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THE LATE PROTEROZOIC OPHIOLITE OF SOL HAMED, NE SUDAN

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ABSTRACT

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The Sol Hamed complex, a sequence from ultramafics, through gabbros, thin sheeted dykes, to pillow lavas, is an ophiolite. It was obducted, tilted nearly to vertical, eroded and covered unconformably by the Nafirdeib Series. This is a volcaniclastic series, dated at 712 ± 58 Ma, the lower part of which includes conglomerates with ophiolitic clasts, olistostromes, one with large oolitic limestone slabs, felsitic and dacitic tuffs, turbidites and black shales, with andesites above. Some of the structures in the ophiolite are attributed to sub-oceanic deformation. Deformation after the deposition of the Nafirdeib Series produced folds and cleavage trending about NE—SW and, more locally, a cleavage trending NW in a shear zone where the ophiolite was thrust northeastwards over the Nafirdeib Series. The ophiolite and the Nafirdeib Series were intruded by the batholithic granite dated elsewhere at ca. 669 Ma. The ophiolite is thought to occur on a suture with the Nafirdeib Series representing part of an island arc sequence.

REGIONAL SETTING AND PREVIOUS WORK

There is widespread agreement that the Pan African basement of the Nubian-Arabian Shield evolved by plate tectonic processes during the Late Proterozoic (Bakor et al.,1976; Garson and Shalaby, 1976; Greenwood et al., 1976, 1980; Gass, 1977, 1981; Shackleton, 1977, 1980). During this period several suites of volcanic and volcaniclastic rocks with island-arc affinities, granitoid plutons and ophiolitic blocks were welded together to form a normal thickness of continental crust. From recent work there now seems little doubt that

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most of the numerous mafic—ultramafic bodies distributed throughout the Nubian—Arabian Shield are fragments of oceanic or back-arc floor. Nearly intact ophiolitic sequences have been described from Saudi Arabia, for example Jabal al Wask (Bakor et al., 1976) and Bir Umq (Frisch and Al-Shanti, 1977), and from the eastern desert of Egypt (Dixon, 1979; Stern, 1979; Nasseef et al., 1980). In the eastern desert of Egypt the ophiolitic rocks lie in a very extensive mélange which overlies continental shelf deposits (Shackleton et al., 1980; Ries et al., 1983). To the south, mafic—ultramafic masses appear to lie in a zone trending NNE/SSW from Sol Hamed in the north, through Wadi Onib, Qala en Nahl and Ingessana further south in Sudan, and perhaps Yubdo in Western Ethiopia and Sekerr in NW Kenya (Fig. 1). One of us (I.M.H.) has been particularly concerned with the detailed investigation of the Sol Hamed ophiolite, while the others are examining the structure, age and geochemistry of the ophiolitic rocks in the course of a project to investigate the Late Proterozoic (Pan African) evolution of the crust in NE Africa. The structure of the Sol Hamed complex and its relationship to adjacent island-arc suites are the subject of this paper.

The geology of the northern Red Sea Hills of Sudan, in which Sol Hamed is situated (Fig. 1), has been reviewed by Vail (1978). Amphibolite-facies gneisses and hornblende schists, and the Kashebib Series (Gabert et al., 1960), are supposedly the oldest exposed rocks, forming a basement on which the greenschist assemblage was deposited unconformably (Vail, 1978, 1979). Up to now, no intact unconformable contact, nor geochronological evidence, can be cited to confirm that the Kashebib Series does represent an older basement. Kabesh and Lofti (1962) divided the greenschist assemblage into two similar associations of greywackes, slates and phyllites with some conglomerates, marbles, calc-silicates and volcanic rocks, mostly andesites with some tuffs and basalts, supposedly separated by an unconformity. The younger group was called the Nafirdeib Series by Ruxton (1956) and included the Oyo Series of Gass (1955).

Intruded into all these rocks is the batholithic granite, from which Cavanagh (1979) obtained Rb/Sr whole-rock ages of 686 ± 18 Ma (2 sigma errors, mean square of the weighted deviates (MSWD) = 1.61, $\lambda^{87}\mathrm{Rb} = 1.42 \times 10^{-11}\ \mathrm{yr}^{-1}$) from the marginal facies and 669 ± 20 Ma (MSWD = 3.58) from the central part of the granite between 21 and 22°N (ages summarized in Neary et al., 1976). Cavanagh (1979) argued that, because the $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ initial ratio of the marginal facies (0.70307 ± 7) is low and not significantly different from that of the main part of the batholithic grainite, the crustal history of the Nafirdeib Series must have been short before being intruded and assimilated by the marginal facies, assuming that the assimilated material was from the Nafirdeib Series and not an earlier, more mafic phase of the intrusion. It was thought that several serpentinites, norites, gabbros and troctolites were subsequently emplaced as small bodies and dykes (Bagnall, 1955; Gass, 1955). However, the serpentinites may prove to be ophiolitic and older.

A younger volcanic and sedimentary sequence, the Awat Volcanics (Ruxton,

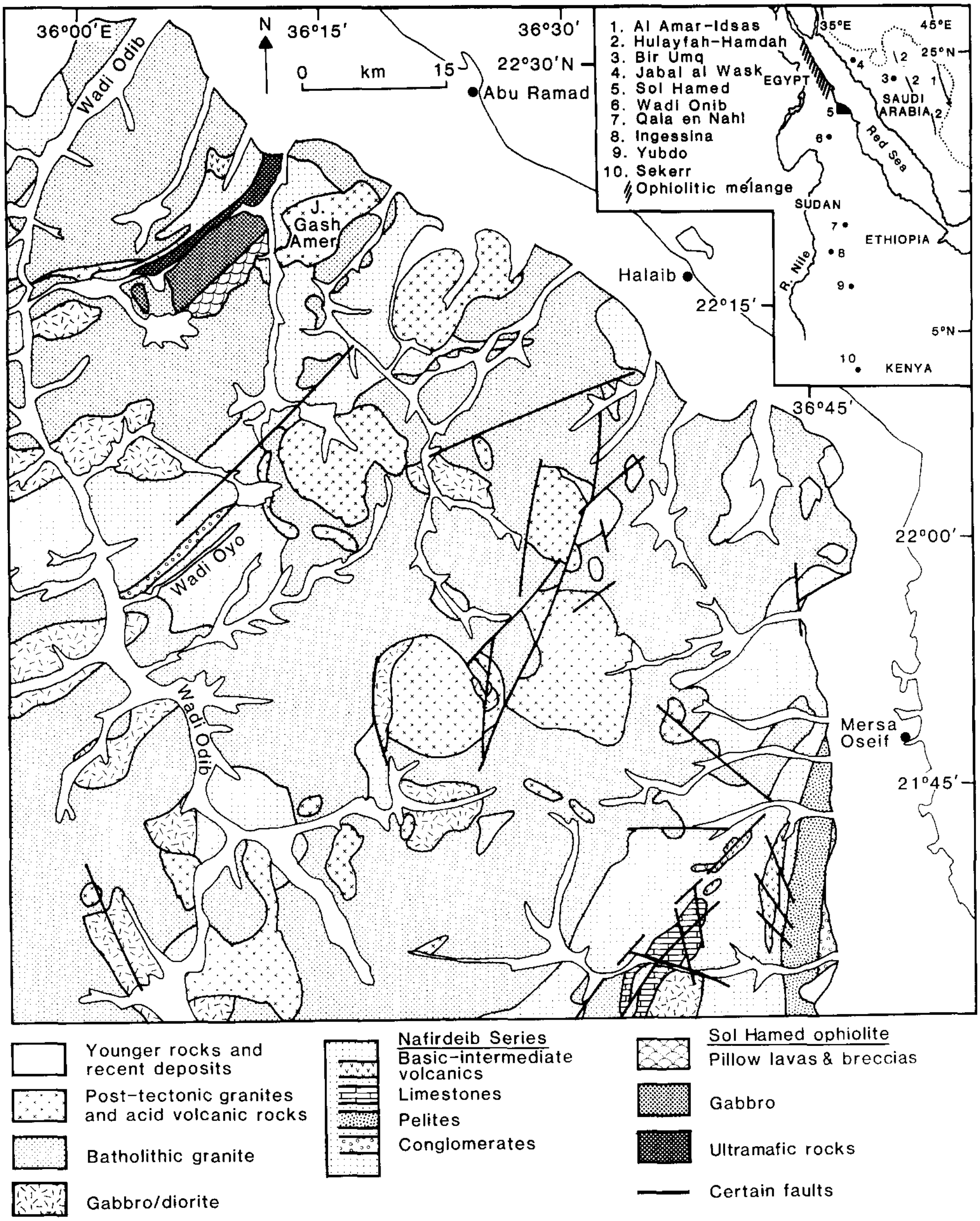


Fig. 1. Geological map showing the regional setting of the Sol Hamed ophiolite in the Red Sea Hills, NE Sudan (after Hussein, 1977). Inset shows the distribution of Late Proterozoic ophiolites in Saudi Arabia and NE Africa.

1956), consists mainly of rhyolites and dacites, with interbedded siltstones, greywackes, conglomerates and intermediate volcanic rocks. These rocks are supposedly less deformed and metamorphosed than, and unconformable on, the older sequences (Kabesh and Lofti, 1962). Cavanagh (1979) obtained a Rb/Sr whole-rock age of 649 ± 18 Ma (MSWD = 1.79) from the Asoteriba Volcanics which are correlated with the Awat Volcanics.

The widespread younger granites were intruded into the volcanic sequences and Cavanagh (1979) obtained a mean Rb/Sr whole-rock age of 633 ± 19 Ma (MSWD = 2.42) from ten of them. The still younger alkaline ring complexes were emplaced at intervals during the Phanerozoic.

Neary et al. (1976) proposed that these volcanic and sedimentary sequences, together with the 600—700 Ma granitic rocks with calc-alkaline chemistry, resemble associations found in an oceanic island arc above a subduction zone. Cavanagh (1979) found that the batholithic granite, the Asoteriba Volcanics and the earliest younger granites all had similar low $^{87}Sr/^{86}Sr$ initial ratios typical of magmas derived from the lower crust or mantle, so supporting the model of Neary et al. (1976). This model is similar to that proposed for volcanic sequences of similar age in Saudi Arabia by Greenwood et al. (1976), Bakor et al. (1976) and Gass (1981), and in the eastern desert of Egypt (Ries, et al., 1983).

In previous work on the Sol Hamed complex, layered gabbros and layered chromite-bearing ultramafic rocks (commonly serpentinised) were described and it was suggested that they were probably part of an ophiolite, although no sheeted dyke complex or pillow basalts were then identified (Hussein, 1977). The island arc affinities of the volcaniclastic sediments were recognized but the relationship between the sediments and the ophiolite complex was not clearly defined.

It can now be demonstrated that the Sol Hamed complex is an almost complete ophiolite sequence, emplaced tectonically and eroded before the eruption and deposition of a sequence of volcanics and volcaniclastic sediments, the Nafirdeib Series, which lies with marked unconformity on the ophiolite.

THE SOL HAMED OPHIOLITE

The Sol Hamed ophiolite (Fig. 2) comprises three NE—SW trending subvertical lithological zones; (1) ultramafic rocks in the NW, (2) gabbros in a central zone and (3) pillow lavas and pillow breccias to the southeast. Between the gabbros and the pillow lavas is a zone of dykes in a gabbro host, which is a poorly developed sheeted dyke complex. This sequence is interpreted as an ophiolite, which faces to the southeast. Trace element and REE studies in progress support an ocean-floor origin for this complex (R. Price, unpublished data). Surrounding the ophiolite is a suite of volcanic and sedimentary rocks, the Nafirdeib Series, which is locally unconformable on, and elsewhere in tectonic contact with, the ophiolite (Fig. 2). Granitoid plutons including the batholithic granite cut both suites of rocks.

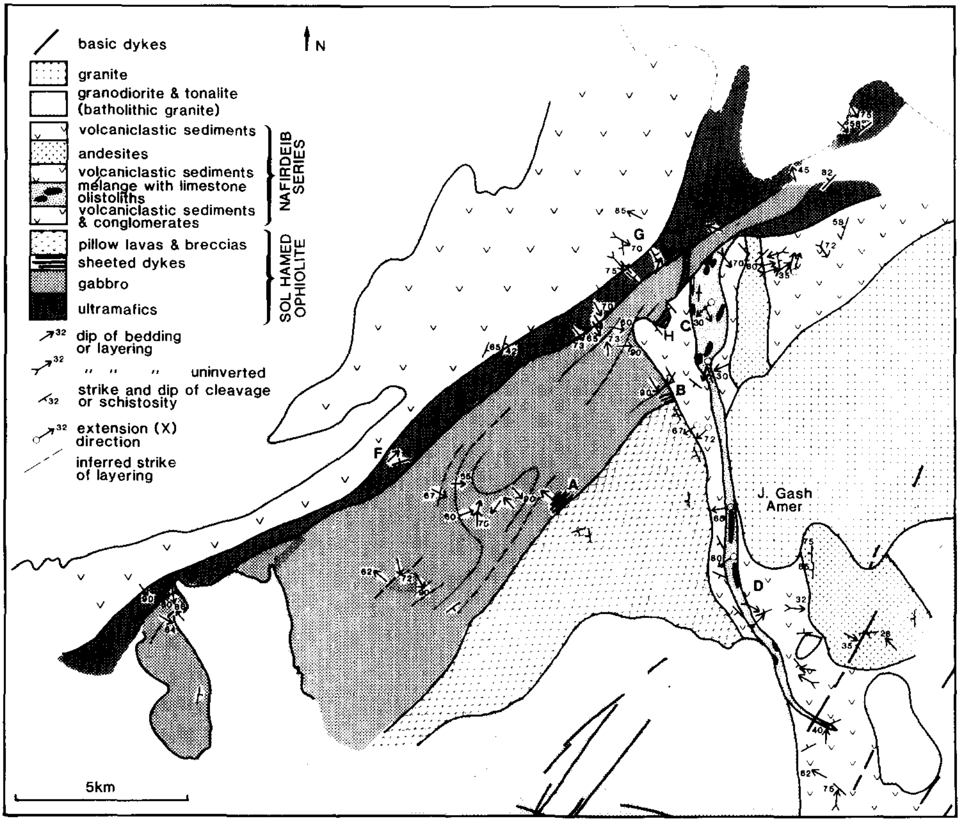


Fig. 2. Geological map of the Sol Hamed ophiolite and surrounding rocks.

The ultramafic rocks

The ultramafic rocks form a zone about 20 km long and between 300 m and 3 km wide (Fig. 2). The contacts with adjacent rocks are poorly exposed, but in the east the junction with the gabbro is clearly tectonic with the two units intersliced. To the northwest the ultramafic rocks are tectonically intersliced with volcaniclastic rocks.

The ultramafic assemblage includes dunites, wehrlites and lherzolites, and probably harzburgites, now extensively serpentinized and in places carbonated, with minor pyroxenites. In the dunites, layers of chromite, typically 0.5—2 cm thick, some of them size-graded, are widespread; thicker podiform chromites have been worked on a small scale in the northeast of the area. The serpentine textures show the wide range of deformation affecting the rocks. The predominant rock type was dunite, in which rare olivine is now preserved. Lizardite mesh textures, commonly veined by chrysotile are found in areas of low deformation. In high deformation zones, fine-grained bladed antigorite is found. These features are similar to those described by Maltman (1978) in Anglesey. In the wehrlites, too, olivine is mostly replaced by lizardite or locally by antigorite but the clinopyroxene remains fresh and exsolution lamellae are preserved. The lherzolites, not previously identified, are characterised by bastite pseudomorphs after orthopyroxene, serpentinised olivine and fresh clinopyroxene. The presence of bastites, which in places accompany the clinopyroxenes, indicate that the pyroxenites probably included websterites. No systematic distribution of these various ultramafic rocks has been recognised. The rocks are extensively cut by small-scale braided shear zones enclosing little-deformed kernels which in places have been rotated. This association of ultramafic rocks is similar to that in the Troodos complex, Cyprus (I.G. Gass, personal communication, 1982).

This ultramafic component of the Sol Hamed ophiolite has characteristics of the transition zone of ultramafic cumulates which lies between the mantle sequence and the layered sequence in many ophiolites (Coleman, 1977). Like other transition zones, that at Sol Hamed is heterogeneous in composition. Many of the rocks appear to be banded, shown by layers of chromite and occasionally peridotite lenses in the dunites, bastite layers in serpentinites and layers richer in clinopyroxene in the wehrlites. This banding is thought to be magmatic. Tectonised harzburgites, which form the major part of the mantle sequence in most ophiolites, seem to be rare in the Sol Hamed complex.

The gabbros

The gabbros occupy a zone almost 20 km long and 4—6 km wide (Fig.2). The contact with the ultramafic rocks is thought to be stratigraphic, but subsequently modified by tectonic movements when more ductile serpentinite was emplaced into the gabbros (Hussein, 1977). In some places there is true serpentine mélange, with disoriented gabbro blocks in a serpentinite matrix. This mélange post-dates the first fabric in the gabbro since it is this fabric which is disoriented.

The northwestern part of the gabbro, adjacent to the ultramafic rocks and hence probably the lower part of the body, is a medium to coarse grained pyroxene gabbro which becomes more leucocratic and typically finer grained towards the southeast. There is a change in the plagioclase composition in the same direction, from An_{70-85} in the northwest to much more sodic compositions in the southeast (Hussein, 1977). Original igneous textures can still be recognized in many places, but metamorphic recrystallization, under middle to upper greenschist facies conditions, is usually advanced. Plagioclase is partly or totally replaced by white mica, epidote and/or zoisite, and the pyroxene by tremolite—actinolite, or more rarely by green hornblende; chlorite, white mica, carbonates and quartz form a fine-grained matrix.

Widespread small-scale magmatic layering strikes mostly between E and N and dips very steeply between S and E. The variations in strike suggest folding (Figs. 2, 3a). Melanogabbro—anorthositic gabbro couplets are typically ca. 5 cm in thickness and are laterally persistent for several metres. Mineral- and size-grading occur locally, but in most examples of layering the boundaries between adjacent mafic and leucocratic layers are sharply defined. There are also numerous examples of continuous grading, from mafic to leucocratic

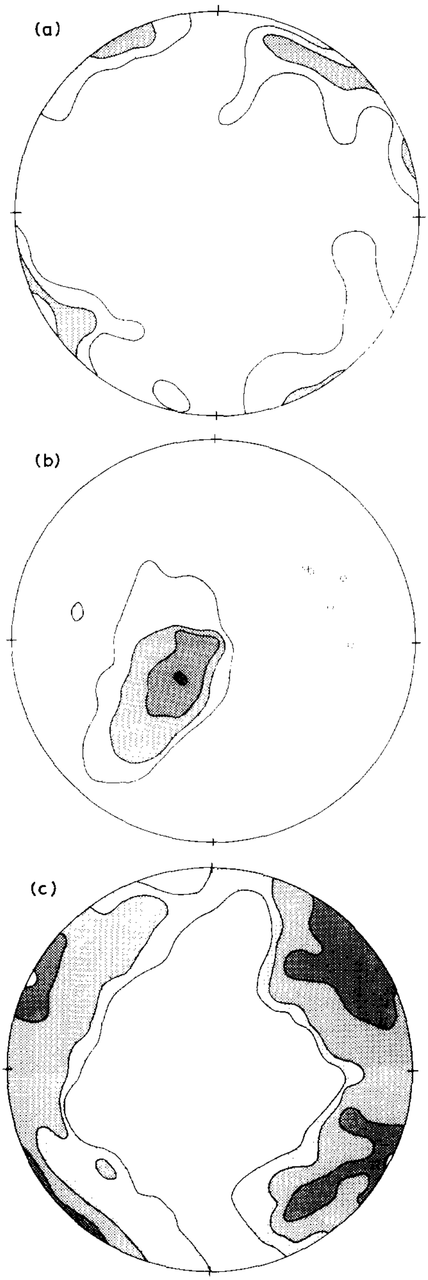


Fig. 3. Stereograms from the Sol Hamed area. (a) Poles to layering in the gabbros of the ophiolite (contour interval 3 and 6%). (b) Stretching direction (contoured at intervals of 2, 4, 10 and 20%) and fold axes (circles) in the Nafirdeib Series. (c) Poles to cleavages in the Nafirdeib Series (contour interval, 1, 2 and 4%).

and back to mafic compositions. Consequently, little reliance is placed on the graded units as facing indicators.

A wehrlite sheet, 100 m thick and more than 1 km long outcrops within the northwestern part of the gabbro, 0.5 km SE of the main ultramafic mass (Fig. 2). Contact relations with the gabbro are obscure and it may be a slice which has been tectonically detached from the main ultramafic mass, but more probably it represents an ultramafic cumulus unit within the gabbro.

The sheeted dykes

At locality A (Fig. 2), about 7 km W of J. Gash Amer, a concentration of approximately 50% dykes occurs. They trend NE—SW, dip steeply, are each ca. 30 cm thick and are separated by screens of fine-grained gabbro. Primary minerals and any chilled margins have been destroyed by recrystallization and the dykes are now an aggregate of epidote and tremolite—actinolite. R. Price records an occurrence of almost 100% sheeted dykes, between the gabbros and pillow lavas, beneath the unconformity at locality B (see Fig. 2).

In this ophiolite the dykes are orientated NE/SW, approximately parallel, rather than at a high angle, to the general NE/SW strike of the layering in the gabbros. A similar relationship in the Semail ophiolite in Oman is thought to be due to magmatic processes at the top of the magma chamber (J.D. Smewing, personal communication, 1982). Tectonic rotation of the sheeted dykes is possible, but would imply higher strains than have been recognised near the dykes.

Pillow lavas

Previously unreported basaltic pillow lavas are well exposed at several localities close to the contact of the ophiolite with the volcaniclastic series, NW of J. Gash Amer (Fig. 2). The pillows have undergone constrictional strain, but the original pillow forms are easily recognisable in YZ sections. Relict primary features include chilled margins, hollow cores now filled with carbonates or quartz, tangentially elongated vesicles and interpillow spaces filled by pillow-breccia, all of which are shallow-water indicators; occasionally chert is found between pillows. Facing directions, where seen, are to the SE. The rest of this component consists of basaltic volcanic breccias, mostly pillow-debris, indicated by numerous fragments with one curved chilled edge. Jasper fragments are locally interspersed.

The overlying oceanic sediments

The deep-sea sediments, which were deposited on top of the pillow lava sequence, are thought to be exposed to the NW of the main ophiolite body (area F, Fig. 2). Here pillow lavas and pillow debris, forming fragments in a volcaniclastic olistostrome, are succeeded southeastwards, and apparently upwards, by a volcaniclastic turbidite olistostrome with red shales, silicified

Fig. 4. Deformed rhyolite. The plagioclase phenocryst has a micropegmatite fringe (area F Fig. 2).

black shales and cherts; an association which might suggest an oceanic environment. However, a thin section of one of the supposed cherts shows it to be a felsite with deformed phenocrysts of quartz and plagioclase, including one crystal of plagioclase with a border of micropegmatite (Fig. 4), so the interpretation of this assemblage is not clear. SE of this unit, and facing southeastwards, are volcaniclastic turbidites. These rocks are in tectonic contact with the highly sheared NW margin of the ophiolite.

This sequence is regarded as redeposited and part of the Nafirdeib Series, but the pillow lavas and possible oceanic sediments contained in it seem to represent the top of the ophiolite which slid, and was incorporated into, the Nafirdeib Series.

THE NAFIRDEIB SERIES

This series contains andesites, dacites, tuffs and volcaniclastic sediments, turbidites, limestone and other sediments, some of shallow-water origin, others perhaps of deep-sea origin. It has been shown from petrological and geochemical studies that the volcanic rocks are mostly andesites, dacites and rhyolites (Hussein, 1977). The stratigraphy of this series, which lies unconformably on the ophiolite, is described from five areas (C,D,E,F and G) shown on Figs. 2 and 5.

The rocks are now generally ascribed to the Nafirdeib Series (Ruxton et al., 1956), although part of the sequence had previously been named the Oyo Series (Gass, 1955), after well-exposed sequences in Wadi Oyo (21° 58′N

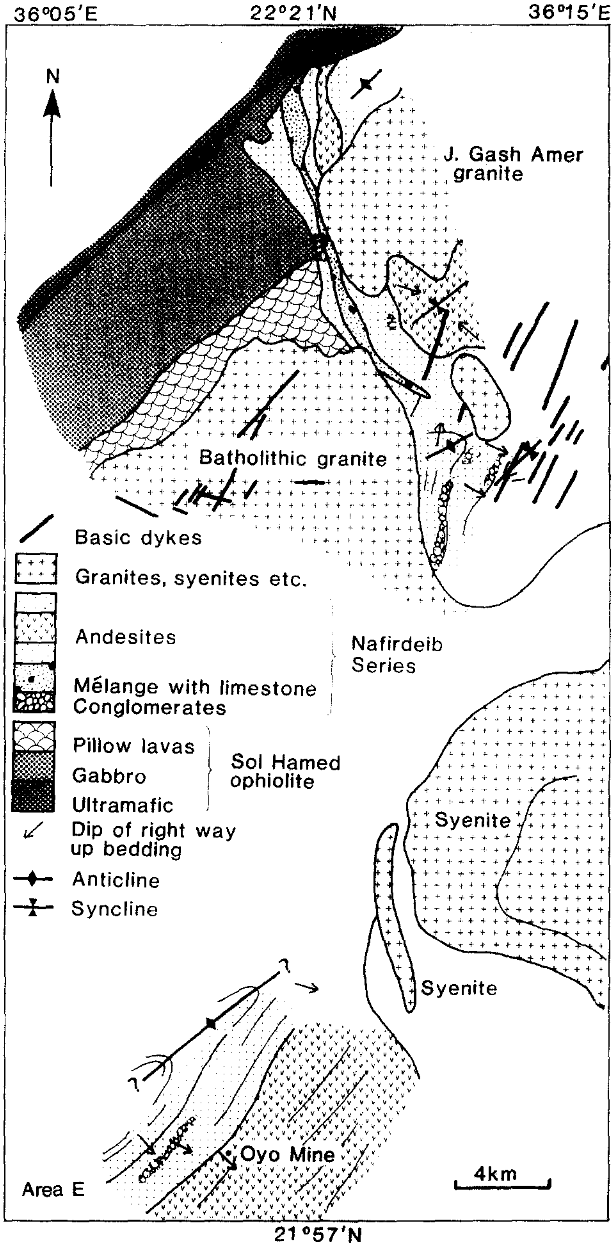


Fig. 5. Geological sketch map of the area between Sol Hamed and Wadi Oyo.

36° 10′E). No general sequence can be recognised; different areas are separated tectonically, or by granites, parts of the sequence are olistostromes and there appear to be rapid lateral variations. Sequences in different areas are described separately before their correlation is discussed.

The area northeast of the ophiolite (area C, Fig. 2)

The unconformity

About 5 km NNW of J. Gash Amer (location B, Fig. 2; see also Fig. 6a, b), an angular unconformity, between the Nafirdeib Series and the Sol Hamed ophiolite, has been found. The unconformity can be mapped north and south from the exposure although it is not so well exposed and the lowest part of the Nafirdeib Series is not seen. At location B, the surface of the ophiolite is highly irregular and deep erosion pockets are filled with poorly sorted unbedded coarse breccias, probably subaerial, containing angular clasts of the underlying ophiolite. The breccias are overlapped by well-bedded, waterlain graded tuffs facing away from the unconformity, indicating that by the time the tops of the ophiolite 'hills' were buried, the ophiolite was submerged. Here the ophiolite has been inverted to dip steeply SW and folded on axial planes which strike NW—SE and dip steeply SW, with hinges plunging steeply SW, so that the strike of the ophiolite is almost at right angles to that of the unconformably overlying Nafirdeib Series.

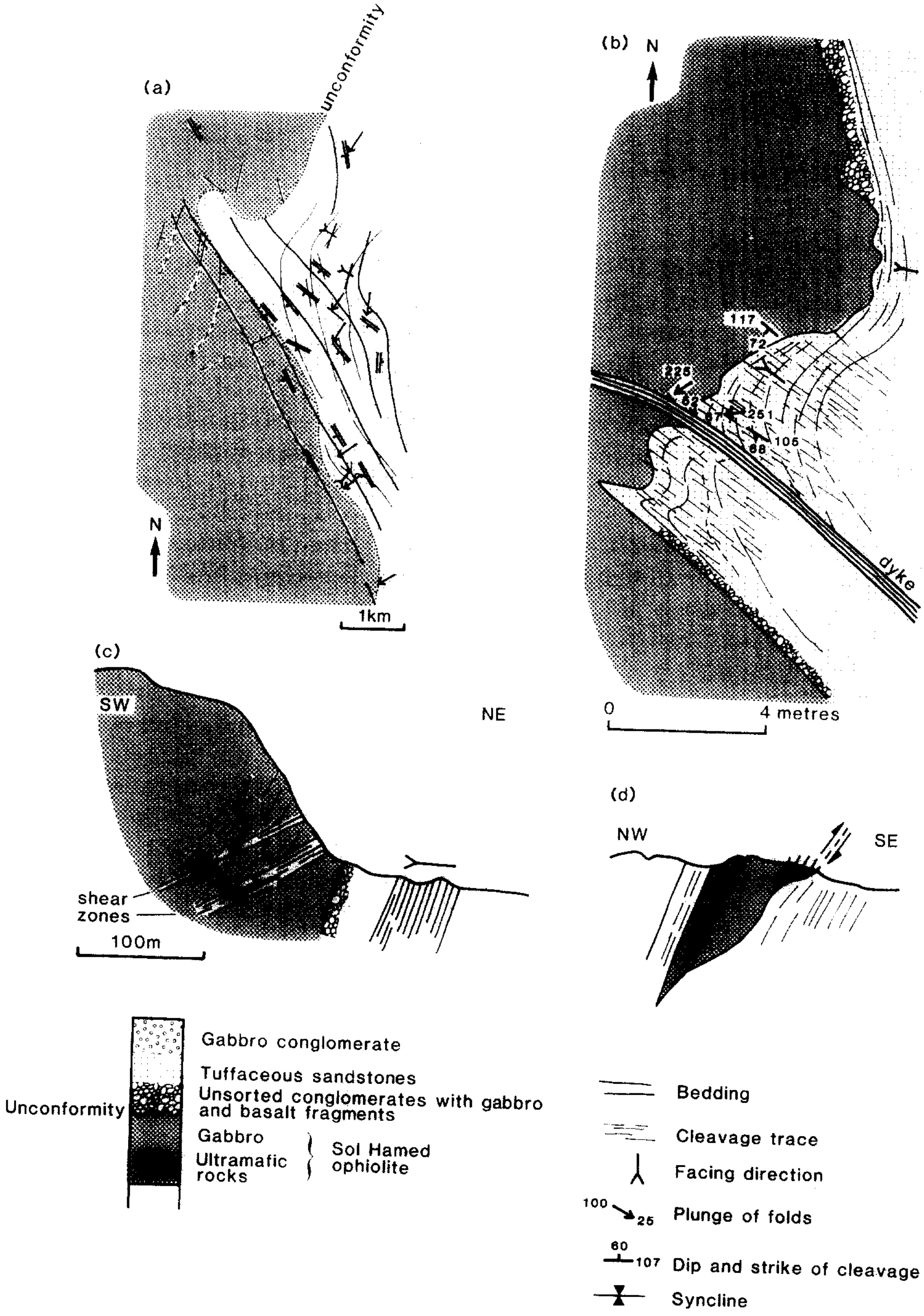
Evidently, at location B, the ophiolite had been uplifted, tilted to a vertical position and deeply eroded, down to the gabbros and sheeted dykes, and farther north to the ultramafics, before the basal beds of the Nafirdeib Series were deposited. The uplifted ophiolite continued to shed debris for some time, for clasts of gabbro are still found in conglomerates higher up in the succession. Gabbro-clast conglomerates are exposed NE, E and SE of the main ophiolite gabbro, and those to the SE lie stratigraphically above the pillow lavas, suggesting transport from the W or NW and a palaeoslope towards the E or SE. The unconformity with the ultramafic rocks is not exposed, but is inferred from the presence of rare serpentinite pebbles, some bearing chromite, in the conglomerates dominated by gabbro clasts and from even rarer serpentinite pebbles elsewhere in the volcaniclastic suite.

The sequence above the unconformity

This appears to be:

(v)	Turbiditic and tuffaceous sediments	
(iv)	Andesites	0.5 km
(iii)	Felsitic tuffs, rhyolites, tuffaceous turbidites	0.1 km
(ii)	Olistostrome with limestone slabs	0.1 km
(i)	Gabbro conglomerates, breccias, bedded volcaniclastics and tuffs	0.2 km

Unconformity
(Thicknesses are only roughly estimated.)


(a)
unconformity
N
1km
(b)
N
117
72
225
62
67
251
105
68
dyke
0
4 metres
(c)
SW
NE
shear zones
100m
(d)
NW
SE
Gabbro conglomerate
Tuffaceous sandstones
Unconformity
Unsorted conglomerates with gabbro and basalt fragments
Gabbro
Ultramafic rocks
Sol Hamed ophiolite
Bedding
Cleavage trace
Facing direction
100
25
Plunge of folds
60
107
Dip and strike of cleavage
Syncline

The gabbro conglomerates, breccias, bedded volcaniclastics and tuffs. The basal conglomerate, described above, passes up into a series of well-bedded (10—50 cm) breccias with subordinate conglomeratic beds. The clasts, usually grain supported and up to 20 cm long, are mainly tablets of platy-bedded limestone or peri-platform ooze deposits and angular to sub-rounded volcanic rocks, dominantly plagioclase-phyric andesites, and quartz-phyric dacites and rhyolites. Black shale, gabbro and serpentinite clasts are less common. The proportion of clasts ranges from exclusively limestone to exclusively volcanic debris. There is a positive correlation between bed thickness and clast size. The matrix varies from blue—grey limestone, through calcareous fine—medium volcanic sand, to volcanic sand, the latter comprising variable proportions of quartz, plagioclase, a range of volcanic rock fragments and argillaceous material. In units dominated by platy limestone clasts there is a strong depositional alignment of the long axes parallel to bedding. In rare instances normal and reverse grading is seen. The less common matrix-supported breccias show little clast alignment, very poor sorting, no grading and the beds are usually thicker than the grain-supported types. The tuffs, mostly acid pyroclasts, which form the upper part of this sequence, are well-bedded, often with grading and sole structures, indicating turbidity current transport.

Olistostrome with limestone slabs. This olistostrome is a chaotic mixture of limestone, black shale, pillow lava, ultrabasic rock, gabbro, acid and andesitic volcanics, which may be in contact with, or supported by, a volcaniclastic sedimentary matrix. This olistostrome is differentiated from the other olistostromes and volcaniclastic debris flows by the size of the limestone slabs within it, and consequently forms a stratigraphic marker horizon (Fig. 2). It pre-dates the development of the first cleavage.

Felsitic tuffs and tuffaceous sediments, rhyolites and conglomerates. This group includes schistose felsites, felsitic fragmental rocks, gritty felsitic tuffs, tuffaceous sediments, turbidites and conglomerates with pebbles of gabbro, acid igneous rocks, dark chert and quartz. The tuffs are finely bedded (2—5 cm) and commonly show gradation up into fine sand tops; small-scale ripple-lamination occurs in places. Clasts are almost entirely acid lavas containing plagioclase and quartz phenocrysts.

Andesites. Blocky andesites and andesitic basalts, some highly vesicular and some brecciated or agglomeratic, form a zone N of J. Gash Amer.

Fig. 6. Details of the unconformity between the Sol Hamed ophiolite and the overlying Nafirdeib Series. (a) Map of locality B (see Fig. 2). (b) Detailed plan of the unconformity at locality B. (c) Section of the unconformity at locality H (see Fig. 2). (d) Interpretative section, showing southeastward thrusting of the Sol Hamed ophiolite over the Nafirdeib Series.

Turbiditic and tuffaceous sediments. These occur E of the andesites and mostly face eastwards away from the andesites, as though overlying them, but at one exposure, close to the andesites, they face westwards. The contact is not seen and it is not certain that they are really younger than the andesites.

The area southeast of the ophiolite complex (area D, Fig. 2).

Here the structure is complicated by a series of folds trending NE—SW, but the olistostrome with limestone slabs can be followed to about 5 km S of J. Gash Amer, after which its course is uncertain. The succession appears to be:

(iv)	Andesitic basalts (top not seen).	1 km ?
(iii)	Turbidites, conglomerates, tuffs	0.5 km ?
(ii)	Olistostrome with limestone slabs	0.1 km ?
(i)	Conglomerates with abundant ophiolite debris, limestones, cherts, turbidites, black shales	1 km ?

The base of the sequence is not seen. The conglomeratic beds, which appear to thicken southwards, are polygenetic with pebbles of ophiolitic gabbro, chert, limestone, acid volcanics and granite. The turbidites show grading and, occasionally, sole structures. Between these various coarse clastic beds are black shales, often cherty or siliceous.

The olistostrome with limestone slabs, traceable for about 7 km SSE from an exposure west of J. Gash Amer, contains conspicuous masses of limestone, the largest of which, W of J. Gash Amer, is about 1 km long, where it is overlain and underlain by dacitic lavas. At the only contact seen, the dacite is strongly sheared against the limestone. The limestone is grey and contains well-preserved though deformed ooliths (Fig. 7). Elsewhere this olistostrome contains boulders of limestones of various sizes in a matrix which is largely of basic igneous origin. There are also limestone and pelitic beds.

The beds overlying the olistostrome are turbiditic sandstones, conglomerates with limestone fragments and acid tuffs. There is more turbidite below the limestone olistostrome. The andesitic basalts are massive dark grey rocks, in places highly vesicular and in parts autobrecciated.

The Wadi Oyo area (area E, Figs. 5, 8b)

This is separated from the areas discussed above by granitic intrusions, which interrupt the continuity of the formations for about 12 km. Beyond this gap is an area, in the centre of which is Oyo Mine (now disused). Here the sequence is:

(iii)	Andesitic volcanics	2 km?
(ii)	Conglomeratic sediments	1 km
(i)	Finer-grained sediments	1 km

Neither the base nor the top of the series is seen. The rocks dip southeastwards and appear to form a continuous right-way-up sequence. The sediments were named the Oyo Series by Gass (1955).

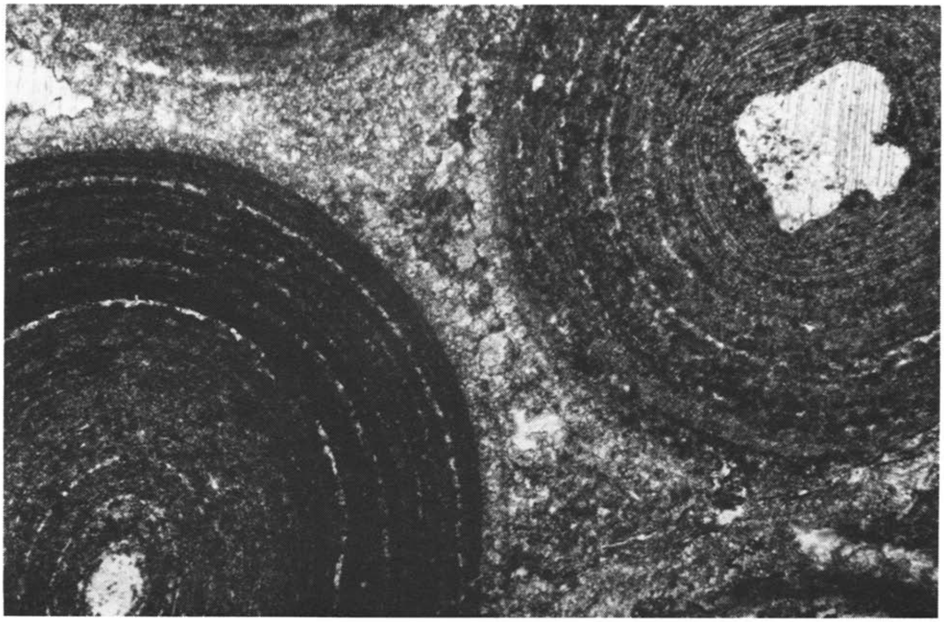


Fig. 7. Ooliths in oolitic marble from an olistostrome in Nafirdeib Series W. of Jebel Gash Amer.

The lower group of sediments consists of grey cleaved mudstones and shales, with interbedded microconglomerates and turbidites. There is a suggestion, from air photographs, of an anticlinal structure within them, about 6 km N of Oyo Mine (Fig. 5) and here the beds may be overturned (Gass, personal communication, 1982). Above these fine-grained sediments is a polygenetic conglomeratic series, containing pebbles of pink felsite, quartz porphyry, granites, andesites, limestone, shale and vein quartz. Pebbles of granitic gneisses have been recorded (Hussein, 1977). Desiccation cracks, shale flakes and ripple marks indicate a shallow-water or terrestrial origin. Andesitic lavas, often highly vesicular, with some interbedded lapili tuffs follow conformably.

The area northwest of the ophiolite (areas F and G, Figs. 2, 8c, d)

The rocks in the northern part of area F are interpreted as an olistostrome, comprising red shales, silicified black shales, cherts and pillow lavas. This association is unlike any seen in the Nafirdeib Series; it suggests an oceanic environment and if so, probably represents the sediments deposited on top of the ophiolite sequence. However, nearer to the main Sol Hamed ophiolite there is a sequence of fine-grained volcaniclastic turbidites, facing southeastwards towards the ophiolite. Northeastwards, the outcrop of these volcaniclastic turbidites widens so that at area G, a thickness of ca. 1 km consistent-

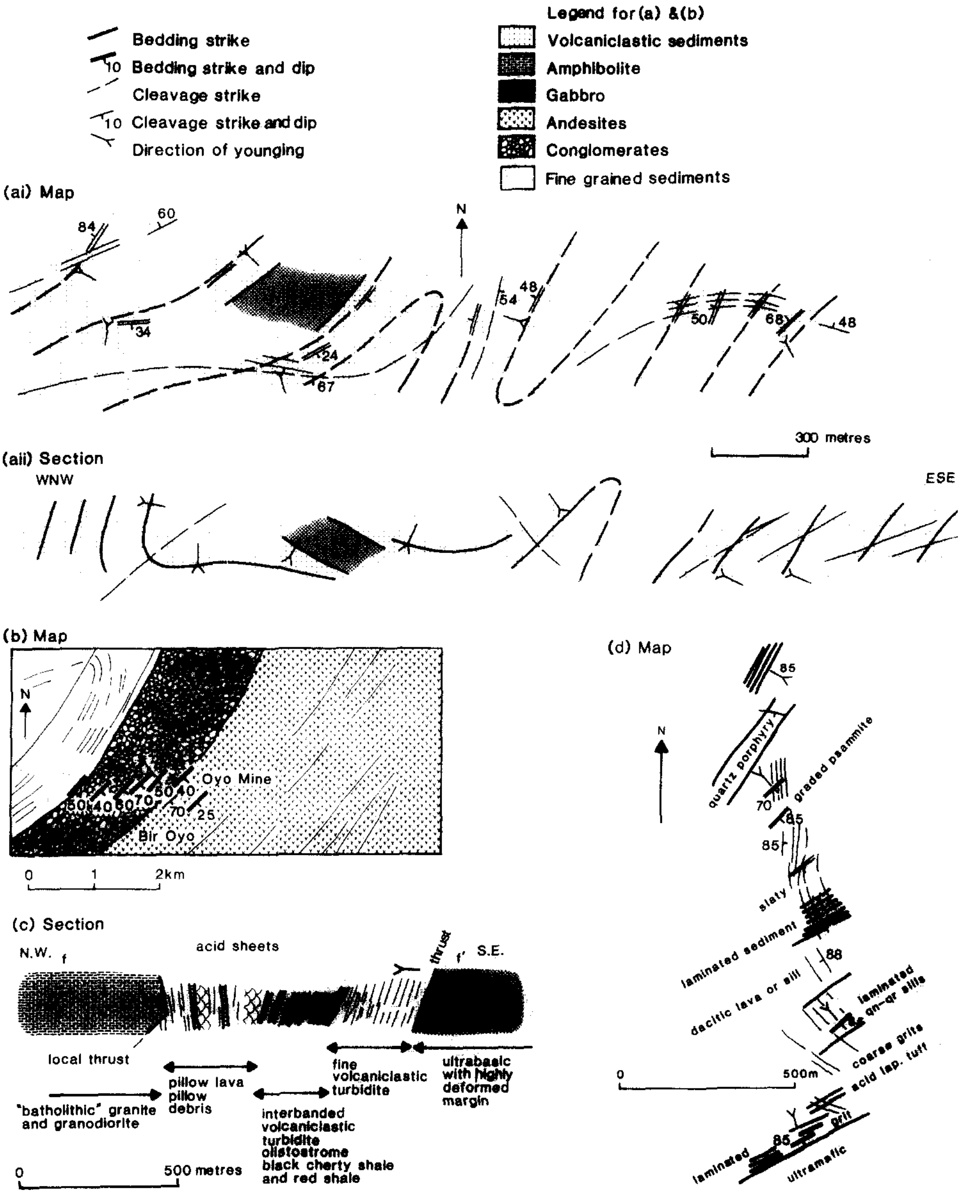


Fig. 8. Maps and interpretative sections (see Figs. 2 and 4). (a) Area D, SE of the ophiolite: map and section showing pre-cleavage folds. (b) Area E, Wadi Oyo: map. (c) Area F, NW of the ophiolite: section. (d) Area G, N of the ophiolite: map.

ly facing southeastwards towards the Sol Hamed Complex, is exposed between the Sol Hamed ultramafic zone and a conspicuous quartz-porphyry sill N of it. The rocks consist of homogeneous and laminated grey slates and siltstones, acid lapilli tuffs, coarse gritty tuffaceous sediments, and a dacitic rock, possibly a sill, about 150 m thick.

Correlation

Within the area studied, the sequence in the Nafirdeib Series varies quite rapidly, but the similarities from area to area are close enough to leave no doubt that they all belong to one assemblage, with ophiolite-dominated conglomerates at the base, limestone-dominated to polygenetic conglomerates above, then thick felsitic and dacitic volcaniclastic sequences, olistostromes, one with huge limestone slabs, and andesitic volcanics towards the top part of the exposed sequence. There appears to be a southward increase in thickness of the conglomerates and of the andesites into the Wadi Oyo area. Much thicker limestones, probably, but not necessarily on the same horizon, are known about 80 km SE of Sol Hamed.

Model for the deposition of the Nafirdeib Series (Fig. 9)

The Nafirdeib Series clearly suggests a volcanic island environment. The breccias in the lower part of the sequence are similar to those described from the New Hebrides Miocene volcanic arc. For the New Hebrides, Mitchell (1970) suggested that fine-grained rudites, with oriented clasts, and structureless rudites were derived from subaerial volcanic rocks in near-shore marine deposits, which were then transported as subaerial or submarine cold lahars into a deeper marine environment. Similarly, the limestone-bearing breccias resemble the structureless calcirudites and fine grained calcirudites with orientated clasts, derived from fore-reef talus, again transported as submarine calcareous mud flows into deeper water. Other facies also compare closely with those described by Mitchell (1970). The environment envisaged for the volcaniclastic suite therefore is that of an island arc, where volcanic

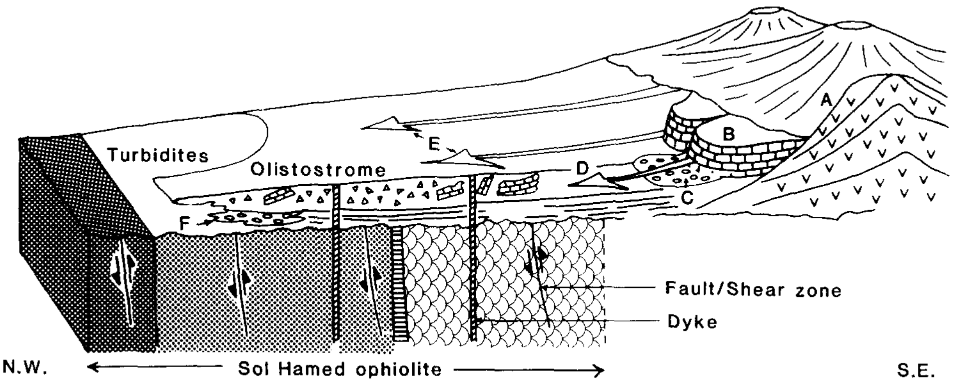


Fig. 9. A generalised model for the formation of the Nafirdeib Series; A— Volcanic Pile, B—Carbonate Platform, C—Peri-platform debris, D—Carbonate debris, E—Volcanic debris, F—Gabbroclast conglomerate (ornament as in Fig. 2).

material, which accumulated subaerially and in shallow water on the volcano flanks, slid off under gravity or was carried down by rivers, or both, and then transported into deeper water by mud flows or lahars.

Fringing the volcanic islands was a carbonate platform on which very shallow water, oolitic and pisolitic, dolomitic limestones and black shales were accumulating. The platform terminated in submarine cliffs below which peri-platform oozes, submarine talus and carbonate sands were deposited on slopes, called by-pass margins by McIlreath and James (1979), leading down to deeper water. Blocks, detached from the cliffs, accumulated as peri-platform talus, or slid further down slope to form the carbonate olistostrome. Channels, cut back into the platform funnelled volcanic debris, from the island through the platform, forming submarine fans on the peri-platform slopes and mixing peri-platform and platform carbonates with volcanic material, and spreading them out towards the basin to form breccias and turbidites (cf. Mitchell and Reading, 1971, Fig. 5 and p. 61). The positions of the volcanic islands and fringing platforms relative to the uplifted Sol Hamed complex are not known.

Units which do not conform to this general model are the breccias, infilling depressions on the ophiolite surface, and the gabbro-pebble conglomerates (Fig. 6b). Both units are characteristic of high-energy, shallow-water conditions and were deposited before the Sol Hamed complex was submerged beneath deeper water.

DEFORMATION HISTORY

The structure of the Sol Hamed area is complex, and incompletely understood, but the main elements are presented as far as possible, in chronological order.

The early flattening fabric in the ophiolite

A penetrative flattening fabric, associated with a mineral lineation, exists in the ultramafic rocks and extends up into the layered sequence. This fabric ($^{F}1$) is a high-temperature ductile fabric, not seen in the surrounding volcanic—sedimentary sequence and is assumed to be related to horizontal ductile shear in the mantle. In most cases it is parallel to the compositional layering, but occasionally there is an angular difference of up to 10°, both in the ultramafic zone and the gabbros, the tectonic fabric generally being the steeper. This fabric is particularly well seen in dunitic pods, in which chromite grains are flattened in a plane oblique to the banding. In the gabbros, both the layering and the flattening fabric appear to be folded on sub-vertical axes. Such folds are suggested by the continuously curving strike of the layering, shown by the broken lines on Fig. 2, and by the girdle, with a vertical axis, found by plotting the gabbro layering on a stereogram (Fig. 3a).

Upturning of the ophiolite

A major pre-Nafirdeib deformation upturned the whole ophiolite slab so that it dips nearly vertically, striking NE—SW and facing SE. Some of the shear zones trending NE/SW within the ophiolite, such as those bounding the serpentinite slice in the gabbros, between locations H and G (Fig. 2), are presumably associated with this deformation, since they do not affect the unconformably overlying Nafirdeib Series.

Shear zones in the ophiolite

Shear zones in two sets, trending NE/SW and E/W, cut the ophiolite and are particularly evident in the gabbros. They are typically between a few centimetres and one metre wide and generally dip steeply with no consistent sense of displacement. These shear zones pre-date the deposition of the Nafirdeib volcaniclastic rocks, but post-date the sub-oceanic fabric. Serpentinites, containing chromites aligned in the earlier planar fabric, have been variably rotated between shear planes giving the relative ages of the two structures. From the style of deformation, it is also inferred that the shear zones are later. The earlier fabric probably reflects a more plastic, deeper level deformation mechanism consistent with structures generated by early ocean-floor processes, whereas the shear zones represent a higher level, less ductile deformation probably connected with the emplacement of the ophiolite. They probably post-date the upturning of the ophiolite, since rotating the ophiolite back to horizontal would also bring the NE—SW shear zones to horizontal, an unlikely attitude.

Pre-cleavage folds in the Nafirdeib Series

In a few places S of J. Gash Amer, small folds can be seen, which are crossed by, and are earlier than, the first cleavage. Elsewhere, larger folds can be inferred from changes in facing direction (if the way-up evidence, mainly grading, is valid) without any corresponding change in bedding-cleavage sense (Fig. 8a). These large pre-cleavage folds may be slump folds. If so, the asymmetry implies slumping from NW to SE (Fig. 8a). A series of small slump folds in a near-by locality indicates slumping from W to E.

Deformation affecting both the Nafirdeib Series and the ophiolite

In the area as a whole the dominant trend of the cleavage, the folds and the strike of the formations is about NE/SW (Fig. 1). The axial traces of the folds N and S of J. Gash Amer, and those suggested by a photogeological study of the area north of Oyo Mine (Fig. 5), are parallel to this NE/SW trend and there is a cleavage, axial planar to these folds. Fold axes with this trend are evident on a stereoplot (Fig. 3b). However, locally the strike of the cleavage varies considerably, but with two maxima trending NE/SW and NW/SE (Fig. 3c). The two maxima correspond to two distinct cleavages, with the NE/SW being the earlier. Crenulation of one by the other has not been seen, probably because the cleavages are often weak and, except in pelitic rocks, are rare. A pencil lineation, produced by the intersection of the two cleavages, is seen NW of the ophiolite. In that area the cleavage trending NW or NNW cuts, at a high angle, across beds, which were already dipping steeply and striking NE/SW, with folds of the same trend. The first cleavage generally dips steeply to the NW (Fig. 3c), but SE dips often occur.

The second cleavage, striking about NW and dipping SW (Fig. 3c), is essentially localised in a shear zone at the NE side of the main part of the Sol Hamed ophiolite. It is associated with a very strong extension lineation plunging SW down-dip on the cleavage (Figs. 2, 3b). This cleavage is axial planar to small folds such as those seen at the exposure of the unconformity (Fig. 6b). Extension parallel to this direction in the shear zone produced constrictional fabrics: in places gabbro pebbles in the overlying Nafirdeib conglomerates are spectacularly stretched with tensile fractures and pressure shadow zones filled with calcite fibres, which have grown parallel to the X direction. Towards the NE, away from the shear zone, the strain diminishes, constrictional fabrics give way to flattening fabrics and then the strain dies out.

Deformation at the base of the ophiolite complex

Near the NW contact of the ophiolite, deformation zones, which increase in intensity down towards the base of the ophiolite, are somewhat irregular, but generally fairly steep. Stretching is mostly downdip, symmetry is $\alpha > k > 1$. This contact is interpreted as a thrust, upon the SE side. In places, along the NW contact of the ultramafic rocks against tuffs (Fig. 8c), intense shearing has reduced the ultramafic rocks to a tectonic mélange.

In the volcaniclastic rocks to the NW of the ophiolite (area G) the later, NW-trending cleavage, curves sinistrally through about 70°, over a distance of 1 km, into the thrust, as though there has been sinistral movement on the contact (Fig. 8a). Deformation may have been intense enough to cause rotation of pebbles and fold hinges into the stretching (movement) direction, or superimposed strains may be responsible.

GEOCHRONOLOGY

The data points on Fig. 10 represent volcanic rocks, basalts and andesites, collected from the Nafirdeib Series within the area shown in Fig. 5. A characteristic feature of Pan-African age rocks in NE Africa and Arabia is the very low Rb values (Gass, 1977). At Sol Hameed very low Rb/Sr ratios (average 0.042) were obtained. Eight points (Table I) give a Rb/Sr whole-rock age of 712 ± 58 Ma with a $^{87}Sr/^{86}Sr$ initial ratio of 0.7023 ± 1 (Fig. 10). The samples

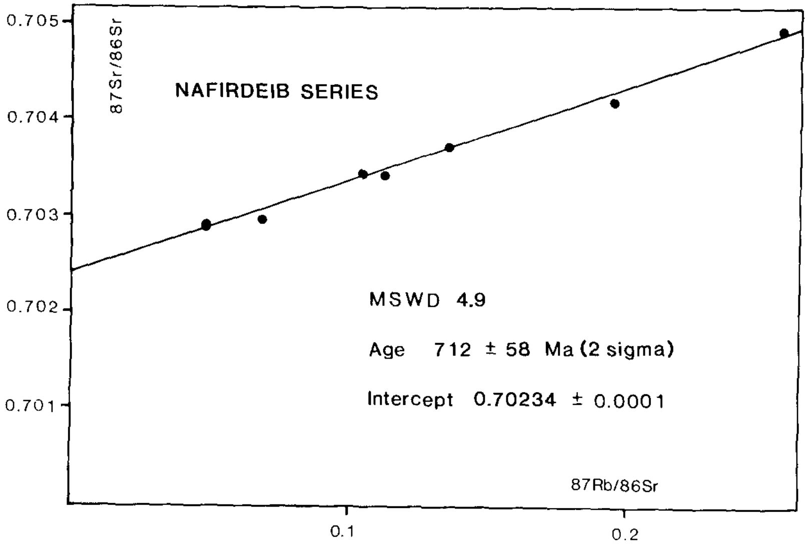


Fig. 10. Rb/Sr whole-rock isochron plot for the Nafirdeib Series.

TABLE I

Rb/Sr data for the Nafirdeib Series

Sample no.	Rb (ppm)	Sr (ppm)	(1) $^{87}Rb/^{86}Sr$ (± 1.0%)	(2) $^{87}Sr/^{86}Sr$ (± 0.01%)
136A	10.71	645.17	0.0492	0.70289
136C	7.97	474.63	0.0492	0.70292
53	17.88	457.76	0.1128	0.70344
83A	18.41	394.10	0.1360	0.70376
83C	22.05	327.91	0.1938	0.70423
89	29.65	336.37	0.2546	0.70499
91	11.17	307.76	0.1041	0.70342
137A	10.17	430.66	0.6941	0.70293

(1) $^{87}Rb/^{86}Sr$ ratios measured by XRF on an automatic Phillips spectrometer at the Geochemical Division, Institute of Geological Sciences. (2) $^{87}Sr/^{86}Sr$ ratios measured on the automated V.G. Micromass 54E mass spectrometer at the Open University. Ratios normalised to a value of 0.71014 for NBS 987. Isochron fitted using a modified version of the technique described by York (1969) assuming $\lambda^{87}Rb = 1.42 \times 10^{-11}\,yr^{-1}$. All errors quoted are at the two sigma level and have been multiplied by $\sqrt{MSWD}$.

show alteration, with abundant chlorite, sericite, some epidote and muscovite, consistent with low-grade greenschist-facies metamorphism, but not sufficient to mask original extrusive textures, such as twinned plagioclase phenocrysts and trachytic textures, although enough perhaps to cause some redistribution of radiogenic Sr and a consequent scatter of data points (Fig.10). In view of the low $^{87}Sr/^{86}Sr$ initial ratio, which plots below the mantle growth curve for that time (Duyverman and Harris, 1982), it is considered, from the age dates, that the Nafirdeib Series was extruded with little or no crustal contamination.

Some geochronological control for the sequence in the Red Sea Hills of Sudan and in the Eastern Desert of Egypt is available:

Red Sea Hills, Sudan	Central eastern desert, Egypt
	Younger granites ca. 615—570 Ma (1,2)
	Hammamat (molasse) sediment
	Dokhan Volcanics 602 ± 13 Ma (3)
	Calc-alkaline volcanics (W. Arak and Massar, W. El Mahdaf, W. Sodmein) ca. 612—618 Ma (2,3)
Younger granites (ten) 633 ± 19 Ma (4)	
Asoteriba volcanics 649 ± 18 Ma (4)	
Batholithic granite (core) 669 ± 20 Ma (4)	W. El Mia granadiorite 671 ± 33 Ma (3)
Batholithic granite (margin) 686 ± 18 Ma (4)	Qtz diorite, southeastern desert 711 ± 7 Ma (5)
Nafirdeib Series (volcanics) 712 ± 58 Ma	
	Older granitoids ca. 987—640 Ma (6)

Sources: (1) Fullagar and Greenberg (1978), (2) Ries and Darbyshire (1983), (3) Stern (1979), (4) Cavanagh (1979), (5) Dixon (1979) and (6) Hashad (1980).

According to the above figures, the Nafirdeib Series is older than the batholithic granite, although the ages overlap when the errors are taken into account. However, the field evidence confirms that the Nafirdeib Series is older and is everywhere intruded by the batholithic granite. The Sol Hamed complex is, therefore, certainly older than ca. 712 Ma and may be of similar age to the Jabal Al Wask ophiolite in Saudi Arabia, from which De la Boisse et al. (1980) obtained a U/Pb zircon age of 880 Ma for a gabbro.

GEOCHEMISTRY

Major and trace element data for the Nafirdeib volcanics are given in Table II. Due to secondary effects, some of the major element values have changed, masking the calc-alkaline nature of these rocks. Plots of Ti against a number of fractionation indicators, e.g. Zr, FeO/MgO, SiO_2 show negative

TABLE II

Major and trace element data for the Nafirdeib Volcanic Series

	Wadi Oyo (area E)		NE of ophiolite (area C)	SE of ophiolite (area D)		
	Basalts (4)	Dacite (1)	Andesites (2)	Basalts (4)	Andesites (10)	Dacites (2)
SiO_2	49.99	64.72	53.58	49.97	58.98	63.71
TiO_2	1.62	0.68	1.14	1.26	0.70	0.56
Al_2O_3	14.38	16.05	13.51	13.98	15.94	15.68
FeO*	11.92	4.52	9.18	10.91	6.60	4.72
MnO	0.18	0.07	0.13	0.16	0.11	0.07
MgO	7.37	2.14	9.88	10.45	5.30	3.87
CaO	8.07	5.31	8.42	8.45	5.21	5.65
Na_2O	3.19	4.51	3.07	2.37	4.14	3.69
K_2O	0.73	0.83	0.60	0.56	0.84	0.55
P_2O_5	0.44	0.14	0.19	0.23	0.15	0.11
LOI	2.43	2.02	—	—	1.88	2.35
Total	100.32	100.99	99.70	98.34	99.85	100.96
Rb	17	18	3	10	12	11
Sr	399	492	491	410	484	504
Ba	—	—	296	226	231	177
Nb	3	5	5	3	3	3
Zr	107	129	118	123	117	82
Y	28	13	18	29	19	12
Cr	—	—	733	350	113	—
Ni	—	—	188	96	38	67

*Total Fe_2O_3 and FeO.

Majors run on Open University EDXRF. Traces run at The Open University and Nottingham University. Average concentrations listed, oxides in wt%, traces in ppm, (—) not analysed.

slopes throughout the evolution of the suite. This is characteristic of calc-alkaline suites and implies magnetite fractionation (Miyashiro and Shido, 1975). Volcanic rocks at destructive plate margins have distinctive geochemical patterns relative to MORB (Pearce et al., 1981; Pearce, 1982). Elements, of low ionic potential (Sr—Ba) are mobilized by fluids driven off the subducted slab and are enriched in arc environments. These elements plus Th, Ce, P and Sr are also enriched in the Nafirdeib volcanics and indicate calc-alkaline affinities (Pearce, 1982). The low ($\leqslant$ 7 ppm) Nb for all SiO_2 values is again characteristic of arc magmas. On a Ti—Zr distribution plot (Fig. 11) most of the data plot within the arc field. The geochemical data support the field evidence for an island arc environment.

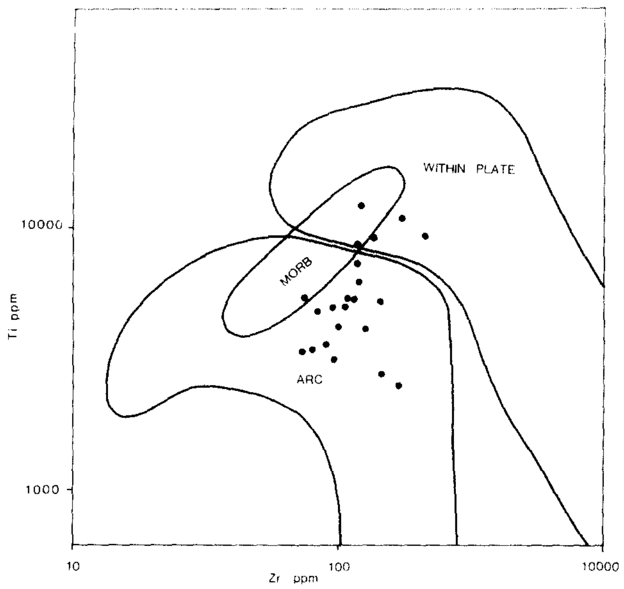


Fig. 11. Ti/Zr plot for the Nafirdeib Volcanic Series.

TECTONIC INTERPRETATION

The main Sol Hamed ophiolite complex dips steeply, generally towards the southeast, and although it is probably not a continuous sequence, but a series of tectonic slices and lenses, the arrangement of the units shows that it faces towards the SE. As it is surrounded by younger rocks, either unconformable on it or intrusive into it, its emplacement can only be inferred from internal structures. Whether it occurs on a suture, or is in an ophiolitic mélange like the ophiolites in the eastern desert of Egypt (Shackleton et al., 1980), cannot be judged from the field evidence at Sol Hamed. Perhaps the fact that it is sheared into slices, like those in the ophiolite on the Indus—Tzangpo suture (Shackleton, 1981), rather than the internally less deformed blocks in the ophiolitic mélange of the eastern desert of Egypt, supports the idea that it lies on a suture. Other ophiolites in Sudan, the nearest at Wadi Onib about 100 km SW of Sol Hamed, appear to lie on a single line, possibly a suture (Fig. 1). No mélange comparable to the regional ophiolitic mélange of Egypt has yet been recognised in Sudan. It is, therefore, suggested that the Sol Hamed ophiolite occurs on a suture. If so, the Benioff zone probably dipped southeastwards, since the ophiolite faces SE. The tectonic environment in which the ophiolite was formed, whether back-arc or open ocean, has not yet been determined.

After, or as a result of, its emplacement, the ophiolite was uplifted and eroded in an evolving island arc, and a large volume of volcaniclastic and volcanic material ranging from rhyolitic, through dacitic to andesitic and perhaps basaltic, accumulated on and around the ophiolite. This calc-alkaline magmatism must imply a Benioff zone outcropping in a trench at least 100 km away, and thus distinct from any earlier Benioff zone through Sol Hamed, if the complex does lie on a suture. The arc complex and the underlying ophiolite were then folded, cleaved and weakly metamorphosed during NW—SE compression and the ophiolite was upthrust relative to its cover, to the ENE. This deformation was not intense and probably does not imply collision. The folded complex was intruded by the grey batholithic granite and the younger granites, such as J. Gash Amer. Syenites, not dated, outcropping between Sol Hamed and Wadi Oyo, (Fig. 5) suggest a transition from island arc to within-plate magmatism.

In the small area studied there is no evidence of older continental basement. There are boulders of granitic gneiss in the Oyo conglomerates in the Nafirdeib Series, but these may well be early tectonized granites of the island arc assemblage, rather than earlier continental basement.

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