Precambrian Ophiolites and Related Rocks
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Chapter 4

NEOPROTEROZOIC OPHIOLITES IN THE ARABIAN SHIELD: FIELD RELATIONS AND STRUCTURE

PETER R. JOHNSON[a], FAYEK H. KATTAN[a] AND
AHMED M. AL-SALEH[b]

[a]*Saudi Geological Survey, PO Box 54141, Jiddah 21514, Saudi Arabia*
[b]*Geology Department, King Saud University, PO Box 2009, Riyadh,*
Saudi Arabia

Ophiolites make up a small but tectonically important part of the Arabian shield. Where most complete, they consist of serpentinized peridotite, gabbro, dike complex, basalt, and pelagic rocks. However, because of folding and shearing, the majority of the ophiolites lack one or more of these diagnostic lithologies. Nonetheless, the incomplete assemblages are identified as ophiolites because they minimally include peridotite and gabbro, in many cases are associated with basalt, and in all cases show evidence of emplacement by thrusting and shearing rather than intrusion. The ophiolites range in age from ~ 870 Ma to ~ 695 Ma, documenting a 200-million year period of oceanic magmatism in the Arabian shield, and are caught up in ~ 780 Ma to ~ 680 Ma suture zones that reflect a 100-million year period of terrane convergence. All the ophiolites are strongly deformed, metamorphosed, and altered by silicification and carbonatization. Low-grade greenschist facies metamorphism predominates, but in places the rocks reach amphibolite grade. Alteration resulted in the development of listwaenite, particularly in shear zones, and locally the only evidence that mafic-ultramafic rocks underlie a given area is the presence of upstanding ridges of listwaenite that are resistant to erosion. S/C fabrics are widespread and indicate that the ophiolites were affected by both strike-slip and vertical displacements. Variations in senses of shear observed along and across the strike evidence considerable strain partitioning during deformation. However, prevailing senses of shear can be discerned for several of the ophiolites that, in conjunction with other structural observations, indicate the main shear trajectories of the shear zones containing the ophiolites. Jabal Ess, Jabal Tharwah, and Bi'r Umq ophiolites were emplaced during periods of dextral transpression on the Yanbu and Bi'r Umq sutures, respectively. The Bi'r Tuluhah ophiolite was emplaced during sinistral transpression of the Hulayfah-Ad Dafinah-Ruwah suture, and the Halaban ophiolite was emplaced during west-directed convergence on the Halaban suture.

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1. INTRODUCTION

Neoproterozoic mafic-ultramafic complexes make up less than 1% of the surface area of the Arabian shield but, starting with the pioneering work of Al-Shanti and Mitchell (1976) and Bakor et al. (1976), they figure prominently in discussions of the origins of the shield because of their possible tectonic significance as remnants of oceanic crust and indicators of arc-arc suturing (Pallister et al., 1987; Stoeser and Camp, 1985). Certainly not all mafic-ultramafic complexes in the region are ophiolites—some are non-diagnostic lenses of sheared serpentinite, some are intrusions in the base of volcanic arcs, and some are layered intrusions—and care must be taken to avoid misidentification, misinterpretation, and spurious correlations (Church, 1988, 1991). Nevertheless, a significant number of complexes have the hallmarks of ophiolites. They are widespread in the shield along shear zones (Fig. 1) and, together with stratigraphic, geochronologic, and structural data, provide evidence of active ocean-floor magmatism in association with development of the tectonostratigraphic terranes in the shield and the process of suturing during terrane amalgamation (Pallister et al., 1988; Johnson and Woldehaimanot, 2003; Genna et al., 2002).

The mineralogy, chemistry, and tectonic settings of Arabian and Nubian shield ophiolites are reviewed by R.J. Stern and colleagues in a companion chapter in this volume. The purpose of this report is to describe the lithology, structure, and field relations of selected Arabian shield ophiolites, thereby providing examples of Neoproterozoic ophiolites and illustrating the outcrop characteristics and degrees of dismemberment and structural complexity that may be expected of Neoproterozoic ophiolites elsewhere. Of the ophiolites selected, Jabal Ess lies on the Yanbu suture at the join between the Midyan and Hijaz terranes in northwestern Saudi Arabia (Fig. 1). The Jabal Tharwah and Bi’r Umq ophiolites lie on the Bi’r Umq suture between the Hijaz and Jiddah terranes. The Bi’r Tuluhah ophiolite is at the northern end of the Hulayfah-Ad Dafinah-Ruwah suture joining the Hijaz-Jiddah-Asir terranes and the Afif terrane. The Halaban and Jabal al Uwayjah ophiolites are parts of the Halaban suture between the Afif and Ad Dawadimi terranes, and the Jabal Tays ophiolite is within the Ad Dawadimi terrane east of the Halaban suture. The Jabal Ess, Jabal Tharwah, Bi’r Umq, Bi’r Tuluhah, Halaban, and Jabal al Uwayjah ophiolites are believed to be rooted in the shear zones with which they are associated and, as such, mark the sites of consumption of oceanic crust. The Jabal Tays ophiolite, in contrast, appears to be part of a structurally detached ophiolite allochthon far traveled from its root zone.

2. JABAL ESS OPHIOLITE

The Jabal Ess ophiolite (Figs. 2, 3) comprises mantle peridotite, isotropic and layered gabbro, a dike complex, pillow basalt, and pelagic sediments metamorphosed in the greenschist facies and is the most complete ophiolite in the Arabian shield (Al-Shanti, 1982). It covers an area of approximately 30 km east-west, and 5 km north-south, and has a minimum estimated thickness of about 3 km. The ophiolite crops out in hills that rise 300 m

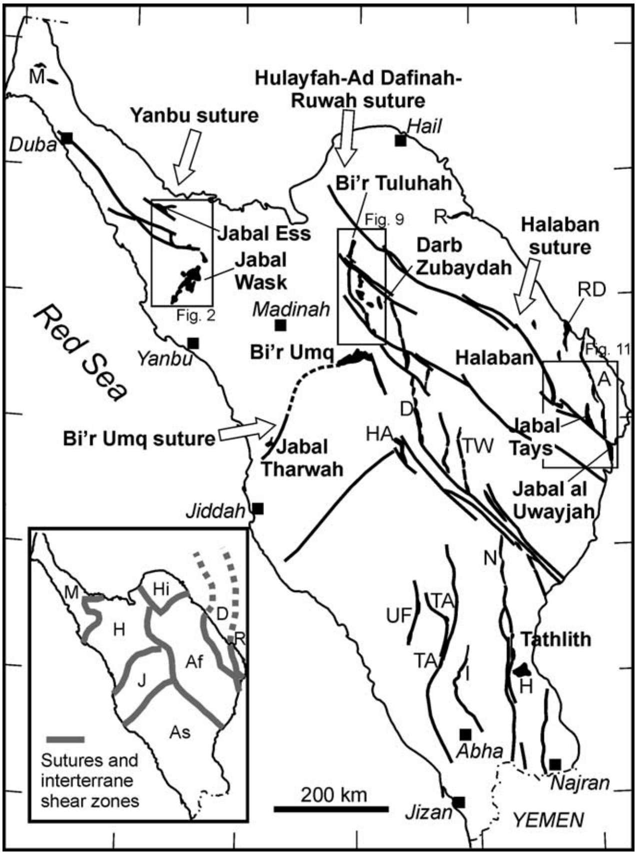

Fig. 1. Mafic-ultramafic complexes and major faults and shear zones in the Arabian shield, Saudi Arabia with an inset showing terranes and interterrane ophiolite-decorated sutures and shear zones. Complexes that satisfy criteria as ophiolites, are named; other mafic-ultramafic complexes (mostly serpentinite lenses along fault zones) are shown by initials. Complexes: A = Al Amar; D = Ad Dafinah; H = Hamdah; HA = Hakran; I = Ibran; M = Muklar; N = Nabitah; R = Rahah; RD = Ar Ridaniyah; TA = Tabalah-Tarj; TW = Tawilah; UF = Umm Fawrah. Terranes: Af = Afif; As = Asir; D = Ad Dawadimi; H = Hijaz; Hi = Hail; J = Jiddah; M = Midyan; R = Ar Rayn. Boxes outline areas of Figs. 2, 9, and 11.

above the surrounding valley bottoms and is well dissected by east- and northeast-flowing drainages, which provide good exposures of the underlying geology. To the east, the northern and southern boundary faults of the ophiolite converge, and the ophiolite tapers and ceases to be recognizable. To the west, the ophiolite is cut by the northwest-trending sinistral fault system of the Da'bah and Durr shear zones. Mafic-ultramafic rocks continue to the south as the Sahluj mélange (named here after Jabal Sahluj) and the Jabal Wask ophiolite (Fig. 2). Together with the Jabal Ess ophiolite, these mafic-ultramafic rocks are

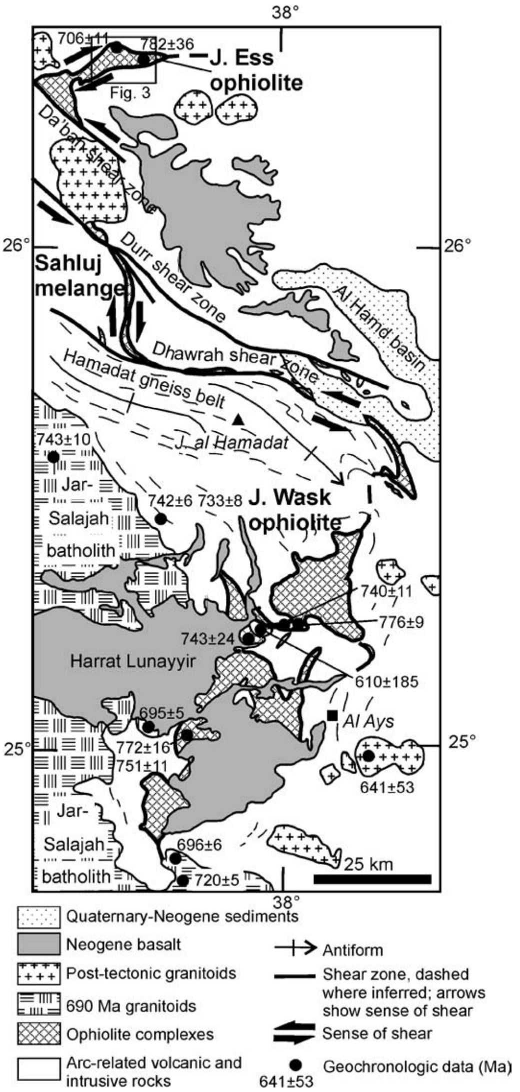

Fig. 2. Simplified geologic map and geochronologic data for the Jabal Ess-Jabal Wask ophiolite zone, which marks the Yanbu suture in the northwestern Arabian shield. Mapping after Kemp (1981) and Hadley (1987). Geochronologic data after Kemp et al. (1980), Ledru and Augé (1984), Claesson et al. (1984), and Pallister et al. (1988). Box shows area of Fig. 3.

parts of the zone of deformed rocks that constitute the Yanbu suture in Saudi Arabia, and its extension in Northeast Africa, the Allaqi-Sol Hamid suture (Kröner et al., 1987; Abdelsalam and Stern, 1995; Johnson and Woldehaimanot, 2003). (For details on the Jabal

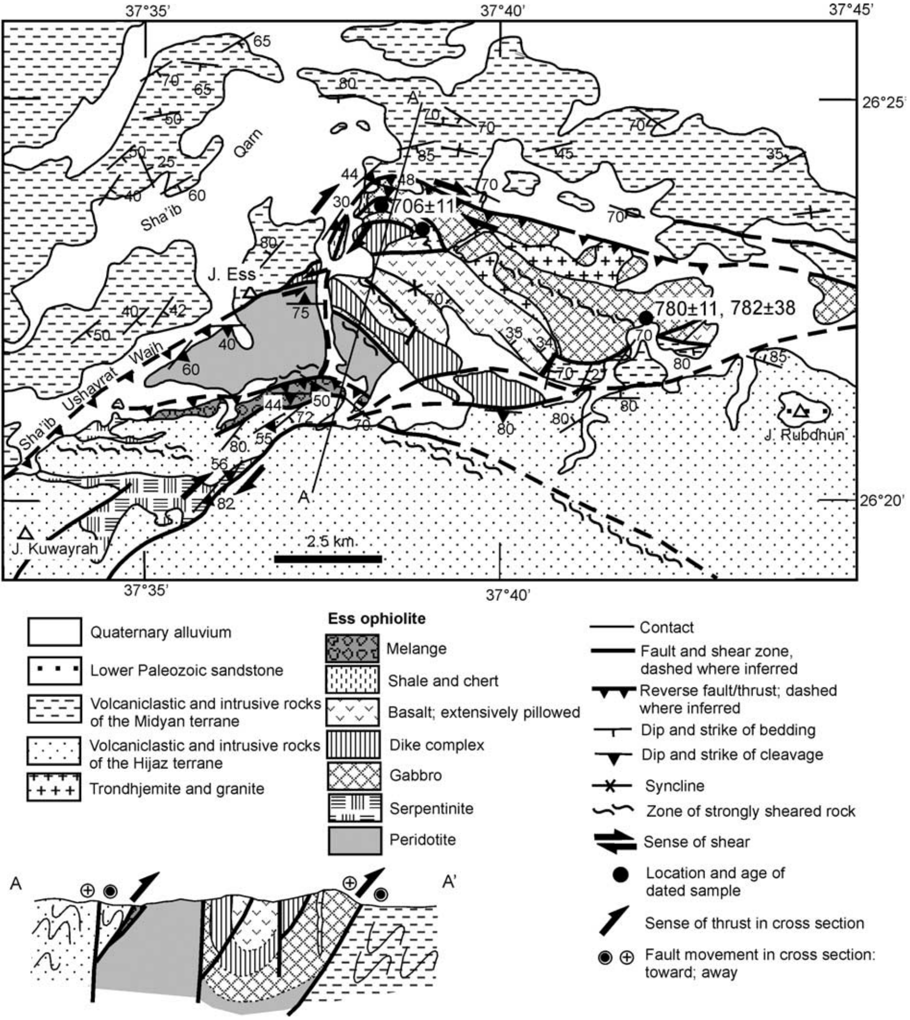

Fig. 3. Simplified map and cross section of the Jabal Ess ophiolite (after Al-Shanti, 1982; Chevrèmont and Johan, 1982b; and this report). Geochronologic data from Claesson et al. (1984); Pallister et al. (1988).

Wask ophiolite, see Bakor et al., 1976; Chevrèmont and Johan, 1982a; Ledru and Augé, 1984.)

Peridotite is mainly exposed on the southern slope of Jabal Ess in the central part of the ophiolite shown in Fig. 3. It is strongly altered and is chiefly black, massive serpentinite in which original textures are rarely preserved although sufficient primary features remain to locally indicate the presence of harzburgite, subordinate tectonized dunite, and cumulate wehrlite, orthopyroxenite, and serpentinite (Al-Shanti, 1982; Chevrèmont and Johan, 1982b). The harzburgite and dunite are concentrated in a zone of mantle peridotite as much as 500 m wide in outcrop. The harzburgite contains 5–20% bastite pseudomorphs after euhedral orthopyroxene in a serpentinized olivine ground mass (Shanti and Roobol, 1979). Dunite contains bastatized pyroxene ghosts and local disseminated chromite and podiform chromite lenses 20 cm across. Enstatite banding and trains of ovoid, stretched chromian spinel define a metamorphic foliation and lineation, which are suggestive of high-temperature subsolidus deformation possibly as a result of plastic mantle flow beneath a spreading ridge (Pallister et al., 1988). Olivine in the peridotite is magnesian rich with fosterite in the range Fo_{91}–$Fo_{92.7}$, orthopyroxene is close to enstatite, and clinopyroxene is mainly diopside (Chevrèmont and Johan, 1982b; Shanti, 1983). Chromiferous spinel is similar to that from modern forearc peridotites (Stern et al., 2004) and is present as anhedral grains enclosing olivine and less commonly as euhedral grains interstitial to the cumulate olivine in the dunite or enveloped in orthopyroxene in harzburgite (Chevrèmont and Johan, 1982b). The cumulate rocks, inferred by Al-Shanti (1982) to be a unit about 400 m wide overlying the harzburgite, consists of serpentinized wehrlite and orthopyroxenite in layers a meter or so thick intercalated with serpentinite several meters thick.

Gabbro is predominantly a dark, relatively featureless, massive rock, but locally has well-developed igneous lamination and rhythmic alternations of melanocratic gabbro and leucocratic anorthosite in layers as much as 20 cm thick (Fig. 4C). The gabbro is metamorphosed and, where strongly deformed, is mylonitized and brecciated, particularly in a narrow zone southeast of Jabal Ess where gabbro is exposed between peridotite and the dike complex and is tectonically intercalated with peridotite (Shanti and Roobol, 1979).

The sheeted dike complex is a unit as much as 600 m wide composed of metadolerite dikes 30 cm to 2 m wide. Its contacts with gabbro, below, and pillow basalt, above, are transitional. Outcrop features of the complex are commonly obscured by extensive desert varnish but, where exposure is favorable, the complex is seen to consist entirely of dikes that have fine-grained chilled margins and fine- to medium-grained cores (Shanti and Roobol, 1979).

The basalt unit includes pillow basalt (Fig. 4D), subordinate massive basalt flows as much as 10 m thick, and very sparse basalt breccia. It is estimated to be up to 300 m thick but because of folding and fault repetition is exposed over a width of nearly 2.5 km (Al-Shanti, 1982). Thin-skinned pillow lava characterized by amygdaloidal cores and rims of chloritized and (or) spherulitic basalt predominates. Khaki, locally siliceous shale and laminated chert crop out as interbeds 50 m thick in the pillow basalt and as isolated, strongly

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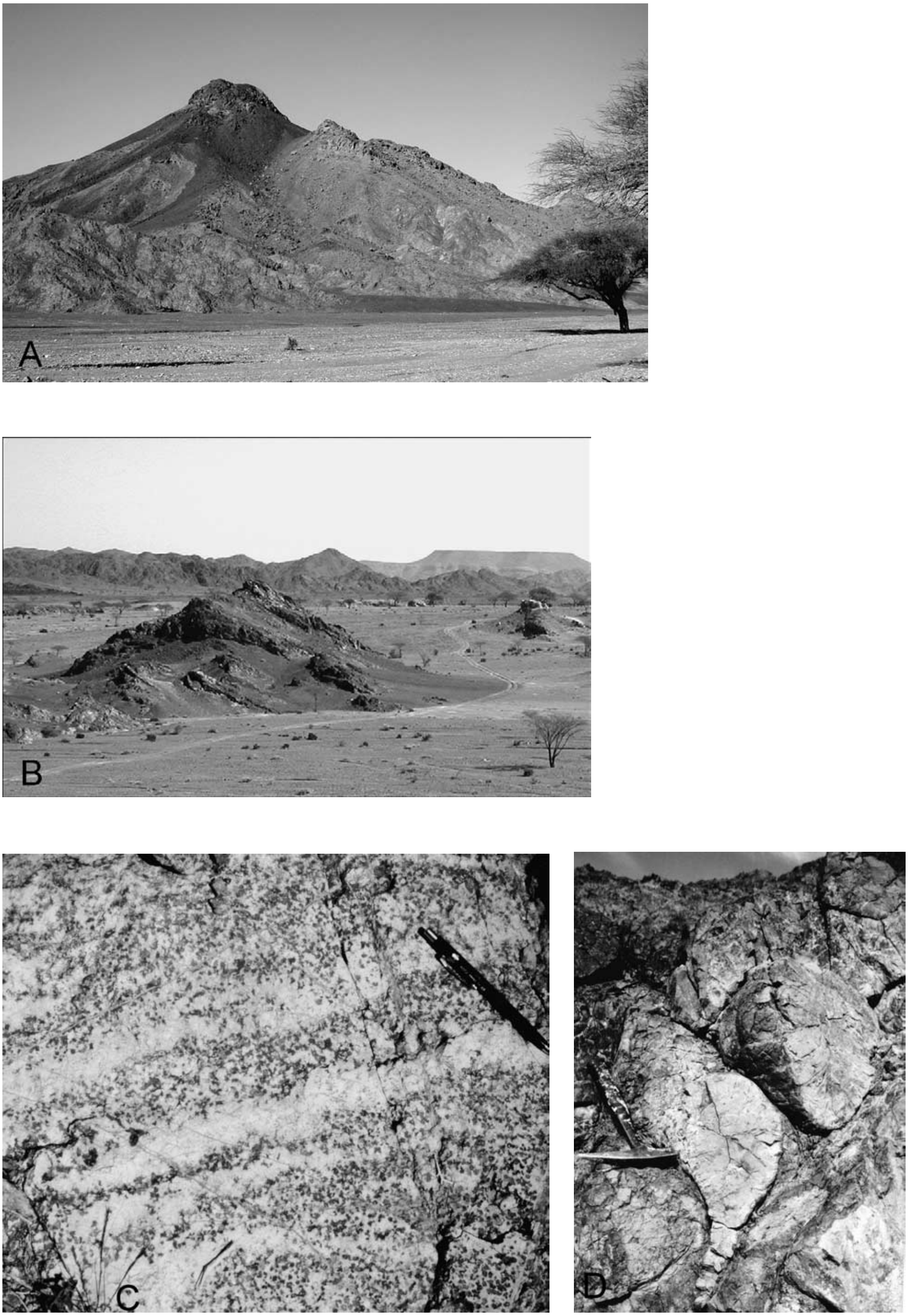
Fig. 4. Features of the Jabal Ess ophiolite. (A) View of Jabal Ess from the south showing north-dipping shear surfaces and (along ridge line) a north-dipping sheet of carbonated and silicified peridotite. Relief about 150 m. (B) South-dipping thrusts in serpentinite mélange at the southern margin of the ophiolite. (C) Rhythmic layering in metagabbro showing anorthosite intercalated with melanocratic gabbro. (D) Pillow basalt. (Photos C and D after Al-Shanti, 1982.)


A
B
C
D

sheared exposures at the northern boundary fault of the ophiolite (Shanti and Roobol, 1979), and are interpreted as pelagic sediments at the top of the ophiolite succession.

The complex is steeply dipping, and the exposures are effectively a cross-section through the ophiolite. The gross distribution of rock types suggests an ophiolite succession younging from south to north but the succession is disrupted by deformation. Igneous layering in the peridotite dips 40°–90°, mostly to the south; the basalt is folded into a series of anticlines and synclines; and the gabbro is repeated by folding and/or thrusting north of the basalt. Shear zones, characterized by serpentinite schist, secondary listwaenite, magnesite, and mélange, are abundant and dip between 30° and 90° south and north. Mélange, composed of angular to subrounded blocks of massive serpentinite, gabbro, dolerite, and basalt up to 50 m in diameter in a yellow to black serpentinite schist matrix, is particularly conspicuous as a subvertical shear zone as much as 500 m wide in the southern part of the ophiolite. A north-dipping unit of chert and listwaenite (Fig. 4A) marks the shear zone at the northern boundary of the ophiolite on Jabal Ess. South-dipping shear zones are common in the northern unit of gabbro and in the southern part of the ophiolite (Fig. 4B), and a subvertical shear zone forms the southernmost boundary of the ophiolite.

S/C shear fabrics are widespread. A dextral sense of horizontal shear predominates, but variation in the sense of shear along and across the ophiolite indicates that there was a large degree of strain partitioning in the ophiolite during deformation. The northern boundary fault, minor shear zones in the northern gabbro, and the shear zone at the southern margin of the ophiolite are dextral (Fig. 5A). A shear zone about 100–200 m south of the northern boundary fault about 1 km east of Jabal Ess summit is sinistral (Fig. 5B). The south dipping shear zones in mélange in the southern part of the ophiolite are both dextral and sinistral (Figs. 5C, D). Indicators of the sense of vertical movement on the shear zones have not been observed, but it is conceivable that south-dipping shears throughout the ophiolite are north-vergent thrusts. Worldwide, suture zones commonly display combinations of horizontal shearing and thrusting that reflect deformation during transpression. The structures at Jabal Ess, suggestive of north-vergent thrusting and regional dextral horizontal shear, are consistent with development under conditions of dextral transpression.

The Jabal Ess ophiolite is directly dated by means of a 780 ± 11 Ma U-Pb zircon age obtained from gabbro in the eastern part of the ophiolite (Pallister et al., 1988) and a 782 ± 36 Ma Sm-Nd mineral model age obtained from the same gabbro sample (Claesson et al., 1984). A younger U-Pb zircon age of 706 ± 11 Ma obtained from trondhjemite that intrudes already serpentinized and sheared gabbro provides a minimum age for ophiolite formation (Pallister et al., 1988). Both U-Pb ages are model ages, obtained by forcing the lower intercept through a fixed point of 15 ± 15 Ma, a procedure commonly applied to U-Pb geochronologic data in the Arabian shield (Cooper et al., 1979).

3. THARWAH OPHIOLITE COMPLEX

The Tharwah ophiolite complex (Nassief, 1981; Nassief et al., 1984; Pallister et al., 1988) consists of mafic-ultramafic rocks preserved as a stack of steeply dipping, northwest-

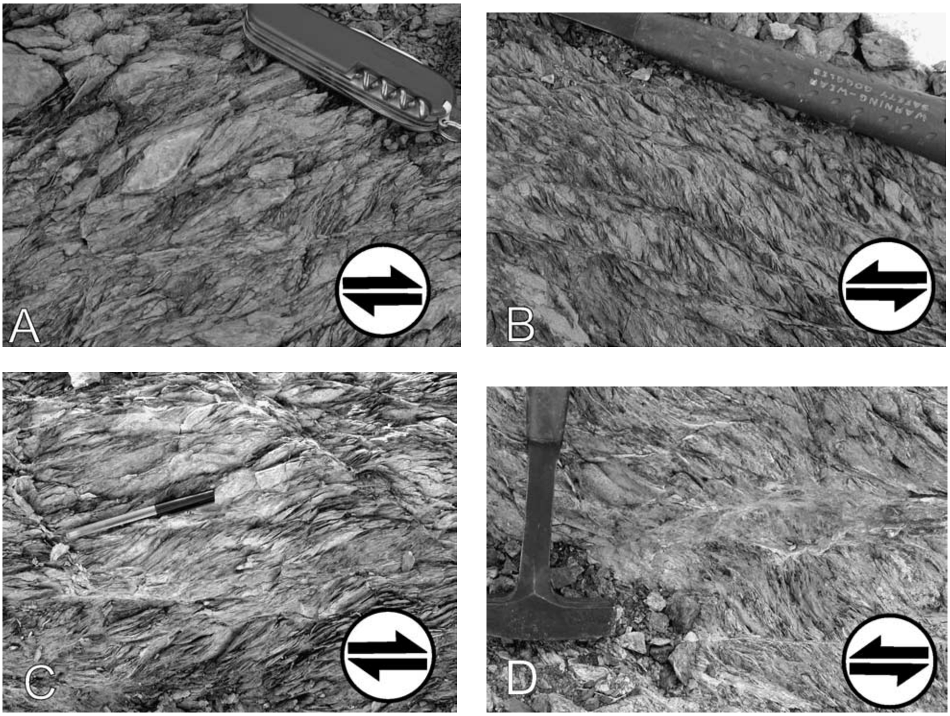


Fig. 5. Typical shear fabrics in the Jabal Ess ophiolite. (A) Dextral shear fabric in shear zone at the northern margin of the ophiolite. Knife for scale, about 10 cm long. (B) Sinistral shear fabric in serpentinite mélange south of the northern margin of the ophiolite. Hammer for scale. (C and D) Dextral and sinistral shear fabrics, respectively, about 5 m apart along strike in serpentinite mélange close to the southern margin of the ophiolite. Pen for scale in (C), hammer for scale in (D).

and southeast-vergent thrust sheets exposed over an area 13 km east-west and 6 km north-south (Fig. 6). Together with adjacent pelagic rocks, the ophiolite is part of the Labunah thrust zone (Ramsay, 1986) and lies in the zone of deformed rocks that constitutes the southwestern part of the Bi’r Umq suture (Pallister et al., 1988; Johnson et al., 2002). The ophiolite is exposed in hills rising 150–200 m above the adjacent Red Sea Coastal Plain. Weathering is locally intense and most rock surfaces are coated in desert varnish that, compounded by pervasive metamorphism and shearing, makes rock identification difficult.

The succession is disrupted and locally inverted. Serpentinized depleted-mantle harzburgite and subordinate dunite together with minor lenses and dike-like bodies of lherzolite and gabbro make up the central part of the complex. Harzburgite contains relict olivine ($Fo_{89.5–93.4}$) (70–90 mode%), bastite pseudomorphs of orthopyroxene ($En_{90–92}$) (15–30%), chromite (< 1%), and clinopyroxenes (< 1%). Dunite is largely serpentinized olivine. Chemically, the chromites resemble chromitiferous spinels in modern-day forearcs (Stern et al., 2004). The rocks are tectonized and have a strong, high-temperature foliation

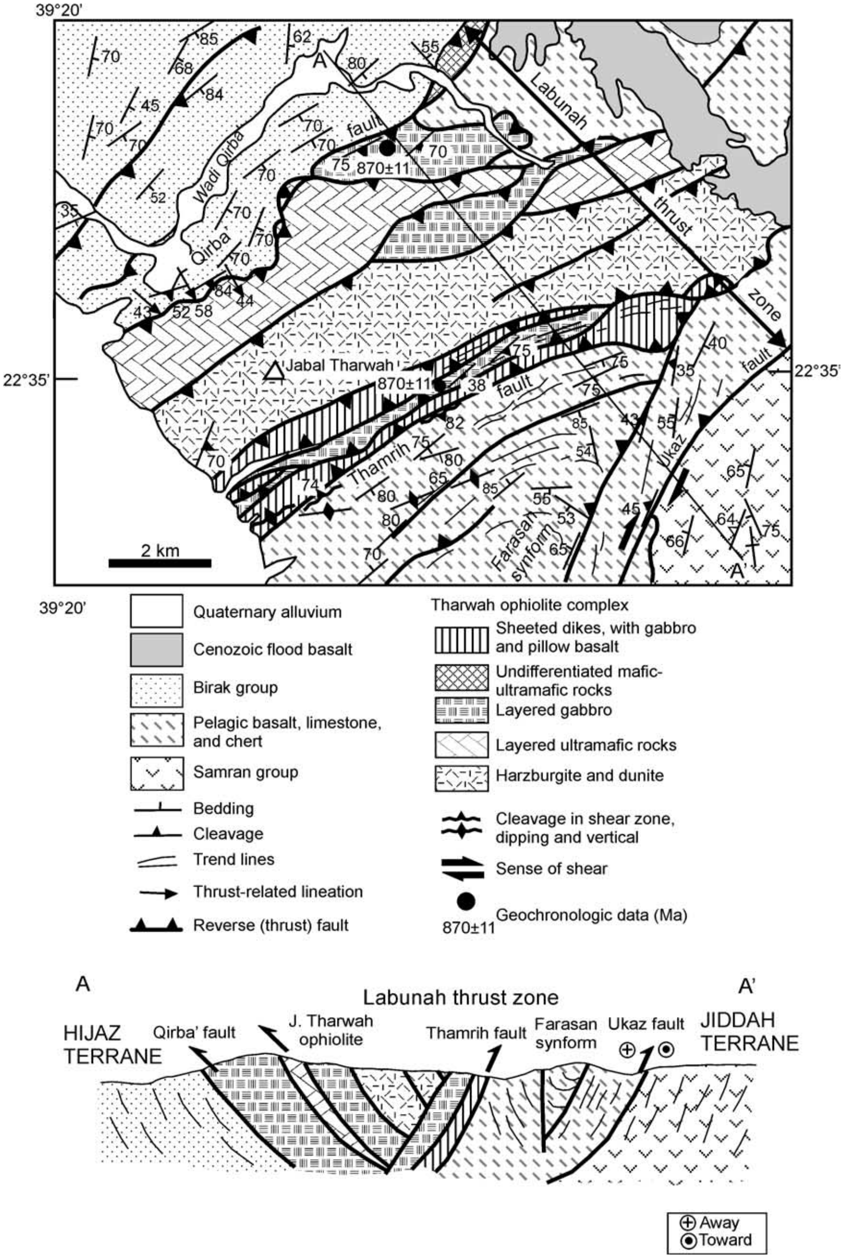


Fig. 6. Simplified map and cross section of the Jabal Tharwah ophiolite (after Nassief, 1981; Nassief et al., 1984; Ramsay, 1986; Pallister et al., 1988; Johnson, 1998). Geochronologic data after Pallister et al. (1988).

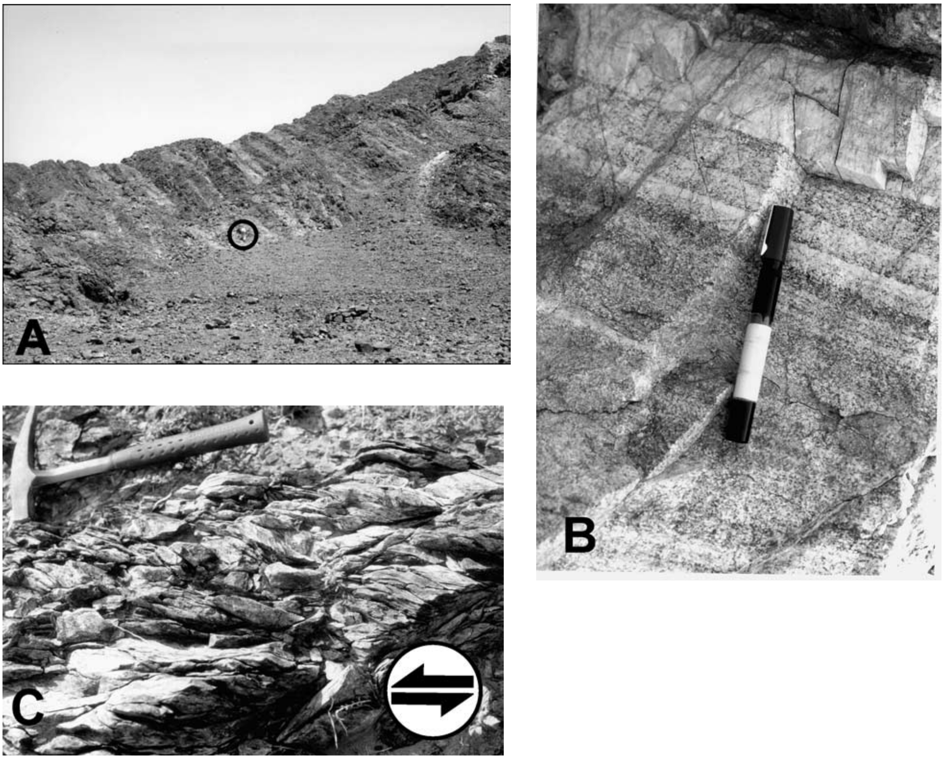


Fig. 7. Features of the Jabal Tharwah ophiolite. (A) Cumulate peridotite showing interlayering of dunite and pyroxenite (circle encloses bent-over person for scale). (B) Rhythmic layering in gabbro (pen for scale 12 cm long). (C) Sinistral shear fabric in the interior of the ophiolite (hammer for scale).

composed of orthopyroxene and chromite grains (Nassief et al., 1984). Cumulate ultramafic rocks crop out in the northern part of the complex as a unit of dunite, lherzolite, and pyroxenite intercalated in layers 1–10 m thick (Fig. 7A). The cumulate rocks are as much as 2.9 km thick, but are probably thickened by deformation from an original thickness of about 1 km (Nassief et al., 1984). Oriented pyroxene produces a weak igneous lamination, but a high-temperature deformational foliation of the type displayed by the peridotite is absent. Olivine is less magnesium rich than in the mantle peridotite ($Fo_{86.5–89.5}$) and clinopyroxene is chiefly diopside. Orthopyroxene, mostly present as exsolution laminae in clinopyroxene, is largely replaced by bastite but is preserved locally as grains of $En_{82–89}$ (Nassief et al., 1984).

Layered to locally massive gabbro is present in the north and south of the complex. It is metamorphosed in the greenschist facies, but has well-developed igneous lamination, cm- to m-scale plagioclase- and pyroxene-rich phase laying (Fig. 7B), and, to a lesser degree, grain-size layering (Nassief et al., 1984). Sheeted dikes crop out in fault-bounded units 10 km long and over 300 m thick at the southern margin of the ophiolite. The dikes are not as well exposed as the dike complex in the Jabal Ess ophiolite and, because of shearing and alteration, their protoliths are not always evident. However, Nassief et al. (1984) report that, in places, dikes comprise 50–90% of the outcrop and are observed to be 1–1.5 m wide, separated by screens of altered gabbro and basalt. Pillow basalt occurs in part of the dike complex. The rocks are strongly sheared and altered but bulbous pillow forms are still discernible (Nassief et al., 1984). Fine-grained argillaceous and cherty sedimentary rocks, carbonates, and basalt interpreted to be pelagic, ocean-floor deposits at the top of the ophiolite are faulted against the main mass of the Tharwah ophiolite south of Jabal Tharwah along the Thamrih fault and appear to be in depositional contact with the ophiolite northeast of Wadi Qirba'. Small lenses and veins of gabbroic pegmatite and leucodiorite or trondhjemite, probably representing late-fractionated derivatives of the gabbroic magma, intrude massive gabbro at the extreme northern edge of the complex along the Qirba' fault.

Layering in the cumulate unit is locally moderately inclined (Fig. 7A), but most structures in the Tahrwah ophiolite are steep. The Qirba' fault dips 50°–80° to the southeast; the Thamrih fault and shear zones within the complex are subvertical. The pelagic rocks south of the complex make up the southwest plunging (40°–50°) Farasan synform (Fig. 6). This has a steeply dipping northwest limb, a more gently inclined southeast limb, and is truncated by a southeast-vergent thrust along the southern flank of Jabal Farasan. The Ukaz fault at the southern boundary of the Labunah thrust zone is an oblique dextral, hanging-wall-up-to-the south steep reverse fault that juxtaposes the pelagic rocks with the Samran group (Johnson, 1998). An exceptional gently inclined fault exposed at a location about 6 km northeast of Jabal Farasan may be a remnant of an original thrust dipping 35°–43° to the northwest.

The structure of the Tharwah ophiolite and the Labunah thrust zone is believed to reflect two phases of progressive deformation (Johnson, 1998). The early phase caused northeast- and southwest-trending tight to isoclinal folding, the development of bedding-parallel shear surfaces, and thrusting. Folding during the second phase created the Farasan synform, folded and steepened early thrusts and shear surfaces, and refolded early isoclinal folds and lineations. The rocks were pervasively affected by non-coaxial strain during both phases of deformation and S/C fabrics, asymmetrical extensional-shear bands, winged porphyroclasts, and quartz-mosaic ribbons are widespread (Johnson, 1998). The Qirba' fault shows evidence of both sinistral and dextral horizontal as well as top-to-the-northwest reverse-slip movements; the Ukaz fault shows top-to-the-southeast and dextral horizontal movements; whereas shears interior to the ophiolite are commonly sinistral (Fig. 7C). Johnson (1998) proposes that the Tharwah ophiolite is a flower structure that developed in a zone of dextral transpression (see the cross section in Fig. 6) and, as in the case of the Jabal Ess ophiolite, the variations in sense of shear indicate considerable strain partitioning during its formation.

Zircon grains from gabbro in the northern and southern parts of the ophiolite yield a near-concordant U-Pb age of 870 ± 11 Ma (Pallister et al., 1988). Other gabbro zircon fractions are highly discordant, yielding ^{207}Pb/^{206}Pb model ages of about 1250 Ma. The 870 Ma result is not robust, but if provisionally accepted as a crystallization age, suggests ocean-floor magmatism 100 million years earlier than the Jabal Ess magmatism. The 1250 Ma age is likely to be an artifact caused by assimilation of xenocrystic zircons, similar to the explanation of anomalously old ages for some Bi'r Umq ophiolite zircon samples (Calvez et al., 1985).

4. BI'R UMQ OPHIOLITE COMPLEX

The Bi'r Umq ophiolite complex consists of serpentinized and carbonate-altered peridotite, gabbro, and mélange (undivided in Fig. 8), and a 1500-m thick succession of spilitic metabasalt, chert, and metatuff assigned to the Sumayir formation (Al-Rehaili, 1980; Al-Rehaili and Warden, 1980; Le Metour et al., 1982; Kemp et al., 1982; Pallister et al., 1988). The complex crops out in an area of about 60 km by 20 km at the northeastern end of the Bi'r Umq suture (Johnson et al., 2002). The ultramafic rocks and gabbro are concentrated in the south close to the Bi'r Umq and Wobbe faults and are a disproportionately small component of the ophiolite in comparison with other ophiolites described here. The ultramafic rocks and gabbro form a chain of discontinuous hills that have moderate relief of 50–75 m and are partly held up by more resistant listwaenite and chert. The Sumayir formation crops out in low-lying exposures north of the Bi'r Umq fault and is extensively covered by colluvium and alluvium. Mélange is mostly in discontinuous exposures along the Bi'r Umq fault. The ophiolite is truncated by the Arj fault on the west (west of the area shown in Fig. 8), a sinistral strike-slip structure belonging to the Najd fault system. The Raku-Mandisa faults truncate the ophiolite on the east. The Raku fault is a dextral shear of uncertain origin; because of poor exposure little is known about the Mandisa fault other than its trace, identified by a narrow, linear zone of listwaenite.

Peridotite at Bi'r Umq is interpreted by Le Metour et al. (1982) to be an ultramafic cumulate consisting of dunite and subordinate, locally cumulus harzburgite. The rocks were pervasively sheared during ophiolite emplacement (Le Metour et al., 1982) and are extensively serpentinized, carbonated, and silicified, which results in the common development of Cu- and Ni-rich listwaenite along shear zones. Olivine in the dunite is thoroughly replaced by serpentine and is only recognized as ghost pseudomorphs. Harzburgite contains cumulus serpentinized olivine and intercumulus bastite-altered orthopyroxene (Le Metour et al., 1982). Small intrusions of hypabyssal trondhjemite, plagiogranite (termed keratophyre by Pallister et al., 1988), diorite, hornblende gabbro, metadiabase, and basalt occur at, or in a separate thrust slice south of, the Bi'r Umq fault (Le Metour et al., 1982; Pallister et al., 1988). The Sumayir formation is predominantly a homogeneous, monotonous unit of fine-grained greenstone derived from basalt flows and tuffs and subordinate pillow basalt and basaltic breccia (Al-Rehaili and Warden, 1980). Diagnostic of their metamorphic grade, the rocks contain sodic plagioclase (An_{5-20}), secondary green tremolite, chlorite, epidote, iron oxide, and carbonate, with local relict clinopyroxenes. Minor metasedimentary units in the greenstone consist of thin-bedded felsic tuff, limestone,

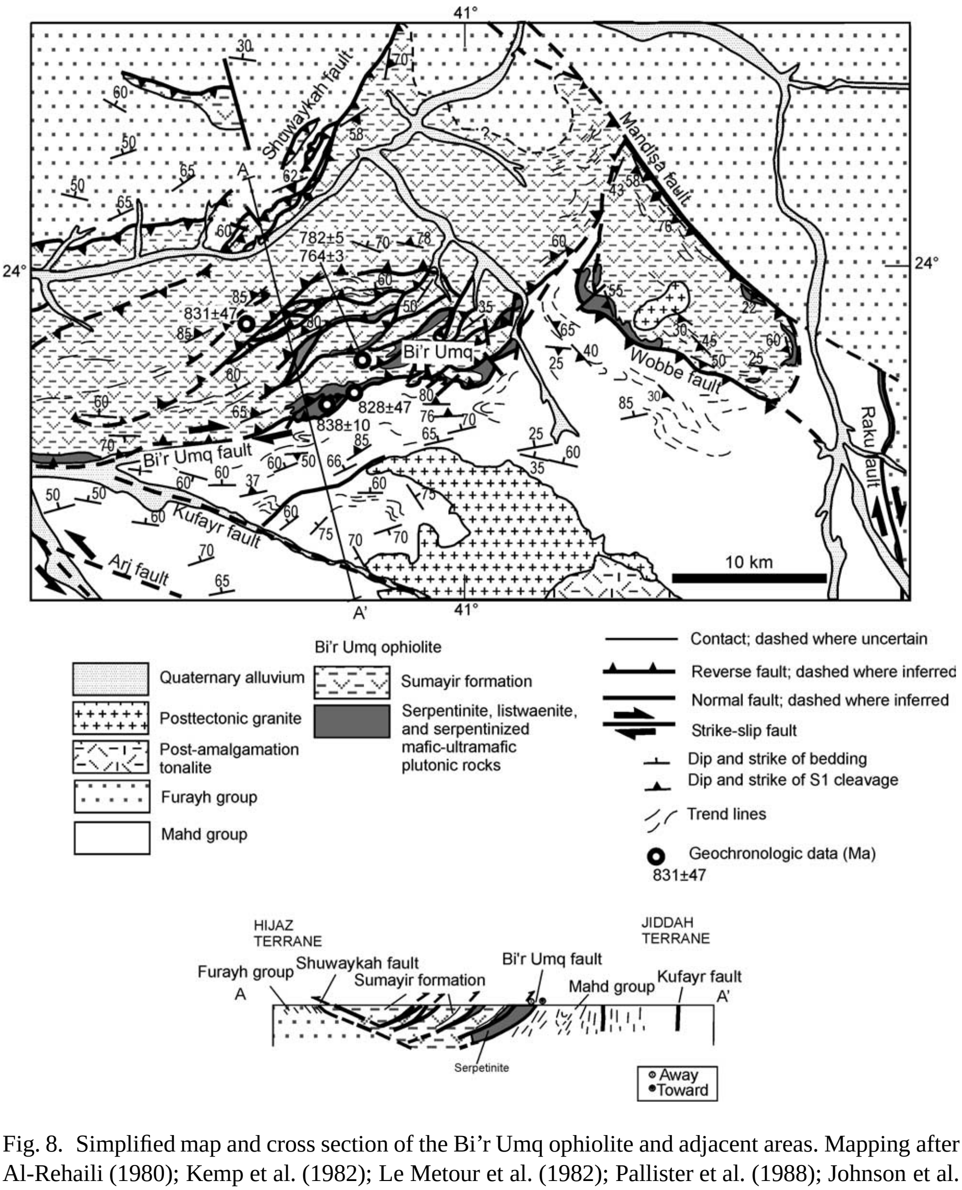


Fig. 8. Simplified map and cross section of the Bi’r Umq ophiolite and adjacent areas. Mapping after Al-Rehaili (1980); Kemp et al. (1982); Le Metour et al. (1982); Pallister et al. (1988); Johnson et al. (2002). Geochronology after Dunlop et al. (1986); Pallister et al. (1988).

chert, and siltstone, locally altered to mafic and felsic schist and amphibolite. Mélange consists of blocks of serpentinite, spilitic basalt, dolerite, and gabbro a few to several hundred meters across in a sheared serpentinite matrix.

Regionally, the Bi'r Umq ophiolite trends east-west, but is broadly folded about a north-south axis and in detail trends west-southwest in the west and east-southeast in the east (Fig. 8). The Bi'r Umq fault at its southern margin is a steeply (50°–70°) north-dipping reverse fault, and the Wobbe fault is a moderately (40°–50°) southwest-dipping reverse fault. The northern Shuwaykah fault is believed to be a high-angle southeast-dipping reverse fault (Johnson et al., 2002). The dip across the Bi'r Umq complex changes from steeply northwest in the south to steeply southeast in the north and the complex is interpreted by Al-Rehaili (1980) to be a large asymmetric synform, although a flower structure of the type shown in the cross section in Fig. 8 is our preferred interpretation. Pillow structures indicate that basalt units are right way up (Al-Rehaili and Warden, 1980). Shear fabrics and the down-dip plunge of stretching lineations indicate an early phase of top-to the south reverse dip-slip movement on a south-vergent thrust along the Bi'r Umq fault; later movement included dextral and sinistral horizontal shear (B. Blasband, written communication, 2001). The kinematics of the Wobbe fault are unknown.

The ophiolite is directly dated by a three-point U-Pb zircon model age of 838 ± 10 Ma obtained from diorite in the ophiolite close to the Bi'r Umq fault (Pallister et al., 1988). Trondhjemite and a pyroxene separate obtained from nearby gabbro yield a composite Sm-Nd isochron age of 828 ± 47 Ma (Dunlop et al., 1986), and Sumayir-formation basalt yields a three-point Rb-Sr whole-rock isochron of 831 ± 47 Ma (Dunlop et al., 1986). Single-point zircon model ages of 764 ± 3 Ma and 782 ± 5 Ma obtained from plagiogranite (or keratophyre) that cuts already serpentinized and carbonated peridotite and is interpreted to be a post-serpentinization and post-obduction intrusion constrain the minimum age of ophiolite emplacement (Pallister et al., 1988).

5. BI'R TULUHAH OPHIOLITE

The Bi'r Tuluhah ophiolite crops out in the northern (Hulayfah) part of the Hulayfah-Ad Dafinah fault zone in the north-central part of the Arabian shield (Fig. 9). The rocks are strongly folded and sheared and together with rocks of the Nuqrah formation constitute a subvertical brittle-ductile shear zone that resulted from sinistral transpression during suturing between the Afif and Hijaz terranes (Quick and Bosch, 1989; Johnson and Kattan, 2001). The suture continues as an ophiolite-decorated shear zone over 500 km to the south and southeast, and is one of the longer sutures recognized in the Arabian shield. Lithologic contacts in the fault zone are mostly faults so that original stratigraphic and structural relations are obscure, but an ophiolite is identified at Bi'r Tuluhah on the basis of the presence of amphibolite, serpentinized peridotite, layered gabbro, and noncumulus gabbro (Delfour, 1977). The ophiolite, the central part of which is shown in Fig. 10, is about 30 km long in a north-south direction and 6 km wide, and crops out in low-relief hills rising 10–40 m above the wadi plain (Kattan, 1983). The rocks are strongly weathered and intense coatings of desert varnish commonly cover outcrop surfaces. Volcanic and volcaniclastic rocks of the Hulayfah formation flank the fault zone on the west and epiclastic rocks and bimodal basalt and rhyolite of the Shammar group and Shammar

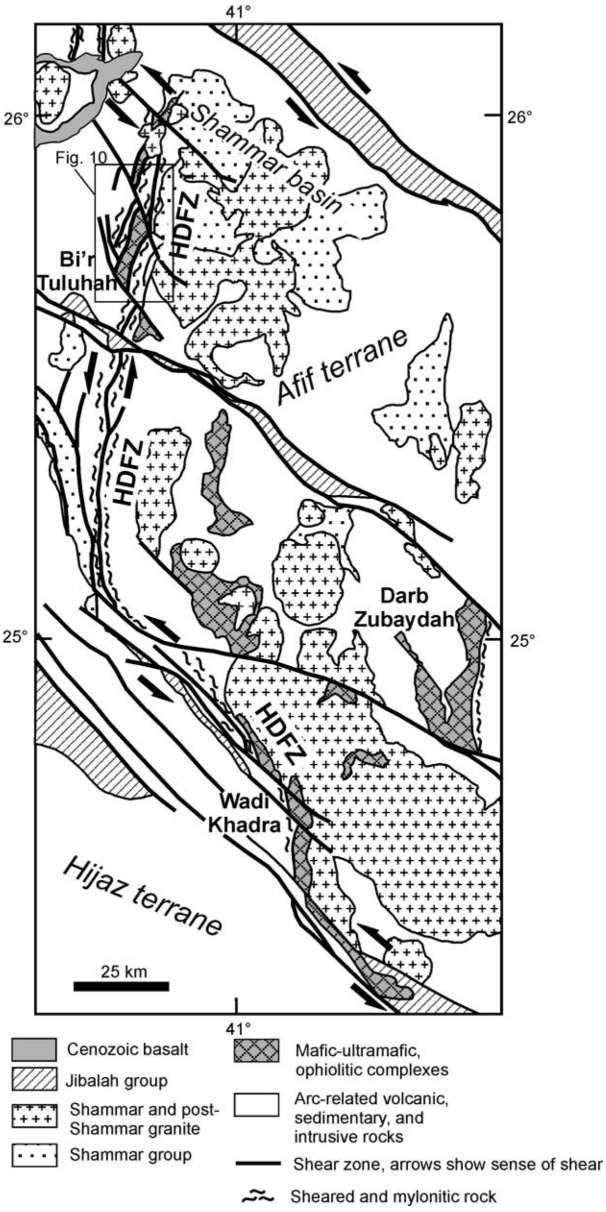


Fig. 9. Simplified geologic map showing the location of the Bi'r Tuluhah, Darb Zubaydah, and Wadi Khadra ophiolitic complexes along and east of the Hulayfah-Ad Dafinah fault zone (HDFZ), part of the Hulayfah-Ad Dafinah-Ruwah suture. The fault zone is overlain and intruded by post-amalgamation basins and granites and displaced by Neoproterozoic III northwest-trending Najd faults. Map after Johnson and Kattan (2001). Box outlines area of Fig. 10.

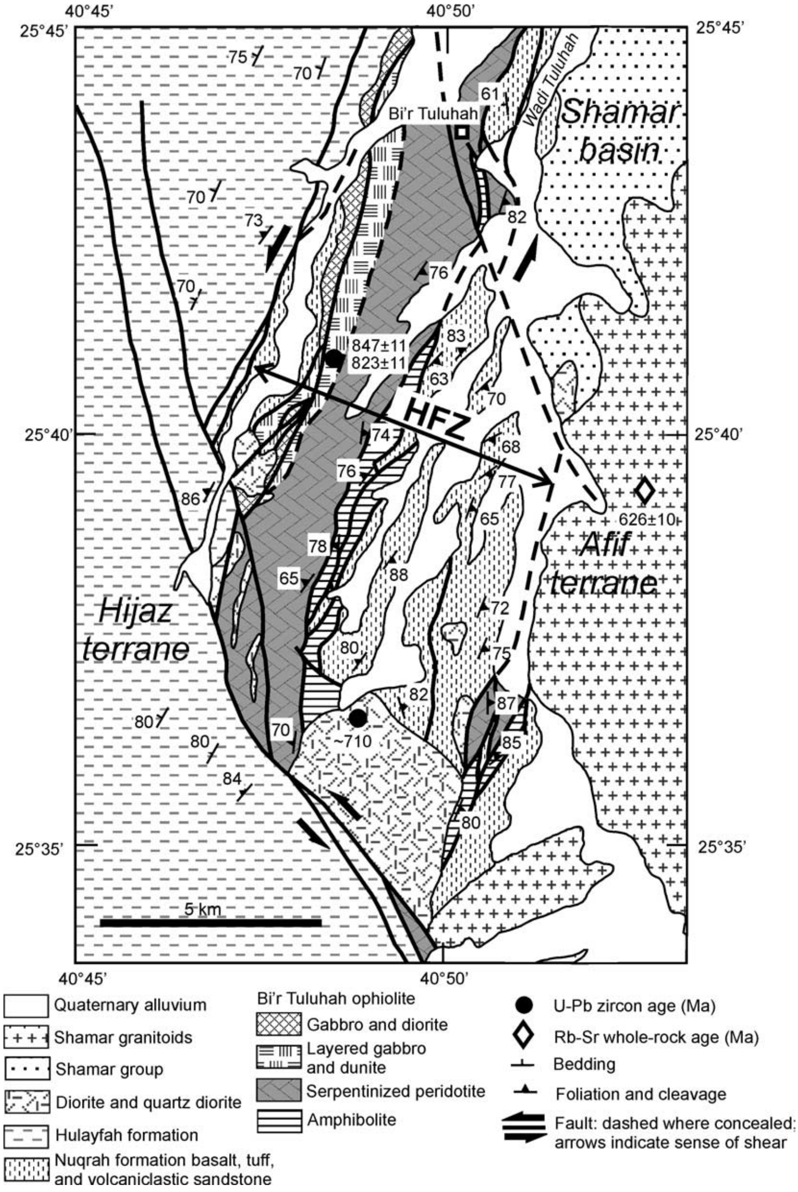


Fig. 10. Simplified map of the Bi’r Tuluhah ophiolite and adjacent areas. Map after Kattan (1983); Le Metour et al. (1983); Quick and Bosch (1989); and Johnson et al. (1989). Geochronologic data after Calvez et al. (1984); Stuckless et al. (1984); Calvez and Kemp (1987); Pallister et al. (1988). HFZ = Hulayfah fault zone.

granites overlie and intrude the fault zone on the east. Post-Shammar northwest-trending sinistral Najd faults dislocate the ophiolite and fault zone on the north and south.

The most extensive unit in the ophiolite is peridotite, which crops out in a zone 2.5 km wide north and south of Bi'r Tuluhah. The rocks are strongly serpenitinized but harzburgite and dunite protoliths are recognized. The rocks are mylonitized and have a strong cataclastic texture although ghost equant grains and a relict granoblastic texture are recognized in thin sections (Kattan, 1983). Serpentinized harzburgite comprises about 15% orthopyroxene, 80% serpentinized olivine presudomorphs, and minor chromite and magnetite. In hand specimen, serpentinized dunite is fine grained and dark gray to green, and in thin section is an aggregate of serpentine minerals that locally have a well-developed boxwork texture derived from the original olivine (Kattan, 1983). It contains anhedral grains of chromite and magnetite, and small lenses of massive chromite. As shown by Stern et al. (2004), the chromites plot on the low-Mg side of the field of present-day forearc chromian spinels, suggesting a suprasubduction origin for the ophiolite.

Layered gabbro and dunite with minor wehrlite, lherzolite, websterite, and olivine clinopyroxenite layered on scales of centimeters to meters occur in a narrow band west of the serpentinized peridotite (Le Metour et al., 1983). Serpentinization obscures primary textures, and it is not clear whether the layered rocks are mantle tectonites or ultramafic cumulates (Quick and Bosch, 1989). A narrow zone of mafic plutonic rocks farther west consists of gabbro and diorite in the north, in the northern half of Fig. 10, and fault slivers of layered gabbro in the south. The northern gabbro and diorite either intrude or are faulted against the ophiolitic rocks, and may postdate ophiolite magmatism (Le Metour et al., 1983). The southern layered gabbro has a cumulus texture in pyroxene- and hornblende-rich phases and may be a cumulate part of the ophiolite succession. Amphibolite, treated by Delfour (1977) as part of the ophiolite, crops out east of the peridotite. Fine-grained amphibolite is strongly schistose and lacks clear textural or relict mineralogic indications of its protoliths. Coarse-grained amphibolite appears to be the result of epidote-amphibolite facies metamorphism of gabbro and diabase (Quick and Bosch, 1989).

Massive, locally pillowed metabasalt and chert together with fine-grained sandstone, keratophyre, and interbedded felsic tuff and minor basalt make up the volcanic-volcaniclastic rocks of the Nuqrah formation located on either side of the mafic-ultramafic units along the fault zone (Le Metour et al., 1983; Quick and Bosch, 1989). Considered in isolation, it is conceivable that the basalt and chert represent pelagic rocks at the top of the ophiolite succession but their association with felsic tuffs and sandstone suggest that they are part of a suprasubduction volcanic arc. The metabasalt is a fine-grained, light gray to gray-green rock, the original structure and texture of which are virtually obliterated by metamorphism. The rock is identified as basalt in the field by its mafic composition, generally massive appearance, and the local presence of pillow structure. In thin section, the basalt has a strongly developed, fine-grained metamorphic foliation composed of saussuritized plagioclase, epidote, carbonate, chlorite, clinozoisite, and iron oxides (Kattan, 1983). Dikes of diabase, gabbro, plagiogranite, and diorite cut all the serpentinized ultramafic rocks, and plutons of diorite and quartz diorite intrude the southern part of the ophiolite.

Structurally, the Bi’r Tuluhah ophiolite is a set of fault-bounded lenses. Together with the flanking Nuqrah formation, the rocks are pervasively cleaved and sheared, and deformation is spread across the entire width of the Hulayfah fault zone, although narrow zones of ultramylonite, schist, and carbonate-altered serpentinite identify discrete shears within the fault zone. All shear surfaces are subvertical, and any low-angle thrusts that may have been originally present have been obliterated or steepened by subsequent deformation.

Model U-Pb zircon ages of 847 ± 14 Ma and 823 ± 11 Ma obtained from plagiogranite (trondhjemite) dikes that intrude serpentinized harzburgite in the center of the ophiolite (Pallister et al., 1988) provide a minimum age for the ophiolite. The dikes have rodingite margins indicating intrusion prior to complete serpentinization and they are interpreted by Pallister and colleagues as forming late during ophiolite magmatism. Together with a U-Pb zircon age of 839 ± 23 Ma obtained from Nuqrah formation rhyolite 40 km east of the Bi’r Tuluhah ophiolite (Calvez et al., 1984), the Bi’r Tuluhah model ages suggest that oceanic crust and volcanic arc rocks were actively forming in the region between 840 and 820 Ma. The age of the Hulayfah formation is weakly constrained by a U-Pb zircon age of 720 ± 10 Ma obtained from tonalite that intrudes the formation west of the Hulayfah fault zone (Calvez et al., 1984). An approximate U-Pb zircon age of 710 Ma obtained from a quartz diorite pluton intruded into the southern part of the ophiolite and fault zone (Fig. 10) constrains the minimum age for ophiolite deformation and alteration (J.S. Stacey, personal communication, cited by Quick, 1991) and approximate U-Pb and Rb-Sr ages between 630 Ma and 615 Ma obtained from the post-amalgamation Shammar group and Shammar “stitching” granites (Stuckless et al., 1984; Calvez and Kemp, 1987) give a minimum age for completion of suturing along the fault zone.

6. HALABAN OPHIOLITE

The Halaban ophiolite is a zone of mafic-ultramafic rocks exposed north and south of Halaban in the eastern part of the Arabian shield (Figs. 11, 12) and located along the Halaban suture at the join between the Afif and Ad Dawadimi terranes. The Ad Dawadimi terrane is strongly deformed and treated by some authors as, itself, part of a larger suture zone referred to as the Al Amar suture (Stoeser and Camp, 1985). The ophiolite consists of metagabbro and subordinate serpentinite. It is bounded on the west by the Halaban-Zarghat fault zone, a complex structure including a west-vergent thrust in the south and a down-to-the-west normal fault in the north, and on the east by the Eastern shear zone (Fig. 12). The rocks west of the ophiolite include mafic plutons, orthogneiss, and amphibolite referred to as the Suwaj domain and late Neoproterozoic sedimentary rocks of the Jibalah group deposited in the Antaq basin. Rocks to the east are low-grade metasedimentary units of the Abt formation and post-amalgamation granitoids. The ophiolitic rocks crop out in hills with relief of about 50 m and are generally well exposed. Unfortunately, the margins of the ophiolite tend to coincide with valleys so that structural details at the boundaries of the ophiolite are largely obscured. From the point of view of the Penrose definition, the rocks in the vicinity of Halaban do not include mantle peridotite, a dike

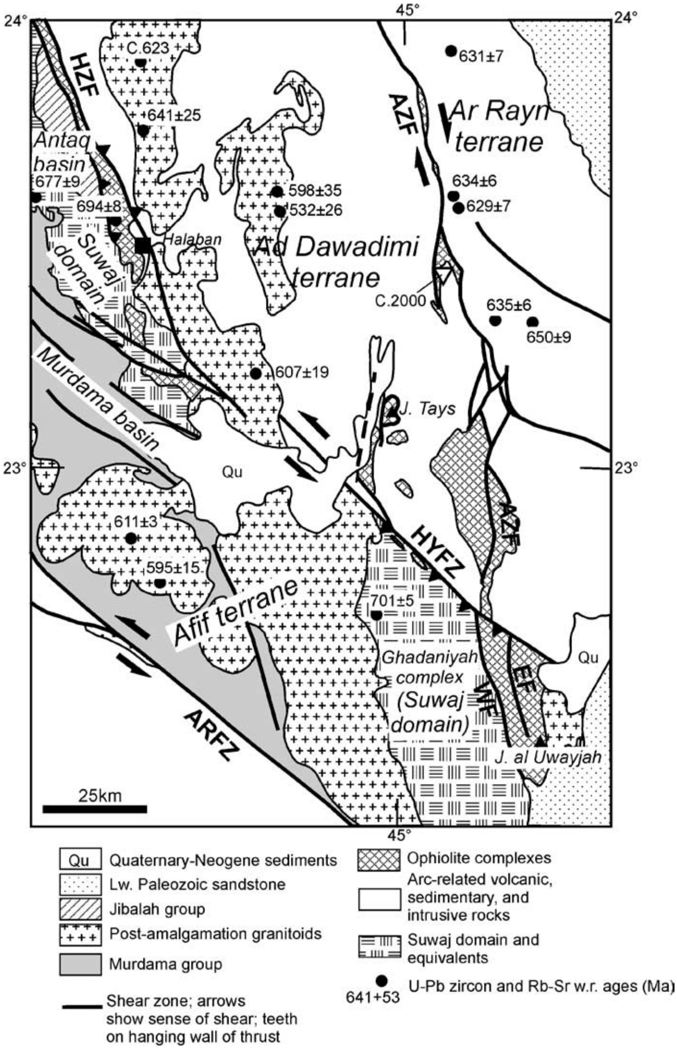


Fig. 11. Simplified geologic map and geochronologic data for the Halaban, Jabal Tays, and Jabal al Uwayjah ophiolite complexes in the eastern Arabian shield. Map after Delfour (1979); Manivit et al. (1985); and this report. Geochronologic data after Calvez et al. (1984); Stacey et al. (1984). Abbreviations: AFZ = Al Amar fault zone; EF = East fault (magnetically inferred); HYFZ = Hufayrah fault zone; HZF = Halaban-Zarghat fault zone; ARFZ = Ar Rika fault zone; WF = West fault (magnetically inferred).

complex, or pillow basalt and, at best, are an incomplete ophiolite. However, north of the area described here, the on-strike continuation of the Halaban rocks includes peridotite, gabbro, serpentinite, listwaenite, and basalt (Al-Shanti and El-Mahdy, 1988). It is possi-

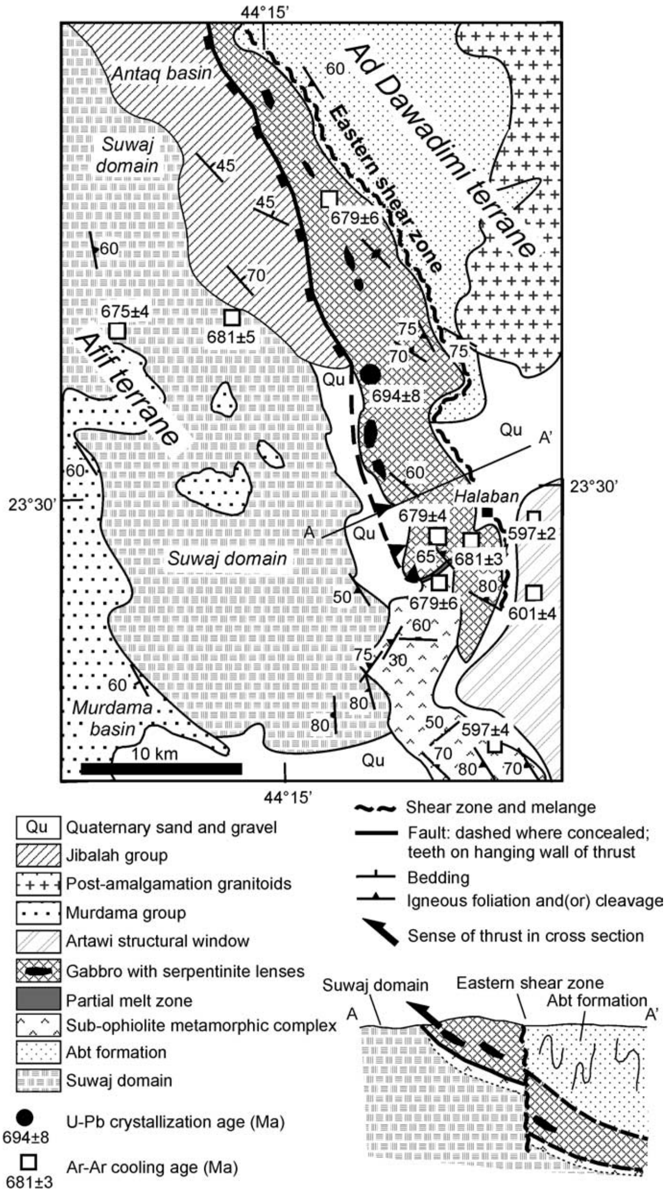


Fig. 12. Simplified map and cross section of the Halaban ophiolite complex and adjacent units, showing the locations and results of geochronologic dating. Map after Delfour (1979), Al-Saleh (1993), and this report; geochronologic data after Stacey et al. (1984), Al-Saleh (1993), and Al-Saleh et al. (1998).

ble that the rocks in the vicinity of Halaban village are the mafic plutonic section of an ophiolite, whereas the mantle part is preserved in the north.

The Halaban rocks are predominantly pale green, well-foliated metagabbro (Al-Saleh et al., 1998). Al-Shanti and El-Mahdy (1988) interpret the foliation as igneous layering and describe microscale igneous lamination and large-scale rhythmic layering caused by differences in mineralogy, grain size, and texture. Some of the foliation, however, is clearly secondary in origin, with oriented metamorphic minerals and quartz ribbons, ductile folding, as well as S/C shear fabrics and Al-Saleh et al. (1998) interpret much of the foliation to be the result of sea-floor metamorphism under greenschist- to amphibolite-facies conditions. The widespread development of actinolite, chlorite, clinozoisite, and albite is inferred to reflect ubiquitous, low-grade, low-temperature, off-axis metamorphism, whereas local amphibolitization of gabbro is inferred to reflect metamorphism close to the spreading axis in conjunction with shearing. Primary feldspar in the gabbro is commonly saussuritized and clinopyroxene tends to be replaced by chlorite and quartz. Lenses of massive black serpentinite and serpentinized lherzolite and olivine websterite occur sporadically along the western margin and axis of the gabbro (Fig. 12). The serpentinite lenses have sharp contacts with surrounding gabbro and are interpreted as ultramafic diapirs emplaced in the gabbro from an originally lower stratigraphic position in the ophiolite (Al-Saleh et al., 1998). Chromite from a small pod south of Halaban village plots close to the fields of chromian spinels from boninite and forearc ophiolites (Stern et al., 2004).

South of Halaban village the gabbro outcrops taper and are structurally underlain by metamorphosed mafic and ultramafic rocks belonging to a sub-ophiolitic metamorphic complex (Al-Saleh et al., 1998). The eastern part of the metamorphic complex contains abundant blocks of serpentinite, 1–20 m across, sheathed by soapstone and small lenses of chromite in a matrix of orthoamphibolite and rodingite. It forms an inhomogeneous unit that may represent an obduction-related mélange. To the west, the metamorphic complex becomes more felsic. It contains no ophiolitic material and was probably largely derived from diorite and tonalite belonging to the Suwaj magmatic arc. The metamorphosed rocks were affected, particularly at their contact with the Halaban gabbro, by partial melting, which resulted in the development of migmatitic gneiss composed of coarse-grained hornblendite, amphibolite and gneissic gabbro and diorite intruded by numerous veins and irregular lenses of trondhjemite. Petrologic studies indicate that the mafic paleosome of the gneiss was partially melted under hydrous conditions; the neosome segregations are chiefly quartz and andesine plagioclase (Al-Saleh et al., 1998).

The Eastern shear zone consists of strongly deformed gabbro, talc schist mélange, and pelitic schist exposed in a zone as much as 1 km wide. The rocks are tectonically intercalated with each other or are present as a mélange comprising irregular, scattered blocks of the various rock types in an anthophyllite-talc schist matrix (Fig. 13A). Gabbro in the Eastern shear zone commonly has a mylonitic texture and is cut by shear zones several centimeters thick that contain S/C fabrics. Altered basalt consists of pumpellyite pseudomorphs of original plagioclase phenocrysts, chlorite, quartz, and hematite, and the pelitic schists are rich in Ca and Mg silicates and believed to be derived from deep-marine argillaceous carbonates (Al-Saleh, 1993).

Fig. 13. Features of the Halaban ophiolite. (A) Mélange from the Eastern shear zone. (B) Brittle-ductile shear in the partial melt zone showing top-up-to-the west displacement.

The steep dips of schistosity and shear surfaces indicate that the Eastern shear zone is subvertical. The western boundary of the ophiolite west of Halaban, in contrast, is inferred to be east dipping in conformity with east-dipping foliations and shear surfaces in the gabbro in proximity to the boundary. Sense-of-shear indicators in the partial melt zone beneath the gabbro (Fig. 13B) suggest that this western boundary was affected by west-directed shearing and the boundary is interpreted by us as a west-vergent thrust that placed the Halaban ophiolite above the Suwaj domain.

Radiometric age determinations are reported from many units in the area. A U-Pb model zircon age of 694 ± 8 Ma obtained from a hypersthene gabbro in the southern part of the ophiolite about 10 km NNW of Halaban (Stacey et al., 1984) constrains the magmatic age of the ophiolite. Several $^{40}Ar/^{39}Ar$ ages of about 680 Ma obtained from amphibolites of the sub-ophiolitic metamorphic complex and from metamorphic hornblendes in the ophiolite gabbro are interpreted to reflect rapid cooling and obduction of the ophiolite (Al-Saleh et al., 1998). U-Pb and $^{40}Ar/^{39}Ar$ dates obtained from Suwaj diorite suggest that the Suwaj domain developed between 681 Ma and 675 Ma (Stacey et al., 1984; Al-Saleh et al., 1998).

7. JABAL TAYS OPHIOLITE

The Jabal Tays ophiolite crops out in the central part of the Ad Dawadimi terrane, 75 km east-southeast of the Halaban ophiolite. The exposures form a group of prominent hills that have a local relief of 220 m rising to a summit of 1057 m above sea level at Jabal Tays, and are surrounded by low-relief exposures of low-grade sandstone, siltstone, conglomerate, and limestone of the Abt formation (Fig. 14). Isolated bodies of gabbro and mafic dikes exposed south of the area shown in Fig. 14 may be detached parts of the ophiolite (Al-Shanti and Gass, 1983), but their exact relation to the Jabal Tays exposures are not clear at this stage because of surficial cover.

Mafic-ultramafic rocks at Jabal Tays include a large amount of undifferentiated serpentinite, subordinate amounts of gabbro intruded by mafic dikes, mélange, serpentinite schist, and listwaenite. Gabbro is variably serpentinized but is fresh enough that igneous lamination and cyclic layering of melanocratic, olivine- and pyroxene-rich gabbro and anorthosite are recognized (Al-Shanti and Gass, 1983). Plagioclase and clinopyroxene in the gabbro have a cumulate texture; orthopyroxene is mostly replaced by chlorite. The serpentinite, which makes up the bulk of Jabal Tays, is variably sheared and typically consists of relatively massive serpentinite cut by shear zones marked by serpentinite schist. The serpentinite protoliths have not been identified but are presumably varieties of mafic and ultramafic rocks. Mélange is uniformly developed at the outer margins of the ophiolite as a zone up to 500 m wide. It comprises irregular blocks of gabbro and massive to schistose serpentinite from a few centimeters to tens of meters across in a serpentinite and talc-schist matrix. Along the western side of Jabal Tays, the mélange creates a distinctive rugged terrain in which the mélange clasts weather out as protuberances (Fig. 15A). Carbonate alteration is widespread in the area, but is particularly prominent in west-dipping shear zones on the southern flank of Jabal Tays, on which basis the mountain is interpreted to be a stack of west-dipping thrusts.

The external contacts of the ophiolite are poorly and discontinuously exposed, but the manner in which the outer contact and mélange zone wraps around Jabal Tays suggests that the ophiolite is a synform (Fig. 14). Where exposed, the outer, structurally lower contact is a shear zone 1–5 m thick discordant with respect to the underlying Abt formation.

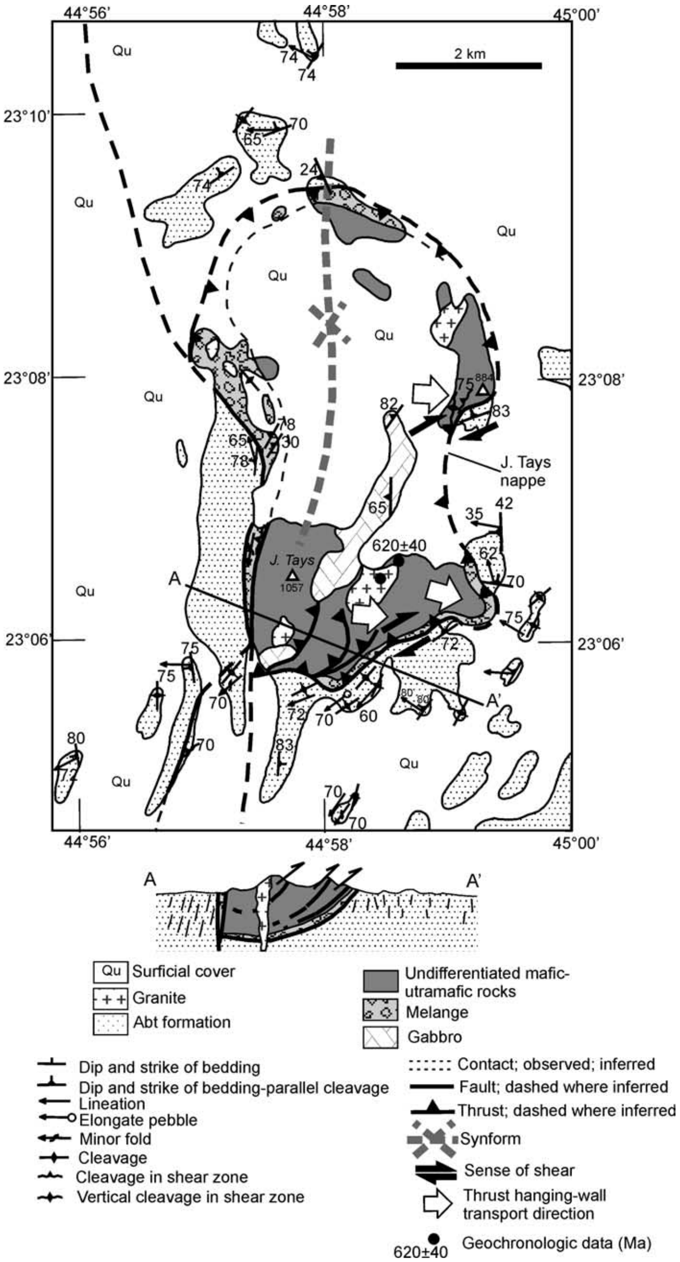


Fig. 14. Geologic map and cross section of the Jabal Tays ophiolite complex. Map after Al-Shanti and Gass (1983) and this report. Geochronologic data after Al-Shanti et al. (1984).

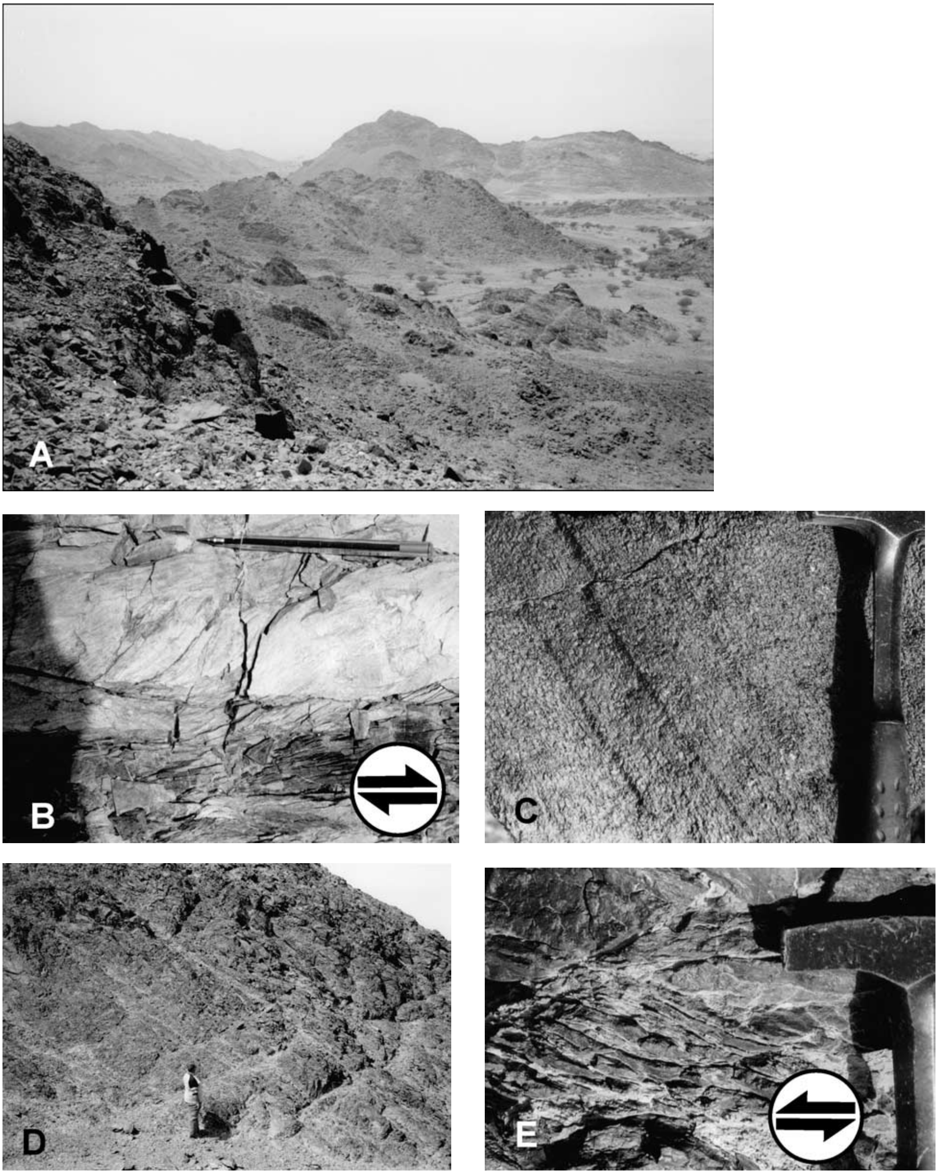


Fig. 15. Features of the Jabal Tays and Jabal Uwayjah ophiolites. (A) View to the southwest of the mélange zone on the western side of the Jabal Tays ophiolite. (B) Dextral shear in the footwall of the Jabal Tays basal thrust. (C) Strongly developed deformational (?) foliation in Jabal Uwayjah gabbro. (D) West-dipping shear surfaces in Jabal Uwayjah serpentinized peridotite. (E) Shear fabric in serpentinized peridotite from locality (D) looking south, showing top-to-left, that is hanging-wall-up-to-east, displacement.

Mesoscale folding in the basal shear zone is indicated by changes in dip of shear surfaces from flat lying (25°–35°) to subvertical over distances of a few meters. S/C shear fabrics indicate dextral-horizontal (Fig. 15B) and hanging-wall up-to-the-east vertical movements along the eastern and southeastern parts of the shear zone, suggestive of the ophiolite being part of an easterly vergent nappe. This inferred transport direction is compatible with an E-W elongated chromite lineation described from deformed gabbro in the central part of the ophiolite (Al-Shanti and Gass, 1983) and with the southwesterly plunge of stretched pebbles observed by us in Abt formation conglomerate in the footwall of the ophiolite on the southeastern flank of Jabal Tays. Whether the mélange along the western margin of the ophiolite is part of the basal thrust upturned by synclinal folding or a secondary mélange created along the north-trending steep fault that appears to truncate the ophiolite on the west is not yet established.

The mafic-ultramafic rocks of the Jabal Tays ophiolite are not directly dated. Their minimum age is weakly constrained by an Rb-Sr whole-rock isochron of 620 ± 40 Ma obtained from trondhjemite that intrudes the mélange zone (Al-Shanti et al., 1984). However, granitoids elsewhere in the Ad Dawadimi terrane are dated 670–640 Ma (Stacey et al., 1984), and the Rb-Sr age is too young to be a meaningful constraint on the ophiolite. By comparison with the Halaban ophiolite, the Jabal Tays body is probably more likely to be about 680 Ma.

8. JABAL AL UWAYJAH OPHIOLITE

The Jabal al Uwayjah ophiolite is exposed at the eastern edge of the Arabian shield in a group of isolated hills of low relief (< 80 m). Because of extensive cover by Quaternary eolian sand, pediment gravel, and wadi alluvium (Fig. 16), exposure is poor, and this characteristic in combination with little recent mapping means that the ophiolite is the least well known in the shield. Overall, it appears to occupy an area of about 45 km N-S and 12 km E-W on the shield but, judging by its aeromagnetic signature, continues 40 km to the southeast beneath the Permian, making it one of the larger ophiolites in the region. The contacts of the ophiolite are concealed and its structure is obscure, but prominent magnetic lineaments suggest major faults occur along the axis and western margin of the ophiolite. Permian sandstone and limestone are unconformable on the ophiolite on the east and amphibolite-grade metadiorite, metagabbro, and amphibolite, and garnet-amphibole gneiss of the Ghadaniyah complex (701 ± 5 Ma; Agar et al., 1992) flank the ophiolite on the west. The Ghadaniyah complex is lithologically and geochronologically similar to the Suwaj domain rocks in the Halaban area, and the two are correlated by Johnson (1996), as is implied by use of the same graphic symbol for the two rock units in Fig. 11.

The most extensive exposures of the ophiolite are in low hills north and south of Jabal al Uwayjah and include serpentinized peridotite, pyroxenite, metagabbro, undifferentiated serpentinite, and minor metabasalt and metaandesite (Manivit et al., 1985). Pyroxenite has relict orthopyroxene (enstatite) and clinopyroxene (augite and diallage), and metagabbro, which is fine grained, strongly foliated (Fig. 15C), and closely resembles the Halaban

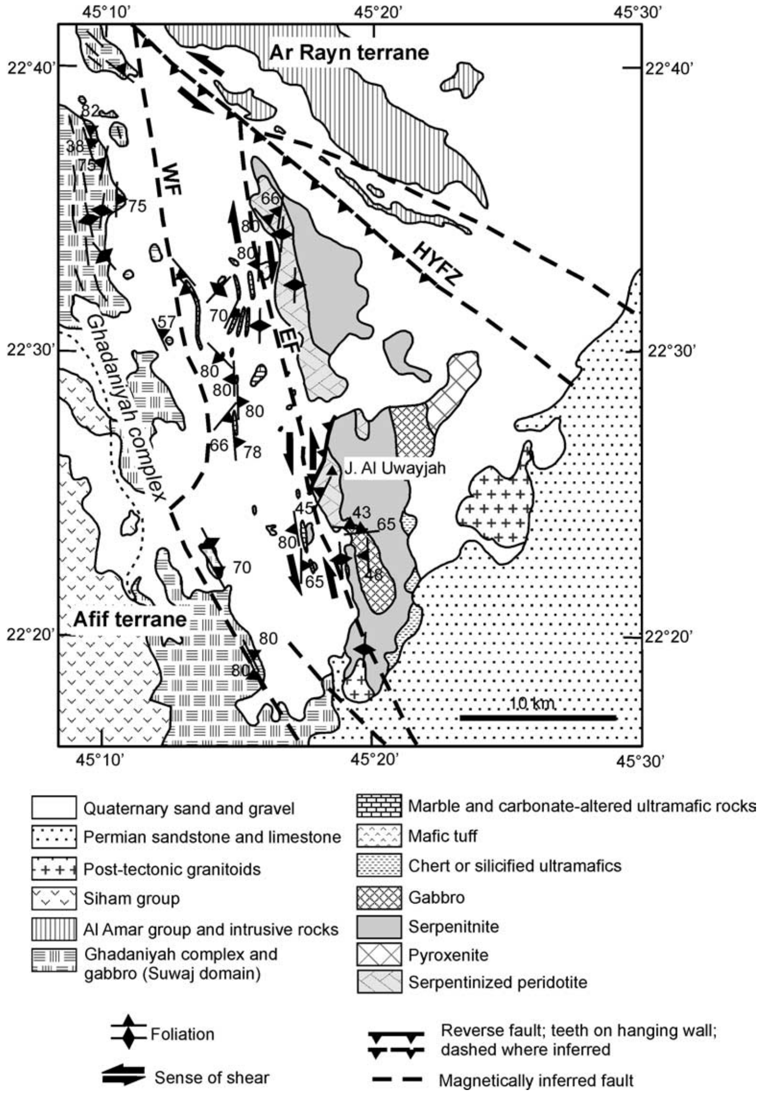


Fig. 16. Map of the Jabal al Uwayjah ophiolite and adjacent units. Abbreviations: EF = Eastern fault; HYFZ = Hufayrah fault zone; WF = Western fault. Map after Bois and Shanti (1970), Brosset (1974), Manivit et al. (1985), and this report.

gabbro, contains relict olivine and pyroxenes pervasively altered to epidote and serpentine. Serpentinite is a black to green rock composed of antigorite, talc, and relict pyroxene. A fine-grained brick-red colloidal and ferruginous siliceous unit located at the contact between the ophiolite and Permian rocks probably represents silicification of serpentinite as a result of weathering. A low-lying area west of the Jabal al Uwayjah hills is virtually devoid of exposures other than discontinuous north-trending ridges of carbonate. Some of the ridges are fine-grained gray or variegated white and gray, massive to thinly layered marble that resembles sedimentary marbles in other parts of the shield. Others, however, are listwaenite, which suggests that, despite the lack of outcrop, bedrock includes a significant amount of ultramafic rock.

Structures in the Jabal al Uwayjah ophiolite are predominantly north trending. They include cleavage in serpentinite and gabbro, foliation in metagabbro, linear outcrops of listwaenite and carbonate, and magnetically inferred faults, two of which dominate the region. The western fault separates the ophiolite from the Ghadaniyah complex. The eastern fault, which locally coincides with ridges of listwaenite, separates the low hills north and south of Jabal al Uwayjah from the area of poor exposure to the west. West-dipping shear zones in serpentinite at the western edge of these hills contain S/C fabrics indicating top-to-the-east reverse slip (Figs. 15D, E), which suggests that the eastern fault may be an east-vergent thrust.

The Jabal al Uwayjah ophiolite is not directly dated but on the basis of lithology is correlated by Brosset (1974) with the Halaban ophiolite. We concur with this correlation, which is consistent with the correlation mentioned above between the Ghadaniyah complex and Suwaj domain on the western flanks of the Jabal al Uwayjah and Halaban ophiolites, respectively, and provisionally infer that the Jabal al Uwayjah ophiolite is about 680 Ma.

9. SUMMARY AND DISCUSSION

Ophiolites are widespread in the Arabian shield. However, as is evident from this review, they are ubiquitously deformed, with the consequence that typical ophiolite successions are not preserved at every occurrence. Nevertheless, sufficient diagnostic lithologic criteria are present to confidently conclude that numbers of the mafic-ultramafic complexes of the shield are indeed ophiolites. Of these, Jabal Ess is one of the most complete (Table 1); Jabal Tays the least complete. Jabal al Uwayjah is the least well known.

Available geochronologic data indicate that the ophiolites developed over a 200-million year period delimited by Jabal Tharwah ($\sim$ 870 Ma) and Halaban ($\sim$ 695 Ma). Jabal Tharwah and Halaban are, in fact, the oldest and youngest ophiolites known in the entire Arabian-Nubian shield (Stern et al., 2004). The western and eastern geographic locations of the Tharwah and Halaban ophiolites conceivably suggest an eastward migration of oceanic floor magmatism in this period in the Arabian shield. However, in the larger setting of the entire region of juvenile Neoproterozoic rocks represented by the Arabian and Nubian shields, there is no unidirectional time-space distribution. Jabal Tharwah is in the middle of the combined Arabian-Nubian shield and younger ophiolites occur to the east, west, north, and south.

Although not a specific topic of this review, it is also evident, in conjunction with a range of structural and stratigraphic information about the adjacent rocks, that ophiolites

Table 1. Summary table showing lithologic components and estimated magmatic ages of selected Arabian shield ophiolites

Ophiolite	Age (to nearest 5 Ma)	Peridotite	Gabbro	Dikes	Basalt	Pelagic sediments
Jabal Ess	780	√	√	√	√	√
Jabal Tharwah	870	√	√	√	√	√
Bi’r Umq	840–830	√	?	?	√	√
Bi’r Tuluhah	845–825	√	√	?	√	?
Halaban	695	√ minor	√	?	√ in the north	?
Jabal Tays		√ serpentinite	√	?		?
Jabal al Uwayjah		√	√	?	√	?

√ = lithology observed; ? = lithology not observed to date.

in the Arabian shield occur along suture zones. The structure and geochronology of the ophiolites are therefore important constraints on the history of suturing. Dating of the Jabal Tharwah-Bi’r Umq ophiolites and associated intrusions imply ocean-floor magmatism in the northwestern part of the shield between ∼ 870–830 Ma and is consistent with development of the Bi’r Umq suture at about 780–760 Ma (Johnson et al., 2002). The 706 Ma age of post-ophiolite trondhjemite at Jabal Ess is consistent with convergence along the Yanbu suture and its Northeast African extension between ∼ 700 Ma and ∼ 600 Ma. The Bi’r Tuluhah ophiolite is the oldest known example of oceanic-floor magmatism along the Hulayfah-Ad Dafinah-Ruwah suture (Johnson and Kattan, 2001), and the Halaban ophiolite constrains oceanic magmatism and suturing in the eastern shield at ∼ 695 Ma and ∼ 680 Ma, respectively.

Structurally, all the ophiolites are complex, and exhibit multiple phases of folding and shearing. Most structures are steep, and unlike some of the Neoproterozoic ophiolites in the Nubian shield (Abdelsalam and Stern, 1993; Schandelmeier et al., 1994), the Arabian examples have few preserved low-angle thrusts. The only candidates for original thrusts identified to date are low- to moderately inclined shears in the southern part of Jabal Ess, in eastern Jabal Tharwah, at the western contact of Halaban, along parts of the Jabal Tays basalt contact, and at the Eastern fault at Jabal al Uwayjah. Other shear zones are subvertical, either because they are folded thrusts, similar to the folding evident in the basal thrust at Jabal Tays, or are steep shear zones that developed during other phases of deformation.

Overall, the available structural evidence is permissive of modeling the Jabal Ess ophiolite as a stack of steepened north-vergent thrusts and horizontal shear zones that resulted from a period of dextral transpression. The Jabal Tharwah and Bi’r Umq ophiolites are possibly both flower structures related to southeast- and northwest-vergent thrusting along the Bi’r Umq-Nakasib suture (Johnson et al., 2002). The Bi’r Tuluhah ophiolite is preserved in a subvertical shear zone that forms the northern part of the Hulayfah-Ad Dafinah-Ruwah shear zone created during sinistral transpression. The Halaban ophiolite is part of a west-vergent allochthon thrust over the eastern margin of the Afif terrane at the Halaban suture. The Jabal al Uwayjah ophiolite is an extension of the Halaban ophiolite, detached from the Halaban rocks by the sinistral and top-to-the-north Hufayrah fault zone (Fig. 11), and its location is evidence that the Halaban suture continues to the edge of the shield and beyond, beneath Permian rocks that flank the shield.

Available information about the Arabian shield ophiolites varies in quality and quantity. Unfortunately, none are known in sufficient detail to fully determine their tectonic setting. Additional, and in some cases, original, petrologic, geochemical, geochronologic, and structural research are required. The ophiolites have a small surface area, but are critical for our understanding of the tectonic history of the shield, and warrant ongoing study and exploration. They testify to the juvenile tectonic environment of the Arabian-Nubian shield; they document the creation of oceanic floor following the breakup of Rodinia; and in their deformed and metamorphosed state they record stages in the subduction and closure of the Mozambique Ocean concurrent with the amalgamation and suturing of the tectonostratigraphic terranes that make up the shield.

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