 (602 Ma; Jackson et al., 2004, in-house ID-TIMS), and 1905 ± 44 Ma for PCA (1865 ± 7.5 Ma; Bracciali et al., 2013).

5. Results

5.1. Zircon U-Pb geochronology

All three samples that yielded zircon gave variably discordant analyses, with a dominant population of data falling between a common lead component, and a ca. 95 Ma lower intercept (Fig. 4). A few analyses gave much older ages, but these are all strongly discordant. For this reason, it cannot be determined whether the ^{207}Pb/^{206}Pb ages represent their primary age, or whether they also comprise large common lead components. For DZ08, ^{207}Pb/^{206}Pb intercept ages range from 729 Ma ($n = 1$), to 1329–1771 Ma ($n = 3$) to 2874 Ma ($n = 1$); corresponding common-lead corrected ^{206}Pb/^{238}U ages are 165–205 Ma ($n = 4$) and 578 Ma ($n = 1$). For DZ10, two older analyses have ^{207}Pb/^{206}Pb ages of 724 and 2139 Ma, and corresponding ^{206}Pb/^{238}U ages of 130 and 565 Ma, respectively. Assuming that the older analyses contain common-lead, concordant common-lead corrected ages are late Neoproterozoic in age (∼565–580 Ma), and Jurassic to Cretaceous. The dominant younger populations spread from ∼115 to 90 Ma. There are no discernible

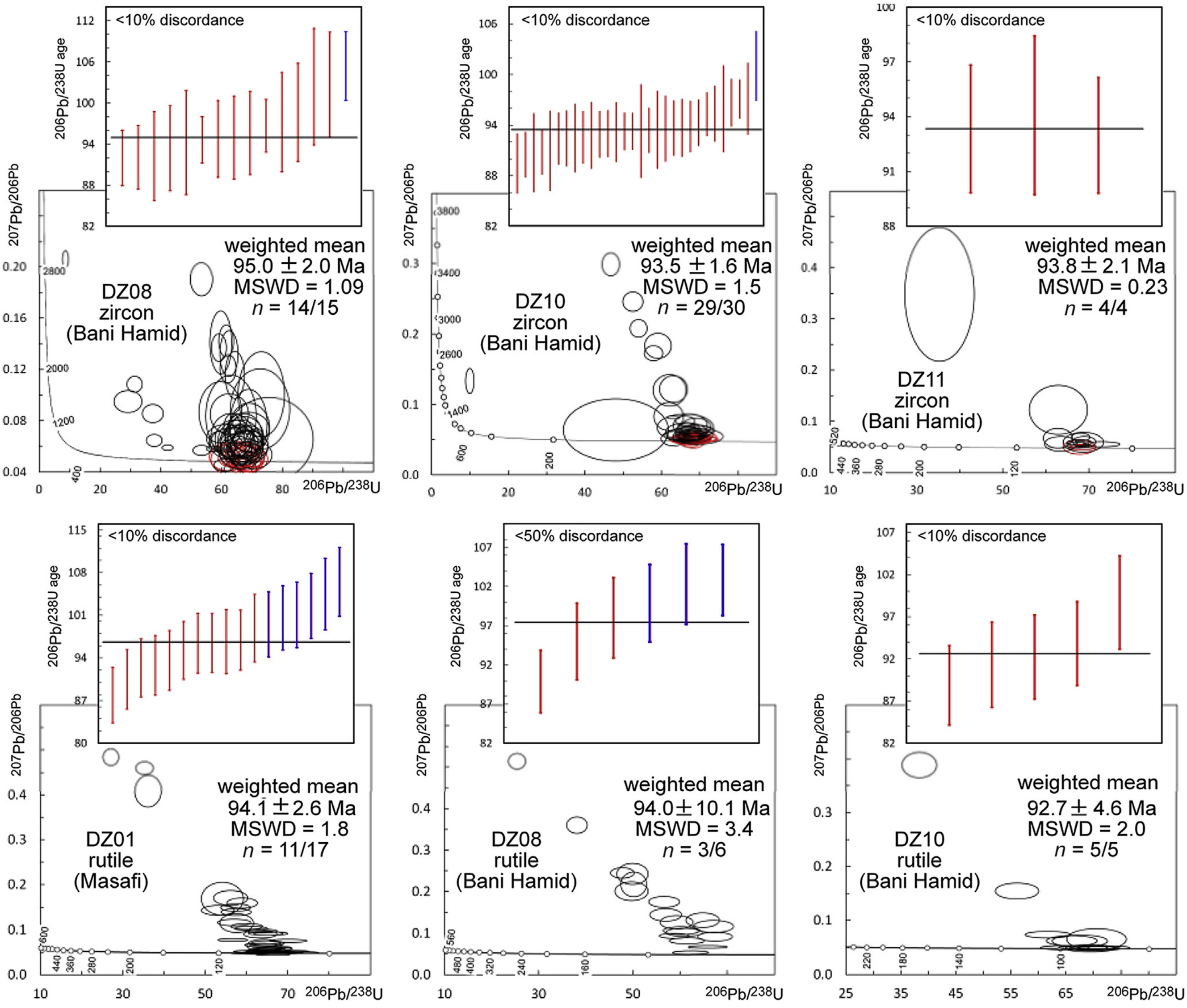

Figure 4. Tera-Wasserburg and weighted average common-lead corrected ^{206}Pb/^{238}U ages of analysed samples, for zircon (top) and rutile (bottom).

populations that can be distinguished based on age alone. Using chemical composition, i.e. Th/U, or chemical zonation (i.e. as seen in CL) can aid the discrimination of zircon populations in cases where different age populations overlap (e.g. Hanchar and Miller, 1993; Whitehouse et al., 1999; Goodenough et al., 2014a; Thomas et al., 2014). However, in this case, there is no systematic between composition or zonation with age.

Various approaches can be taken to determine the youngest zircon growth or resetting event within a population of data (e.g. Fedo et al., 2003; Dickinson and Gehrels, 2009; Gehrels, 2011). With detrital studies, using the youngest cluster of concordant ages is one typically used approach (e.g. Jones et al., 2009; Thomas et al., 2015), others look at multiple ages of the youngest and most concordant analyses (e.g. Spencer et al., 2014a), and others look at the single ages of the most concordant analyses (e.g. Spencer et al., 2014b). Here we have no *a priori* evidence regarding whether the analytical population represents a detrital, metamorphic or mixed origin of dates. Therefore, a conservative approach at determining the youngest single 'event' is taken, whereby the common lead corrected ages of the youngest population of concordant (>90% concordance) analyses are distinguished, based on the MSWD statistics. This approach only removes one analysis from each of DZ08 and DZ10, therefore not shifting the age significantly from a mean of the entire concordant dataset. For DZ08, fourteen out of fifteen concordant analyses give 95.0 ± 2.0 Ma (MSWD = 1.09). For DZ10, twenty nine out of thirty concordant analyses give 93.4 ± 1.6 Ma (MSWD = 1.5). For DZ11, four out of four concordant analyses give 93.8 ± 2.1 Ma (MSWD = 0.23). The low MSWD of the concordant populations indicates that they can be treated as a single population (within the analytical uncertainty).

5.2. Rutile U-Pb geochronology

All three samples that yielded rutile define mixing lines between a common lead component, and lower intercept ages at c. 95 Ma (Fig. 4). The rutile may be entirely from new growth during metamorphism, or maybe older rutile that has been reset during metamorphism. In either case, the youngest age is required, which should indicate the timing of cooling through the closure temperature for U-Pb in rutile. This age is calculated the same way as for zircon above, except that in DZ08, no concordant analyses could be used, so a 50% discordance cut-off was used instead. For this reason, the resultant age should be regarded with less confidence than the others. For DZ01, eleven out of seventeen concordant analyses give 94.1 ± 2.6 Ma (MSWD = 1.8). For DZ08, three out of six concordant (>50% concordance) analyses give 94.0 ± 10.1 Ma (MSWD = 3.4). For DZ10, five out of five concordant analyses give 92.7 ± 4.6 Ma (MSWD = 2.0).

6. Discussion

6.1. Interpretation of ages

One of the original intentions of this study was to attempt to determine detrital ages from the metamorphic rocks to ascertain their origin. The ages in this study overlap that of the ophiolite formation and of previous estimates on ophiolite obduction, and the rocks themselves have been affected by medium (DZ01) to high-grade metamorphism (DZ08, DZ10, DZ11). From a previous age determination of carbonatite volcanism (103 Ma; Grantham et al., 2003) within associated volcano-sedimentary rocks of the Masafi area, magmatism producing zircons may have been not much older, but possibly exhibiting a greater range than this single determination. The zircon ages from our study could thus be interpreted as primary ages of magmatic rocks that have fed into the sedimentary basins, therefore providing maximum ages of deposition. Alternatively, the zircon ages could be affected by metamorphism, and provide evidence for the timing of this event. Various lines of evidence support the latter.

Primarily, the ages obtained in our study overlap the previous estimates for the timing of obduction. These are based on melt pods within the Bani Hamid amphibolites (95.7–92.4 Ma) and the overlying Harzburgite nappe (93.2 Ma) (Styles et al., 2006), and can be constrained by cooling ages of the metamorphic sole at ~95–93 Ma (Hacker et al., 1996). If the zircon ages reflected volcanism, then these would have to supply sediments that were being buried and metamorphosed at the same time, within analytical uncertainty (<2 Ma). The textures of the zircon reveal weakly-defined sector zoning, weak and coarse oscillatory zoning, and in some cases a complete lack of zoning. These features, and their multi-faceted shapes, are all typical of granulite-facies zircon domains (see Corfu et al., 2003) but not of volcanic zircons or those from the ophiolite (e.g. Rioux et al., 2012). The zircon grains are not rounded, as would be typical, but not definitive of a detrital origin. Evidence of overgrowths is visible in some grains, but no distinctly younger domains mantling older domains were evident from the geochronological data. The composition of the grains based on Th/U, is variable.

Rutile is not a common accessory mineral in oceanic volcanic rocks, so the single age populations in the samples are interpreted as recording rutile growth during metamorphism. In summary, the extent to which the younger zircon population (with concordant ages of ~103–91 Ma) represents (1) in its entirety resetting of older zircon, (2) growth of new zircon, and/or (3) primary detrital zircon, remains somewhat equivocal. However, the lines of evidence are strongly in favour of the interpretation that the ages determined here are documenting high-grade metamorphism of the host rocks.

6.2. Metamorphic sole or remnants of an ancient continent?

A major question concerning the metamorphic rocks of the UAE, is whether they represent the metamorphic sole to the UAE-Oman ophiolite and formed during its obduction during the late Cretaceous, or whether they contain remnants of older continental crustal basement that were deformed and subjected to a metamorphic overprint during ophiolite obduction. How to distinguish between these hypotheses?

The first line of evidence comes from the metamorphic evolution that is to be expected from ophiolite obduction. The metamorphic sole of many ophiolites worldwide is typically thin (Wakabayashi and Dilek, 2003), up to a maximum thickness of a few hundred metres, and shows a reverse metamorphic gradient, waning away from the over-riding obducted slab. This process can thus be considered to be an extreme form of thermal or contact metamorphism, in which the sole rocks are heated by the sub-ophiolitic mantle rocks that are over 1000 °C. This type of localised metamorphism will only occur during subduction inception, when the sole rocks are in contact with hot mantle, prior to its cooling during continued subduction of cold oceanic lithosphere (Hacker et al., 1996; Wakabayashi and Dilek, 2003). An increase in metamorphic facies is recorded locally, immediately adjacent to the contact between the ophiolite and the metamorphic rocks of the Masafi-Ismah and Bani Hamid areas, is indicative of this type of metamorphism. The age of obduction-related metamorphism in the UAE rocks, was previously indirectly established from zircons that formed during crystallisation of the tonalitic melt segregations (~95–92 Ma; Styles et al., 2006), and here, is established through zircon and rutile ages of meta-sedimentary sole rocks (~95–93 Ma). The spread in ages may reflect melting during initial contact metamorphism, but also later on during exhumation and emplacement.

The second line of evidence comes from the lithologies themselves. Those of the metamorphic rocks are compatible with sediments being deposited in a continental-slope to deep-marine environment (Styles et al., 2006; Thomas and Phillips, 2014). These are the rocks that would typically be deposited in an ocean-margin setting to be later overridden by an ophiolite in a subduction zone setting, that would then form a metamorphic sole to the ophiolite if accreted to its base. Volcanic rocks of late Cretaceous age (Grantham et al., 2003; Styles et al., 2006) found within the upper parts of the sequences of metamorphic rocks are compatible with formation in submarine volcanoes, and thus agree with a deep marine setting. The lithological sequence of the metamorphic packages are thus compatible with, but not exclusive to an origin of the metamorphic rocks as sediments and volcanics deposited on the continental margin prior to obduction, and that were metamorphosed during the subduction-obduction process.

The third line of evidence, and that provided by the new data presented here, comes from the ages of the metamorphic rocks. If they included fragments of older Arabian crust, then a complex age pattern of older primary ages, overprinted by older metamorphism, and possible subsequent overprinting by obduction-related metamorphism, would be envisaged. The age patterns presented here instead, record only very sparse older ages and a dominant age population interpreted as metamorphic zircon growth during ophiolite obduction. A caveat to this is that a deep marine basin may receive little input of continental detritus, and would thus be sparse in terms of older (detrital) zircons (as observed in the dated samples). Volcanism within the basin may supply some zircons, but mafic magmatism, which predominated in the metamorphic rock sequences and in the unmetamorphosed Hamrat Duru Group, is generally zircon-poor. Zircon and other dateable heavy minerals from metamorphic rocks across UAE are, as we have seen, sparse. The zircons that have been recovered and reported here do not display characteristics of a volcanic origin. Thus, the geochronological data do not support the notion that the metamorphic rocks comprise older Arabian continental crust.

6.3. *Rapid burial and exhumation*

The notion of rapid cooling of the Semail ophiolite has previously been discussed by Hacker et al. (1996), who presented cooling ages (Ar-Ar hornblende, biotite and muscovite) from ophiolitic and metamorphic sole role rocks across the UAE and Oman. The post obduction history of uplift is discussed by Jacobs et al. (2015), who presented apatite fission-track and zircon/apatite U/Th-He thermochronology. Fig. 5 integrates the new data presented here with geo- and thermochronology of the metamorphic sole and overlying ophiolite in the UAE. New age constraints on high-temperature metamorphism of the metamorphic sole recorded by zircon overlap with previous estimates based on the age of trondhjemitic melts (Styles et al., 2006), which are interpreted as being derived from anatexis of the sole rocks during obduction. New cooling age constraints provided by rutile (closure temperature ~650 °C), which overlap with the zircon ages (temperature of metamorphism ~825 °C), confirm the very rapid cooling that was indicated previously by hornblende Ar-Ar ages (closure temperature 550 °C) from across the metamorphic sole of the UAE and Oman (Hacker et al., 1996). The essentially overlapping ages from zircon, through rutile to hornblende, imply a rapid cooling rate of >200 °C/Ma as suggested by Hacker et al. (1996). This initial rapid cooling can be explained by plate-velocity exhumation (e.g. Parrish et al., 2006; Warren et al., 2008) of the metamorphic sole rocks to shallow depths, occurring very soon after their initial burial. This process can be driven by buoyancy if the sole rocks were more felsic on average than the mafic to ultramafic mantle and oceanic lithosphere (see Erdman and Lee, 2014 and references therein). Minerals with lower closure temperatures, muscovite and biotite, indicate a possible slowing of cooling after initial exhumation to >50 and <150 °C/Ma (Hacker et al., 1996). The thermochronology of Jacobs et al. (2015) indicates that cooling continued to about 100 °C by 70 Ma, averaging a cooling rate of 20 °C/Ma from 90 to 70 Ma.

The age of the sediments of the metamorphic sole is at least as young as 103 Ma, as indicated by volcanic rocks of this age in their upper portion (Grantham et al., 2003). The youngest age of the original sedimentary strata is not constrained, meaning that a direct timespan between deposition and metamorphism during

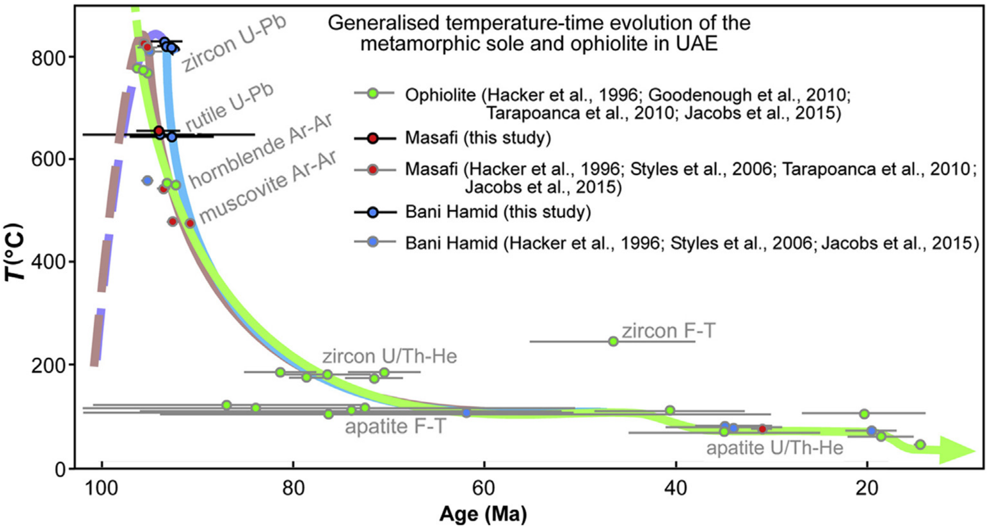

Figure 5. Cooling history of the Semail ophiolite (green curve) and metamorphic sole rocks in the UAE (Masafi area, red curve; Ban Hamid, blue curve), based on new and published studies. Average closure temperatures used are ~650 °C for rutile U-Pb, ~560 °C for hornblende Ar-Ar, 480 °C for muscovite Ar-Ar, 250 °C for zircon fission track, 170 °C for zircon U/Th-He, 100 °C for apatite fission-track and 70 °C for apatite U/Th-He. Data are plotted at variable temperatures so that uncertainties can be discriminated.

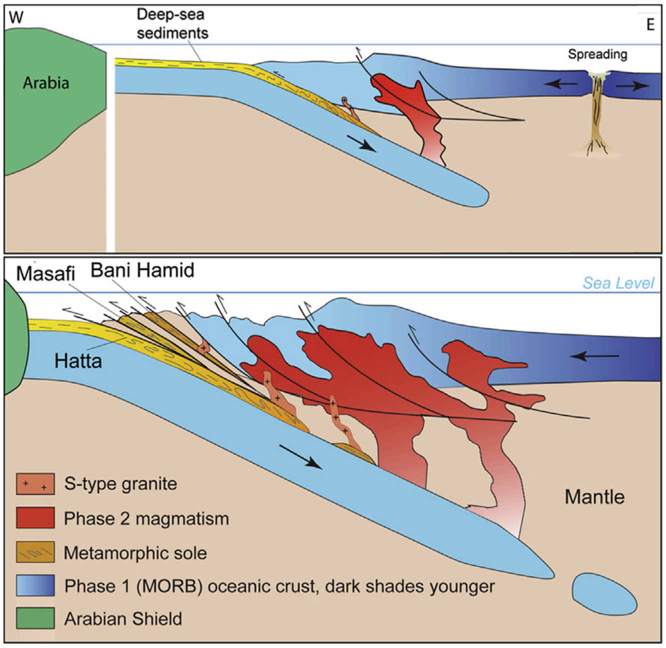

Figure 6. Schematic cross sections showing the evolution of the metamorphic rocks in terms of subduction of ocean-floor sedimentary and volcanic rocks (top), which are intruded by minor S-type granite magmatism; buoyant extrusion and partial exhumation of metamorphic sole rocks (bottom). Modified after Goodenough et al. (2014b).

obduction cannot be determined. The oceanic crust of the overriding ophiolite ranges in age from 96.5 to 94.5 Ma, overlapping with the age of metamorphism. Therefore there was certainly less than 10 Ma between deposition of the exposed metamorphic rocks, and their burial during subduction. The fact that Phase 1 ocean crust formation is currently not known to be older than ~96.5 Ma (Goodenough et al., 2010; Rioux et al., 2012, 2013), indicates that sea-floor spreading, subduction and ophiolite obduction all occurred within 2–3 Ma.

6.4. *History of deposition, burial and exhumation*

Cooper et al. (2014) and Cowan et al. (2014) reviewed the history of metamorphic sole rocks in Oman. The data presented in this study indicate that the exposed metamorphic rocks of the UAE do not comprise fragments of older Arabian crust. Following this conclusion, we present here a brief synopsis of the history of the equivalent metamorphic rocks in the UAE and the overlying ophiolite.

Sedimentation occurred on the Arabian passive margin of Neotethys throughout the Mesozoic, up until the late Cretaceous. The deep marine basin included episodes of mafic volcanism in the late Cretaceous, including carbonatites (ca. 103 Ma; Grantham et al., 2003). Subduction was initiated in a NE direction in the late Cretaceous, with ages of oceanic crust ranging from ca. 96.5 to 94.5 Ma (Styles et al., 2006; Goodenough et al., 2010; Rioux et al., 2012, 2013). Formation of oceanic crust occurred via a Mid-Ocean Ridge, forming Phase 1 magmatism, and via the subduction zone, forming Phase 2 magmatism (see Fig. 6; Goodenough et al., 2014b). The deep-sea sediments of the passive margin were subducted to at least 45 km, and were accreted to the overlying hot mantle (e.g. Gnos, 1998; Searle and Cox, 2002). An initial phase of rapid exhumation of the sediments as a metamorphic sole occurred, and then was followed by slower exhumation as the sole rocks and overlying ophiolite overthrust the Arabian shelf, and the continental crust. Some sediments, i.e. the Bani Hamid Group, were subducted to the greatest depth and metamorphosed to the highest grade. Other sediments, such as those in the Hatta zone, were less deeply subducted and consequently only metamorphosed to greenschist facies, and did not come into contact with the hot mantle (see Fig. 6). Continued convergence caused thickening and stacking of both the sole rocks, and of the ophiolite itself. In Oman, the subduction history was much longer. Permian basalts, underlying the Cretaceous passive margin sediments, and overlying the Arabian basement, were subducted to eclogite facies depths, before being exhumed up the same subduction channel at ~80 Ma (Warren et al., 2003, 2005). This marks the end of the obduction history.

Limestone sedimentation in the Santonian (ca. 83 Ma) on the Arabian margin shelf marks the end of orogenesis in the UAE. The lack of significant volumes of clastic sedimentation in the succeeding foreland basin sequences suggests that the obduction was not followed by large amounts of erosional unroofing (Jacobs et al., 2015). Thermochronological data indicate rapid cooling of the upper ophiolitic crust to below 100 °C by 70 Ma, whereas the metamorphic sole remained hotter for longer, perhaps at this temperature until the Miocene (Tarapoanca et al., 2010; Jacobs et al., 2015).

The Zagros orogeny involved the final closure of Neotethys, with collision between the Afro-Arabian plate and Eurasia, peaking in the Miocene (Agard et al., 2011; Mouthereau et al., 2012). Thrust and nappe structures in the UAE may have been reactivated at this time. Thermochronological data suggest accelerated erosion between ca. 45 and 35 Ma (Jacobs et al., 2015). The last exhumation that exposed the rocks we see today at the surface occurred in the Neogene, according to the thermochronological data (Jacobs et al., 2015), which also corresponds to a main phase of the Zagros orogeny.

7. Conclusions

Geochronological data from metamorphic rocks exposed in the UAE provide no evidence that they include older Arabian continental crust. Zircon is absent in many samples, and was only recovered from 3 samples (out of 14 collected), from rocks of the highest metamorphic grade. The youngest zircon age populations at 95 ± 2.0, 93.8 ± 2.1 and 93.5 ± 1.6 Ma, are interpreted as recording high-grade metamorphism within the Bani Hamid rocks, induced during their subduction burial and heating from the overlying mantle. Only a very few discordant older, presumably detrital, zircon grains were seen. Less precise, but overlapping rutile ages within the Masafi and Bani Hamid areas, at 94.1 ± 2.6, 94.0 ± 10.1 and 92.7 ± 4.6 Ma, are interpreted as metamorphic rutile growth, with the ages recording rapid cooling through ~650 °C during exhumation of these units. The new age data overlap with previous estimates of metamorphism, based on anatectic melt pods within the metamorphic rocks at 95.7–92.4 Ma (Styles et al., 2006). Combined, the data suggest a possible prolonged period of metamorphism, which is worthy of further detailed investigation, and that represents peak pressures during subduction, the thermal effect of the overlying ophiolitic mantle rocks, and possible later stages of melting and/or metamorphism during the obduction and emplacement process.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.gsf.2015.12.003.

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