Structure and metamorphism beneath the obducting Oman ophiolite: Evidence from the Bani Hamid granulites, northern Oman mountains

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ABSTRACT

The Cretaceous Semail ophiolite (northern Oman and the United Arab Emirates) includes an intact thrust slice of Tethyan oceanic crust and upper mantle formed above a northeast-dipping subduction zone that was the site of initiation of obduction. The normal metamorphic sole of the Semail ophiolite comprises a highly condensed sequence of hornblende + plagioclase ± garnet amphibolites with small enclaves of garnet + clinopyroxene granulites immediately beneath the mantle sequence peridotites, tectonically underlain by a series of epidote amphibolite and greenschist facies lithologies in a highly deformed ductile shear zone. Peak metamorphic conditions of 770–900 °C and 11–15 kbar indicate metamorphism at depths far greater than can be accounted for by the preserved thickness of the ophiolite (~15 km). In the mountains of northern Oman, the 1.2-km-thick Bani Hamid thrust sheet is composed of intensely folded granulite and amphibolite facies rocks within mantle sequence peridotites, exhumed by late-stage out-of-sequence thrusting along the Bani Hamid thrust. The Bani Hamid thrust slice includes two-pyroxene amphibolites, dunites (± hornblende, cordierite, sapphirine), diopside + andradite garnet + wollastonite + scapolite marbles and calc-silicates and amphibolites (hornblende + plagioclase ± clinopyroxene ± biotite) with localized partial melting, intruded by hornblende pegmatites. The Bani Hamid granulites represent metamorphosed cherts and calcareous turbidites probably derived from the distal Haybi Complex and Oman Exotic limestones, which have an alkaline basaltic substrate. Metamorphic modeling using the program THERMOCALC in the system NCKFMASHTO (Na2O-CaO-K2O-FeO-MgO-Al2O3-SiO2-H2O-TiO2-O) gives peak pressure-temperature conditions of 850 ± 60 °C and 6.3 ± 0.5 kbar, a pressure that is much lower than that of the metamorphic sole, suggesting a different origin. The 206Pb/238U zircon dates indicate that the gabbroic crust of the ophiolite formed by ridge magmatism from before 96.1 to 95.5 Ma. The 206Pb/238U zircon dates from the metamorphic sole range from 95.7 to 94.5 Ma, and suggest that metamorphism and melting was either synchronous with or slightly postdated ridge magmatism. The Bani Hamid granulites are younger; zircon and titanite U-Pb dates span ca. 94.5–89.8 Ma. Peraluminous granitic dikes intruding the mantle sequence peridotites are as young as 91.4 Ma and likely reflect localized partial melting of crustal material during the late stage of the obduction process. A minimum of 130 km shortening is recorded by restoration of the major folds within the Bani Hamid thrust sheet, and more than 30 km offset has occurred along the west-directed breaching out-of-sequence Bani Hamid thrust. These rocks may be representative of deep-level duplexes imaged on recent seismic sections across the mountains of northern Oman–United Arab Emirates.

INTRODUCTION

The Semail ophiolite of northern Oman and the United Arab Emirates (UAE) (Figs. 1 and 2) is thought to represent a slice of oceanic crust and upper mantle formed at a fast-spreading ridge (Glennie et al., 1973; Lippard et al., 1986; Nicolas et al., 1989; Searle and Cox, 1999; Goodenough et al., 2010) during the Cenomanian. The ophiolite preserves a complete oceanic crustal sequence as much as 7–8 km thick, including layered peridotites and gabbros, isotropic gabbros, late cross-cutting wehrlites, sheeted dikes, and pillow lavas with interleaved radiolarian cherts. The crustal section is underlain by an ~12–15 km thickness of upper mantle harzburgites and dunites (Fig. 3). New high-precision 206Pb/238U zircon dates suggest that the early magmatism associated with the lower Geotimes or V1 volcanism in the Oman part of the ophiolite occurred during the narrow time span of ca. 96.1–95.5 Ma, thus dating formation of the ophiolite crustal sequence (Rioux et al., 2012a, 2012b). Late gabbros, trondhjemites, and tonalites have U-Pb zircon dates of 95.3–95.1 Ma (Rioux et al., 2012a), likely related to subduction below the ophiolite.

The Oman ophiolite forms the structurally highest of a series of thrust sheets placing progressively more distal Tethyan units (Haybi Complex) over more proximal thrust slices (Hawasina Complex and Sumeini Group). The entire allochthon was emplaced into a Late Cretaceous flexural foreland basin (Aruma Group) that is above the middle Permian to middle Cretaceous shelf...
Figure 1. Geological map of the Oman mountains showing location of the Bani Hamid area. UAE—United Arab Emirates.
Figure 2. Landsat photo of the mountains of northern Oman–United Arab Emirates showing key structural features and location of the Bani Hamid thrust sheet. Also shown are lines of the D1 and D4 seismic profiles. J.—Jebel; ST—Semail thrust; Hyb—Haybi thrust.

Figure 3. Generalized section through the ~20-km-thick Semail ophiolite thrust sheet tectonic stratigraphy, showing the general structures and lithology of the oceanic crust and upper mantle rocks.
carbonate sequence (Fig. 4). Clues to how the ophiolite was obducted onto the former passive continental margin of Arabia are mainly in the metamorphic sole of the ophiolite as well as an enigmatic and unique thrust slice, the Bani Hamid thrust sheet, composed of granulite facies partly retrogressed to amphibolite facies assemblages in the mountains of northern Oman–UAE.

The metamorphic sole to the ophiolite consists of a narrow thrust slice of hornblende + plagioclase ± garnet amphibolites with small enclaves of garnet + clinopyroxene granulite, epidote amphibolite, and a variety of greenschist facies metasedimentary rocks including piemontite (Mn epidote) quartzites, marbles, and rare metavolcanics. The sole records an inverted and highly condensed P-T gradient and shows intense mylonitic fabrics (Searle and Malpas, 1980, 1982; Ghent and Stout, 1981; Hacker and Mosenfelder, 1998; Gnos, 1998; Searle and Cox, 2002; Searle and Ali, 2009). Peak P-T conditions in sole localities in Oman are 770–900 °C and 11–13 kbar (Cowan et al., 2014).
The implied depths of metamorphism are higher than can be explained by the preserved thickness of oceanic lithosphere in the ophiolite. Restoration of thrust sheets beneath the Semail ophiolite complex in the northern Oman mountains show at least 400 km of shortening in the proximal (Sumeini Complex), slope and basin (Hawasina Complex), and distal trench (Haybi Complex) sedimentary rocks structurally beneath the ophiolite (Cooper, 1988; Searle and Cox, 1999; Searle, 2007).

The $^{206}\text{Pb}/^{238}\text{U}$ zircon ages from garnet amphibolites and tonalitic partial melt pods and veins from the Wadi Tayyin metamorphic sole locality in Oman range from 94.69 ± 0.12 to 94.48 ± 0.23 Ma (Warren et al., 2005; Rioux et al., 2013), suggesting that peak metamorphism slightly postdated ridge magmatism at this locality. Styles et al. (2006) reported “concordia ages” of 95.29 ± 0.21 Ma and 95.69 ± 0.25 Ma for felsic leucocratic melts from amphibolite sole exposures in the Masafi area (UAE). The timing of ridge-related magmatism has not been dated in the UAE, but is constrained to be older than 95.74 ± 0.32 to 96.40 ± 0.29 Ma (Styles et al., 2006; Goodenough et al., 2010), indicating that the sole metamorphism and partial melting were either synchronous with or slightly postdated ridge magmatism in the UAE. Unpublished $^{206}\text{Pb}/^{238}\text{U}$ zircon dates showing that leucocratic melting in the Sumeini sole locality in northern Oman was synchronous with ridge magmatism were reported by Rioux et al. (2014).

The Bani Hamid thrust sheet in the northern Oman mountains is a 1.2-km-thick sheet of high-temperature granulites that have been thrust into the harzburgite-dunite section of the mantle sequence (Fig. 5). As far as we are aware, such thick granulites are not known from any other subophiolite metamorphic sole. The Semail ophiolite has been structurally repeated by out-of-sequence thrusting along the Bani Hamid thrust and the granulites have been exhumed from depths of ~20–25 km beneath the already obducted ophiolite. The Bani Hamid rocks include enstatite + diopside quartzites (± hornblende, cordierite, sapphire), diopside + andradite garnet + wollastonite + scapolite calc-silicates, and amphibolites (hornblende + plagioclase ± clinopyroxene ± biotite) with localized partial melting, intruded by hornblende pegmatites (Gnos and Kurz, 1994; Gnos, 1998). Published U-Pb zircon dates from Bani Hamid rocks range from 93.2 to 91.8 Ma (Styles et al., 2006), younger than the ophiolite and the normal amphibolite sole rocks. The Bani Hamid granulates represent metamorphosed dolomitic cherts and calcareous turbidites associated with alkali volcanics, probably derived from the distal Haybi Complex, and are tight to isoclinally folded at all scales (Searle et al., 2014).

In the UAE a series of leucocratic dikes ranging from andalusite-cordierite-biotite monzogranites to garnet-tourmaline leucogranites intrude into the mantle sequence of the Khawr Fakkan block (Peters and Kamber, 1994; Cox et al., 1999). These crustal melt granites are thought to have been derived from partial melting of a pelitic metasedimentary source beneath the ophiolite (Searle and Cox, 2002; Searle et al., 2014). These dikes are very distinct from the plagiogranites formed by partial melting of hornblende gabbros in the roof of the magma chamber that are present along the length of the Semail
ophiolite (Rollinson, 2009). Styles et al. (2006) reported a single date of 91.38 ± 0.23 Ma for a mixed tonalite-microgabbro from the Dadna area.

In this paper we present results from new structural mapping of the Bani Hamid granulites and new thermobarometry results and pseudosection modeling of high-temperature metaalkali basalts and orthopyroxene-bearing quartzites. Peak metamorphic conditions are supplemented by Zr-in-titanite thermometry from granulite facies quartzite, and new timing constraints are provided by high-precision U-Pb zircon dating of an amphibolite and small-scale leucocratic dike and laser ablation U-Pb titanite dating of quartzite and marble samples. We use these data to constrain depths and timing of metamorphism. We use our structural mapping constraints to restore the Bani Hamid thrust sheet in relation to the known geometry of the Semail ophiolite thrust sheet and present a tectonic evolution based on our new data combined with U-Pb timing constraints (Styles et al., 2006; Rioux et al., 2012a, 2013). We speculate on the composition and structure of the lower crust as imaged on recently acquired deep seismic profiles across the mountains in northern Oman and the UAE (Rouré et al., 2006; Tarapoanca et al., 2010; Naville et al., 2010). We integrate geological constraints from the northeastern Oman mountains where high-pressure eclogites have been exhumed east of Muscat (As Sifah eclogites; Searle et al., 1994, 2004; Warren et al., 2003; Agard et al., 2010), and from the northern mountains where the Bani Hamid granulites crop out, to formulate a model for ophiolite obduction and emplacement.

### STRUCTURAL SETTING OF THE BANI HAMID GRANULITES

Two major outcrops of granulite-amphibolite facies metamorphic rocks are present in the northern ophiolite (Khawr Fakkan block), the Wadi Ham thrust slice, and the Bani Hamid thrust sheet. The Wadi Ham sheet is structurally beneath the Bani Hamid thrust sheet and is cut by the Wadi Ham fault (Fig. 2). The Bani Hamid thrust, which places the granulite-amphibolite facies rocks over a lower ultramafic unit, continues to the southwest along the top of the Wadi Ham granulite amphibolites. This fault is one of several late-stage out-of-sequence thrusts that tectonically repeats the entire ophiolite and underlying metamorphic rocks. Another such thrust is the Masafi-Dibba thrust that places the entire Khawr Fakkan ophiolite slice in the eastern mountains over a structural base of the Bani Hamid granulite facies rocks continues into the harzburgite mantle sequence to the northeast as the granulite amphibolites of Bani Hamid plunge beneath the exposure level.

### PETROGRAPHY

The Bani Hamid metamorphic rocks are very distinct from the normal sub-ophiolite metamorphic sole. They are mainly composed of quartzites, calc-silicates, and marble with minor amphibolite and no pelites. They are uniformly high-temperature assemblages of granulite or upper amphibolite facies (Allemand and Peters, 1972; Searle and Malpas, 1980; Gnos and Kurz, 1994; Gnos and Nicolas, 1996; Searle and Cox, 2002).

#### Quartzites

Three different types of quartzite are found in the Bani Hamid and Wadi Ham thrust slices. Clinopyroxene quartzites (Ca-Mg) are the most common and occur as massive bands interbedded with marbles and calc-silicates. They contain quartz + clinopyroxene + andradite garnet + hornblende + titanite ± enstatite and show a variety of deformation fabrics from coarsely annealed recrystallized grains to mylonites (Fig. 7). The second type is more aluminous (Mg-Al) orthopyroxene quartzites containing quartz + aluminous enstatite + cordierite + spinel ± kyanite + biotite + chlorite. Enstatites may form aggregates enclosing magnetite, hematite, green spinel, plagiopogite, plagioclase, and sapphire (Gnos and Kurz, 1994). Cordierites contain fibrous sillimanite and spinel inclusions. Occasionally both diopside and enstatite are found in the same quartzite layer. These assemblages are found mainly in the structurally lower western part of the Bani Hamid thrust sheet immediately above the Bani Hamid thrust. Gnos and Kurz (1994) described sapphireine + corundum assemblages confined to a single Al-rich layer in Wadi Madhah, along the northwestern part of Bani Hamid. Sapphireine occurs together with spinel and shows small blebs of magnetite or hematite. The third and least common type is Mn-rich cordierite quartzites that commonly contain quartz + pyroxmangite + cordierite + spessartine garnet + sillimanite + piemontite or other Mn-rich silicates. Retrogressive reactions show cordierite breaking down to the green-schist facies association kyanite + chlorite (Figs. 8A, 8B) and the formation of biotite + quartz symplectites, typical of retrogressed granulites (Figs. 8C, 8D).

None of these compositions is typical of clastic sedimentary quartzites, and they are most likely derived from cherts. Gnos and Kurz (1994) presented major and trace element analyses of a variety of Bani Hamid quartz-rich rocks, and noted that the trace element patterns are atypical for quartzites and, particularly for the Ca-Mg-quartzites, show relatively high concentrations of elements typical of basalts. Possible protoliths include hydrothermally altered...
Figure 6. Photograph and annotated section of the Bani Hamid sequence along Wadi Shis, looking southwest. Cpx—clino-pyroxene.
silicified basalts, cherts with diagenetic dolomite, or cherts mixed with volcaniclastic material, in keeping with their association with amphibolites. The mineral assemblage and major element composition of enstatite-cordierite quartzites indicate that the added material is close to the composition of chlorite, another common product of the hydrothermal alteration of basic volcanic rocks (cf. Vallance, 1967). The Mn quartzites, however, represent more characteristic oceanic cherts. All three types of quartzite show wide variation in the proportion of quartz to silicate minerals, and include bands and segregations dominated by the silicate assemblage.

Calcereous Rocks

Typical calc-silicate and impure marble assemblages contain calcite and wollastonite with varying amounts of diopside, large brown andradite-grossular garnet, and minor amounts of quartz, plagioclase, and titanite (Fig. 9). The marble bands show extreme deformation with extensive flow folding and small enclaves of isoclinally folded calc-silicates and quartzites completely enclosed in marble (Figs. 10A, 10B). Similar mixed calc-silicate, marble, and quartzite bands are found in the normal metamorphic sole, for example in...
the Sumeini window (Searle and Malpas, 1980, 1982; Searle and Ali, 2009), where they are also thought to represent metamorphosed Haybi Complex distal sedimentary rocks.

Metabasic Rocks

The metabasic units consist of amphibolite and pyroxene granulite, generally with a medium-grained granoblastic texture (~2 mm) and a weak gneissic fabric. While some are simple hornblende + plagioclase ± clinopyroxene amphibolites, a significant proportion are biotite bearing with abundant opaque oxides. The dominant oxide phase is titanohematite. These features suggest that an important protolith is alkali basalt rather than a mid-oceanic ridge basalt (MORB)-like tholeiite. These alkali basalts have a geochemical signature (high bulk Ti) almost identical to that of the alkali basalts in the Haybi Complex (Searle et al., 1980; Searle, 1984). Metamorphosed alkali peridotites (jacupirangites, wehrlites) and gabbros were reported (Searle, 1984) from the Wadi Ham metamorphic sequence; this supports the inference that these rocks are metamorphosed equivalents of the Haybi Complex. Lenticular pods of green, almost pure diopside occur along the uppermost part of the Bani Hamid thrust sheet along Wadi Shis. These unusual rocks could be the result of high-temperature calcium-rich metasomatic fluids pumped along the bounding thrust immediately above.

THERMOBAROMETRY AND MICROSTRUCTURES

Determining precise metamorphic conditions for the Bani Hamid granulites has proved problematic because of the lack of rock types and assemblages amenable to conventional thermobarometry. Metapelites are lacking, and metabasic rocks do not contain garnet. Gnos and Kurz (1994) summarized the metamorphic geology and described an occurrence of sapphirine coexisting with quartz and aluminous spinel, potentially diagnostic for ultrahigh-temperature metamorphism, in an oxidized enstatite-bearing Mg-Al quartzite. The high Fe³⁺ content of the sapphirine and its intimate association with composite titanohematite–magnetite–spinel oxide grains gave rise to uncertainty over the phase relationships and equilibration temperature of the assemblage, and so Gnos and Kurz looked to independent methods of pressure-temperature (P-T) estimation; they cited temperatures of 830 ± 20 °C for quartzites and 835 ± 44 °C for amphibolites, using the two-pyroxene geothermometer of Brey and Köhler (1990). This geothermometer is calibrated for peridotites, rather than for metabasic and quartz-rich rocks. Nevertheless, the results appear plausible in comparison with geothermometry on related rocks (Gnos and Kurz, 1994) and in the context of phase equilibrium constraints. Limits to pressure were based on experimentally determined constraints: a minimum of 6.5 kbar was determined from the composition of spinel enclosed in cordierite, calibrated against the experiments of Seifert and Schumacher (1986), and a maximum of 9 kbar was calculated from the upper stability limit of hydrous Mg-cordierite adjusted for Fe (XFe = 0.9) and the likely volatile content of the cordierite.
Conventional and multiequilibrium thermobarometry was used by Cox (2000) on a variety of rock types, with scattered results, some of which were cited in Searle and Cox (2002). Garnet-clinopyroxene thermometers applied to calc-silicate assemblages gave results that differ greatly between calibrations, presumably because of the unsuitable chemical composition of the Ca-rich garnets. Multiequilibrium results using THERMOCALC (Powell and Holland, 1988) in average P-T and average P mode gave 838 ± 286 °C, 14.7 ± 2.8 kbar for a metabasic granulite (OM135), 10.5 ± 1.1 kbar at assumed 850 °C for an Mg-Al quartzite (JC107), and 12.9 ± 2.0 kbar at 860 °C for a Ca-Mg quartzite. These diverse and imprecise pressure results are significantly higher than those of Gnos and Kurz (1994), and overlap those for the main ophiolite sole (Cowan et al., 2013).

For this study, two samples were analyzed in order to apply modern equilibrium phase diagram techniques to the problem. The metabasic biotite two-pyroxene granulite OM135 investigated by Cox (2000) was chosen for reanalysis, as it shows the fullest assemblage and least retrogression of the available suite. The peak assemblage is inferred to be plagioclase + clinopyroxene + orthopyroxene + biotite + hematite. Green hornblende forms rims on pyroxene and is interpreted as a retrograde phase. Orthopyroxene shows partial breakdown to amphibole and a fine-grained aggregate with the composition of talc. The second sample is AC13-34, a quartz-rich cordierite-orthopyroxene gneiss of the Mg-Al-quartzite lithology collected during field work in this study. It has a coarse-grained gneissic texture, and the high-grade minerals show relatively little alteration.

Mineral analyses were performed on a JEOL JSM-840A scanning electron microscope (SEM) in the Department of Earth Sciences, University of Oxford, which is equipped with an Oxford Instruments Isis 300 energy-dispersive analytical system. The accelerating voltage was 20 kV, with a beam current of 6 nA, and a live counting time of 50 s. The system was calibrated with a range of natural and synthetic standards, and a ZAF correction procedure was used. The beam current was checked regularly and the count rate calibrated every 120 min using a cobalt metal standard. Representative mineral analyses are listed in Table 1.

The rocks show high-variance assemblages and define few useful geothermometers and barometers. However, it is significant that neither the metabasite nor the Mg-Al gneiss contains garnet, in contrast to the main metamorphic sole, in which garnet-clinopyroxene amphibolite and relic garnet granulite enclaves are characteristic at the highest grade. In addition, hornblende-bearing metabasites have locally undergone partial melting. A more useful approach, which can incorporate these constraints on P-T conditions, is to use calculated equilibrium assemblage diagrams (pseudosections).

Bulk compositions for the two samples were calculated by combining mean microprobe analyses of homogeneous major phases in proportion to their modal volume in the rock (cf. Carson et al., 1999). Volume proportions were determined from area measurement using optical microscopy, SEM back-scattered electron imaging, and image analysis of scanned thin sections using the software JMicrovision (Roduit, 2007). The pseudosections were calculated using the software THERMOCALC (Powell and Holland, 1988; Powell et al., 1998) version 3.33, using the internally consistent thermodynamic data set of Holland and Powell (1998) updated to version 5.5 (November 2003). Solid-solution phases were modeled in the system NCKFMSHTO (Na2O-CaO-K2O-FeO-MgO-Al2O3-SiO2-H2O-TiO2-O) using activity formulations for amphibole from Diener...
et al. (2007) and Diener and Powell (2012), garnet, biotite and silicate liquid from White et al. (2007), feldspars from Holland and Powell (2003), and Fe-Ti oxides from White et al. (2000). The Green et al. (2007) activity model for clinopyroxene was found to be unsuitable for high-\(T\) pyroxenes containing significant Ca-Tschermak and enstatite solid solution and low jadeite, and an alternative formulation in the system Na\(_2\)O-CaO-FeO-MgO-Al\(_2\)O\(_3\)-SiO\(_2\), extended from the CMAS (CaO-FeO-MgO-Al\(_2\)O\(_3\)-SiO\(_2\)) model developed in Green et al. (2012), was supplied by T.J.B. Holland (2014, personal commun.).

### Metabasite (OM135)

Pyroxene compositions are relatively uniform and do not show obvious compositional zoning. Orthopyroxene has ~2 wt% Al\(_2\)O\(_3\) and ~0.5 wt% CaO. The clinopyroxene contains ~3.2 wt% Al\(_2\)O\(_3\), which is accommodated mostly as Ca-Tschermak's molecule, and the Na\(_2\)O content is low. The plagioclase composition is a labradorite with 58% ± 2% anorthite. Biotite flakes oriented in the gneissic foliation have a uniform composition for most elements, with as much as 3 wt% TiO\(_2\), but show a spread in XMg values from 0.67 to 0.79. The abundant oxide phase is a titanohematite that forms composite grains with some magnetite. The green amphibole, which forms rims on pyroxene grains, is dominantly magnesiohornblende (6.5–7.1 Si per formula unit, p.f.u.) with a low X\(_{Na,M4}\) of 0.035 and a relatively small content of Na and K in the A site (up to ~0.3). Actinolite is a minority with ~7.6 Si p.f.u. These analyses are consistent with a retrograde origin for amphibole.

Two-pyroxene geothermometers appropriate for metabasic rocks (e.g., Lindsley, 1983) indicate temperatures between 700 and 900 °C but are insufficiently precise to improve on the existing peak temperature estimates of between 800 and 900 °C. Modeling in granulite facies rocks, where aqueous fluid is not in excess, requires attention to the amount and behavior of the compo-

### Table 1. Representative Mineral Analyses Used for Geothermobarometry

| Sample | AC13-34 | AC13-34 | AC13-34 | AC13-34 | AC13-34 | AC13-34 | AC13-34 | OM-135 | OM-135 | OM-135 | OM-135 | OM-135 | OM-135 | OM-135 | OM-135 | OM-135 |
|--------|---------|---------|---------|---------|---------|---------|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Mineral | Opx     | Opx     | Crd     | Pl      | Ilm     | Hem     | Cpx     | Opx    | Pl     | Hbl    | Bt     | Hem    |        |        |        |        |
| Analysis | core    | rim     | mean    | representative | mean of 4 | mean of 3 | mean    | mean   | mean   | mean   | mean   | mean   | mean   | mean   | mean   | mean   |
| SiO\(_2\) | 48.53   | 52.69   | 49.40   | 51.10   | 0.14   | 0.15   | 51.86   | 54.73   | 53.72   | 48.20   | 37.63   | 0.77   |        |        |        |
| TiO\(_2\) | 0.18    | 0.07    | 0.00    | 0.07    | 46.62  | 19.53  | 0.32    | 0.08    | 0.02   | 0.67    | 2.70   | 18.06  |        |        |        |        |
| Al\(_2\)O\(_3\) | 7.79   | 3.06    | 34.08   | 32.31   | 0.26   | 0.34   | 3.20    | 1.87    | 29.56   | 8.80    | 15.32  | 0.26   |        |        |        |        |
| Cr\(_2\)O\(_3\) |        |        |        |        | 0.11   | 0.04   | 0.05    | 0.07    | 0.30   |        |        |        |        |        |        |        |
| FeO\(_3\) | 2.52    | 0.69    |        |        |        | 12.35  | 61.57   | 3.23    |        |        |        |        |        |        |        |
| FeO | 18.59   | 18.54   | 3.55    | 0.00    | 37.31  | 16.72  | 6.05    | 13.90   | 0.25   | 5.78    | 11.04  | 15.53  |        |        |        |
| MnO | 1.40    | 1.59    | 0.27    | 0.00    | 3.91   | 0.67   | 0.29    | 0.63    | 0.01   | 0.21    | 0.15   | 0.36   |        |        |        |
| MgO | 21.29   | 24.04   | 11.30   | 0.05    | 0.23   | 0.14   | 14.20   | 28.11   | 0.05   | 16.51   | 17.45  | 0.12   |        |        |        |
| CaO | 0.19    | 0.06    | 0.01    | 14.33   | 0.04   | 0.03   | 23.57   | 0.52    | 12.33  | 12.91   | 0.03   | 0.03   |        |        |        |
| Na\(_2\)O | 0.00    | 0.00    | 0.00    | 3.27    | 0.06   | 0.01   | 0.40    | 0.02    | 0.17   | 0.67    | 0.10   | 0.00   |        |        |
| K\(_2\)O | 0.00    | 0.00    | 0.00    | 0.09    | 0.02   | 0.00   | 0.03    | 0.01    | 0.08   | 0.56    | 9.84   | 0.02   |        |        |
| Total | 100.48  | 100.73  | 98.69   | 101.22  | 99.16  | 97.61  | 94.28   | 100.38  |        |        |        |        |        |        |

**Note:** Opx—orthopyroxene; Crd—cordierite; Pl—plagioclase; Ilm—ilmenite; Hem—hematite; Cpx—clinopyroxene; Hbl—hornblende; Bt—biotite.
nent H₂O. In OM135 the relevant constraints on successful modeling are that hornblende occurs only as a retrograde phase, and that partial melting has locally occurred in similar, hornblende-bearing metabasites. Therefore, conditions for the peak assemblage should be located in an amphibole-free field at or near the solidus.

In OM135 the calculated assemblage proved to be sensitive to the bulk H₂O content. At 0.5 mol% H₂O hornblende is a ubiquitous phase up to and beyond the solidus. Figure 11A shows an isobaric T-m(H₂O) section, on which the field of hornblende-bearing assemblages terminates toward low water contents, with a steep boundary in the temperature range of interest at −0.5 mol% H₂O. On this basis, a water content of 0.4 mol% was chosen for locating the granulite facies equilibration conditions in P-T space. Figure 11A also predicts that at higher bulk-rock H₂O contents, hornblende-bearing two-pyroxene granulite, and clinopyroxene-amphibolite are stable both below and above the solidus between 800 and 900 °C. This is consistent with the observed range of peak assemblages in Bani Hamid metabasites and with the appearance of melt segregations in amphibole-bearing varieties. It suggests that the variation in mineral assemblage may be controlled as much by initial water content as by variation in other major components.

The calculated P-T field for the observed solid assemblage (Fig. 11B) occurs over a broad area bounded at high pressure by the incoming of garnet and at high temperature by the solidus. The position of the solidus at a given H₂O content should be of reasonable reliability, because the melt composition is trondhjemitic and well approximated by the melt model of White et al. (2007). However, relationships at higher temperature carry uncertainty, because the activity model for silicate liquid is optimized for granitic compositions and is 0.135 ± 0.01. This isopleth is in the upper part of the assemblage field just above 6 kbar, in the temperature range 780–910 °C.

This rock is dominated by porphyroblasts of pinkish-brown aluminous enstatite (>35 vol%) with uniform XMg = 0.67 ± 0.02 but with varying Al₂O₃ content. The maximum Al₂O₃ of 7.72 wt% was recorded in the core of a 3 mm grain. Rim compositions ranged down to 3.92 wt%, and rim composition profiles over length scales of 20–150 µm consistent with diffusional closure on cooling were recorded using qualitative line scans. Cordierite (6–8 vol%) forms small grain blasts of uniform composition with XMg = 0.85. A small amount of biotite occurs mostly as ragged flakes associated with orthopyroxene and much or most is likely to be of retrograde origin. Plagioclase is partly sericitized; fresh gains are calcic (~70% anorthite). The Fe-Ti oxides form complex composite crystals commonly made up of titanohematite showing lamellar exsolution of ilmenite, surrounded by associated magnetite and matrix phases with a moat of Mn-bearing ilmenite (see Table 1 for representative analyses). The peak oxide phase is likely to have been a titanohematite with significantly higher Ti content.

The modeled bulk composition used an estimated water content appropriate for the near-anhydrous high-grade assemblage, based on the nominal water content of the modal minerals and assuming that the cordierite contained ~0.5 H₂O per formula unit. The peak assemblage field in the P-T pseudo-section (Fig. 11C) is constrained by presence of cordierite (with or without biotite) and the absence of garnet or sillimanite or evidence for melting. The inferred field is between ~750 °C and the calculated solidus at ~900 °C, and at pressures below the curve defining the appearance of garnet, which has a shallow P-T slope and is at 75–8 kbar in the range 750–900 °C, and the limit for cordierite, which is at ~6.5 kbar at 800 °C.

The key compositional variable is the Al content of orthopyroxene. This is a geothermometer in garnet-bearing assemblages, as investigated by Hensen and Harley (1990), Carrington and Harley (1995), and Harley (1998). In the natural pyroxene and in the solution model used in this study, this is quantified as the mole fraction of Al in the M1 site (XMg,M1). The values of this parameter are a little lower than the tetrahedral Al content, and of the commonly used parameter 0.5x (total Al per 6 oxygens) because of the presence of Fe²⁺ in M1. The calculated isopleths in the garnet-orthopyroxene fields in Figure 11C are a little shallower in slope than those plotted by Harley (1998; Fig. 4C), but agree well in position in the pressure range 7–10 kbar. In the absence of garnet and in coexistence with cordierite, the controlling equilibrium is likely to be 2MgAl₂SiO₆ (in orthopyroxene) + 3SiO₂ = Mg₂Al₄Si₅O₁₈ (cordierite), for which the end-member equilibria have a large positive volume change, suggesting that the isopleths should be sensitive to pressure. As expected, the isopleths of XMg,M1 have a shallow slope in the relevant fields in Figure 11C.

In the natural pyroxene, the value of XMg,M1 depends on the accuracy and precision of the entire analysis, and particularly on Si and on the effect of re-calculation for Fe²⁺. The total Al content of the core composition group varies from 0.28 to 0.34 Al p.f.u. With allowance for Fe²⁺ in M1 the mean value of XMg,M1 is 0.135 ± 0.01. This isopleth is in the upper part of the assemblage field just above 6 kbar, in the temperature range 780–910 °C.

### Peak P-T Conditions

The P-T estimates for these rocks, and particularly the determination of maximum pressure, depend on the calculated position of field boundaries in high-variance assemblages. The data set uncertainties as calculated by THERMOCALC and based on the least-squares fit to end-member enthalpies are small, typically ±2–10 °C, or 0.2–0.4 kbar, both on assemblage boundaries and on composition isopleths. The position of low-variance assemblage boundaries is controlled largely by end-member properties and is insensitive to bulk composition. However, for the boundaries of high-variance assemblages, such as the incoming of garnet in the metabasite OM135, uncertainty in the bulk composition will dominate. Analytical uncertainty on microprobe analyses adds a small contribution to the bulk composition calculation. In addition, a certain amount of bias in selecting, grouping, and averaging analyses is almost unavoidable, as is the extent to which analyses are projected into the system that can be modeled, according to the concept of an ideal analysis.
Figure 11. Calculated phase relations for Bani Hamid samples, using bulk compositions (in mol% oxides). OM135: H2O 0.40, SiO2 44.955, Al2O3 10.010, CaO 13.676, MgO 8.774, FeO 13.481, K2O 0.365, Na2O 2.174, TiO2 1.916, O 4.248. AC13–34: H2O 0.196, SiO2 64.390, Al2O3 3.994, CaO 0.548, MgO 16.720, FeO 10.609, K2O 0.192, Na2O 0.307, TiO2 1.796, O 2.499. (A) T–m(H2O) section for OM135 metabasite. Solidus emphasized with solid purple curve. Peak assemblage is in field labeled Cpx Opx Bt. Abbreviations: Cpx—clinopyroxene, Opx—orthopyroxene, Bt—biotite, Liq—liquid, Pl—plagioclase, Kfs—K-feldspar, Hem—hematite, Mag—magnetite, Hbl—hornblende. Vertical dotted line indicates the water content chosen for the pressure-temperature (P–T) section. (B) P–T section for OM135 metabasite, with solidus emphasized in solid purple and low-P limit of garnet (Grt) stability marked by dashed red curve. Observed peak assemblage occupies the large field labeled Cpx Opx Bt Mag. Qz—quartz. (C) P–T section for orthopyroxene-quartzite AC13-34. Solidus emphasized in purple, low-P limit of garnet stability in red, high-P limit of cordierite (Crd) stability in blue. Contours of X Al,M1 in orthopyroxene are shown for subsolidus fields. The area consistent with the observed peak assemblage and Al content of Opx is shaded in gray. Ilm—ilmenite; Sill—sillimanite.
discussed by Powell and Holland (2008). In practice, however, the largest uncertainty is probably the quantification of modal proportions of minerals for the bulk composition. A test in which the volume proportions of all phases in OM135 were randomly varied with a normally distributed relative uncertainty of 10% (2σ) propagated to an uncertainty of ±30 °C (2σ) in the position of the orthopyroxene-out curve, ±20 °C for the solids curve over the pressures of interest, and ±0.9 bar for the incoming of garnet at 850 °C. In contrast, the position of the garnet-in boundary in the orthopyroxene-quartzite AC13–34 is not sensitive to bulk composition variation. This is largely due to the low Ca content of the rock, leading to the control of garnet and cordierite stability by well-constrained equilibria in the subsystem FMAS(H) [FeO-MgO-Al2O3-SiO2, (H2O)].

On this basis, the best estimate of peak equilibration for AC13–34 is 850 ± 60 °C and 6.3 ± 0.5 kbar. This is consistent with the assemblage field for the metabasite OM135, and may be taken as the best estimate of peak equilibration for the Bani Hamid granulites. It plots at the low end of the pressure range estimated by Gnos and Kurz (1994). In contrast, the variable and higher pressure estimates of Cox (2000) were based on imprecise multiequilibrium thermobarometry that was not checked for consistency with the observed mineral assemblages. Assuming a relatively dense burden of 2900 kg/m³ that includes mantle material, this pressure is equivalent to peak burial at 22.5 ± 2 km. Neglecting the constraint of the Al content of orthopyroxene, the upper limit of the observed assemblage field and the incoming of garnet are at ~75 kbar, placing a maximum depth of burial for the Bani Hamid unit at ~27 km.

U-Pb GEOCHRONOLOGY

U-Pb Zircon Geochronology by Isotope Dilution–Thermal Ionization Mass Spectrometry

In order to date the timing of metamorphism in the Bani Hamid thrust sheet, we carried out isotope dilution–thermal ionization mass spectrometry U-Pb zircon dating on an amphibolite (131205M04; Universal Transverse Mercator, UTM, coordinates 0423233 2795438) and a crosscutting dike (131205M05; UTM 0423284 2795477). The sampled dike is ~5 cm wide, consists of plagioclase + amphibole, and crosses the amphibolite foliation; the dike composition is similar to other nearby leucocratic pods and segregations concordant with the amphibolite foliation, and all are probably related to localized melting in this area. Zircon dissolution and U-Pb analyses were carried out in the radiogenic isotope laboratory at the Massachusetts Institute of Technology (Cambridge, Massachusetts). Single zircons and grain fragments were dissolved following the chemical abrasion method (Mattinson, 2005), modified for single grain analyses, as described in Rioux et al. (2012b, supplemental material). The 206Pb/238U dates were corrected for initial exclusion of 230Th during zircon crystallization using the Th/U of the analyzed zircon, calculated from the measured 206Pb/238U date and 208Pb/206Pb, and a melt Th/U = 2.63 ± 0.90, based on observed Th/U of modern mid-ocean ridge basalts, as discussed in Rioux et al. (2015). All 206Pb/238U dates discussed here for these samples are Th corrected.

Isotope dilution–thermal ionization mass spectrometry (ID-TIMS) U-Pb data are reported in Supplemental Table 1 and plotted in Figure 12. Zircons from 131205M04 had low U concentrations and yielded 0.3–2.1 pg of radiogenic Pb (Pb*), resulting in relatively large uncertainties for 4 of the 6 dated fractions. The data define a single concordant population (mean square of weighted deviates [MSWD] of the weighted mean = 0.54), and the 2 most precise analyses yielded 206Pb/238U dates of 94.55 ± 0.14 Ma and 94.41 ± 0.21 Ma. We interpret these dates to reflect the timing of metamorphic zircon growth. Zircons from 131205M05 yielded precise results that define a spread of data along concordia, with 206Pb/238U dates of 92.906 ± 0.059 to 92.572 ± 0.055 Ma. To image the structure of the 131205M05 zircons, we mounted 14 grains and imaged them by cathodoluminescence (CL). The imaged grains had relatively simple zoning (Supplemental Fig. 1), with no clear evidence for the presence of older cores or younger rims. After imaging, we plucked three of the imaged zircons out of the mount for dating (iz1–iz3). Given the absence of clear cores or rims in the imaged zircons, we interpret the spread in the U-Pb dates from this sample to reflect assimilation of slightly older whole zircons from adjacent amphibolites and melt pods. Following this interpretation, the youngest zircon date provides the best estimate of the crystallization age of the dike (92.572 ± 0.055 Ma).

Styles et al. (2006) dated four samples from the Bani Hamid thrust sheet by ID-TIMS U-Pb zircon geochronology. Reported dates are “concordia dates” calculated in Isoplot (Ludwig, 2003). The dates are not Th corrected, and correcting the ages would likely increase the reported dates by 80–100 k.y. A date of 92.43 ± 0.15 Ma was obtained from a felsic melt pod in an amphibolite, while an impure marble gave a zircon date of 92.72 ± 0.39 Ma. Also reported were dates for a granitic intruding calc-silicate at 93.22 ± 0.29 Ma and a mafic pegmatite sill intruding quartzite at 91.84 ± 0.18 Ma. The dates from the felsic melt pod and impure marble are within uncertainty of our new dates from the small discordant vein, suggesting peak metamorphism and melting ca. 92.6 Ma.

U-Pb Titanite Geochronology, Titanite Trace Element Analysis, and Zr-in-Titanite Thermometry by Laser-Ablation Split-Stream Inductively Coupled Plasma Mass Spectrometry

All titanites in this study were analyzed in thin section by laser-ablation split-stream inductively coupled plasma mass spectrometry at the University of California, Santa Barbara; U-Pb and trace element data were collected simultaneously on the same spot analyses. U-Pb data were reduced using BLR (Aleinikoff et al., 2007) as a primary titania standard and at least two secondary standards were included in each run as further monitors of accuracy. Trace elements were reduced with 40Ca as an internal standard, assuming 19.25 wt% total Ca in titanite. We used NIST SRM 610 glass (Pearce et al., 1997; Rocholl et al., 1997) as a primary standard for all trace elements in JC98 and for rare
Supplemental Text File. Titanite analytical methods.
Please visit http://dx.doi.org/10.1130/GES01199.S3 or the full-text article on www.gsapubs.org to view the Supplemental Text File.

Supplemental Table 2. Complete titanite U-Pb and trace element LASS data. All data are corrected for initial Th exclusion. Gray bands represent 2σ uncertainties on concordia based on decay constant uncertainties of 0.107% (238U) and 0.136% (235U) (Jaffey et al., 1971). Data reduction and plotting were done using the Tripoli and U-Pb_redux software packages (Bowring et al., 2011; McLean et al., 2011). Abbreviations: plag—plagioclase; amphib—amphibole.

Supplemental Figure 2. Chondrite normalized rare earth element patterns for four titanite samples. Note the similar pattern regardless of trace element (TE) primary reference material (RM) used. Please visit http://dx.doi.org/10.1130/GES01199.S4 for the full-text article on www.gsapubs.org to view Supplemental Figure 2.

Figure 12. U-Pb concordia diagrams of single-grain and grain fragment zircon isotope dilution–thermal ionization mass spectrometry dates (ages on concordia are in Ma). All data are corrected for initial Th exclusion. Gray bands represent 2σ uncertainties on concordia based on decay constant uncertainties of 0.107% (238U) and 0.136% (235U) (Jaffey et al., 1971). Data reduction and plotting were done using the Tripoli and U-Pb_redux software packages (Bowring et al., 2011; McLean et al., 2011). Abbreviations: plag—plagioclase; amphib—amphibole.

earth elements (REE) in JC106; TNT150 titanite glass (Klemme et al., 2008) was used as a primary standard for Zr in JC106. Al, Si, Fe, Ti, Zr, and other elements were included in the trace element routine for both samples to monitor for contamination by other phases. All chondrite-normalized REE patterns were calculated using chondritic values from McDonough and Sun (1995). Further details of the method are contained in the Supplemental Text File and Supplemental Figure 2, and additional information is available in Spencer et al. (2013) and Kylander-Clark et al. (2013). Complete U-Pb and trace element data are available in Supplemental Table 2. Stated 2σ date uncertainties in this study include in-run errors and decay constant errors only; zircon dates determined by this method have an external uncertainty of 2% (explained in Supplemental Text File). Zr-in-titanite temperatures were calculated using the Hayden et al. (2008) calibration; we report propagated external 2σ uncertainties on the temperature results, which include errors in Zr abundance, pressure, a_{SiO2}, and the thermodynamic calibration of the thermometer.

Sample JC86 is a calcite + diopside + wollastonite + plagioclase + titanite + garnet marble (Fig. 13A). Minor alteration of diopside, wollastonite, and plagioclase are observed in thin section; calcite, titanite, and garnet are pristine. Subhedral 100–300-μm-diameter titanites generally occur in association with diopside and plagioclase, and more rarely as isolated grains surrounded by calcite. Two –200-μm-diameter grains in contact with diopside define a single age and trace element population (Fig. 13A). The regressed lower intercept date for this sample is 91.0 ± 1.1 Ma (MSWD = 1.4). Because JC86 lacks quartz, and therefore a_{SiO2} is uncertain, we did not attempt Zr-in-titanite thermometry for this sample.

Sample JC106 is a diopside quartzite, with hornblende and epidote overgrowths on diopside interpreted as retrograde phases (Fig. 13B). Titanite occurs in two textural settings: smaller, 200–400-μm-diameter subhedral grains are present in the quartz-dominated matrix, whereas larger subhedral to euhedral grains (to 1200 μm diameter) are associated with diopside-dominated aggregates. Grains from both textural settings were analyzed, and define three distinct trace element populations: (1) a light (L)REE-enriched, high-Zr population defined by spots within the core of a single matrix grain, (2) a less LREE-enriched, lower Zr population defined by matrix rims and some whole matrix grains, and (3) an LREE-depleted, low-Zr population from large grains in contact with diopside (Fig. 13B). The first two populations yield appreciable U for dating, whereas the third population had low U concentrations and the Pb analyses were dominated by common Pb; only those spots from the third population with U above detection limits (and therefore sufficient precision in the 206Pb/238U ratio) were included in the isochron calculation. All three populations plot on a single, well-defined isochron. The regressed lower intercept date for this sample is 89.8 ± 1.5 Ma (MSWD = 0.79).

Zr-in-titanite temperatures were calculated for JC106 at the peak pressure reported earlier in this study (6.3 ± 0.5 kbar), and values of a_{SiO2} = 1.0 and a_{TiO2} = 0.75 ± 0.25 were adopted to account for the presence of quartz and titanite without rutile. Weighted mean averages of these results yield a temperature...
of 792.7 ± 28.8 °C for the first trace element population (matrix cores), 743.3 ± 26.2 °C for the second population (matrix rims and some whole grains), and 732.0 ± 25.7 °C for the third population (grains in diopside aggregates) (Fig. 13C). Along with textural constraints, the calculated Zr-in-titanite temperatures suggest that titanite neo- or recrystallization occurred at or near peak metamorphic conditions and continued during cooling. However, calculated Pb closure temperatures for the analyzed titanite grains, for cooling rates of 10–100 °C/m.y., are <700 °C for both JC98 and JC106 (Dodson, 1973; Cherniak, 1993). These relationships indicate that the reported titanite dates are cooling ages from high temperature. The U-Pb zircon and titanite dates suggest a protracted metamorphic history over 4.8 ± 1.5 m.y. from 94.55 ± 0.14 Ma to 89.8 ± 1.5 Ma for the Bani Hamid granulites.

Figure 13. Titanite U-Pb and trace element data from Bani Hamid. (A) Tera-Wasserburg concordia diagram and chondrite-normalized rare earth element (REE) plot for marble sample JC98. The data define a single age and trace element population. CI—carbonaceous chondrite; MSWD—mean square of weighted deviates. (B) Tera-Wasserburg concordia diagram and chondrite-normalized REE plot for quartzite sample JC106. The data yield three distinct trace element populations, identified by different colors and discussed in the text. One of the populations (in green) contained only a subset of spot analyses with sufficient U for isotopic analysis. The three trace element populations plot on a single isochron. (C) Zr-in-titanite temperatures and propagated external 2σ uncertainties for the three trace element populations in JC106; colors match those in B. The legend for all symbols is shown in the inset box and is discussed in the Supplemental Text File.
**METAMORPHIC SUMMARY AND PROTOLITHS**

The tectonic stratigraphy of the Bani Hamid granulites appears to be a sequence with metaalkali basalts along the base overlain by carbonates, calc-silicates, and quartzites at higher levels. Almost no clastic pelitic rocks are exposed. There are several possible unmetamorphosed protolith sources, notably (1) the Sumeini Group shelf-slope carbonates, (2) proximal Hamrat Duru Group turbidites, in which there are stratigraphic horizons of carbonates (e.g., Nayid Formation), sandstones (Guwayza Formation), and cherts (e.g., Sidr Formation), (3) distal Hawasina thrust sheet composed mainly of abyssal radiolarian cherts, and (4) Haybi Complex thrust sheet immediately beneath the Semail ophiolite, composed mainly of Late Triassic Oman Exotic reefal limestones above an alkali basaltic substrate, cherts, and mélanges.

The Sumeini Group comprises more than 700 m stratigraphic thickness of well-bedded limestone conglomerates and calcarenites of platform margin and slope facies origin (Fig. 4) with almost no chert or volcanic components (Watts, 1987, 1990; Searle and Cooper, 1986; Cooper et al., 2014). The stratigraphy of the Sumeini Group directly correlates to the time-equivalent shelf carbonates on the Arabian autochthon (Glennie et al., 1973, 1974; Robertson and Searle, 1990; Searle et al., 1983, 1990). Although the Bani Hamid calc-silicates could be derived from Sumeini-like lithologies, the lack of siliceous cherts or volcanics makes this unlikely to be the protolith of the Bani Hamid granulites. The shelf-slope-proximal basin facies Hamrat Duru Group shows a range of lithologies including limestone and sandstone turbidites, two horizons of cherts (Late Triassic and Late Jurassic), and some shaley horizons, with rare basaltic silts (Cooper, 1988, 1990; Bernoulli and Weissart, 1987; Bechennec et al., 1990; Blechschmidt et al., 2004). These rocks could be suitable protoliths for the Bani Hamid granulites except for the lack of major volcanic horizons and the fact that, whereas the quartzite and carbonate units in Bani Hamid are relatively thick, the Hamrat Duru units are thin and interbedded. The distal Hawasina Complex rocks are unlikely protoliths of the Bani Hamid granulites, because although the abundant cherts would be suitable source rocks for the two-pyroxene quartzites, there is almost no carbonate material and only a very few minor basaltic intrusives in the Halfa, Hulw, and Shamal Formations (Glennie et al., 1974).

The most suitable protolith sources for the Bani Hamid granulites are the rocks seen in the most distal allochthonous unit beneath the ophiolite, the Haybi Complex thrust sheet (Fig. 14). These rocks are immediately beneath the mantle sequence harzburgites and its metamorphic sole where attached, and include Oman Exotic reef limestones as much as 800 m thick, which usually have an alkali basaltic basement (Searle et al., 1980; Searle and Graham, 1982; Pillevuit et al., 1997). Exotic limestones such as Jebel Mshit in the central Oman mountains (Fig. 15) are Late Triassic oceanic seamounts forming carbonate guyots above an alkali basaltic substrate immediately beneath the Semail ophiolite thrust sheet. Other exotics (e.g., Jebel Kawn) are overlain by a cap of latest Triassic–Jurassic radiolarian cherts reflecting a drowning of the oceanic guyot at the end of the Triassic (Fig. 14). The Haybi Complex also includes trench-type mélanges with both serpentinite and sedimentary matri-
and trondhjemites in the ophiolite crust were crystallizing. Some sort of slab the mantle beneath the ophiolite at the same time that ridge-related gabbros amphibolite-granulite metamorphism at depths of ~40 km was occurring in Lippard et al., 1986; Rioux et al., 2013; Searle et al., 2003, 2004, 2014), where tonic setting of the ophiolite (Searle and Malpas, 1980, 1982; Pearce et al., 1981; normal MORB (MacLeod et al., 2013) to support a suprasubduction zone tec-
morphic sole suggest that metamorphism and melting in the sole may have been either synchronous with or rapidly followed ridge magmatism (Warren et al., 2005; Styles et al., 2006; Rioux et al., 2012a, 2013). Current U-Pb dates from the meta-
morphic sole clearly shows that the heat source for metamorphism was in the overlying mantle, but a deeper mantle than that preserved in the ophi-
lite. As the rocks in the subduction channel exhumed, ductile shearing gave way to brittle thrusting and high-level imbrication, as seen along the Masafi corridor in UAE and various tectonic windows along the eastern margin of the Oman mountains, for example, the Sumeini, Aejudi, and Hawasina windows and along Wadi Tayyin in the eastern mountains (Searle, 1985, 1988a, 2007; Cowan et al., 2013).

As the ophiolite obduction process continued, the Haybi Complex thrust sheet was progressively underthrust beneath the ophiolite together with its accreted metamorphic sole (Fig. 17C). These predominately carbonate and quartzite rocks were unable to subduct to more than middle or lower crustal depths due to low density and buoyancy and were therefore jammed against the subduction zone at depths of ~22–27 km. Continued compression led to tight isoclinal folding at all scales in the Bani Hamid granulites. Simple restora-
tion of the large-scale folds shows a minimum of 130 km internal shortening, and the west-directed breaching out-of-sequence Bani Hamid thrust shows a minimum of 30 km offset. At higher structural levels, the metamorphic sole, Haybi Complex, and Hawasina Complex thrust sheets were imbricated by thin-skinned thrust processes and subsequently folded across the Dibba zone (Searle, 1988a).

The final stage in the evolution of the Bani Hamid granulites involved late-stage west-vergent out-of-sequence thrusting along the Bani Hamid thrust (Fig. 17D). This late thrust places a more outboard complete ophiolite unit (Khaw Fakkan block) along the hanging wall onto a more inboard mantle se-
quence unit to the west. Another late-stage breakback thrust, the Masafi-Dibba thrust, cuts through the ophiolite, truncating the lower mantle sequence and attached amphibolite-greenschist sole along the Masafi corridor in its footwall.
Figure 16. Late Cretaceous time chart showing all published U-Pb age data from the Semail ophiolite, the normal metamorphic sole, the Bani Hamid thrust sheet (amph—amphibolite), and the par-aluminous granite dikes in Oman and the United Arab Emirates (UAE) (Warren et al., 2005; Styles et al., 2006; Rioux et al., 2012a, 2013). Each data point represents a single dated sample. Dates from Rioux et al. (2012a, 2013) are the youngest precise single grain date from each sample. The Styles et al. (2006) and Warren et al. (2005) dates are not corrected for initial exclusion of $^{230}$Th during zircon crystallization, which would increase the dates by ~80–100 k.y. Age uncertainties are 2σ. Two dates from Styles et al. (2006) are plotted under both the Bani Hamid and granite dikes columns. We exclude four dates from Warren et al. (2005) from ridge-related (V1) tonalites and trondhjemites because the analyses were done before the widespread adoption of the chemical abrasion method and subsequent analyses of one of the samples by Rioux et al. (2014) suggested that the reported dates may be affected by Pb loss.
The Bani Hamid thrust is, therefore, a later structure cutting through, or breaching, the overlying Semail ophiolite, and the upper thrust is also a breaching thrust cutting across the earlier Semail thrust as shown in Figure 17D.

At some stage between peak granulite metamorphism (Fig. 17C) and out-of-sequence thrust culmination (Fig. 17D), localized crustal melting resulted in production of small-scale tonalitic to leucogranitic melts ca. 91.4 Ma. These small granitic dikes commonly contain biotite and variable amounts of garnet, tourmaline, andalusite, muscovite, and cordierite (Peters and Kamber, 1994; Cox et al., 1999; Searle and Cox, 2002). These minimum melt peraluminous granites require a muscovite- or biotite-rich pelitic source. This presents a problem, because none of the Bani Hamid granulite lithologies are suitable source rocks. The normal metamorphic sole also contains lithologies (metabasaltic amphibolites, metacherts, metacarbonates in greenschists) that are unsuitable protolith source rocks for these crustal melts. Some uncommon shaley assemblages
are occasionally present in the mélanges in the Haybi Complex immediately beneath the ophiolite (Searle and Malpas, 1980, 1982). We propose that some minor pelitic component of the Haybi Complex could be buried beneath the eastern UAE part of the mountains, beneath the region where the granitic dikes now occur (Khaw Fakkam block, Ras Dadnah area). More work is required to determine the precise sources of these enigmatic leucogranitic dikes.

**DISCUSSION AND CONCLUSIONS**

**Comparisons of Bani Hamid with the Normal Metamorphic Sole**

The Bani Hamid thrust sheet in northern Oman (Madhah enclave) and the UAE (Fujairah) differs from the normal metamorphic sole in several key respects.

1. Whereas the normal metamorphic sole rocks show a narrow (~50–150 m) section of amphibolites, with garnet + clinopyroxene granulite facies enclaves in the upper part, epidote amphibolites, and greenschist facies rocks, the Bani Hamid thrust sheet shows a 1.2 km structural thickness of granulite facies mafic and diopside-enstatite-cordierite quartzites with minor amphibolites.

2. The metamorphic sole rocks show a pronounced inverted metamorphic gradient beneath the Semail thrust along the base of the ophiolite; however, the Bani Hamid rocks are all at granulite or uppermost amphibolite facies.

3. The sole rocks are found in the same structural position along the entire Oman mountains; however, the Bani Hamid granulites are only found in one location in the north. It is not clear whether these high-temperature granulites are also present at depth in Oman, but remain buried and unexposed, or whether they are actually restricted to the northern mountains. However, in the UAE, in addition to the Bani Hamid metamorphism, the late leucocratic dikes that intrude the mantle section provide evidence for a prolonged high-temperature event (ca. 91.4 Ma; Styles et al., 2006). Similar young dikes have not been identified in the Oman portion of the ophiolite (Rioux et al., 2012a, 2013), suggesting a distinct tectonic history.

4. Whereas the metamorphic sole rocks are always found along the base of the ophiolite mantle sequence, the Bani Hamid granulite-amphibolite thrust sheet is surrounded by mantle sequence peridotite, and has been thrust up by the out-of-sequence Bani Hamid thrust that breaks back in the sequence.

5. Although both the metamorphic sole rocks and the Bani Hamid rocks are thought to be metamorphosed equivalents of the Haybi Complex (basaltic oceanic rocks, Mn-rich cherts, distal carbonates), the proportions of metamorphic quartzite and marble in Bani Hamid is far greater.

6. Although the P-T conditions of the amphibolite-granulite sole rocks (770–900 °C; 11–15 kbar) imply a much deeper and more distal location in a subduction zone setting beneath the ophiolite, the P-T conditions of the Bani Hamid rocks (850 ± 60 °C; 6.3 ± 0.5 kbar) show a much shallower level of formation. The high temperatures from both the sole and the Bani Hamid rocks suggest that heat must have been provided from the hanging-wall mantle peridotites.

7. Current U-Pb zircon age data suggest that amphibolite facies metamorphism in the sole may be synchronous with or immediately postdate formation of the ophiolite crust by ridge magmatism (Wadi Tayyin, 94.7–94.5 Ma; Masafi, 95.7–95.3 Ma; Warren et al., 2005; Styles et al., 2006; Rioux et al., 2013). In contrast, U-Pb zircon ages on Bani Hamid rocks are younger, ranging from 94.5 to 91.8 Ma (Styles et al., 2006; Rioux et al., 2014; this study). Extremely high temperatures in the overlying mantle peridotites must have occurred for ~4 m.y. from 95.7 to ca. 92 Ma to explain the high-temperature granulites in both the normal metamorphic sole rocks (Cowan et al., 2013) and the Bani Hamid thrust sheet (this study). The U-Pb titanite ages from Bani Hamid (91.0 ± 1.1 Ma and 89.8 ± 15 Ma, considering external uncertainties) reported here are interpreted as high-temperature cooling ages, and are significantly younger than both the ophiolite and the normal metamorphic sole.

**Deep Seismic Constraints from the UAE**

Four deep seismic profiles were shot by WesternGeco (2005) on behalf of the Ministry of Energy of the UAE and preliminary results were presented by Batty et al. (2004), Tarapoanca et al. (2010), and Naville et al. (2010). In addition, a new aeromagnetic survey in the UAE was carried out by Fugro (Batty et al., 2004; Styles et al., 2006). The northern seismic line (D4) crosses the Dibba zone and northernmost part of the ophiolite to Ras Dadnah and the southern line (D1) crosses the main Khaw Fakkam ophiolite block and Bani Hamid thrust slice just south of Masafi (Fig. 18). The two other lines are strike parallel, one (D3) along the axis of the foreland inland from Ras al-Khaimah–Dubai, the other (D2) along the middle of the ophiolite from the Dibba zone to south of Masafi. These deep seismic lines were depth migrated and combined with industry lines, well data, and outcrop studies. Imaging structures beneath the ophiolite slab is extremely problematic, but enhanced refraction and reflection stacks were used to interpret possible deep structures beneath the mountains. The north-south D2 profile through the Masafi window shows a thick sedimentary pile below the ophiolite, but it was not possible to distinguish the shelf carbonate units from the Sumeini and Hawasina thrust sheets (Naville et al., 2010; Tarapoanca et al. (2010) showed thrust stacks cutting through the Permian–Cretaceous shelf carbonate on a trend south of the Musandam culmination. Combined with exposed geology in the UAE and Oman parts of Musandam, these thrusts are known to affect the pre-Permain basement, Permian–Mesozoic shelf carbonates, the Late Cretaceous foreland basin, and the Paleogene sedimentary cover. Thrust tip lines are truncated by the middle Miocene unconformity in a seismic section west of Musandam (Ricateau and Riche, 1980; Searle et al., 1983, 2014; Dunne et al., 1990). Other thrusts imaged on the seismic sections cut through the subophiolite sheets and the shelf carbonates, but it is uncertain if these are late-stage ophiolite emplacement–related Late Cretaceous thrusts or mid-Cenozoic (Musandam type) thrusts associated with the initial continental collision. The east-dipping normal fault bounding the southeast margin of Musandam and the northwest margin of the Dibba zone.
Figure 18. Two seismic profiles across the northern Oman–United Arab Emirates (UAE) mountains showing interpreted structures (from Rouré et al., 2006; Tarapoanca et al., 2010; Naville et al., 2010). Abbreviations: Sgrp—supergroup; Cret., K.—Cretaceous; Pg—Paleogene; L.—lower; U.—upper. Reproduced with permission from Arabian Journal of Geosciences (Springer, Heidelberg).
The thickness of the ophiolite is constrained as zero at Masafi to ~5 km depth beneath Dadnah on the east coast. Presumably the eastern margin of the Semail ophiolite is an east-dipping normal fault offshore Dadnah–Khor Fakkan, in order to accommodate the thick Cenozoic sediments in the Gulf of Oman shelf. We suggest that the stacked up thrust sheets imaged beneath the ophiolite on the D4 and D1 seismic lines could be equivalent units to the Bani Hamid metamorphic rocks or inboard equivalents of stacked up Sumeini and Hawasina shelf margin thrust sheets. Only more detailed seismic imaging will be able to constrain this deep subophiolite structure in more detail.

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