Ophiolite in the Oman: The Open University Project

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Some of the most important work on ophiolites in recent years has been carried out by international research teams studying Late Cretaceous oceanic crust exposed in the Oman. This review summarizes the development and scientific results of one such project led by the Open University in England. These studies provide a foundation for current research in the Oman largely directed to the search for mineral deposits, hydrocarbons and groundwater. (Ed)

Introduction

For almost fifty years the term "ophiolite" was used and abused until, under the unifying paradigm of plate tectonics, participants in a Penrose Conference 13 years ago redefined the term as an association of mafic and ultra-mafic igneous rocks occurring in a specific stratigraphic order (see box below). Although any generic significance was specifically excluded from this definition, over the following decade it was increasingly accepted that ophiolites, so defined, represent fragments of oceanic lithosphere formed at fossil constructive margins. On being obducted rather than subducted, such fragments were commonly intensely deformed by the tectonic processes that emplaced them on continental or island arc margins.

Relatively undeformed ophiolites are rare, and it is unfortunate that until the mid-1970s about the largest, best exposed and least deformed of them in the mountains of northern Oman, was, because of its seclusion in a geographically remote and politically changeable region, only accessible to Shell Oil Company geologists attached to the Petroleum Development Organization (PDO) of the Oman Government.

Following the nineteenth century studies, largely by officers of the Indian Geological Survey, and prior to the present cycle of university-based research, most of our information on the Oman ophiolite came from these company geologists. In a major and remarkably prescient paper published in 1928, Lees identified the Semail Igneous Series, now termed the Semail ophiolite. He proposed that this formed a large thrust sheet, the Semail Nappe, composed of serpentinite, gabbro, diorite and basic lavas. Later workers disputed the allochthonous nature of the igneous rocks, but Lees' interpretation was fully substantiated by the detailed study in the late 1960s by Glennie and his Shell Oil Company colleagues (Glennie et al., 1974). This work included two 1:500,000 coloured geological maps and has been the basis of all subsequent work.

Although primarily concerned with the sedimentary rocks, one member of the Glennie team, B.M. Reinhardt (1969), was the first to describe it in modern terms as an ophiolite complex. He recognized that the basal serpentinite unit is mainly harzburgitic with a high temperature mineralogy and tectonic fabric, and that the peridotites pass upwards through gabbros and diabase dikes into spilitic pillow lavas, which he regarded as having been formed at an axial zone of an

oceanic ridge. Palaeontological dating of intra-lava pelagic sediments showed the ophiolite to be of Upper Cretaceous (Cenomanian-Coniacian) age.

Development of the Project

In 1970 the Oman Government began to welcome overseas scientists. The first sign of this change was the invitation to two U.S. Geological Survey geologists (R.G. Coleman and E.H. Bailey) to visit the Sultanate and evaluate the mineralogical potential of the Oman mountains. Coleman and Bailey specifically recommended that the Oman Government should encourage the investigation of the ophiolite by visiting scientists. As a result, in 1975 a group from the Open University (OU, Great Britain) began studies continuing to 1981 based on regional mapping of the northern part of the ophiolite (Fig. 1). Meanwhile, in 1976 a combined USGS-University of California (UoC) team began the detailed study of a 25 km wide N-S strip across the southern part of the ophiolite from Muscat.

In 1975 the first OU geologists visited Oman to investigate the possibility of working there. It took only a few days to realise that the Semail Nappe is indeed a magnificent

"Ophiolite refers to a distinctive assemblage of mafic to ultramafic rocks. It should not be used as a rock name or as a lithologic unit in mapping. In a completely developed ophiolite the rock types occur in the following sequence, starting from the bottom and working up:

- 1) Ultramafic complex, consisting of variable proportion of harzburgite, lherzolite, and dunite, usually with a metamorphic tectonite fabric (more or less serpentinized);
- 2) Gabbroic complex, ordinarily with cumulus textures commonly containing cumulus peridotites and pyroxenites and usually less deformed than the ultramafic complex;
- 3) Mafic sheeted dike complex;
- 4) Mafic volcanic complex, commonly pillowed.

Associated rock types may include (i) an overlying sedimentary section typically including ribbon cherts, thin shale interbeds, and minor limestones; (ii) podiform bodies of chromite generally associated with dunite; and (iii) sodic felsic intrusive rocks.

Faulted contacts between mappable units are common. Whole sections may be missing. An ophiolite may be incomplete, dismembered, or metamorphosed ophiolite. Although ophiolite generally is interpreted to be oceanic crust and upper mantle, the use of the term should be independent of its supposed origin."

- Conference Participants, 1972

Figure 1: Major tectonostratigraphic divisions of the Oman Mountains. Research areas of Open University and USGS-University of California groups outlined.

ophiolite, similar in many respects to the then better known Troodos massif of Cyprus. All present were convinced that it was a research area of the highest potential. It was envisaged that the area would be used as a training ground for Saudi, Omani and British graduate students who would work under the supervision of Dr. I. El Boushi, then Geological Advisor to the Sultan of Oman, and academic staff from OU and King Abdulaziz University (KAU) in Saudi Arabia. Geological maps on the scale of 1:100,000 would be produced, under an informal agreement with no contractual obligations on any of the parties.

A grant of £10,000 from the Royal Society of London paved the way for a detailed feasibility study of the ophiolite in 1976 by J.D. Smewing, A.D. Lewis, K.O. Simonian and D.T. Aldiss. This fully confirmed that high quality geological studies could be made in this well exposed and relatively undeformed terrain. When it became likely that no KAU personnel would be further involved, Dr. El Boushi agreed that the OU group should proceed alone. Fortunately, after the project was identified by the OECD as being most appropriate scientific research in a developing country, financial support amounting to some £110,000 was obtained from the U.K. Ministry of Overseas Development. These funds provided four post-graduate studentships, as well as

travel and subsistence costs. Together with additional finance from the National Environment Research Council and the Open University, the project continued until 1981 when field studies were concluded. The follow-up work is now nearing completion.

To illustrate the way the work was organized, Table 1 shows the persons involved in the project and the periods over which they were associated with the project. Allowing for other activities particularly by the academic staff and associated scientists, the time spent on the project realistically adds up to just over 48 man-years.

The project was based in the coastal town of Sohar, some 200 km NW of the capital, Muscat (Fig.1). The group had four Land Rovers, and field work was done either individually or in pairs in 5-15 day spells from "fly-camps" in the mountains. Once or twice a year as many project personnel as possible would combine with the USGS-UoC and PDO geologists to visit localities of special interest.

Access to the mountains was primarily along wadis as far as motor vehicles could be driven. Traverses were then made on foot into the adjacent hills. Several parties made continuous traverses from west to east across the

Figure 2: Characteristic rugged landscape in harzburgites of the Mantle Sequence. Far peak is about 10 km distant.

Persons directly associated with the OU Oman ophiolite project.

	75	76	77	78	79	80	81	82	83	84	85
ACADEMIC STAFF											
I.G. Gass											
J.A. Pearce											
J.A. Fleet											
R.M. Shackleton											
RESEARCH FELLOWS											
J.D. Smewing (OU)											
K.O. Simonian (OU)											
A.D. Lewis (OU)											
S.J. Lippard (OU)											
C.R. Neary (BSGS: chromites)											
D.I. Mallick (BSGS: remote sensing)											
R.B. Evans (BSGS: geophysics)											
RESEARCH STUDENTS											
D.T. Aldiss											
N.A. Brown											
M. Graham											
M.P. Searle											
T. Alabaster											
A.W. Shelton											
D.A. Rothery											
P. Browning											
G. Stanger											
S. Roberts											
I.D. Bartholomew											
ASSOCIATED SCIENTISTS											
N.I. Christensen (Seattle)											
J. Malpas (Memorial)											
A.H.F. Robertson (Edinburgh)											
A.G. Smith (Cambridge)											
N.H. Woodcock											
D. Elliot (John's Hopkins)											
P. Tippitt (Texas)											

basement. The overlying allochthonous units are a complex sequence of thrust slices of Tethyan facies rocks comprising nappes of slope and basin facies sediments, deep water sediments of Triassic to mid-Cretaceous age (the Hawasina series), Triassic volcanics, exotic limestones and olistostromes of the Haybi Complex and the Semail Nappe. These allochthonous units were emplaced in Campanian and are overlain unconformably by neo-autochthonous sediments of Maastrichtian to Recent age. As a result of Miocene folding, tectonic windows of the autochthonous and allochthonous sediments occur along the axis of the mountains in the Hawasina Window and Jebel Akhdar Range (Fig. 1).

In Figure 3, anticlinal structures in the Maastrichtian-Tertiary limestones can be seen on the western desert margins of the mountains. The darkest outcrops are principally mantle sequence rocks of the Semail

Figure 3: A LANDSAT multi-spectral image of part of the northern Oman mountains approximately centred on Sohar. The scene is approximately 180 km across, the lower margin corresponding to lat. 23°30'N.

mountains. Although the summer months are uncomfortably hot, the winter months (November to April) are climatically agreeable even for strenuous field work, the one major problem being occasional heavy rains that flood the wadis that provide the only means of access to motor vehicles in this rugged terrain. The field work was carried out with the aid of air photos at scales of 1:25,000 to 1:80,000, and the data were transferred to maps at 1:100,000, which provided the basis for the four 1:100,000 scale coloured geological maps and the 1:250,000 compilation map (see list of maps in Episodes, 1983/4, p. 54).

The Geology of the Oman Mountains

The Oman mountains, dominated by the Semail ophiolite nappe, extend in an 800 km long, 75 km wide are parallel to the western coast-line of the Gulf of Oman. The mountains are mostly between 500-1,500 m high, though some reach 3,000 m, and are rugged, bare and rocky with little or no vegetation cover (Fig.2). The mountains are part of the Alpine-Himalayan chain (see Şengör, this issue - Ed.) and as such are geologically distinct from the rest of Arabia, from which they are separated by the Rub al Khali or Empty Quarter.

Geologically the region can be divided into three divisions forming arcuate zones parallel to the coast-line (Figs. 1 and 3). The structurally lowest rocks are autochthonous Late Precambrian to Cretaceous carbonate sediments, which overlie a Pan-African (600-900 Ma) crystalline continental

Figure 4: "Banded Unit" at the base of the Semail Nappe. Interlayered lighter coloured dunites (d) and harzburgites (h). Height of cliff is about 150 m, and the large dunite mass near the top is about 100 m across and 25 m thick.

Ophiolite Nappe, the cumulate gabbros being lighter grey and merging into the sheeted dikes and lavas that form the eastern foothills of the range. In the SE corner, is the Hawasina Window with its exposures of the Hawasina series beneath the Semail Nappe. On the Batinah coastal plain to the NE of the mountains allochthonous sediments overlying the Semail Nappe are in turn unconformably overlain by Eocene limestones forming a line of outcrops parallel to the coast.

Evidence, largely from the allochthonous Haybi Complex, suggests that at about 220 Ma (Late Triassic), the Arabian continental mass rifted, accompanied by alkaline and then tholeiitic volcanism (Searle et al., 1980, Lippard and Rex, 1982). This was the beginning of the evolution of the Neotethyan ocean in which the Semail ophiolite was to form some 125 Ma later.

The Semail Nappe, which outcrops over nearly 20,000 km², consists entirely of ophiolitic rocks, with thicknesses up to 20 km. Post-emplacement faulting and folding has broken the nappe into fourteen more-or-less structurally intact blocks (Fig. 1) within which the ophiolite stratigraphy is largely undisturbed. The base of the Semail Nappe is everywhere marked by a clearly identifiable thrust immediately above which are up to 500 m of intensely sheared and mylonitized basal peridotites. Because in many places this basal unit consists of alternating layers of dunite and harzburgite, it has been termed the "banded unit" (Fig. 4).

Immediately below the thrust is a 0-500 m thick thrust slice of metamorphic rocks that display an inverted metamorphic zonation with the highest (upper amphibolite) grade rocks adjacent to the ophiolite. The grade decreases downwards away from the thrust until within a few hundred metres the underlying rocks are unmetamorphosed. Coexisting mineral assemblages show that the highest grade rocks formed at about 850°C and 4.5 kb (Searle and Malpas, 1980).

Geochemical studies by Searle and Malpas (1982) suggest that these metamorphics were formed from ocean-floor basalts and sediments overridden by the ophiolite nappe during the

early stage of its emplacement from the oceanic lithosphere. During and after emplacement, the initially 15-20 km-thick ophiolite was tectonically reduced in thickness; gravity studies (Shelton, 1984) indicate that the ophiolite nappe now has a structural thickness of 5-10 km. The nappe thins eastwards under the coastal plain so that its tapering eastern boundary coincides approximately with the present coast-line.

After the emplacement of the approximately 95 Ma old ophiolite at 90-75 Ma, some 600 m of Maastrichtian to Lower Miocene sediments were deposited. These were deformed by the mid-Miocene earth movements that produced the tectonic windows within the mountains. The post-Miocene history of the area was one of repeated uplift of the mountains and subsidence of the flanks with concomitant sedimentation. The cycles of repeated uplift are witnessed by a series of elevated gravel terraces flanking the present-day wadi system.

The Semail Nappe

In the various undeformed blocks, the Semail Nappe can be readily divided into a mantle sequence consisting of tectonized peridotite (mainly harzburgite) with associated dunite bodies and a crustal sequence. The latter can be further subdivided into a lower plutonic unit with layered, largely gabbroic rocks that underlie an upper unit of non-layered high-level gabbros, diorites, tonalites and trondhjemites. These plutonic rocks are separated from an extrusive sequence, largely of pillowed basalts, by a sheeted dike complex. In the following we discuss the various

Figure 5: Consensus model of oceanic constructive margin magmatism. From Gass and Smewing (1981). (a) extrusion of lavas, (b) dike injection, (c) formation of cumulate layering and (d) formation of dunite and chromite pods.

ophiolite units from the base upwards highlighting those aspects where OU project studies have been particularly significant.

The thickness of the various ophiolite blocks depends largely on the thickness of the mantle sequence present, and this varies from 4.5 to 11 km. Studies on the mantle sequence have concentrated on the tectonic fabric, the occurrence within the dunite of chromitite bodies, and serpentinization and its relation to hydro-geochemistry. It is now widely accepted that the tectonized peridotites at the base of most coherent ophiolite complexes represent uppermost oceanic mantle from which basaltic melts have been extracted. Geochemical studies of the Oman mantle whole rocks and mineral phases (Brown, 1983; Browning, 1982) confirm this.

In those blocks where the thickest mantle sequences occur, and at levels over 10 km below the petrological moho (Figs. 5 and 6) the harzburgitic character of the sequence becomes progressively more lherzolitic (less depleted) towards the base, although no composition appropriate to pristine undepleted mantle have been found. Because the dunite bodies within the harzburgite display cumulate textures and have geochemistry compatible with the precipitation of olivine and chromite from picritic melts, they are regarded as the cumulates left behind within an harzburgitic host when the melt escaped into higher level magma chambers directly beneath the spreading axis (see Figs. 4 and 5).

Studies on the tectonic fabric of ophiolitic mantle sequences, mainly by A. Nicolas and his colleagues at Nantes, have identified the presence of a high temperature, relatively low pressure foliation produced by diverging convection beneath a spreading axis. Bartholomew (1984), using the strike of the sheeted dikes as a palaeovertical, deduced that in the Oman the harzburgite foliation indicated divergent flow away from diapiric centres along the spreading axis. Bartholomew was also able to identify two foliations both of which were produced at high (>1,000°C) temperatures.

Serpentinization processes are relevant to gravity, magnetic (Shelton, 1984) and hydrogeochemical (Stanger, 1985) studies, since between 60-85% of the mantle sequence has been serpentinized. Shelton showed that there is a direct, though not very precise, correlation between the degree of serpen-

Figure 6: Petrological moho (dotted line) between mantle sequence harzburgites (h) below and smooth weathering dunites (d) and gabbros (g) above.

Figure 7: Typical sequence through 500 m of cumulate layered rocks in the Semail ophiolite showing variations in phase chemistry with height. Owb - olivine websterite, 2pg - two pyroxene gabbro, 2pog - two pyroxene olivine gabbro, g - gabbro, w - websterite. Scale refers to vertical distance above the petrological moho. From Smewing (1981).

tinization (as indicated by loss on ignition during analysis) and overall bulk rock density. He also identified a discrepancy in the degree of serpentinization as deduced from seismic (Vp) studies and from laboratory-determined densities on collected specimens. The seismic evidence suggested about 40% serpentinization, whereas the collected specimens imply about 65-100% alteration. Shelton suggests that, as the specimens were mainly collected along wadis that are largely fault controlled, the degree of serpentinization they display is probably greater than average.

The lack of deformation in the serpentinite minerals is evidence that the low temperature (<450°C) serpentinization process occurred much later than the high temperature convective deformation that formed beneath the spreading axis. Stanger (1985) identified two serpentinization episodes. The first, bearing no relation to present-day surfaces or water tables, is pervasive throughout the mantle sequence and was probably impressed whilst the ophiolite was still beneath sea-level. The second, lower temperature serpentinization, is related to the main present-day groundwater pathways and is regarded as being due to the abundant presence of deuteritic water in parts of the mantle sequence.

One of the most impressive features of the Semail ophiolite is the variability of the layered plutonic rocks that overlie the mantle sequence. These show not only marked thickness variations (0.5-6 km), but also differences in the sequences of rock types developed as a result of different timing of

crystallization of the cumulus mineral phases (Smewing, 1980; Browning, 1982). Detailed investigations of individual sections (Fig. 7) show the presence of numerous cycles, each cycle consisting of a basal ultramafic unit in sharp contact with the underlying rocks and an upper mafic unit (Fig. 8).

Both Smewing and Browning explain this phenomenon as being due to periodic influxes of new Mg-rich magma, a mechanism entirely in keeping with the diapir model invoked to explain the dunitic masses in the mantle sequence. Browning, following the model of Huppert and Sparks (1980), proposed that the dense incoming magmas did not always mix freely with all the melt already in the chamber. Rather these magma influxes ponded at the base of the chamber where they underwent dominantly olivine crystallization to form the basal ultramafic layer. Only when the

Figure 8: Rhythmic layering on a cm-scale in olivine gabbro cumulates. The dark bases to each unit are rich in olivine and clinopyroxene. Hammer head is 15 cm long.

density of the magma was sufficiently reduced by this process did it mix with the overlying melt to produce the mafic cumulate layer.

Smewing et al. (1984) also showed that the basal part of the layered sequence has been deformed by the same process that produced the foliation in the mantle sequence. This deformation dies out upwards and is rarely preserved for more than 300 m above the petrological moho. In the area investigated by the USGS-UoC team, where abundant cumulate dunite occurs at the base of the layered sequence, the term transition zone has been used to describe these deformed layered rocks (Boudier and Coleman, 1981). All the OU workers who studied these layered rocks found that, if the strike of the sheeted dikes was taken as a palaeovertical, then the layering in the gabbros was not horizontal but increased in inclination up the sequence (Fig. 9). Rothery (1982) and Browning (1982) proposed that was due to the

Figure 9: Proposed oceanic spreading ridge model based on the Semail Ophiolite (Wadi Bani Kharus N-S section in SE corner of OU area shown on Figure 1). From Browning (1982).

crystallization of the gabbros on the flanks of magma chambers rather than due to crystal accumulation at the base of the chamber. This in turn supported the proposal that small magma chambers existed along the spreading axis rather than a large continuous chamber of the "infinite onion" variety.

The sheeted dike complex of the Semail ophiolite is between 1 and 2 km thick and consists nearly 100% of vertical basic dikes (Fig. 10) mostly between 0.5 and 1 m thick. There are narrow (<50 m) gradational contact zones with the underlying gabbro and overlying lava units that contain gabbro and lava screens respectively. Throughout its length the dominant strike of the sheeted dikes in the Semail Nappe is N-S to NW-SE, but in the north near Wadi Hatta (Fig. 1) a dominant ESE trend has been explained by Smewing (1980) as being due to dike injection along a leaky transform fault zone. Four separate dike types identified geochemically (Pearce et al., 1981) are related to spreading-axis magmatism and three phases of subsequent off-axis igneous activity that are more clearly evident in the extrusive sequence.

The upper part of the Semail ophiolite consists of up to 2,000 m of pillowed basalts, with some andesitic and rhyolitic extrusives, cut by a wide variety of intrusives. The extrusives are intercalated with and overlain by deep water sediments. The sequence as a whole is the product of submarine volcanism and sedimentation close to a spreading axis.

Pearce and others (1981) and Alabaster (1982) divide the volcanic rocks into five units from the bottom upwards: the Geotimes, Lasail, Alley, Clinopyroxene-phyric and Salahi units. The Geotimes unit, so named because a photograph of a pillow lava outcrop in Wadi Jizi (Fig. 11) was once featured on the cover Geotimes magazine, consists of 750-1,500 m of reddish brown basaltic to andesitic pillowed and massive lavas whose chemistry is similar to that of most of the directly underlying sheeted dikes.

In contrast, the basalts of the overlying Lasail unit are green in outcrop and can be readily distinguished from the Geotimes lavas both petrographically and geochemically. Since

they occur in restricted areas, some 20-30 km across, where they attain local thicknesses of 750 m and are associated with andesitic to felsitic cone sheets and sills, Alabaster (1982) suggested that the Lasail volcanics represented centralized volcanic sea-mounts built on the newly created oceanic crust of the Geotimes unit.

Figure 10: Sheeted dike complex, height of section approximately 50 m.

Figure 11: Geotimes unit pillow lavas. Tree on right is 1.5 m high.

Overlying both these lower units are the highly vesicular pillow basalts and associated acidic rocks (including rhyolitic pitchstones) of the Alley unit. The Clinopyroxene-phyric unit consists of small-volumes of picritic or ankaramitic flows associated with NW-SE trending faults and localized dike sets. The uppermost Salahi unit is only found in one locality where it forms up to 100 m of pillowed and massive alkali basaltic lavas. Trace element geochemistry and cpx compositions suggest a diversity of tectonic settings for the five extrusive units. These range from supra-subduction zone spreading for the Geotimes unit (transitional from mid-ocean ridge basalts to island arc tholeiites) to incipient arc for the Lasail and Alley/Clinopyroxene-phyric units (island arc tholeiites) and off-axis in the case of the Salahi unit (within-plate basalts).

Intrusive into, and widely distributed along the extrusive unit are late intrusive complexes that have been divided petrologically into (i) large (1-5 km) gabbro-diorite-plagiogranite bodies and (ii) small (<1 km), more dike-like, peridotite-gabbro complexes, often oriented along NW-SE trends. These complexes are interpreted as the plutonic equivalents of the Lasail and Alley-Clinopyroxene-phyric lava units. Parts of the Semail ophiolite, particularly the mantle sequence and the base of the layered sequence, are locally intruded by small sheet-like bodies of deformed biotite or K-granites. These have been dated at 85 Ma and have the geochemical and isotopic signature of crustal melts. They are interpreted as having formed during emplacement of the ophiolite onto the continental margin.

All the Semail ophiolite, including the mantle sequence, has been affected by hydrothermal metasomatism produced by the circulation of sea-water through newly created, hot oceanic lithosphere. In places, particularly when subjected to second stage hydrothermal processes driven by late stage magmatism (Alabaster, 1982), this metasomatism has produced Cyprus-type massive, cupriferous sulphides that are currently being mined in the Wadi Jizi area.

That the Semail ophiolite represents a section of "normal" oceanic lithosphere formed at a spreading axis in a major ocean basin was the consensus opinion of the special 1981 volume (86B4) of the Journal of Geophysical Research on the Oman ophiolite. This view has been challenged by members

of the Open University group such as Pearce and others (1981) and Alabaster et al. (1982) who, while recognizing that the main sequence of the ophiolite must have formed at a constructive plate margin, have suggested that the complex magmatic evolution and the geochemistry of the crustal sequence are more compatible with formation in a short-lived marginal ocean basin located above a subduction zone.

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Anthony W. Shelton joined the Oman Ophiolite Project as a Research Student in 1977 to conduct a gravity survey and paleomagnetic investigation. He has also been involved in continental margin studies of the Gulf of Aden and the paleomagnetism of supraphiolite sediments in Cyprus.

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