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Subduction zone metamorphism during formation and emplacement of the Semail ophiolite in the Oman Mountains

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Abstract – The metamorphic sole along the base of the Semail ophiolite in Oman records the earliest thrust slice subducted and accreted to the base of the ophiolite mantle sequence. In the Bani Hamid area (United Arab Emirates) a *c.* 870 m thick thrust slice of granulite facies rocks includes garnet + diopside amphibolites, enstatite + cordierite + sillimanite + spinel ± sapphirine quartzites, alkaline mafic granulites (meta-jacupirangites) quartzo-feldspathic gneisses and calc-silicates. The latter contain garnet + diopside + scapolite + plagioclase ± wollastonite. P–T conditions of granulite facies metamorphism are in the range 800–860 °C and 10.5 ± 1.1 kbar to 14.7 ± 2.8 kbar. Garnet + clinopyroxene + hornblende + plagioclase amphibolites from the metamorphic sole record peak P–T conditions of 840 ± 70 °C and 11.6 ± 1.6 kbar (THERMOCALC average P–T mode) and 840–870 °C and 13.9–11.8 kbar (conventional thermobarometry) with low degrees of partial melting producing very small melt segregations of tonalitic material. Pressure estimates are equivalent to depths of 57–46 km beneath oceanic crust, much deeper than can be accounted for by the thickness of the ophiolite. ^{40}Ar/^{39}Ar hornblende ages from the amphibolites range from 95–93 Ma, synchronous with formation of the plagiogranites in the ophiolite crustal sequence (95 Ma), eruption of the Lasail (V2) volcanic sequence and deposition of Cenomanian–Turonian radiolaria in metalliferous sediments between the Geotimes (V1) and Lasail (V2) lavas. Protoliths of the metamorphic sole were Triassic–Jurassic and early Cretaceous Haybi volcanic rocks, Exotic limestones and quartzites and were clearly not equivalent to the Semail ophiolite rocks, showing that initiation of subduction could not have occurred at the ridge axis. Heat for metamorphism was derived from the mantle sequence harzburgites and dunites which were at or around 1100–1500 °C. All data from the sub-ophiolite metamorphic sole in Oman and the United Arab Emirates indicate that the ophiolite was formed in a Supra-Subduction zone setting and that obduction occurred along a NE-dipping high-temperature subduction zone during Late Cretaceous times.

Keywords: Oman, ophiolite, subduction, mid-ocean ridges, metamorphism.

1. Introduction

The Semail ophiolite is the most complete and best exposed ophiolite complex in the world (Fig. 1). It is composed of ~8–12 km of upper mantle peridotites (mainly harzburgite and dunite, with minor intrusions of wehrlite, pyroxenite and gabbro-norite) and 4–7 km of oceanic crustal rocks, including cumulates, isotropic gabbros, trondhjemites (plagiogranites), sheeted dykes and pillow lavas (Allemann & Peters, 1972; Glennie *et al.* 1974; Coleman, 1981; Lippard, Shelton & Gass, 1986; Nicolas, 1989). Thin pelagic sediments, notably radiolarian cherts, metalliferous sediments and umbers, overlie the pillow lava sequence. The entire ophiolite thrust sheet was emplaced at least 250 km west and southwest onto the Arabian passive margin during the Late Cretaceous period (Glennie *et al.* 1973, 1974).

Controversy still exists as to the tectonic setting of the Semail ophiolite and its obduction or emplacement mechanism. There are two major models for the tectonic setting of the Oman ophiolite:

(1) A Mid-Ocean Ridge setting where obduction was initiated at the ridge axis (e.g. Hopson *et al.* 1981; Pallister & Hopson, 1981; Boudier & Coleman, 1981; Boudier *et al.* 1985; Boudier, Ceuleneer & Nicolas, 1988; Ceuleneer, Nicolas & Boudier, 1988; Nicolas *et al.* 1988, 2000; Hacker, 1991, 1994).

(2) A Supra-Subduction Zone setting where the ophiolite was generated above a NE-dipping subduction zone (e.g. Searle & Malpas, 1980, 1982; Pearce *et al.* 1981; Alabaster, Pearce & Malpas, 1982; Lippard, Shelton & Gass, 1986; Searle & Cox, 1999).

Figure 2 shows a simplified tectonic stratigraphy of the ophiolite and metamorphic sole rocks with known geochronological ages (after Hacker, Mosenfelder & Gnos, 1996). The upper arc volcanic sequence of the Semail ophiolite (Lasail lavas or V2 unit) are only exposed in the northern and central Oman Mountains and are not exposed in the southeastern part of the mountains. The evidence to decide which model is more applicable to the Oman ophiolite comes from

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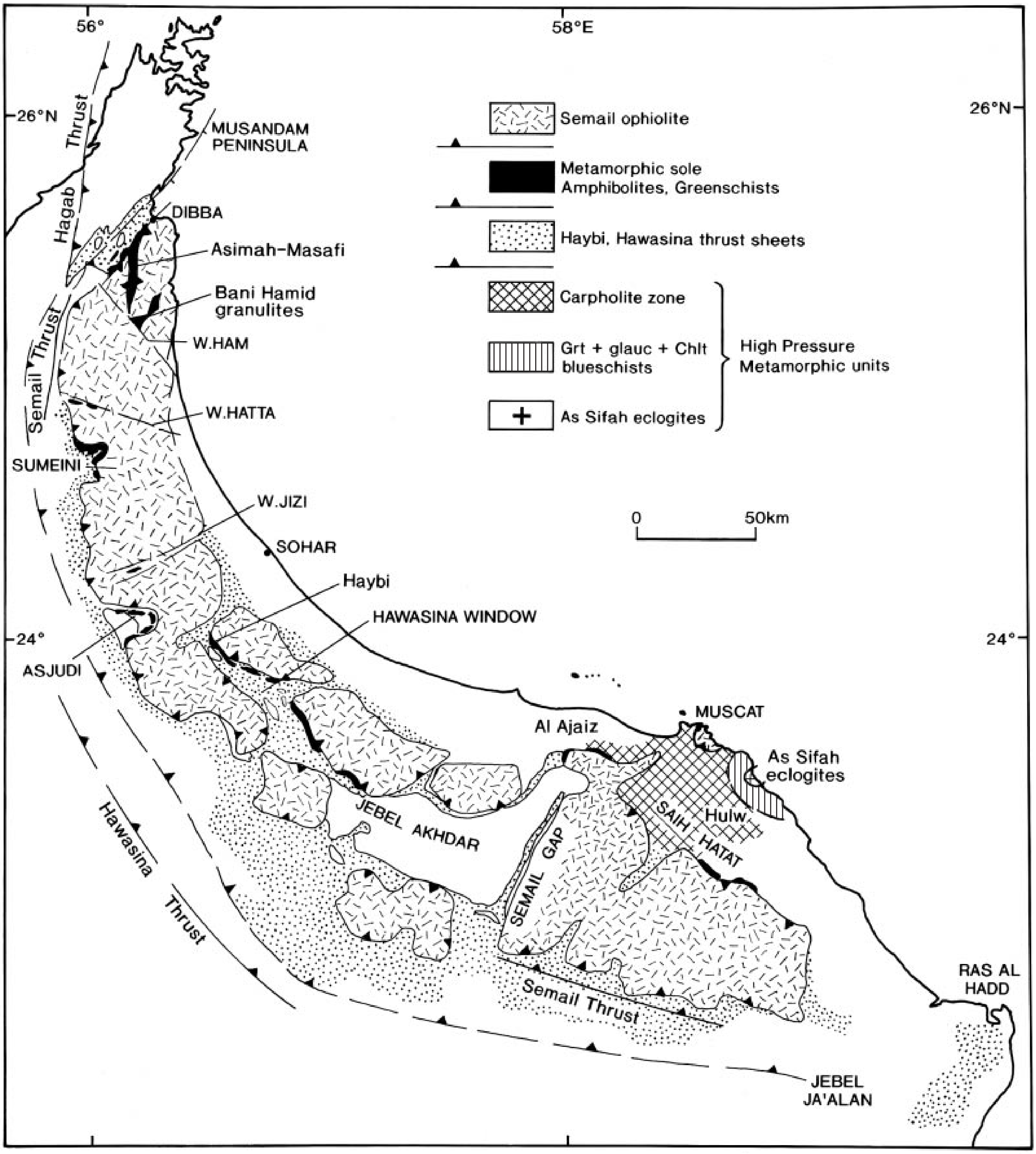


Figure 1. Geological sketch map of the Oman Mountains showing the distribution of metamorphic sole rocks and the high-pressure terrain of the southeastern Oman Mountains.

three major sources: geochemistry of the ophiolite volcanic sequence, geochronology of the ophiolite crustal sequence and metamorphic sole, and the protolith source, *P–T* conditions and petrogenesis of the metamorphic sole. The critical early history of oceanic detachment and tectonic setting of the ophiolite is held in the sub-ophiolite metamorphic sole.

In this paper we describe the petrology, structure, geochemistry and thermobarometry of the metamorphic sole throughout the Oman Mountains. We use trace element geochemistry to constrain the protolith source of the amphibolites. We use thermobarometry to constrain the *P–T* conditions and depth of subduction zone metamorphism along the base of the ophiolite. We review the geochronology of the metamorphic sole and compare the ages to those of the ophiolite. Finally we discuss the merits of the two contrasting tectonic models to constrain the setting and emplacement history of the Semail ophiolite.

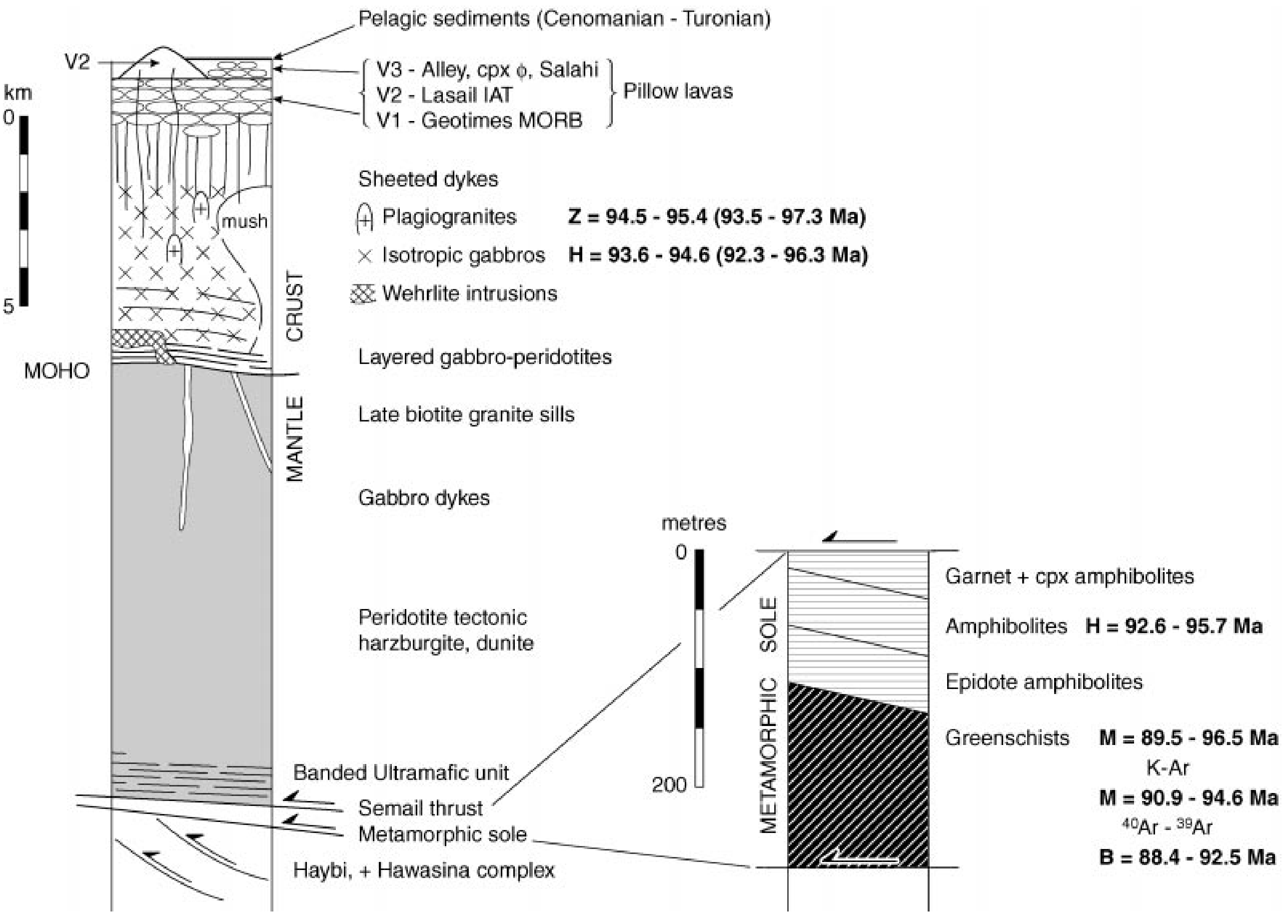


Figure 2. Simplified section through the Semail ophiolite and metamorphic sole (modified after Hacker, Mosenfelder & Gnos, 1996) showing Pb/U zircon (Z) ages (Tilton, Hopson & Wright, 1981), ^{40}Ar/^{39}Ar hornblende (H), muscovite (M) and biotite (B) ages (Hacker, 1994; Hacker, Mosenfelder & Gnos, 1996). Ophiolite V1 Geotimes pillow lavas have a Mid-Ocean ridge basalt (MORB) geochemistry whereas Lasail lavas are Island Arc type tholeiites (IAT).

2. Semail ophiolite metamorphic sole

The metamorphic sole to the Semail ophiolite was initially studied in detail in the northern Oman Mountains by Allemann & Peters (1972), M. P. Searle (unpub. Ph.D. thesis, Open Univ., 1980), Searle & Malpas (1980, 1982), Bucher (1991), M. Bucher & D. Kurz (unpub. M.Sc. thesis, Univ. Berne, 1991), E. Gnos (unpub. Ph.D. thesis, Univ. Berne, 1992), Gnos (1998) and Gnos & Kurz (1994), and in the southeastern Oman Mountains by Ghent & Stout (1981). Subsequent work was carried out in the Green Pool area in Wadi Tayyin, south of Saih Hatat (southeastern Oman Mountains) by Hacker (1994), Hacker & Mosenfelder (1996) and Hacker, Mosenfelder & Gnos (1996). The following six points are characteristic of the Oman sub-ophiolite metamorphic sole:

(a) The base of the Semail ophiolite is marked by a narrow zone of amphibolite and greenschist facies rocks showing an inverted metamorphic temperature and pressure gradient.

(b) Garnet + clinopyroxene amphibolites immediately below the peridotite formed at ~850 °C and 11–14 kbar (Gnos, 1998; J. S. Cox, unpub. D.Phil. thesis, Univ. Oxford, 2000) at 95–93 Ma (Lanphere, 1981; Hacker, 1994). The beginnings of partial melting at the highest temperatures formed small tonalitic melt pods (Searle & Malpas, 1982).

(c) Ductile shearing and later thrusting condensed the sub-ophiolite metamorphic sole. Upper and lower boundaries of the metamorphic sole are thrust faults. In intact sequences, emplacement-related fabrics in the amphibolites are parallel to fabrics along the basal part of the ophiolite mantle sequence (Banded Ultramafic Unit: Searle & Malpas, 1980, 1982).

(d) Heat for metamorphism must have been supplied from the recently formed and still hot ophiolite mantle sequence peridotites above the metamorphic sole. Zircon ages from ophiolitic plagiogranites (Tilton, Hopson & Wright, 1981) and amphibole ages from the sub-ophiolite amphibolites (Gnos & Peters, 1993; Hacker, 1994; Hacker, Mosenfelder & Gnos, 1996) are both ~95 Ma.

(e) Greenschist facies meta-sediments were accreted to the base of the amphibolites at lower pressures and shallower depths during later thrusting.

(f) Final thrust emplacement of the Semail ophiolite and its metamorphic sole onto the Arabian continental margin involved at least 250 km of emplacement northeast to southwest. The metamorphic sole is now present along the base of the ophiolite, either parallel to the basal peridotite or in imbricate stacks beneath.

Several localities where the metamorphic sole is well exposed have been studied in detail.

2.a. Sumeini Window

The most complete section through the metamorphic sole where it is still attached to the base of the ophiolite in Oman occurs in the Sumeini Window of northern Oman (Fig. 3). This area was mapped at 1 : 20 000 scale by M. P. Searle (unpub. Ph.D. thesis, Open Univ., 1980), Searle (1985) and Searle & Malpas (1980, 1982) who also carried out geochemistry and thermobarometry on the amphibolites. Approximately 40 metres of garnet + clinopyroxene amphibolites (grt + cpx + hbl + pl ± qtz ± sphene) occur immediately below the Semail thrust with minor amounts of diopside + garnet marble (cpx + hbl + cal ± grt ± wollastonite ± orthoclase). Almandine garnets in the amphibolites have the average composition $Al_{50}Gr_{33}Py_{14}Sp_{3}$. A few aplite veins cut the amphibolites and these contain spessartine-rich garnet with average compositions of $Al_{40}Sp_{60}$. At the highest structural levels of the metamorphic sole very small pods and veins of tonalitic partial melts were derived from *in situ* partial melting of the amphibolites at temperatures > 850 °C (Searle & Malpas, 1980, 1982). Isoclinal folding of the amphibolites and greenschists are widespread and mineral stretching lineations are aligned 055–075° ENE. Fabrics within the amphibolites are emplacement-related ductile shear fabrics which are parallel to the fabrics along the base of the ophiolite. Banded harzburgites (olivine + orthopyroxene ± chrome spinel), lherzolites (chrome diopside + enstatite + olivine + spinel) and dunites (olivine ± chrome spinel) have emplacement-related shearing fabrics which die out above the lower 50–100 m thick Banded Ultramafic Unit.

The high-temperature garnet + clinopyroxene amphibolites pass structurally downward to finer-grained amphibolites without garnet or clinopyroxene and further down into epidote-rich amphibolites (actinolite + epidote + plagioclase + quartz + sphene). Veins of rodingite containing hydrogrossular garnet + diopside + muscovite + calcite indicate Ca-metasoma-

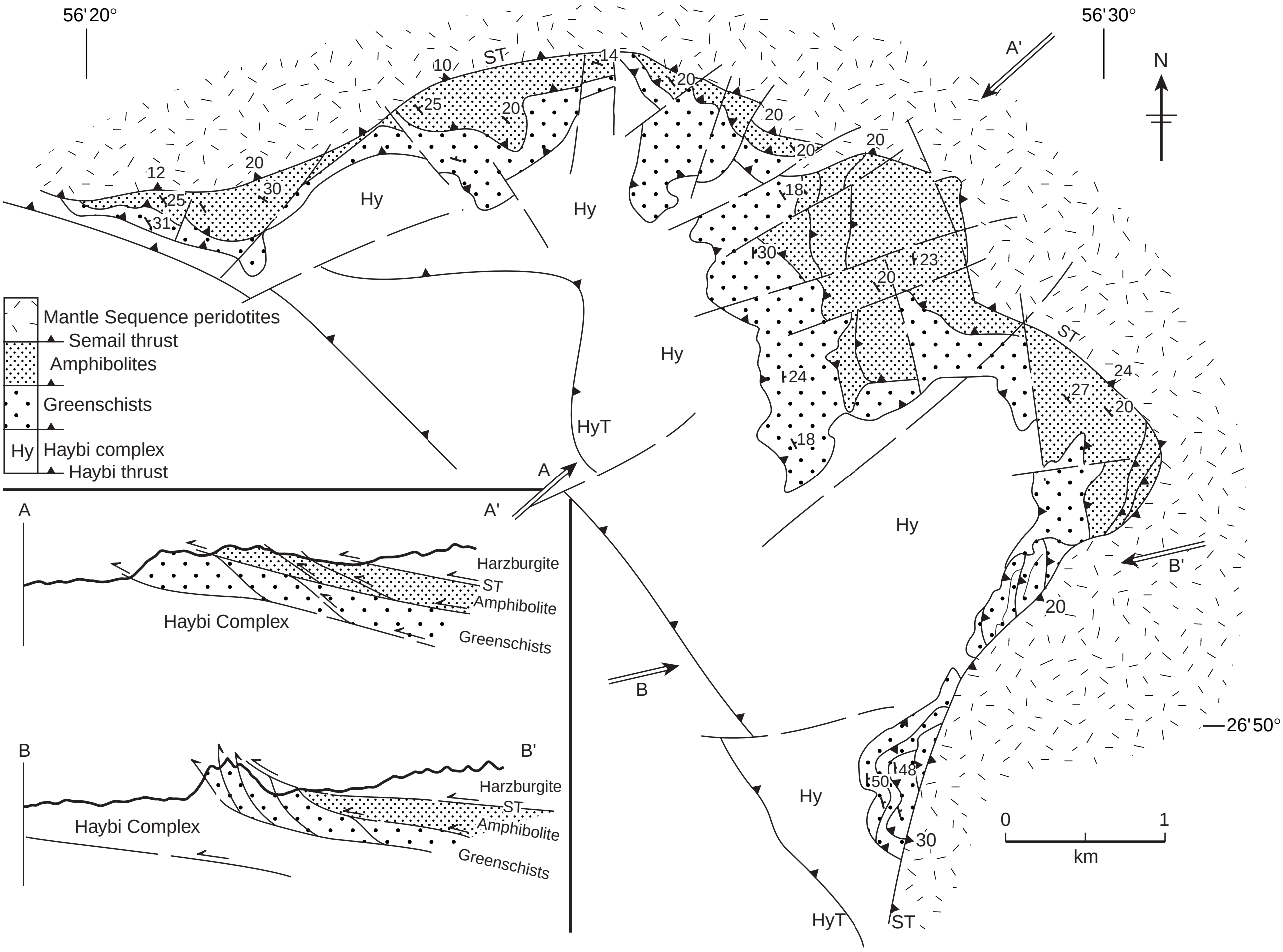


Figure 3. Geological map of the Sumeini Window, northern Oman (after M.P. Searle, unpub. Ph.D. thesis, Open Univ., 1980).

tism (Searle & Malpas, 1980). High-temperature serpentinization (antigorite + talc ± crysotile, asbestos) and silicification is also present in varying degrees along the base of the ophiolite. A thrust contact separates these amphibolite and epidote amphibolite rocks from a series of greenschist facies meta-sedimentary units including piemontite, stilpnomelane and white mica-bearing quartzites, marbles and rare pelitic bands. The base of the greenschist facies sole is a thrust placing these metamorphic rocks over a series of un-metamorphosed mélanges, distal Tethyan sedimentary rocks, Triassic 'exotic' limestones and alkaline volcanic rocks, termed the Haybi complex (Searle & Malpas, 1980, 1982). The Haybi complex is a distinct structural package which separates the Semail ophiolite above from the Middle Permian to Late Cretaceous Hawasina complex sedimentary rocks below.

2.b. Wadi Tayyin

The Green Pool area in Wadi Tayyin (southeastern Oman Mountains) shows a discontinuous thrust slice of amphibolite facies metamorphic sole rocks still attached to the base of the ophiolite. The original mapping of this area was carried out by R. Coleman and R. Gregory, and thermobarometry and geochronology carried out by Ghent & Stout (1981), Hacker & Mosenfelder (1996) and Hacker, Mosenfelder & Gnos (1996). The highest levels of the sole are again composed of garnet + clinopyroxene + hornblende + plagioclase assemblages with rare pods of tonalitic to monzodioritic partial melts (plagioclase + quartz + apatite + epidote + hornblende). Grain size decreases from ~2 mm at the highest levels to < 0.5 mm within 50 m of the peridotite contact. Garnet is present only in the upper 4 m. Structurally below the amphibolite a series of meta-cherts locally containing Mn-garnet and piemontite quartzites. Ghent & Stout (1981) reported greenschist facies assemblages below the amphibolites but Hacker & Mosenfelder (1996) showed that these rocks were actually lower amphibolite facies, thrust over un-metamorphosed sediments with no intermediate greenschists. Ductile deformation fabrics result from non-coaxial simple shear with a significant component of flattening. Isoclinal folds are common throughout the amphibolite sole. Stretching lineations are aligned 015–050° NE and a series of small scale E–W-aligned brittle normal faults cut the section showing down-to-the-SSE motion. These normal faults are probably related to the late-stage culmination of the Saih Hatat shelf carbonate + pre-Permian basement dome to the north. A large-scale E–W-aligned listric normal fault along the southern margin of shelf carbonates has down-faulted the entire ophiolite to the south. Most of the Haybi and Hawasina thrust sheets, which overlie the shelf carbonates and underlie the ophiolite have therefore been faulted out.

2.c. Al Ajaiz (Al Ajal)

The metamorphic sole outcrop at Al Ajaiz (Fig. 1) forms a thin (~20 m thick) dismembered thrust slice detached from the base of the ophiolite and juxtaposed against a lower structural unit (Triassic shelf carbonates of the Mahil Formation) by later, Tertiary normal faulting along the late Cretaceous Semail thrust. Garnet and diopside amphibolites have been strongly altered with garnet pseudomorphed by aggregates of chlorite and magnetite. The presence of sub-ophiolite amphibolites at Al Ajaiz shows that the metamorphic sheet underlies the whole ophiolite sheet, and is not only present along the leading edge (western margin) of the mountains.

2.d. Asjudi

The Asjudi Window in the central Oman Mountains was mapped by M. P. Searle (unpub. Ph.D. thesis, Open Univ., 1980) at 1 : 20 000 scale. The metamorphic sole in this area has been broken up into blocks and enclosed within a ductile sheared serpentinized harzburgite forming a tectonic mélange. Both amphibolites and greenschists are present in the blocks and some larger 'knockers' also have earlier imbricate thrusts. Many of the blocks show an alignment parallel to the fabric along the base of the ophiolitic mantle sequence and have been disrupted by the passive flow of serpentinite around each block. The serpentinite acted as a ductile décollement horizon along the which the ophiolite was emplaced.

2.e. Haybi–Hawasina Window

Metamorphic sole amphibolites and greenschists are present along the base of the ophiolite in many localities around the margin of the Haybi–Hawasina Window (Searle, 1985; Searle & Malpas, 1980, 1982; Searle & Cooper, 1986). Garnet amphibolites are present along Wadi Hawasina in the 10 m immediately beneath the Mantle sequence peridotites. Imbricate faulting has disrupted the sole rocks during the later thin-skinned phase of thrust emplacement and hence thicknesses of the metamorphic sheet cannot be used for determining a thermal gradient. Greenschist facies rocks of the metamorphic sole include marbles clearly derived from the Triassic Oman Exotics (Searle & Graham, 1982), quartzites with piemontite, stilpnomelane and phengite, and meta-volcanic rocks which are metamorphosed equivalents of the Triassic Haybi volcanic complex (Searle *et al.* 1980). Unusual alkali ultramafic rocks, jacupirangites and alkali gabbros intrude the distal parts of the Hawasina complex thrust sheet immediately beneath the metamorphic sole (Searle, 1984). All structural units immediately beneath the Semail ophiolite are related to the Haybi complex and are clearly not related in any way to the

Semail ophiolite, showing that detachment of the ophiolite could not have occurred along the ridge axis.

2.f. Asimah–Masafi (United Arab Emirates)

The largest aerial extent of sole rocks occurs in the far north of the Oman Mountains in the Dibba zone of the United Arab Emirates. This area was mapped originally by Allemann & Peters (1972), and later by M. P. Searle (unpub. Ph.D. thesis, Open Univ., 1980), F. Stössel & U. Zeigler (unpub. M.Sc. thesis, Univ. Berne, 1985), M. Bucher & D. Kurz (unpub. M.Sc. thesis, Univ. Berne, 1991), E. Gnos (unpub. Ph.D. thesis, Univ. Berne, 1992) and Gnos (1998). Near Masafi, the metamorphic sole consists of garnet and diopside amphibolites (up to 80 m thick) at the peridotite contact passing down into hornblende + plagioclase amphibolites then into epidote ± quartz amphibolites and finally into quartzites. Gnos (1998) found kyanite in a garnet amphibolite boulder (unfortunately not *in situ*). He determined pressures of 11 ± 2 kbar at temperatures of 800 ± 100 °C for the garnet–diopside amphibolite, which is consistent with the presence of kyanite. This pressure is equivalent to over twice the thickness of ophiolite preserved in the Oman Mountains and must suggest a subduction-related metamorphism along the base of the ophiolite. Many of the quartzites are Mn-rich rocks containing piemontite and braunite. Meta-volcanic rocks are almost exclusively alkaline or transitional alkaline to tholeiitic, with blueish magnesioriebeckite amphibole and several carbonatite occurrences (Ziegler, Stoessel & Peters, 1991; Bucher, 1991; M. Bucher & D. Kurz, unpub. M.Sc. thesis, Univ. Bern, 1991). In the Dibba zone, which separates the ophiolite from the Musandam shelf carbonates, the metamorphic sole is strongly imbricated, in places with slivers of serpentinized harzburgites. The entire Haybi and Hawasina complexes have also been affected by a series of listric normal faults showing down-to-the-SE throw, associated with the culmination of the Musandam shelf carbonates and their pre-Permian basement (Searle, 1988*a*,*b*).

3. Bani Hamid granulite facies sole

A unique thrust sheet of high-temperature granulite facies metamorphic rocks crops out in the Bani Hamid area of the northern Oman Mountains. These rocks were studied in reconnaissance by Allemann & Peters (1972) and M. P. Searle (unpub. Ph.D. thesis, Open Univ., 1980) and in more detail by F. Stössel & U. Zeigler (unpub. M.Sc. thesis, Univ. Berne, 1985), M. Bucher & D. Kurz (unpub. M.Sc. thesis, Univ. Bern, 1991), E. Gnos (unpub. Ph.D. thesis, Univ. Bern, 1992) and J. S. Cox (unpub. D.Phil. thesis, Univ. Oxford, 2000). Approximately 2 km outcrop width of granulites are bounded by the Semail thrust at the top (southeast) and a later out-of-sequence thrust, the Bani Hamid thrust along the base (northwest side). The following points characterize the Bani Hamid granulite facies sole:

(a) Lithologies are dominantly quartzites (quartz + enstatite + cordierite + sillimanite + spinel ± sapphirine) and calc-silicates (calcite + grossular + wollastonite + diopside + scapolite + K-feldspar ± spinel), indicating a probable proximal sedimentary source region to the continental margin.

(b) Mafic granulites are generally alkaline and Ti-rich basaltic–gabbroic rocks, more akin to the alkaline volcanic rocks within the Haybi thrust sheet (Searle *et al.* 1980). Garnet amphibolites are uncommon but they also have a more alkaline geochemistry.

(c) *P*–*T* conditions are uniform across the Bani Hamid thrust slice in the range 800–860 °C and 10.5 ± 1.1 kbar–14.7 ± 2.8 kbar (Gnos, 1998; J. S. Cox, unpub. D.Phil. thesis, Univ. Oxford, 2000). There is no inverted pressure or temperature gradient, as seen in the normal sub-ophiolite metamorphic sole.

(d) The timing of peak granulite facies metamorphism is not well constrained, but ^{40}Ar/^{39}Ar hornblende cooling ages suggest a minimum age of ~ 95.3 ± 0.5 Ma (Gnos & Peters, 1993; Hacker, Mosenfelder & Gnos, 1996), similar to the age of ophiolite formation and amphibolite facies metamorphism along the base of the ophiolite elsewhere in the Oman Mountains.

(e) Quartzo-feldspathic and calc-silicate gneisses have ε_{Nd} values ranging from 2.3 to –6.5 and ε_{Sr} values ranging ranging from 52 to 76 (Zeigler, Stoessel & Peters, 1991; Cox, Searle & Pedersen, 1999). The granulite facies rocks probably represent the metamorphosed equivalents of the Haybi thrust sheet (Searle & Cox, 1999).

Most of the rock units within the Bani Hamid granulites can be correlated with similar lithologies in the greenschist–amphibolite facies Asimah metamorphic sole area in the United Arab Emirates (Zeigler, Stoessel & Peters, 1991; Searle & Cox, 1999). It is therefore highly likely that both thrust sheets represent variably metamorphosed equivalents of the unmetamorphosed Permo-Triassic and Jurassic Haybi complex, structurally beneath the ophiolite throughout the Oman Mountains. Rare metasedimentary material, both restitic garnet + biotite aggregates and unassimilated banded quartzite enclaves have been observed in leucogranite dykes intruding the ophiolite mantle sequence along the eastern part of the mountains in the United Arab Emirates (Cox, Searle & Pedersen, 1999). The presence of these enclaves further suggests that the underlying Bani Hamid thrust sheet was the source for melting of the leucogranites (Cox, Searle & Pedersen, 1999).

4. Geochemistry and protoliths of metamorphic sole

Major and trace element geochemistry of the volcanic units of the Semail ophiolite has been extensively

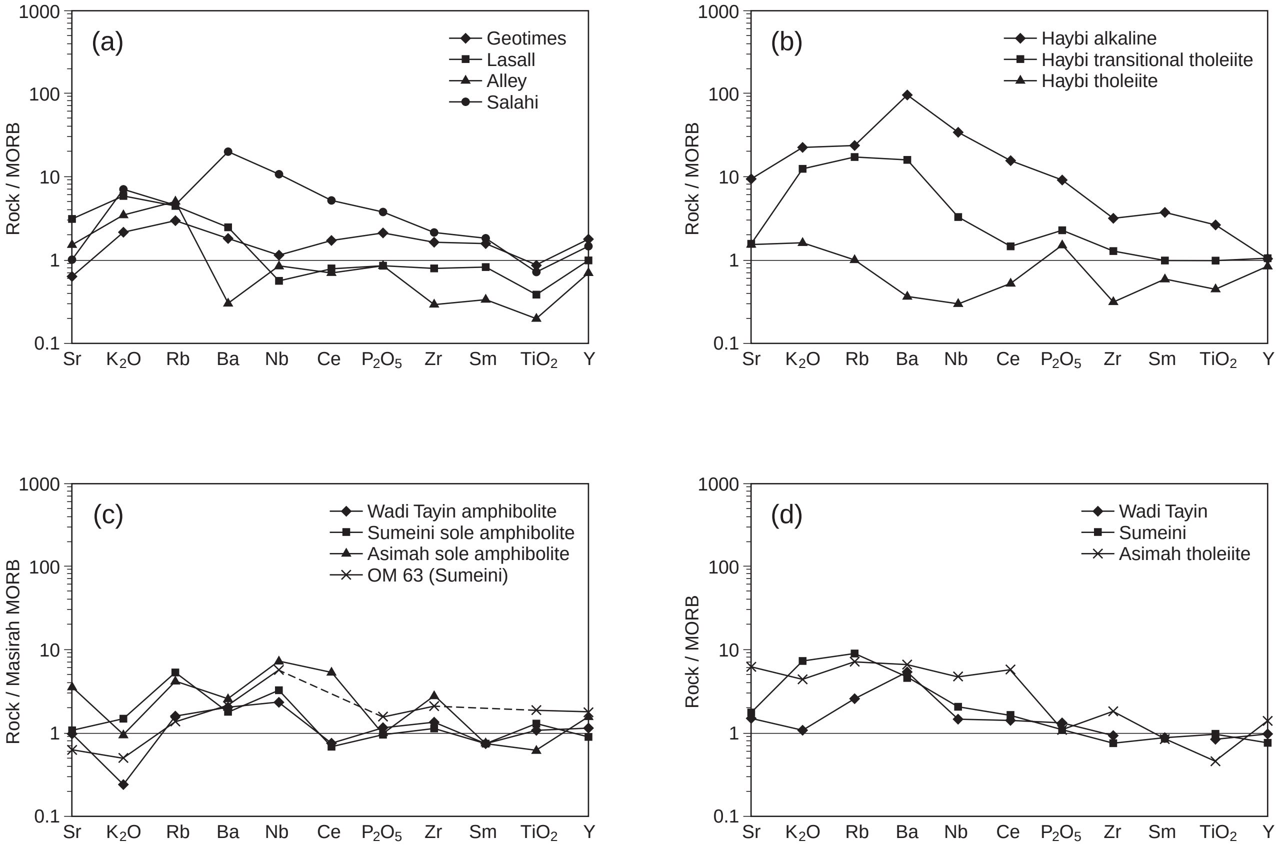


Figure 4. Spider diagrams for potential protolith rocks of the metamorphic sole from a variety of locations in the Oman Mountains, normalized to a standard MORB (Pearce & Cann, 1971) and MORB from the Masirah ophiolite (Meyer, Mercolli & Immenhauser, 1996). (a) The volcanic units of the Semail ophiolite (Pearce *et al.* 1981; Alabaster, Pearce & Malpas, 1982) show an increasing arc component with stratigraphic height from Geotimes up to Lasail units, measured by an increasing LILE concentration which is larger than that shown by the metamorphic sole amphibolites. (b) Volcanic rocks from the Haybi thrust sheet immediately underlying the metamorphic sole (Searle *et al.* 1980) show a highly alkalic unit with a tholeiitic unit towards the top in a few localities only. New analyses (c, d) show metabasaltic amphibolites from Asimah, Wadi Tayyin and Sumeini all have similar flat profiles, that appear to correlate most closely with the Masirah island off-ridge alkali basalts or components of the Haybi volcanic rocks.

studied by Pearce *et al.* (1981) and Alabaster, Pearce & Malpas (1982), and geochemistry of the Triassic–Jurassic Haybi volcanic rocks beneath the ophiolite has been published by Searle *et al.* (1980). Major, trace and rare-earth element geochemistry of the sub-ophiolite amphibolites has been published by Searle & Malpas (1982). Figure 4 shows spider diagrams for all potential protoliths of the metamorphic sole from a variety of locations in the Oman Mountains (see also Table 1). Volcanic units from the Semail ophiolite show an increasing arc component with stratigraphic height (from Geotimes to Lasail unit) and with time, measured by increasing LILE concentrations (Pearce *et al.* 1981; Fig. 4a). Volcanic units within the Triassic–Jurassic Haybi volcanic sequence show an alkalic composition, except for some of the younger volcanic rocks towards the top, which show a depletion of Ba, Nb, Zr, Ti and Y (Searle *et al.* 1980; Fig. 4b).

New geochemical analyses of the metamorphic sole amphibolites from Asimah, Wadi Tayyin and Sumeini (Fig. 4c,d) have been normalized to a standard MORB (Pearce *et al.* 1981) and also to a MORB from the ~145–150 m.y. old Masirah ophiolite (Meyer, Mercolli & Immenhauser, 1996). These data show that the garnet amphibolites have flat normalized MORB trace element patterns with limited enrichment of large-ion lithophile elements (LILE), similar to the tholeiitic Haybi volcanic rocks, and distinct from the LILE-enriched upper units of the Semail ophiolite volcanic sequence.

Lithologies of the Bani Hamid granulites are quartzites, carbonates, alkali and Ti-rich mafic volcanics (some containing ultramafic xenoliths including glimmerites) and gabbros similar to rocks the Haybi thrust sheet in the Dibba zone structurally beneath the ophiolite. They are very clearly not related in any way to the ophiolite complex. If these granulite facies rocks were the deepest and hottest, and first to form along the base of the ophiolite, then it must be absolutely clear that detachment could never have occurred along the ridge axis. If detachment did occur at the ridge

Table 1. Selected major and trace elements used in the construction of the spider diagrams in Figure 4

	OM 63	Sumeini	Asimah	Tayin	Masirah MORB	MORB
Sr	120.0	208.0	714.0	174.0	180.0	120.0
K_2O	3400.0	10500.0	6400.0	1600.0	6500.0	1500.0
Rb	4.4	17.0	14.0	5.0	3.0	2.0
Ba	100.0	90.0	129.0	108.0	48.0	20.0
Th	bdl	0.3	6.0	na	na	0.2
Ta	na	0.3	na	na	na	0.2
Nb	12.0	7.0	16.0	5.0	2.0	3.5
Ce	na	na	57.0	na	10.0	10.0
P_2O_5	2200.0	1400.0	1300.0	1600.0	1300.0	1200.0
Zr	125.0	69.0	166.0	80.0	57.0	90.0
Hf	na	2.0	na	na	na	2.4
Sm	na	2.8	3.0	na	3.7	3.3
TiO_2	21300.0	14500.0	7000.0	12500.0	10800.0	15000.0
Y	45.9	23.0	41.0	29.0	25.0	30.0
Yb	na	na	na	3.0	3.1	3.4
Sc	53.0	3.6	19.0	na	na	40.0
Cr	201.0	168.0	122.0	270.0	258.0	250.0

All data in ppm; na – not analysed; bdl – below detection limit.
Data sources: OM 63 – J. S. Cox (unpub. D.Phil. thesis, Univ. Oxford, 2000); Sumeini – M. P. Searle (unpub. PhD thesis, Open Univ., 1980); Asimah – Zeigler, Stoessel & Peters (1991); Tayin – Ghent & Stout (1981); Masirah MORB – Meyer, Mercolli & Immenhauser (1996); MORB – Pearce (1983).

axis, then the sole amphibolites should be similar to the Semail ophiolite lavas, and they are clearly not. The fact that most of the protoliths of the Bani Hamid granulites were proximal quartzite and carbonate sedimentary rocks is surprising, but could be explained if the subduction zone was much closer to the Arabian continental margin in the northern part of the mountain belt, whereas in the south it was some distance away within the Tethyan ocean. This model would support the clockwise rotation of the ophiolite during the emplacement process from palaeomagnetic evidence, with the pole of rotation located near the northern end of the ophiolite (E. Gnos, pers. comm. 2001). The garnet + clinopyroxene amphibolites are mostly meta-basalts, whereas the greenschist facies sole rocks are dominantly meta-sedimentary rocks (quartzites with less common marbles and rare pelites).

5. Thermobarometry of the metamorphic sole

5.a. Sub-ophiolite amphibolites

Peak temperatures of the garnet + clinopyroxene amphibolites in the metamorphic sole have been constrained at 775–875 °C using the Fe–Mg exchange garnet–clinopyroxene thermometer (Searle & Malpas, 1980; Ghent & Stout, 1981; Hacker & Mosenfelder, 1996; Gnos, 1998). Pressures were less well constrained due to the absence of pelitic assemblages, but were estimated using the jadeite content of clinopyroxenes. Gnos (1998) estimated peak pressures of 11 ± 2 kbar in the garnet + diopside amphibolites from Asimah, pressures that are consistent with the presence of kyanite. New *P–T* estimates from the Oman amphibolites have been determined using a variety of conventional thermometers and barometers as well as the average *P–T* method using Holland & Powell's (1998) THERMOCALC (J. S. Cox, unpub. D.Phil. thesis, Univ. Oxford, 2000) and are very similar to those obtained by Gnos (1998). Peak amphibolite facies metamorphism in the sole was 840–870 °C and 11.8–13.9 kbar using conventional thermobarometers (Kohn & Spear, 1990; Moecher, Essene & Anovitz, 1988). THERMOCALC *P–T* conditions are 840 ± 70 °C and 11.6 ± 1.6 kbar (Fig. 5a). These *P–T* conditions are similar in numerous sole localities along the base of the ophiolite, showing that the rocks formed in the same subduction zone setting along the length of the Oman Mountains.

Leucocratic partial melt pods and lenses are present throughout the upper levels of the amphibolite sole in the Sumeini area (Searle & Malpas, 1980, 1982). Typical monzodioritic to tonalitic assemblages contain plagioclase (average $\sim An_{30}$), quartz, hornblende and biotite with occasional K-feldspar. Thermobarometry on these tonalitic melts show that they formed at temperatures of 656 ± 17 °C using the Holland & Blundy (1994) hornblende–plagioclase thermometer and pressure around 5.6 ± 0.6 kbar using the Al content in hornblende barometer of Anderson & Smith (1995). These *P–T* conditions are lower than the peak *P–T* recorded by the garnet + clinopyroxene amphibolites, and are interpreted to have formed during the prograde heating of the sole during early detachment.

5.b. Bani Hamid granulites

E. Gnos (unpub. Ph.D. thesis, Univ. Berne, 1992) and Gnos & Kurz (1994) estimated peak *P–T* conditions of the Bani Hamid granulites at 800 ± 50 °C and 6.5–9 kbar

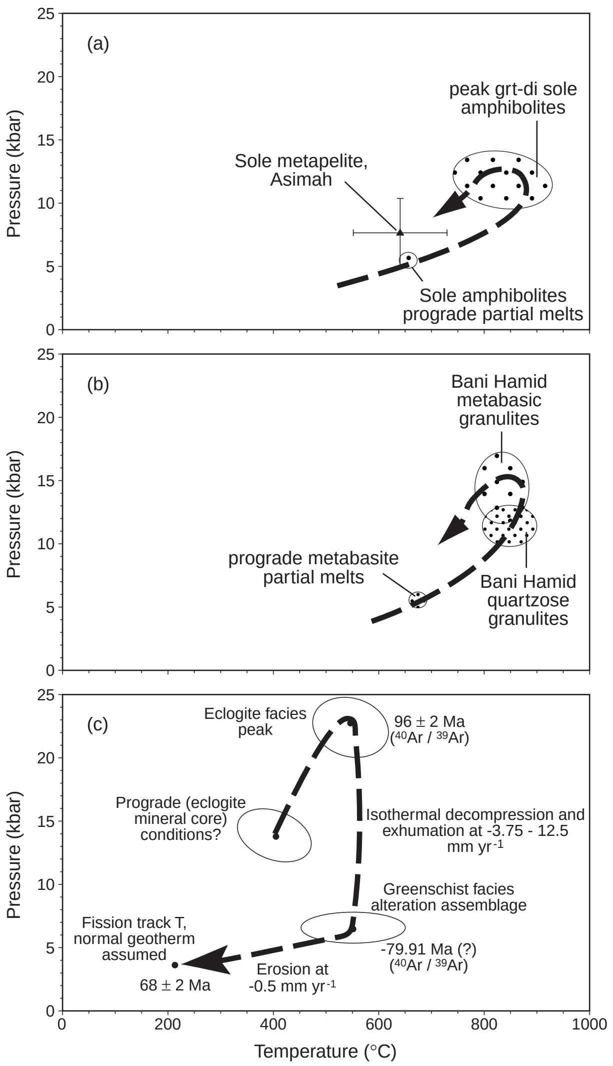


Figure 5. Pressure–temperature diagrams showing new thermobarometric data for (a) the metamorphic sole amphibolites and potential *P–T–t* path. Limited partial melting of the amphibolites is inferred on the prograde path and peak *P–T* conditions are 840 ± 70 °C. Anticlockwise *P–T* path is consistent with the heat source being the hot mantle sequence peridotites immediately above the sole. (b) *P–T–t* evolution of the Bani Hamid granulites in the United Arab Emirates metamorphic sole. Error ellipses are derived from THERMOCALC in average *P–T* mode. The inferred anticlockwise *P–T* path is similar to the classic amphibolite sole in Oman with heat derived from the thrusting of hot peridotite which must have been at temperatures of > 1000 °C. (c) *P–T–t* evolution of the As Sifah eclogite including *P–T* data from Searle *et al.* (1994), Fission Track data from Saddiqi *et al.* (1995) and ^{40}Ar/^{39}Ar data from Miller *et al.* (1999). Peak eclogite pressures are 20–23 kbar and the rocks show a clockwise *P–T* path with isothermal decompression from 20–6 kbar during extremely rapid exhumation. Prograde heating of initially cold rocks during subduction of the continental margin was followed by rapid thrusting, back up the same subduction zone. ^{40}Ar/^{39}Ar data shows that exhumation was largely completed by 79 Ma (Early Campanian), following which, much slower cooling occurred until the fission track ages of ~68 ± 2 Ma during the Maastrichtian.

using two-pyroxene thermometry, the restricted stability field of spinel + quartz, and the presence of sillimanite and cordierite. New thermobarometry presented here has been derived from microprobe data in conjunction with petrogenetic grids derived experimentally and the self-consistent thermodynamic dataset of Holland & Powell's (1998) THERMOCALC v2.75. Granulite metabasites containing the assemblage enstatite + diopside + plagioclase + phlogopite, have *P–T* conditions of 864 ± 15 °C and 14.7 ± 2.8 kbar (Fig. 5b). Peak pressures are difficult to estimate in metabasites due to the absence of garnet in all metabasite assemblages from the Bani Hamid granulites. Petrogenetic grids have been used to qualitatively constrain *P–T* conditions of calc-silicates marbles and are consistent with those derived independently for other assemblages. Metabasic quartzites from the Bani Hamid granulites containing the assemblage andradite garnet + diopside + quartz + plagioclase have *P–T* conditions 860 ± 100 °C and 12.9 ± 2.0 kbar. Metasedimentary quartzites containing enstatite + cordierite + spinel + quartz have *P–T* conditions of ~850 °C and 10.5 ± 1.1 kbar (Fig. 5b). These pressures are equivalent to 57–46 km depth beneath an oceanic crust-mantle hanging-wall, a much greater thickness than can be accounted for by the thickness of the ophiolite. The *P–T* conditions of the Bani Hamid granulites therefore suggest metamorphism occurred along a high-temperature subduction zone during initial detachment of the Semail ophiolite. The inferred anticlockwise *P–T–t* paths with peak temperatures at 840 ± 70 °C are consistent with their origin in an oceanic subduction zone with a high temperature geotherm, and the heat supplied from the young, still hot oceanic mantle sequence peridotites.

Figure 5c shows the *P–T–t* path for the high pressure eclogites at As Sifah in the southeastern Oman Mountains (Searle *et al.* 1994) where old, cold continental crust of the thinned leading edge of the Arabian plate was dragged down the subduction zone to approximately 90–100 km and rapidly exhumed along the same zone following an isothermal decompression path up to around 15 km depth. The protolith of these eclogites are thought to be Permian volcanic flows and sills within the shelf carbonate sequence which must also have been subducted to these depths. The eclogites only occur in the southeastern Oman Mountains, but it is possible that much of the leading (northeastern) edge of Arabian continental crust buried off the northeast coast of Oman may also be at eclogite facies grade.

6. Geochronology of the metamorphic sole

Ages from the metamorphic sole rocks in Oman and UAE are summarized in Figure 2 after Hacker, Mosenfelder & Gnos (1996). Ten hornblende samples from Wadi Tayyin gave ages ranging from

94.9 ± 0.5–92.6 ± 0.6 Ma. Six hornblendes from the Sumeini amphibolites gave a slightly older age of 94.9 ± 0.2 Ma. White micas from Wadi Tayyin have a weighted mean age of 92.4 ± 0.2 Ma and those from Sumeini have a similar weighted mean age of 92.7 ± 0.2 Ma (Hacker, Mosenfelder & Gnos, 1996). The age of peak granulite facies metamorphism in Bani Hamid is less well known, however, ^{40}Ar/^{39}Ar and K–Ar hornblende ages of 95.3 ± 0.5 Ma from metabasic granulites overlap with the mean hornblende age of 94.9 ± 0.2 Ma for the amphibolite facies metamorphism in the Asimah area (Gnos & Peters, 1993; Hacker, Mosenfelder & Gnos, 1996). These cooling ages from the metamorphic sole are consistent with their metamorphism (at depths of ~40 km from the pressures) being simultaneous with magmatic crystallization of the ophiolite crustal sequence (Tilton, Hopson & Wright, 1981), consistent with our proposal that subduction zone metamorphism was occurring beneath an active spreading centre and a crystallizing magma chamber at the same time. This is consistent with a supra-subduction arc setting for the origin of the ophiolite and is not consistent with a mid-oceanic ridge setting.

Figure 6 summarizes the geochronological constraints and our tectonic interpretation of events. The age of peak high-pressure eclogite metamorphism remains poorly constrained and several attempts at ^{40}Ar/^{39}Ar dating have been hampered by excess Ar which is inhomogeneously distributed amongst different crystals. However, our sample MS6, which gave the *c.* 20 kbar pressure estimate (Searle *et al.* 1994) gave an ^{40}Ar/^{39}Ar muscovite integrated age and a plateau age of 89.3 ± 1.8 Ma. Further recent attempts at ^{40}Ar/^{39}Ar dating of rocks from As Sifah by B. Hacker (pers. comm.) have revealed interpreted ages of ~92 Ma. Miller *et al.* (1999) also carried out ^{40}Ar/^{39}Ar dating and showed that the deepest high-pressure rocks at lower structural levels in the As Sifah area cooled through the closure temperature for muscovite and phengite (between 350–450 °C) between 131–82 Ma. Mica cooling ages from the low-grade rocks at higher structural levels are 76–70 Ma (Miller *et al.* 1999).

7. Tectonic models

7.a. Mid-Ocean Ridge (MOR) model

Many of the early proponents of a Mid-Ocean Ridge setting for the Semail ophiolite worked in the southeastern Oman Mountains where the upper volcanic sequence (Lasail lavas or V2 volcanics) is missing (Coleman, 1981; Hopson *et al.* 1981; Pallister & Hopson, 1981). Several of the later proponents of the MOR model simply ignore the evidence and facts from the metamorphic sole (Boudier *et al.* 1985, Boudier, Ceuleneer & Nicolas, 1988; Ceuleneer, Nicolas & Boudier, 1988; Nicolas *et al.* 1988, 2000). Three lines of evidence point to the fact that this model cannot be correct.

Firstly, if initial detachment occurred at the spreading centre, then the protolith of amphibolites, which were the first rocks to accrete to the base of the ophiolite, should be similar to the volcanic sequence at the top of the ophiolite on the other side of the spreading centre. Geochemistry of the amphibolites and the composition of other rocks in the metamorphic sole and Haybi complex (ocean island, off-axis alkaline volcanic rocks, Permian and Triassic exotic limestones, etc.) suggest that the protolith of the amphibolites was not the same as the Semail ophiolite volcanic sequence (Searle & Malpas, 1980, 1982). These studies suggest that old (Triassic–Jurassic), cold oceanic crust was subducted beneath the ophiolite and heated up by remnant heat from the mantle peridotites to form the amphibolites. Clearly the protolith of the amphibolites was not the Semail ophiolite lavas, and therefore the model of subduction initiation at the ridge axis can be confidently excluded.

Secondly, thermobarometry of the amphibolites in the metamorphic sole shows that peak conditions reached 760–870 °C and 11–15 kbar (Gnos, 1998; J. S. Cox, unpub. D.Phil. thesis, Univ. Oxford, 2000; this paper), equivalent to 57–46 km depth beneath oceanic crust. These depths are much greater than can be accounted for by the thickness of the ophiolite and suggest that metamorphism must have occurred within a narrow subduction zone setting beneath the ophiolite mantle sequence. There is absolutely no evidence for the subduction zone dipping SW under the continental margin as proposed by Gregory, Gray & Miller (1998) for the southeastern Oman Mountains. It seems inconceivable that a subduction zone at least 90–100 km deep could have been active, dipping SW beneath Oman during the Late Cretaceous without any geological trace of it along the margin, which was a typical stable, fossiliferous, shallow marine, passive continental margin (Glennie *et. al.* 1973, 1974).

Thirdly, geochronology of the ophiolite and the metamorphic sole clearly shows that at ~95 Ma whilst the ophiolite crustal sequence was forming (U–Pb zircon ages from plagiogranites: Tilton *et al.* 1981), metamorphic sole amphibolites were metamorphosed and cooling through the 500 °C isotherm at the same time (^{40}Ar–^{39}Ar ages from hornblendes 95–92 Ma: Gnos & Peters, 1993; Hacker, 1994; Hacker, Mosenfelder & Gnos, 1996). This clearly could not have happened in a Mid-Ocean Ridge setting, but it could easily have occurred in a fore-arc setting, where old, cold basaltic protolith rocks were subducted to > 45 km depth beneath a young, hot peridotite.

7.b. Supra-Subduction Zone (SSZ) model

The model we favour (Fig. 7) involves one continuous Late Cretaceous stage of ophiolite obduction (Lippard,

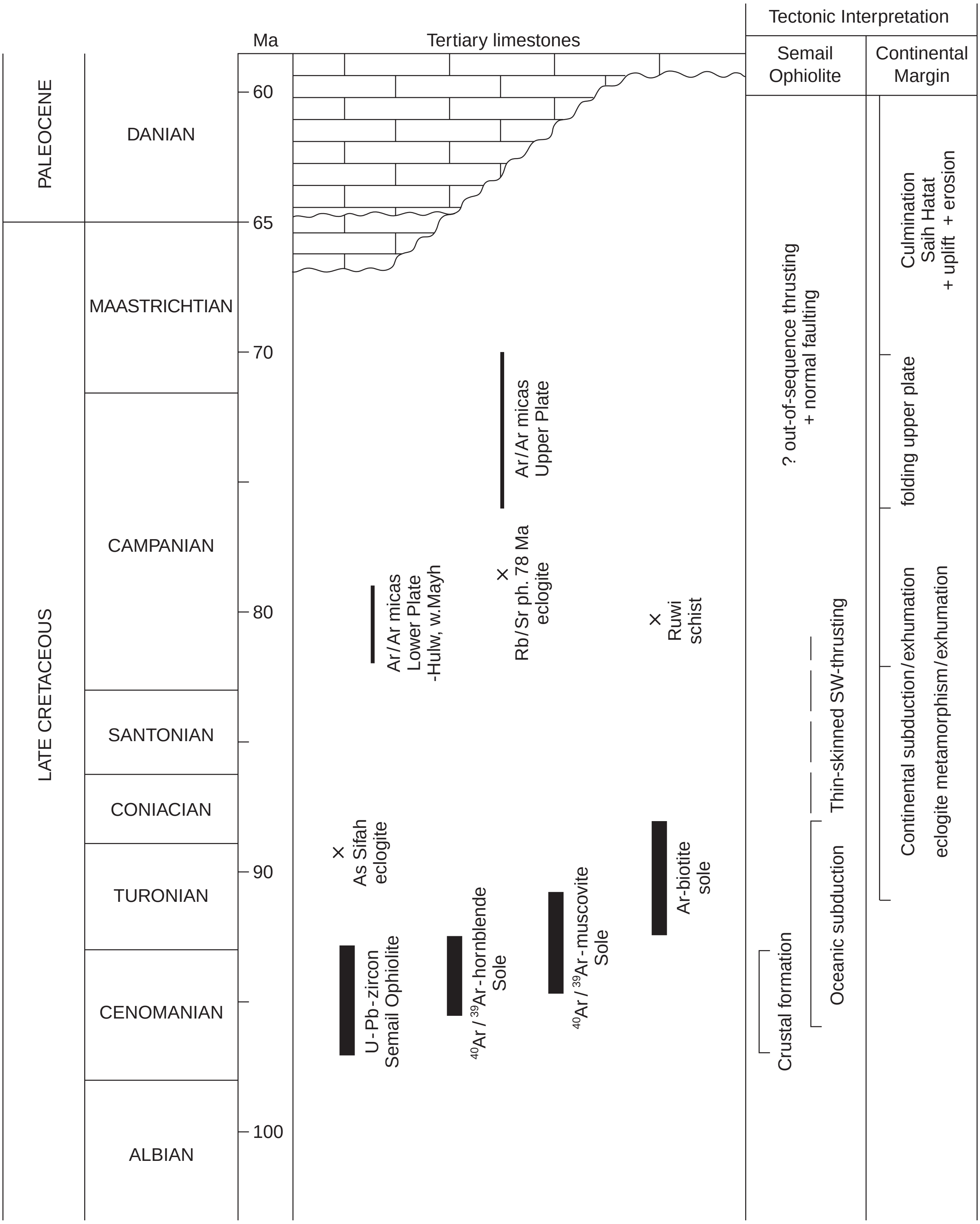
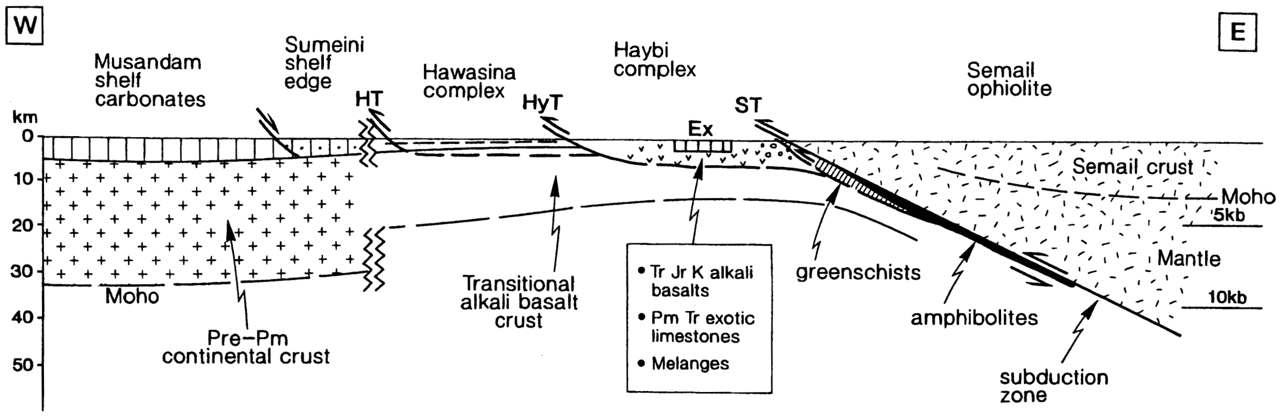


Figure 6. Time chart summarizing all the relevant geochronological data used for interpreting the obduction history of the Oman ophiolite. U–Pb zircon ages from Tilton, Hopson & Wright (1981), ^{40}Ar/^{39}Ar data is from Hacker (1994), Hacker, Mosenfelder & Gnos (1996), Lippard, Shelton & Gass (1986), Searle *et al.* (1994), and Miller *et al.* (1999). Our tectonic interpretation is shown on the right side.

(a) 96 – 90 Ma Cenomanian



(b) 90 – 85 Ma Turonian–Santonian

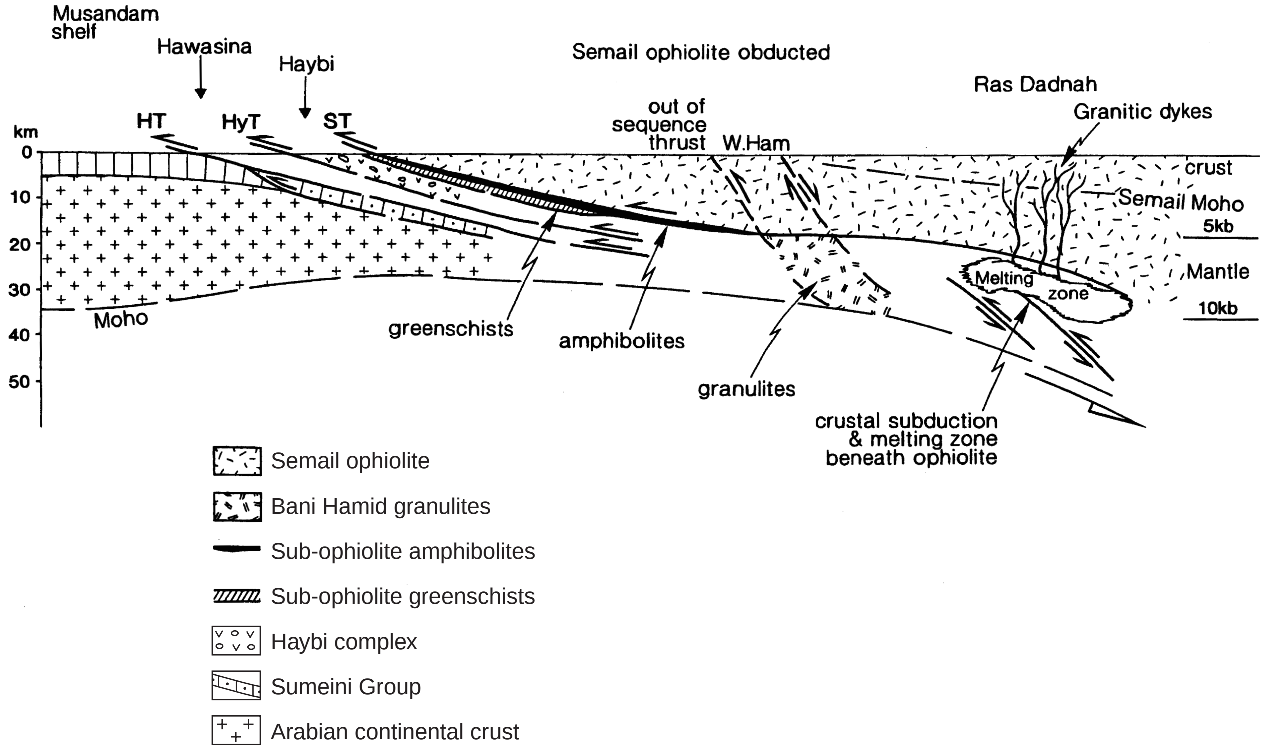


Figure 7. Model for the supra-subduction zone setting of the Oman ophiolite showing the early formation of the granulite, amphibolite and greenschist facies metamorphic sole forming along an E- or NE-dipping Late Cretaceous subduction zone beneath the ophiolite. Later melting of Haybi-type protoliths beneath the eastern part of the ophiolite generated crustal melt granites which intruded up through the Mantle sequence peridotites as dykes and emplaced around the level of the Moho (Cox, Searle & Pedersen, 1999). The final subduction of the leading edge of the Arabian continental crust is not illustrated here but follows the same model as that proposed by Searle *et al.* (1994) for the southeastern Oman Mountains. HT – Hawasina thrust; HyT – Haybi thrust; ST – Semail thrust; Ex – Oman exotic limestones.

Shelton & Gass, 1986; Searle & Malpas, 1980, 1982; Goffé *et al.* 1988; Searle *et al.* 1994; Searle & Cox, 1999) showing the following evolution through time:

(1) Formation of the ophiolite complex in an intra-oceanic Supra-Subduction Zone setting ~97–95 Ma (Pearce *et al.* 1981; Alabaster, Pearce & Malpas, 1982). The discontinuity between the Geotimes V1 and Lasail V2 lavas may represent the timing of initiation of the subduction zone which dipped away from the continental margin towards the northeast.

(2) Obduction of the ophiolite southwestwards above a NE-dipping subduction zone; formation of the granulite (~850 °C and 10.5–14.7 kbar; ~95 Ma), amphibolite (840–870 °C and 11.8–13.9 kbar; 95–93 Ma) and greenschist facies inverted metamorphic sole.

(3) Subduction of the thinned leading edge of the Arabian plate basement led to high-pressure metamorphism of the carpholite, blueschist and eclogite zone rocks (~20–23 kbar; 78–90 km depth: Searle *et al.* 1994).

(4) Exhumation of the high pressure rocks back up the same subduction zone (Turonian–Santonian, early Campanian). Intense deformation and shortening of the shelf carbonates around the northern end of Saih Hatat attests to the choking of the subduction zone by the Arabian continental margin shelf sequence.

(5) Extensional shearing along major post-metamorphic detachments such as the Upper plate–Lower plate discontinuity of Miller, Gray & Gregory (1998) and the major ductile shear zones above the As Sifah eclogites (Searle *et al.* 1994) (Campanian–early Maastrichtian).

In this model the older (pre-95 Ma) ^{40}Ar/^{39}Ar ages of white micas from the As Sifah eclogites (Montigny, Le Mer & Whitechurch, 1988; El-Shazli & Lanphere, 1992; Searle *et al.* 1994; Miller *et al.* 1999) are regarded as unreliable, and probably affected by excess ^{40}Ar. The distinctive high-pressure rocks (carpholite, blueschist and eclogite facies) crop out around the Saih Hatat culmination stretching from the Muscat area south-eastwards to beyond Quriat (Fig. 1; Goffé *et al.* 1988; Searle *et al.* 1994; Gregory, Gray & Miller, 1998). Whereas the sub-ophiolite metamorphism is restricted to a narrow zone along the base of the Semail ophiolite throughout the Oman Mountains, the high-pressure terrain is a regional metamorphism affecting all units from pre-Permian basement up to the Semail ophiolite. The deepest structural levels occur around the village of As Sifah, where eclogite facies rocks record pressures up to ~20 kbar, just below the quartz–coesite boundary and hence verging on Ultra-High Pressure metamorphism (Searle *et al.* 1994).

8. Conclusions

(1) The best estimates of the age of the Semail ophiolite crustal sequence come from U–Pb zircon ages of plagiogranites from which ten samples span 97.3 ± 0.25–93.5 ± 0.25 Ma with a mean age of 94.8 ± 0.1 Ma (Tilton, Hopson & Wright, 1981). Radiolaria from cherts within the Geotimes (V1) lavas are Cenomanian in age and foraminifera from sedimentary rocks interbanded within the Lasail (V2) arc tholeiite lavas are Cenomanian–Turonian in age (Tippit, Pessagno & Smewing, 1981; Beurrier *et al.* 1987).

(2) The best time constraints on amphibolite and granulite facies metamorphism in the metamorphic sole are 94.9 ± 0.5–92.6 ± 0.6 Ma, from ^{40}Ar/^{39}Ar dating of hornblendes. These ages are identical to the age of crystallization of the ophiolite crustal sequence. White mica cooling ages are slightly younger at 92.7 ± 0.2 Ma (Gnos & Peters, 1993; Hacker, 1994; Hacker, Mosenfelder & Gnos, 1996).

(3) New thermobarometry of the garnet + clinopyroxene amphibolites in the metamorphic sole from Sumeini, Wadi Tayyin and Asimah confirm peak metamorphic *P–T* conditions of 870–840 °C and 13.9–11.8 kbar. The heat source was the mantle sequence peridotites which must have been at temperatures at, or around, 1100–1500 °C.

(4) Pressures recorded by the amphibolites are equivalent to depths of 54–46 km depth, much deeper than can be explained by the thickness of the overlying ophiolite (a 15–20 km thick ophiolite would record pressures of 3.8–5.1 kbar along the base). Metamorphism therefore must have occurred along a subduction zone at least 38 km beneath the Moho.

(5) The protolith of the metamorphic sole amphibolites are E- and N-type MORB with similar trace element profiles to the tholeiitic components of the Triassic–Jurassic Haybi volcanic rocks (Searle *et al.* 1980) and the crust of the late Jurassic (145–150 Ma: Peters *et al.* 1996) Masirah ophiolite. Lower grade metamorphic rocks in the sole are clearly the metamorphosed equivalents of the underlying Triassic exotic limestones, alkali basalts and alkaline ultramafic sills (Searle *et al.* 1980; Searle, 1984), Triassic–Jurassic Mn-rich sediments of the Haybi complex. None of the metamorphic sole rocks can be correlated with the Semail ophiolite crustal sequence and therefore detachment could not have occurred at the ridge axis.

(6) Geochronology of the ophiolite crustal sequence and the amphibolite sole rocks suggests that the amphibolites formed at depths greater than 46 km beneath the ophiolite at the same time (~95 Ma). This could only happen in a supra-subduction zone setting, and not at a normal mid-ocean ridge.

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