The Oman–UAE ophiolite is the largest piece of oceanic crust exposed on land, yet debate continues about its origin. It has been variously considered as an ideal analogue for a fast-spreading mid-ocean ridge and as a typical suprasubduction zone ophiolite. A resolution to this conundrum comes from the recognition of at least two different phases of magmatism, with the second phase being most voluminous in the northern blocks of the ophiolite. The first phase was formed at an oceanic spreading centre; petrological and geochemical evidence clearly shows that the second phase was formed above a subduction zone.

**INTRODUCTION**

The rugged Al Hajar Mountains of the United Arab Emirates (UAE) and north-eastern Oman are formed by the world’s largest, best-exposed ophiolite (FIG. 1). The Oman–UAE ophiolite (also known as the Semail ophiolite) forms part of the chain of Tethyan ophiolites, which extends across Europe and Asia and preserves the remnants of the late Palaeozoic to Mesozoic Palaeo- and Neo-Tethyan oceans. The Oman–UAE ophiolite extends over a distance of more than 500 km from its northern tip at Dibba in the UAE to the eastern coast of Oman. It comprises 12 individual thrust-bounded blocks, many of which are separated by first-order fault zones, and includes all the main components of a classic ophiolite (as defined by Penrose Conference participants in 1972; Dilek and Furnes 2014 this issue) in a sequence up to 20 km thick (Lippard et al. 1986).

The Oman–UAE ophiolite was overthrust (obducted) westwards onto the eastern margin of the Arabian Shield during the late Cretaceous. The continental margin comprised Precambrian basement rocks overlain by up to 4 km of Palaeozoic to Mesozoic (Tethyan) platform carbonates and deformed deeper-water volcanosedimentary units (Lippard et al. 1986). Obduction resulted in loading of the eastern edge of the Arabian Plate and the formation of a foreland basin. This basin was infilled by late Cretaceous to Palaeogene sediments, and these overlie the western margin of the ophiolite.

The Oman–UAE ophiolite has been studied in much detail over the last forty years and has been described in a number of special volumes (Coleman 1981; Lippard et al. 1986; Boudier and Juteau 2000; Styles et al. 2006). Early work interpreted it as a classic ophiolite, with a mantle suite comprising serpentinised peridotites overlain by a crustal sequence of layered gabbro, high-level gabbro, a sheeted dyke complex, and pillow lavas (FIG. 2A) (Lippard et al. 1986). Consequently, it was considered as a fine example of an ophiolite formed by sea-floor spreading at a mid-ocean ridge (MOR) (Coleman 1981) and has been proposed as an ideal analogue for oceanic crust, particularly crust that formed at a fast-spreading ridge (Nicolas et al. 1994).

However, work in the northern blocks of the ophiolite (Lippard et al. 1986; Styles et al. 2006) has led to the recognition of much greater complexity, notably the presence of large volumes of younger magmatic rocks which cross-cut, and clearly post-date, the standard ophiolite succession and which have island arc–type geochemical characteristics. Such characteristics have also been recognised in the earlier, spreading centre magmatic suite, and this led some authors to suggest that the Oman–UAE ophiolite formed in a suprasubduction zone (SSZ) setting (Alabaster et al. 1982). This different perspective has led to continuing debate over the geodynamic setting of the ophiolite. Some authors downplay the significance of the later magmatism and continue to interpret the Oman–UAE ophiolite as having formed at a fast-spreading mid-ocean ridge (Nicolas and Boudier 2011).

Over the past decade, our work has focused on the less well-known northern section of the ophiolite in the UAE. We have systematically mapped the two northernmost blocks in detail and we have studied their petrography, mineralogy, geochemistry and geochronology (Styles et al. 2006; Goodenough et al. 2010). The northern part of the ophiolite contains voluminous later magmatic phases, making it a crucial area for deciphering the origin and evolution of the Neo-Tethyan oceanic crust. This paper reviews the findings from our work in the UAE and considers what they tell us about the history of the Oman–UAE ophiolite as a whole.

**MAGMATIC HISTORY IN THE NORTHERN BLOCKS OF THE OMAN–UAE OPHIOLITE**

The two most northerly segments of the ophiolite, the Khor Fakkhan and Aswad blocks, lie within the UAE (FIG. 1). Easy access and excellent exposure in three dimensions have allowed detailed study of the earlier, sea-floor spreading–related magmatism, which we term Phase 1, and the relationships and internal features of widespread cross-cutting intrusions, which are collectively described as
Phase 2 magmatism. These respectively correlate with the V1 and V2 episodes recognised in the volcanic succession further south in Oman (Alabaster et al. 1982; Ernewein et al. 1988). Some of the key features of the two phases are described in Table 1.

The Khor Fakkan and Aswad blocks each contain large volumes of mantle rocks, made up of variably serpentinitised harzburgite and dunite (Fig. 2a). The dunite occurs as networks of veins up to about 1 m wide within the harzburgite; these veins represent melt channels within the mantle that were exploited by both Phase 1 and Phase 2 magmas (Kelemen et al. 1995). The mantle rocks pass upwards into the Moho Transition Zone (MTZ), a region of gradational change between the mantle and the crust (Boudier and Nicolas 1995). It typically consists of massive dunite at the base, overlain by a ‘Mixed Unit’ comprising variable quantities of dunite, wehrlite, pyroxenite, and gabbro (Benn et al. 1988; Goodenough et al. 2010). In the UAE, the MTZ is a major part of the sequence, being locally over 1000 m thick (Fig. 2a). Wehrlites and pyroxenites are abundant, intruding and clearly post-dating Phase 1 crustal gabbros; these ultramafic intrusions are consequently ascribed to Phase 2 magmatism.

The MTZ is overlain by a Phase 1 crustal sequence, in which layered gabbros pass upwards into high-level gabbros, a sheeted dyke complex, and pillow lavas. The layered gabbros vary in thickness from ~500 m to over 1000 m, and are characterised by centimetre- to metre-scale rhythmic igneous layering. They grade upwards into massive high-level gabbros that range from strongly foliated to ‘varitextured’ (showing significant grain size and textural heterogeneity on the centimetre to metre scale). Mafic dykes become more abundant in the upper parts of the high-level gabbro, merging into a classic sheeted dyke complex, which fed the overlying pillow lavas. However, the key feature highlighted in this paper is the presence of the voluminous Phase 2 intrusive suite. In the Aswad block, these later intrusions include wehrlite and pyroxenite in the MTZ and the lower part of the crust, together with a complex network of gabbro, microgabbro, diorite, basalt and tonalite intrusions that cut across the entire Phase 1 crustal suite and locally intrude the mantle rocks (Fig. 2a). Together, Phase 2 intrusions make up around half of all crustal exposure in the UAE, a far higher proportion than has been recognised elsewhere (Goodenough et al. 2010). The Phase 2 gabbros and diorites are very heterogeneous, but in many areas they are characterised by a generally finer grain size and a more felsic source composition than the Phase 1 gabbros, even where they cut across the MTZ and mantle rocks. Pegmatitic gabbro and diorite are also common within Phase 2, and they are typically associated with tonalites and hybrid intrusions that show magma mingling textures. The Phase 2 intrusions take the form of dykes, sills and irregular bodies up to several kilometres across (Fig. 3). They are commonly associated with syn-intrusion faults and ductile shear zones, suggesting that their distribution and emplacement were structurally controlled.

The Phase 1 and Phase 2 lithologies show some clear mineralogical and textural differences that indicate contrasting environments of formation. The Phase 1 layered and high-level gabbros are mineralogically similar to each other, with early formed euhedral olivine and plagioclase laths, the latter having a parallel orientation in layered gabbro. Clinopyroxene may also form euhedral crystals, but commonly occurs as large grains poikilitically enclosing olivine and plagioclase. These textures indicate a crystallisation sequence of olivine–plagioclase–clinopyroxene, a sequence that is typically found in near-anhydrous magmas and is commonly seen in mid-ocean ridge basalts (MORBs). Hornblende is found locally in these gabbros. In contrast, many of the Phase 2 rock types show evidence of formation from different magmas. Wehrlites in the MTZ and the lower parts of the crustal section are typically poikilitic, with clinopyroxene forming large plates up to several centimetres across enclosing rounded crystals of olivine. Plagioclase, where present, is generally interstitial. These features indicate an olivine–clinopyroxene–plagioclase crystallisation sequence, indicative of hydrous magmas containing around 5 wt% water (Koepke et al. 2009). The more-evolved intrusions emplaced into the crustal section are very variable in composition, ranging from gabbros to tonalites. Some gabbros are similar in mineralogy to Phase 1 gabbros, but primary amphibole and/or orthopyroxene are present in many areas whilst olivine is rare, again indicating a more hydrous magma. The gabbros grade into more felsic rocks with increasing amounts of quartz and plagioclase. It is notable that, in the UAE, all the felsic lithologies, such as tonalites, belong to Phase 2 magmatism.

The gabbros and other coarse-grained rocks of the crustal section have textures that indicate a cumulate origin, and their bulk geochemistry has been affected by those cumulative processes. However, the compositions of volcanic rocks and dykes are closer to those of primary magma, and so their bulk-rock geochemistry can be used to interpret source composition and tectonic setting. In the UAE, Phase 1 dykes and pillow basalts have MORB-like geochemistry, but with small negative Nb and Ta anomalies (Fig. 4) that could point towards formation in a marginal basin setting. In contrast, Phase 2 dykes have features, such as significant negative Nb and Ta anomalies and light rare earth element depletion (Fig. 4), that are characteristic of magmas formed in a suprasubduction zone (SSZ) setting (Goodenough et al. 2010). The geochemistry of chrome spinels in the mantle harzburgites and dunites can also be used to distinguish between MOR and SSZ settings. The analysis of spinels from
the Oman–UAE ophiolite has provided evidence for spatial and temporal changes from an anhydrous MOR setting to a hydrous SSZ setting (Python et al. 2008; Rollinson and Adetunji 2013).

Based on the evidence from the UAE discussed above, we propose that Phase 1 magmatism occurred at a spreading centre, which may have been at a mid-ocean ridge but was more likely in a marginal basin above a newly initiated subduction zone (MacLeod et al. 2013). Phase 2 magmas were hydrous and record the initial stages of arc magmatism. Now, we turn our attention further south to Oman and investigate whether this model holds true for the whole Oman–UAE ophiolite.

**IS THE MAGMATIC HISTORY CONSISTENT ALONG THE LENGTH OF THE OPHIOLITE?**

The structural blocks of the Oman–UAE ophiolite can be divided into three main groups, with the blocks within each group showing similar characteristics but also differences from the other groups. The northern blocks include Khor Fakkan and Aswad in the UAE, as well as the Fizh and Salahi blocks in northern Oman; the central blocks around Jebel Akhdar include the Sarami, Haylayn and Rustaq blocks; and the south-eastern blocks, to the east of the Semail Gap, are Semail and Wadi Tayin (FIG. 1).

The proportion of Phase 2 magmatic rocks varies significantly along the length of the ophiolite, although in some areas Phase 2 gabbros may not have been recognised. The two gabbro phases commonly look similar at the outcrop scale; and mapping of the intrusive relations on a wider scale is needed to clearly identify the second-phase gabbros. The distribution of Phase 2 indicated on the map (FIG. 1) is based on comparison of our own maps of the UAE with the national geological maps of Oman. It is clear from these maps that there is a close correlation between Phase 2 magmatism (as described above) and the Late Magmatic Units mapped in Oman, both of which are ascribed to formation from hydrous magmas. The Late Magmatic Units are thus considered here to be part of Phase 2, and are shown as such on FIGURE 1. Whilst there is some debate about the origin of these later magmas (Koga et al. 2003), they are typically hydrous in nature, and we consider it likely that they are related to the second magmatic phase throughout the ophiolite. Their origin is worthy of further investigation.

Large amounts of Phase 2 magma are found in the MTZ, which shows notable lateral thickness variations (Boudier and Nicolas 1995). In the north, the MTZ is locally over 1000 m in thickness, but in the central blocks it is typically around 10 m thick (Benn et al. 1988), although some discrete large masses of wehrlite, locally forming 20–40% of the plutonic section, have been identified (Juteau et al. 1988). At the south-eastern end of the ophiolite, in the Maqsad area of the Semail block, an area of thick MTZ (500–750 m) is considered to have formed at a zone of mantle upwelling and is known as the Maqsad Diapir. The current interpretation is that this sequence formed beneath a mid-ocean ridge (Boudier and Nicolas 1995). Within the Maqsad Diapir, the MTZ is largely made up of dunite with gabbro lenses, although large areas of wehrlite are present around the edges of the diapir and are suggestive of Phase 2 magmatism (Clénet et al. 2010). The absence of wehrlite within the diapir itself provides evidence for it being formed during the Phase 1 magmatic episode.

Late intrusive complexes have been identified in all the northern and central blocks of the ophiolite, although they are less voluminous in Oman than in the UAE (Lippard et al. 1986; Adachi and Miyashita 2003). These intrusions include wehrlite, gabbro, diorite and tonalite, are locally orthopyroxene-bearing, and are commonly associated with faults; we equate them to the Phase 2 plutonic rocks in the UAE. Study of the mineral chemistry in some of these Phase 2 intrusive complexes has shown that the later gabbroic intrusions typically have more calcic plagioclase at any given Mg# [i.e. atomic Mg/(Mg + Fe)] of olivine and clinopyroxene, whereas the early crustal gabbros have more sodic plagioclase (Yamasaki et al. 2006). Similarly, the clinopyroxenes of Phase 2 magmas are lower in TiO2, Na2O and Al2O3 (Adachi and Miyashita 2003; Goodenough et al. 2010). All these features are compatible with crystallisation from hydrous magmas in a SSZ setting (Yamasaki et al. 2006).

The central and northern blocks of the ophiolite have a thick sequence of extrusive volcanic rocks (basalts and andesites) containing several distinct units that can be correlated over a considerable distance (Alabaster et al. 1982). The basal Geotimes unit, also termed V1 (Ernewein et al. 1988), has the geochemical characteristics of lavas formed at a spreading centre, potentially in a marginal basin setting (Alabaster et al. 1982). This unit is overlain by the Lasail, Alley and Cpx-phyric units (collectively termed V2), which include boninitic rocks and are geochemically akin to island arc lavas (Alabaster et al. 1982; Lippard et al. 1986; Ishikawa et al. 2002), although some authors have suggested that parts of the V2 sequence formed by second-stage melting of the spreading centre mantle source (Ernewein et al. 1988; Godard et al. 2006). As with Phase 2 gabbros, clinopyroxenes in the Lasail, Alley and Cpx-phyric units are lower in TiO2 and Na2O than in the Geotimes unit, and they are thus considered to be the extrusive equivalents of Phase 2 intrusions. The uppermost Salahi

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**FIGURE 2** Schematic cross-sections through the Oman–UAE ophiolite. (A) Early view of the ophiolite structure, after Boudier and Nicolas (1985). (B) Ophiolite structure based on mapping in the UAE (Styles et al. 2006). MTZ = Moho Transition Zone.
unit post-dates the main episodes of ocean crust formation and has a within-plate geochemistry; it is not discussed further here.

It is clear that Phase 2 magmatism is an important part of all the northern and central blocks of the Oman–UAE ophiolite, although there appears to be a general southwards decrease in volume. By contrast, in the south-eastern blocks, Phase 2 magmatism is much less abundant. No large, late, intrusive bodies have been described, although areas of wehrlite and pyroxenite have been mapped (FIG. 1). The volcanic succession in the south-eastern blocks is thin and poorly preserved, and Phase 2 volcanic units have not been identified there. Furthermore, a study of chrome spinels in mantle dykes along the length of the ophiolite has indicated clear spatial variations in magma type; the SSZ (Cr-rich) component decreases from the north to the south-east, and MORB-type compositions are particularly common in a zone centred on the Maqsad Diapir (Python et al. 2008). The evidence indicates that the south-eastern blocks have not been affected by Phase 2 magmatism to the same extent as the central and northern blocks.

**TIMING OF PHASE 2 MAGMATISM**

Considering the wealth of research that has been carried out on the Oman–UAE ophiolite, few high-precision radiometric ages had been obtained until very recently. The general age of the ophiolite was originally established by U–Pb dating of zircon grains in ‘plagiogranites’, the most evolved magmas and hence those with the highest zircon contents. A number of samples from along the length of the
Ophiolite gave ages ranging from around 93.5 to 97.9 Ma, which were considered at the time to represent the time of formation of the ophiolite crust (Tilton et al. 1981). More recently, U–Pb dating of zircon grains from several tonalite and trondhjemite intrusions along the length of the ophiolite has been carried out using modern methods (ID-TIMS), producing more precise results (Warren et al. 2005; Goodenough et al. 2010; Rioux et al. 2012, 2013). All these intrusions were dated at between 94 and 96.1 Ma, and notably, the majority of tonalites and trondhjemites along the length of the ophiolite fall within a narrow age range of 95.3 ± 0.5 Ma. Since the tonalites and trondhjemites typically represent the latest part of the ophiolitic crust and are considered to be part of Phase 2, this age constrains the last stages of crustal formation. Distinctly earlier tonalite and trondhjemite ages (96.1–95.8 Ma) came from the southernmost Wadi Tayin block, which has little Phase 2 magmatism, and these ages are associated with Phase 1 (Rioux et al. 2012).

Recently published U–Pb ages for gabbros also cover much of the length of the ophiolite. Phase 2 gabbros in the southernmost blocks give ages of 96.40 ± 0.29 Ma (the Khor Fakkhan block) and 95.74 ± 0.32 Ma (the Aswad block) (Goodenough et al. 2010). Gabbro ages in the central blocks are from ~96.2 to 95.4 Ma (Rioux et al. 2013); these ages are considered to represent Phase 1 magmatism, but they overlap with the ages for Phase 2 magmatism in the northern blocks. In the southern Wadi Tayin and Semail blocks, several samples of Phase 1 gabbro have similar ages in the range 96.4–95.5 Ma (Rioux et al. 2012, 2013). Ar–Ar ages have also been obtained from hornblende-bearing gabbros and tonalites in Oman, again likely to be part of the Phase 2 magmatism, and these rocks range in age from 93.6 ± 0.5 Ma to 96.3 ± 1.3 Ma (Hacker et al. 1996). Overall, the crust of the Oman–UAE ophiolite was largely formed in the 96.4 to 95 Ma period. The transition from Phase 1 to Phase 2 magmatism occurred during this time, and may have begun first in the northern blocks of the ophiolite.

A number of workers have discussed the timing of ophiolite obduction. Both Ar–Ar and U–Pb dating of rocks in the metamorphic sole below the ophiolite indicate an early, rapid phase of intraoceanic thrusting at ~95–93 Ma (Hacker et al. 1996; Warren et al. 2005; Styles et al. 2006; Rioux et al. 2013). These ages overlap with the latter parts of Phase 2 magmatism.

The timing of subsequent translation onto the continental crust remains controversial. Metamorphism and melting in continental rocks in the UAE are considered to be associated with ophiolite emplacement onto the continental margin and have been dated at ~93–92 Ma (Styles et al. 2006). However, in the Saih Hatat area at the southeastern end of the ophiolite, eclogites are thought to have formed during subduction of continental crust associated with overthrusting of the ophiolite. Zircon grains in these rocks have been dated at ~82–79 Ma (Warren et al. 2005). These ages indicate that subduction continued along the southern Oman part of the Arabian margin long after it ceased further north in the UAE. This might mean that the northern and central blocks of the Oman–UAE ophiolite were emplaced onto the continental margin significantly earlier than the south-eastern blocks.

**ORIGIN OF PHASE 2 MAGMATISM**

The northern and central blocks of the Oman–UAE ophiolite are characterised by spreading centre–type Phase 1 magmatism overprinted by voluminous Phase 2 magmatism (Table 1). The amount of Phase 2 magmatism decreases southwards along the ophiolite. Petrological criteria indicate that the Phase 2 magmas were more hydrous than the basaltic, MORB-like magmas of Phase 1. However, the source of the hydrous fluids in these magmas continues to be debated.

A number of geochemical criteria – including the whole-rock geochemistry of volcanic rocks and dykes, and the chemistry of clinopyroxenes in gabbros and chrome spinels in the mantle peridotites – indicate a suprasubduction zone origin for the Phase 2 magmas. Despite this, some authors argue for the formation of both magmatic phases at a mid-ocean ridge (or possibly a spreading ridge in a large marginal basin). Whilst it is generally agreed that Phase 2 magmas were hydrous, it has been suggested that this could be due to seawater penetrating into a mid-ocean ridge magma chamber from above, rather than to fluids released from a subducting slab below (Boudier et al. 2000), with the geochemistry of Phase 2 magmas explained by melting of an already depleted mantle (Goddard et al. 2006). This model does not easily explain the large volumes of Phase 2 magmatic rocks in the northern blocks, nor why their equivalents are not found at modern mid-ocean ridges. In addition, the evidence from chrome spinels indicates that the hydrous magmas were derived from beneath the Moho Transition Zone.

We conclude, therefore, that Phase 1 crust in the Oman–UAE ophiolite was formed at a spreading centre, probably in a marginal basin above an infant subduction zone (MacLeod et al. 2013). Phase 2 magmas were emplaced as that subduction zone developed (Fig. 5), and the influence of fluids from the subducting slab increased both with time and towards the north within the ophiolite. Compression above the subduction zone led to intraoceanic thrusting at the time of Phase 2 magmatism, with magmas being emplaced into the crust along shear zones. When these suprasubduction zone magmas were being emplaced in the northern part of the ophiolite, the southern part was continuing to form at a spreading centre.

**Table 1**

<table>
<thead>
<tr>
<th>Phase 1 magmatism</th>
<th>Phase 2 magmatism</th>
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</thead>
<tbody>
<tr>
<td>Classic ophiolite sequence with a clear ‘stratigraphy’</td>
<td>Cross-cutting magmatism, forming irregular, heterogeneous igneous bodies on all scales</td>
</tr>
<tr>
<td>Cross-cut by faults and shear zones</td>
<td>Associated with faults and shear zones</td>
</tr>
<tr>
<td>Harzburgite, dunite, layered to isotropic gabbro, microgabbro, basalt</td>
<td>Dunite, wothrite, clinopyroxene, very heterogeneous gabbro, tonalite and trondhjemite, mafic–felsic mingled magmas</td>
</tr>
<tr>
<td>Mineralogy dominated by plagioclase, clinopyroxene and olivine</td>
<td>Mineralogy dominated by plagioclase and clinopyroxene, with variable amounts of olivine, orthopyroxene, hornblende and quartz</td>
</tr>
<tr>
<td>Olivine–plagioclase–clinopyroxene crystallisation sequence (anhydrous magmas)</td>
<td>Olivine–clinopyroxene–plagioclase crystallisation sequence (hydrous magmas)</td>
</tr>
<tr>
<td>MORB-like magma geochemistry</td>
<td>SSZ-type magma geochemistry with depletion in Nb, Ta and light rare earth elements</td>
</tr>
<tr>
<td>MORB signatures in associated mantle spinels</td>
<td>SSZ signatures in associated mantle spinels</td>
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ACKNOWLEDGMENTS

A large number of papers have been written about the Oman–UAE ophiolite, but because of space constraints, we refer only to a small selection of them here; we therefore acknowledge the work of many authors beyond those mentioned in the reference list. Marguerite Godard, Harald Furnes and Sumio Miyashita are thanked for their constructive comments on an earlier version. Yildirim Dilek and John Valley are thanked for their editorial handling. This paper is published with the permission of the Executive Director of the British Geological Survey.

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