

## **Geology and Geochemistry of Jabal Ghadarah Ophiolitic Mélange, Zalim Quadrangle, Central Saudi Arabia**

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**Abstract.** The Precambrian rocks encountered at Jabal Ghadarah area can be grouped into: metaultramafites, arc metavolcanosedimentary rocks, syn- to late-orogenic granitoids, intramontane molasse-type sediments and post-orogenic monzogranite. At Jabal Ghadarah, the meta-ultramafic rocks and associated listvenites are mainly exposed along a NNE trending thrust fault dipping to the east, in contact with the arc metavolcanosedimentary rocks. The metaultramafites are characterized by the presence of numerous fragments of variable sizes (metagabbros, metabasalts, schists, amphibolites and marble). Major and trace elements distribution indicates that the metagabbros, metabasalts and amphibolites are tholeiitic in character and of ocean floor affiliation. The amphibolites were derived either from mafic or ultramafic protoliths. Chromite from the serpentinite and listvenite show a wide range of major oxides contents comparable to Alpine-type chromite. The metaultramafites and associated rock fragments are interpreted as an ophiolitic mélange imbricated with the arc metavolcanosedimentary sequence during accretion of the Arabian shield, contrary to the intrusive nature suggested by earlier workers.

### **Introduction**

#### ***Previous Studies – Regional***

The area of Zalim quadrangle has been studied by many workers, because it is known for the presence of great number of gold occurrences including Zalim mine, which was operated for a short period in early 1950's and rapidly closed

after a very limited production. The area witnessed numerous exploration activities during the nineties of the last century. Currently numerous prospects are under exploration activities by Ma'aden company and two promising gold-bearing listvenite prospects, namely Al Mansura and El Messara, were defined along Bir Tawila thrust.

Also the geology of the quadrangle drew the attention of many workers because of its location on the Nabitah suture zone (Agar, 1984a and Viland, 1986). Understanding the geology of this part of the shield helps greatly in interpreting its evolution.

The area of the present study occupies the north central part of Zalim quadrangle and is located in the central eastern edge of the Nabitah suture zone and orogenic belt (Fig. 1). The Nabitah orogenic belt defines a 100-200 km wide zone of crustal deformation, remobilization and plutonism along the margins of the Asir, Hijaz, and Afif terranes (Schmidt *et al.*, 1979 & Stoeser and Camp, 1984). The belt consists of broad, linear complexes of synorogenic unfoliated to gneissic granitoid plutonic rocks, separated by regions of middle greenschist to amphibolite-grade metamorphic rocks (Stoeser and Camp, *op. cit.*). The southern and central part of the orogenic belt contains a north-trending linear belt of ultramafic and mafic rocks (Fig. 1), which was interpreted by Frisch and Al Shanti (1977) as being an ophiolitic complex along a suture zone between two juxtaposed arcs. Schmidt *et al.*, (*op. cit.*) supported this interpretation and referred to this zone as Nabitah suture (Fig. 1). They described the major tectonic features of the belt and interpreted them as representing a major episode of westward-directed nappe formation and crustal upturning related to collision between the western part of the shield and a continental block to the east (Ar Rayn Plate).

Stoeser and Camp (1984) defined the Nabitah orogenic (or mobile) belt and interpreted the suture zone and belt as marking the site of collision between the Afif terrane and the western arc terranes. They showed by U/Pb zircon dating that the synorogenic plutonism within the southern part of the belt occurred between 680 and 640 Ma. The western part of the belt developed within the western arc terranes and incorporated much of the Tarib arc assemblages of the Asir terrane in the south and Hijaz arc assemblage of the Hijaz terrane in the north (Fig. 1). Similarly, the eastern part of the belt is superimposed over the continental margin of the Afif terrane in the north and over a continental margin similar to the Ar Rayn terrane in the south.

During the last two decades, the great similarity in both structural fabric elements and composition between the on-land ophiolites and the present day oceanic lithosphere was detected by many workers (*e.g.* Gass, 1968; Dewey and Bird, 1971; Christensen and Salisbury, 1975 & Gass and Smewing, 1981). Such similarity led to the conclusion that these ophiolites are essentially allochthon-

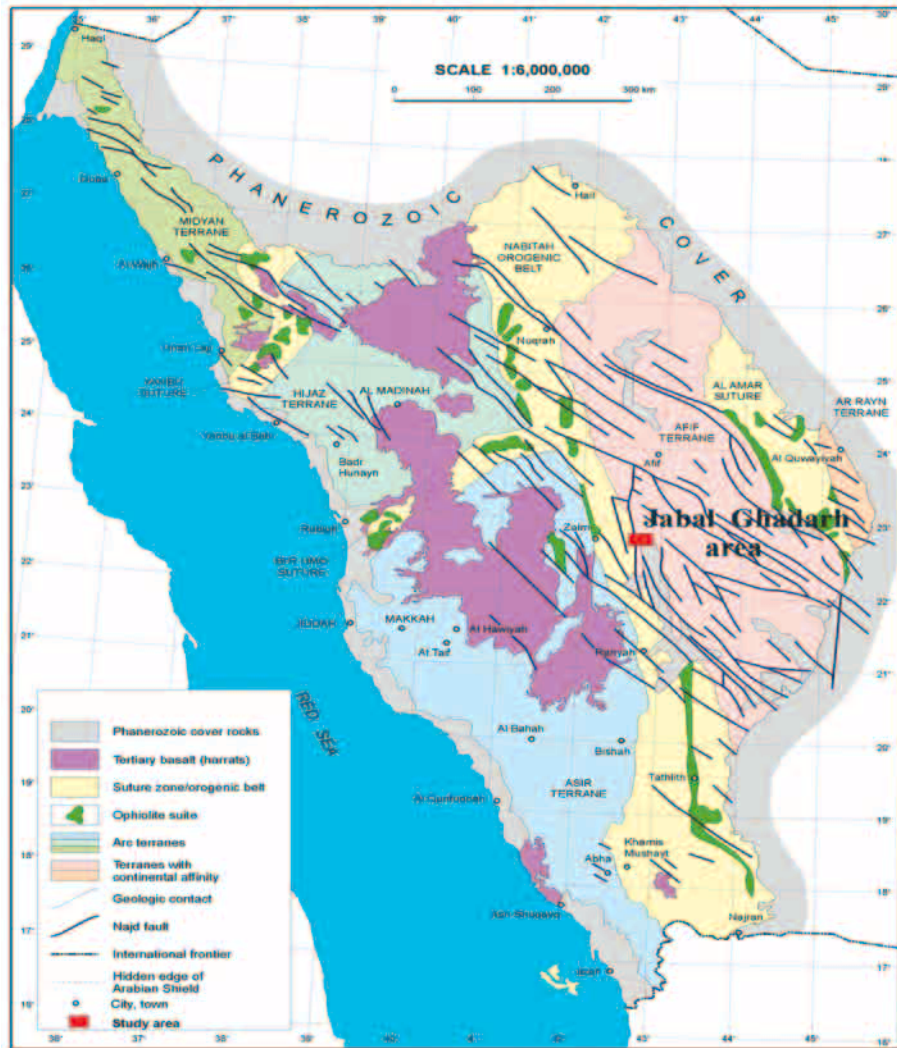


Fig. 1. Tectonic sketch map of the Arabian Shield showing terranes and suture zones (modified after Stoesser and Camp, 1984).

ous fragments of oceanic crust and upper mantle (*e.g.* Coleman, 1971 and 1977; Church, 1972; Hutchinson; 1975 and Gass, 1981). However, the mechanism of tectonic emplacement of ophiolites into continental margins is still a subject of controversy. According to Gansser (1974) an ophiolitic *mélange* is defined as an olistostromal and tectonic mixture of ophiolitic material and sediments of oceanic origin with exotic blocks, reflecting areas, which have subsequently disappeared. In the present study the term ophiolitic *mélange* as given by Gansser (*op. cit.*) is adopted in a descriptive sense.

Ophiolitic *mélange* has been described from different parts of the Arabian Shield, *e.g.*, Al Amar-Idsas belt, Jabal Humayyan-Jabal Sabhah belt, Al Bi-jadiyah-Halaban belt, Hulayfah-Hamdah-Nabitah belt, Jabal Ess-Jabal Al Wask belt and Bir Umq-Jabal Thurwah belt (Bakor *et al.*, 1976; Stoeser and Camp, 1984; Al Shanti, 1993; El-Mahdy and Al Shanti, 2001 & Al Shanti and El-Mahdy, 2001; Al-Saleh and Boyle, 2001) (Fig. 1) and the Nubian Shield (El Sharkawy and El Bayoumi, 1979; Shackleton *et al.*, 1980; Basta, 1983; Abdel Wahed, 1985; Kroner, 1985; Abdel Wahed *et al.*, 1986; Takla *et al.*, 1990 & Johnson *et al.*, 2003).

Amphibolites have been described as a common component of the ophiolitic *mélange* *e.g.* Oman (Lippard *et al.*, 1986), Newfoundland (Williams and Smythe, 1973), Haimour, Eastern Desert Egypt (Abd El-Naby, *et al.*, 2000), Alaska (Harris, 1987), Southern Tibet (Huot *et al.*, 2002), Northwest Syria (Al-Riyami *et al.*, 2002) as well as the amphibolites associated with ophiolitic belts in the Arabian Shield (Letalenet, 1979, Worl and Elsass, 1980; Kemp *et al.*, 1982 & Le Metour *et al.*, 1983).

### **Previous Work on the Study Area**

The study area is covered mainly by a group of metavolcanosedimentary rocks and metasediments, which were intruded by a group of granitoid rocks. The Bir Tawilah thrust runs nearly N-S at the center of the area and is decorated by numerous bodies of ultramafic rocks altered to listvenite (Fig. 2).

Feybesse and LeBel (1984) described the rocks east of the Bir Tawilah thrust as micaceous fine-grained schists of the As Siham formation, while the Bani Ghayy group metasediments, which consist of conglomerate, greywacke and sandstone and located west of the listvenite was described as Murdamah group.

During geological and mineral exploration studies of Siham-As Suq belt, El-sass and Vaillant (1983) described the Bir Tawilah gold mineralization as being associated with quartz and listvenite, occurring along a major thrust fault.

Agar (1984b and 1985) studied the succession of the Bani Ghayy group metasediments west of the Jabal Ghadarah-Bir Tawilah thrust and mentioned that the

Bani Ghayy group was deposited in elongated grabens filled with sedimentary rocks of the Bani Ghayy group (conglomerates, greywackes, and limestones, with subordinate siltstones). The Bani Ghayy group is associated with bimodal volcanics and the presence of deformed ultramafic rocks within internal faults, which suggest that the grabens were floored, in part, by primitive mantle-derived crust. Agar (1984b and 1985) considered the sediments east of the Bir Tawilah thrust belong to Siham group.

Labbé (1984) carried out mineral exploration studies in the Bir Tawilah district, and found that the gold in the wadi alluvial sediments near Jabal Ghadarah, was derived from a hill 1800m long and 150m wide, and is associated with quartz veins in listvenitized ultramafic rocks. Nineteen alluvial samples were collected from the wadis, which drain Jabal Ghadarah. Fourteen samples of them displayed gold grains.

Labbé (1984) described the Jabal Ghadarah pluton as medium-grained quartz leucodiorite rich in pyrite, which intrudes the Murdamah group rocks to the west of the listvenite. This pluton appears to post-date the overthrust and is not affected by the north-south schistosity parallel to the fault which affected the Murdamah group rocks. Labbé (*op. cit.*) mentioned that the "... Bir Tawilah thrust fault is injected by a strip of mainly ultramafic rocks (dunite) metamorphosed and altered to serpentinite, chlorite serpentine schist. Commonly such rocks were subsequently transformed to listvenites ...". Labbé (*op. cit.*) described two types of listvenite from Bir Tawilah thrust fault: 1) Banded silicified listvenite, which represents the magnesian pole (about 30% MgO) and 2) Red ferruginous listvenite that represents the calcic pole (about 36% CaO).

Viland (1986) classified the volcanosedimentary rocks into early Hulyfah (to the east of the Bir Tawilah thrust), and late Hulyfah (west of the Bir Tawilah thrust), and were described as flysch-type sediments deposited in a forearc environment. These volcanosedimentary rocks were intruded by several granitoid plutons. The metasedimentary rocks exposed at Jabal Bani Ghayy were considered as a separate unit, (Murdamah group molasse-type sediments), which is younger than Hulyfah volcanosedimentary rocks.

Billa (1987) carried out mineral exploration at Jabal Al Gadhara and mentioned that the Jabal Ghadarah gold prospect is hosted by a small granodiorite intrusion of late proterozoic age along the contact between the proterozoic metasedimentary rocks and the carbonatized ultramafic rocks (listvenite). A surface investigation and percussion drilling totalling 1227m have defined an ore body with indicated reserves of at least 330,000 tons of ore grading 3.2 g/t Au. Billa (*op. cit.*) described mafic volcanic rocks at the contact between ultramafic and metasediments and considered them to represent volcanic activity associated with the ultramafic intrusion.



Fig. 2. Photogeological map of Jabal Ghadarah area (After Al Jahdli, 2004).

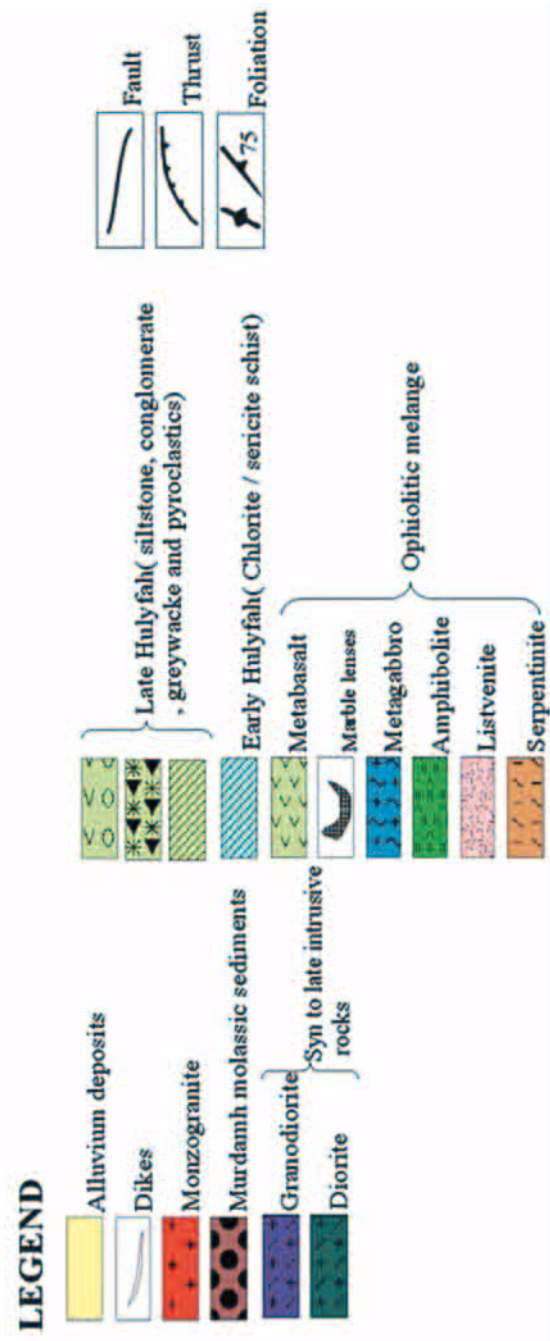


Fig. 2. Contd.

The geology of Zalim quadrangle was studied by Agar (1988) and reported that the Jabal Ghthylib (Ghadarah) is associated with Au-Ag mineralization which is hosted by granodiorite pluton. The listvenite in Bir Tawilah district was described as fault gouges material (deformed ultramafic rocks) and contains anomalous values of nickel and chromium and pods of serpentinite.

The metasediments to the east of Jabal Ghadarah-Bir Tawilah thrust was described by Agar (*op. cit.*) as Nawm Formation, which belongs to the Siham group (volcanic arc). The Nawm formation consists of basalt, andesite, shale, tuffaceous sandstone, siltstone and marble with minor amount of ultramafic bodies, which occur as sills.

### ***Aim of the Study and Methods***

The aim of the present study is to characterize the ultramafic rocks and associated rock fragments petrographically and chemically in order to define their tectonic setting.

The chemical analysis were carried out at Saudi Geological Survey, Jeddah. The major oxides were analyzed by atomic absorption, while the trace elements were determined by ICP techniques (Perken-Elmer Model 2000). For chromite analysis, SEM-EDX (Philips Model XL30) house at the Central laboratories of the Egyptian Geological Survey, Cairo was used at 40 kV accelerating voltage and a resolution for w. (3.5  $\mu$ m).

### **Field Relations and Petrography**

The term ophiolitic *mélange* is introduced for the first time to describe the geology of the study area. The ophiolitic *mélange* consists of ultramafic rocks (serpentinites and listvenite), metagabbros, metabasalts, marble lenses and amphibolites. The ophiolitic *mélange* occupies the hanging wall of the major Bir Tawilah thrust fault. The footwall is represented by the late Hulyfah volcanosedimentary rocks. The listvenite zone along the Bir Tawilah major thrust fault marks the contact between the late Hulyfah volcanosedimentary rocks and the ophiolitic *mélange* (Fig. 2). These serpentinites have been considered as intrusive by Agar (1984a & b and 1988) and Billa (1987).

### ***Ultramafic Rocks***

The ultramafic rocks are common and, represented by serpentinites and listvenites. They are irregular in distribution and size, from mountains (such as Jabal Ghadarah) to vast flat areas with small blocks of outcrops, especially at the north central part of the study area. Also, the ultramafic rocks occur in the north eastern part closer to the contact with the younger granite of Awjah com-

plex. The sheared serpentinites are supposed to be the matrix of the ophiolitic mélange.

The serpentinites are sheared and best exposed in the north central part (Fig. 2). They occur as large flat or small unmappable outcrops. The serpentinites are green to dark green, brownish to yellowish in color and sometime exhibit mesh texture. Magnesite occurs as veinlets along the joint planes and fractures in the serpentinites. Microscopically, the serpentinites are sheared, banded and composed of antigorite, lizardite, bastite, talc and accessory opaques (Plate 1a).

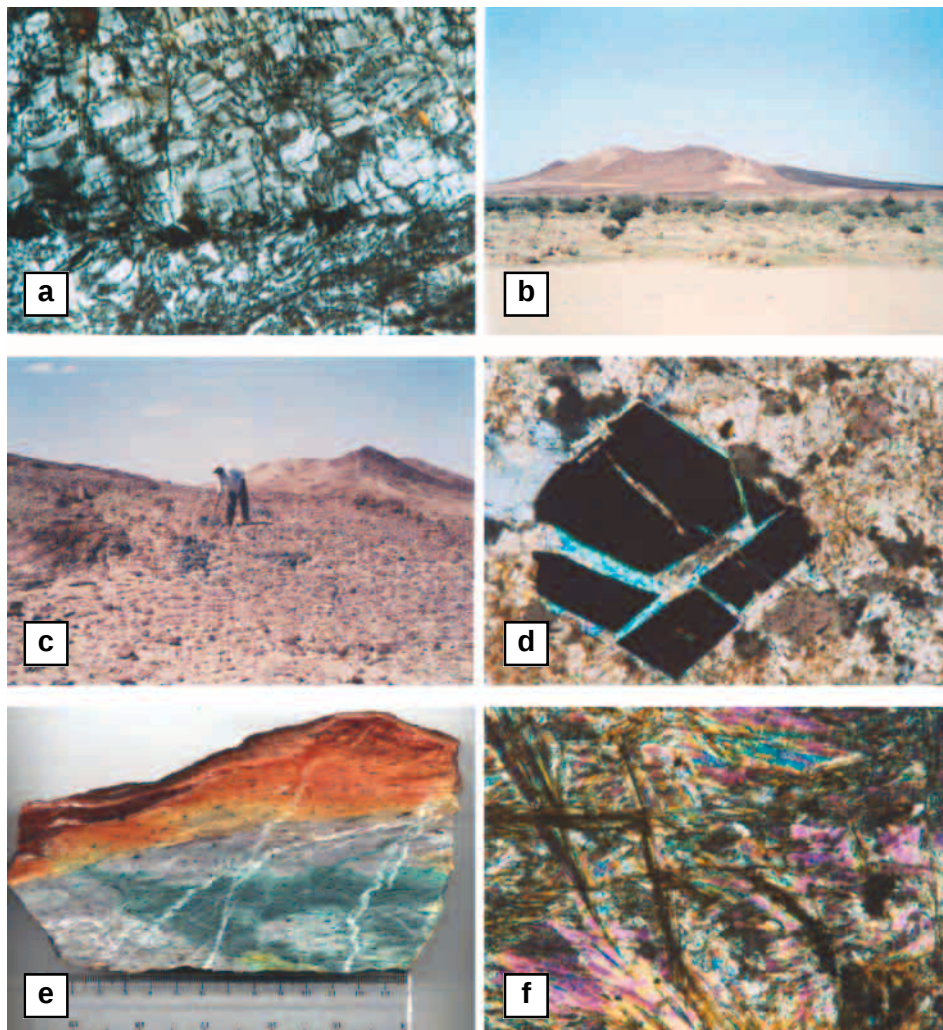
The listvenites of Bir Tawilah area extend for more than 12 km along the Bir Tawilah thrust fault which is dipping to the east. The listvenites and related rocks are between 1-300 m thick in the outcrop. The best outcrop is represented by Jabal Ghadarah, which consists of a group of hills oriented north-northeast/south-southwest and rising about 40 m above the surrounding area (Plate 1b).

The listvenite contains fragments of mafic and ultramafic rocks (Plate 1c). These fragments range from 2 to 10 m across. The Bir Tawilah listvenite is affected by the Najd left lateral strike-slip faults striking N30°-50°W (Fig. 2). The listvenite at Jabal Ghadarah occurs as massive to highly fractured blocks. The fresh listvenite is greenish gray in color and contains fresh disseminated sulphides, green fuchsite and disseminated chromite and magnetite in addition to carbonate (Plate 1d). Upon weathering listvenites are gradually altered to brownish to reddish brown colored rocks (Plate 1e).

Metamorphosed serpentinites and listvenites were found near the contact with the Awja monzogranite intrusion, and are characterized by the association of olivine, talc, tremolite, magnesite and dolomite (Plate 1f and Plate 2a). Such assemblage is characteristic to amphibolite hornfels facies. Similar assemblages have been described from metamorphosed serpentinites from Canada (Paktunc, 1984). These rocks can be classified into: 1) Talc tremolite metaserpentinites and 2) Talc lizardite listvenite.

The talc tremolite metaserpentinites are found at the northeastern sector of the study area. They are brownish to yellowish in color, sheared and form flat unmappable outcrops. The metaserpentinites are associated with amphibolites adjacent to the Awja monzogranitic intrusion. These rocks have been formed by thermal metamorphism of serpentinites as evident from the presence of minor serpentine minerals and chromite.

The talc lizardite listvenite is recorded in the north central part of the study area where listvenite is present in contact with the Awja monzogranite. They are fine grained brownish to yellowish and massive to slightly foliated. The rocks consist of serpentine minerals (lizardite), carbonate (magnesite), talc and accessory opaques (Plate 2b and c). The opaque minerals are represented main-



- a) Serpentine minerals (antigorite) in sheared serpentinite. T.S (Thin Section), C.N (Crossed Nicol's),  $\times 25$ .
- b) Listvenite at Jabal Ghadarah (foreground) and late Hulyfah volcanosedimentary rocks (background). Looking south.
- c) Mafic fragments incorporated within listvenite at Jabal Ghadarah. Looking north.
- d) Development of fuchsite along fractures and boundaries of fractured euhedral chromite crystal in calcite listvenite. T.S., C.N.,  $\times 200$ .
- e) Polished slab of fresh listvenite showing fuchsite (green) and opaque minerals (chromite). The upper part of the sample shows oxidation of listvenite.
- f) Talc (T) and tremolite (Tr) in metamorphosed serpentinite. T.S., C.N.,  $\times 100$ .

ly by chromite, and sulphides (pyrite and pyrrhotite) and magnetite. Chromite occurs as euhedral to subhedral isolated crystals. Magnetite occurs as recrystallized fine euhedral to subhedral grains and usually altered to martite. Sulphides (pyrite and pyrrhotite) occur as fine and disseminated grains. They also form drop-like inclusions within carbonates.

### ***Metagabbros***

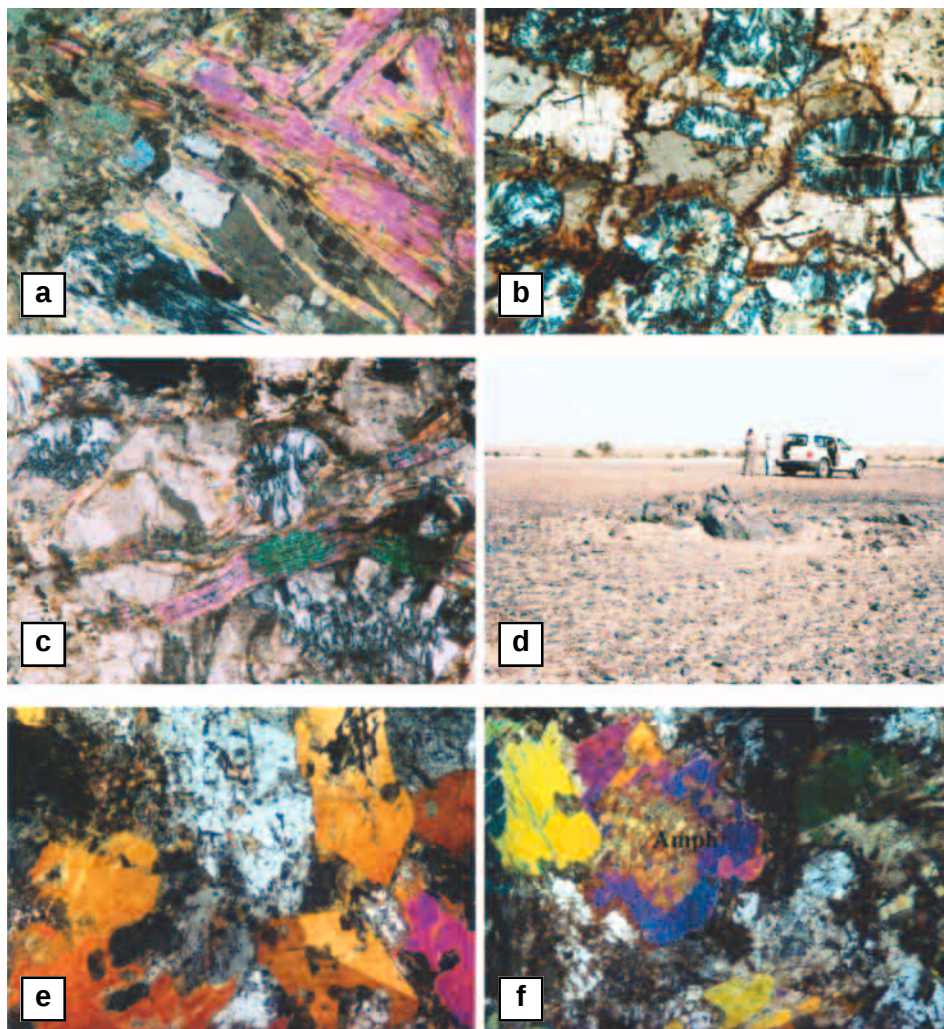
The metagabbros are mostly observed as isolated large blocks or slices. Small size blocks and fragments (0.5 to 10 m across) are also common. In most cases the metagabbros are intimately associated with serpentinites as large fragments (Plate 2d). The metagabbros are medium to coarse grained, black to dark green in color and composed mainly of plagioclase and amphiboles.

Microscopically, the metagabbros are composed of plagioclase, amphiboles, pyroxene and accessory opaques. Chlorite, calcite, and epidote represent the alteration minerals. Amphiboles, mainly represented by hornblende, occur as large anhedral to subhedral crystals of brownish green color and show corroded and irregular boundaries. These crystals are between 1.5 to 4 mm in length and are randomly oriented (Plate 2e). Some amphibole crystals show well developed twinning (Plate 2e). Actinolite is common and occurs as aggregates of fine fibrous and acicular crystals. The feldspars, mainly represented by plagioclase, occur as coarse to fine anhedral crystals (Plate 2e). Plagioclase is partly or completely enclosed within hornblende forming subophitic and ophitic texture (Plate 2e). These crystals are moderately altered to sericite and carbonate. Sometime fine acicular actinolites are formed at the expense of some plagioclase crystals. Pyroxene crystals are commonly surrounded by amphibole coronas (actinolite and hornblende) (Plate 2f). Ilmenite and rutile are the opaque minerals that have been found in the metagabbros. They constitute about 2% of the total volume of the rock and occur as disseminated fine anhedral grains (0.1 to 0.2 mm size).

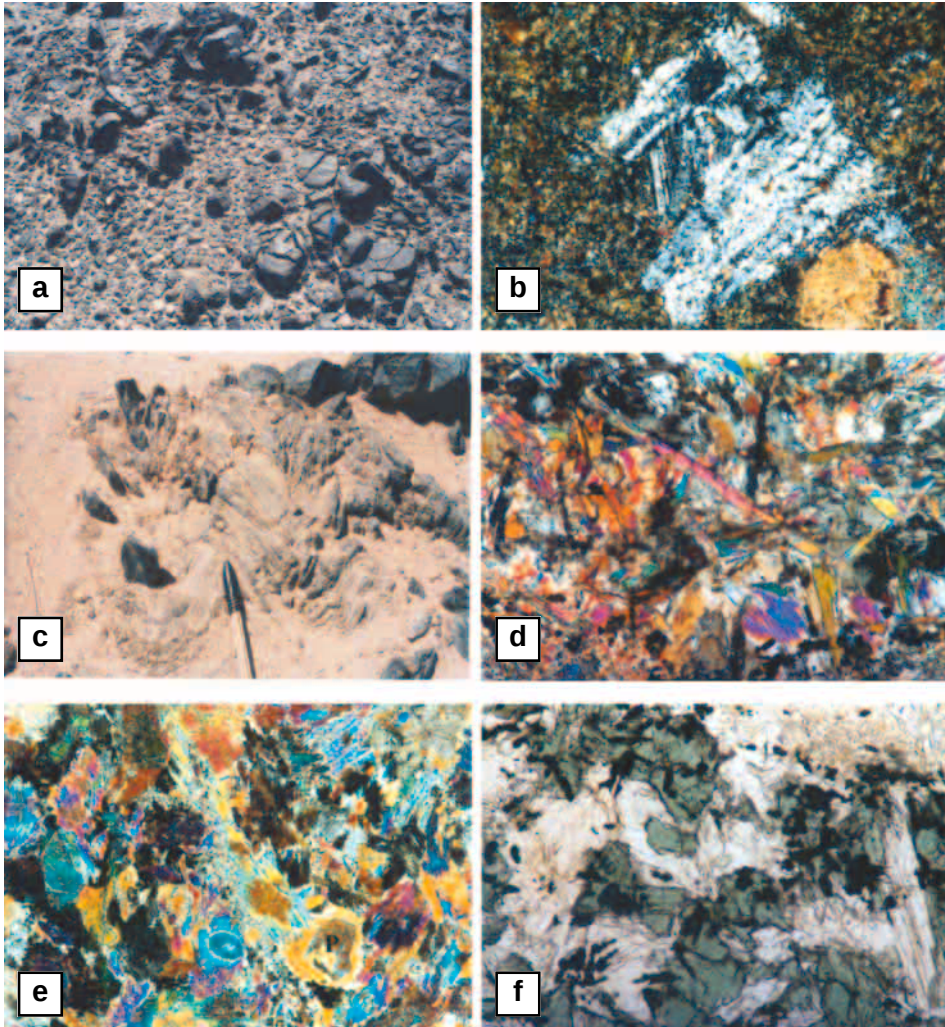
### ***Metabasalts***

The metabasalt occurs as a large mass at the north central part of the study area. Small size blocks and fragments are also recorded within the listvenites and serpentinites, especially at Jabal Ghadarah. The metabasalt is fine-grained black to green in color and locally show exfoliation (Plate 3a).

Microscopically, these rocks are essentially composed of plagioclase, actinolite and augite. Actinolite, the main constituent mineral of the rock, occurs as fine fibrous and acicular aggregates that seems to have been formed at the expense of pyroxene. The latter forms porphyritic crystals showing lammellar twinning (Plate 3b). Sometime few relicts of pyroxene crystals are observed.



- a) Talc in upper right corner and serpentine in left corner incorporated within carbonate groundmass in metamorphosed serpentine. T.S., C.N.,  $\times 200$ .
- b) Lizardite pseudomorph after olivine interstitial to magnesite. Notice magnesite is altered to iron oxides along grain boundaries Talc-lizardite listvenite. T.S., C.N.,  $\times 200$ .
- c) Talc formed at the expense of magnesite and serpentine minerals in talc-lizardite listvenite. T.S., C.N.,  $\times 200$ .
- d) Metagabbro block incorporated within serpentinite host rock.
- e) Euhedral twinned hornblende crystals and altered plagioclase. Notice ophitic and sub-ophitic intergrowth of plagioclase and hornblende. Metagabbro. T.S., C.N.,  $\times 25$ .
- f) Fine aggregates of amphiboles (Amph) pseudomorph after pyroxene enclosed within a prismatic hornblende. Metagabbro. T.S., C.N.,  $\times 25$ .



- a) Small blocks of metabasalt showing onion-like weathering.
- b) Metabasalt showing porphyritic plagioclase crystals embedded in actinolite and epidote groundmass. Notice euhedral augite crystal in the lower right side. T.S., C.N.,  $\times 63$ .
- c) Microfolding in highly deformed amphibolite.
- d) Spinel bearing amphibolite showing randomly oriented actinolite crystals. T.S., C.N.,  $\times 63$ .
- e) Pyroxene relict (P) in the core of actinolite crystals. Spinel-bearing amphibolite. T.S., C.N.,  $\times 25$ .
- f) Green spinel associated with magnetite in spinel-bearing amphibolite. T.S., C.N.,  $\times 100$ .

### ***Amphibolites***

The amphibolites crop out at the north central and northeastern part of the study area. They form large blocks as well as smaller unmappable elongated fragments. Locally marble lenses occur within the amphibolites. The amphibolites are usually dark green to black and highly foliated, but sometimes massive small blocks are observed. The amphibolites exhibit well developed minor folds related to different phases of deformations (Plate 3c). According to the field relation between the serpentinites and the amphibolites, the latter are interpreted as fragments from the metamorphic sole usually associated with the ophiolitic mélange.

Microscopically two types of amphibolites have been identified: 1) Spinel-bearing amphibolite, and 2) Spinel-free amphibolite.

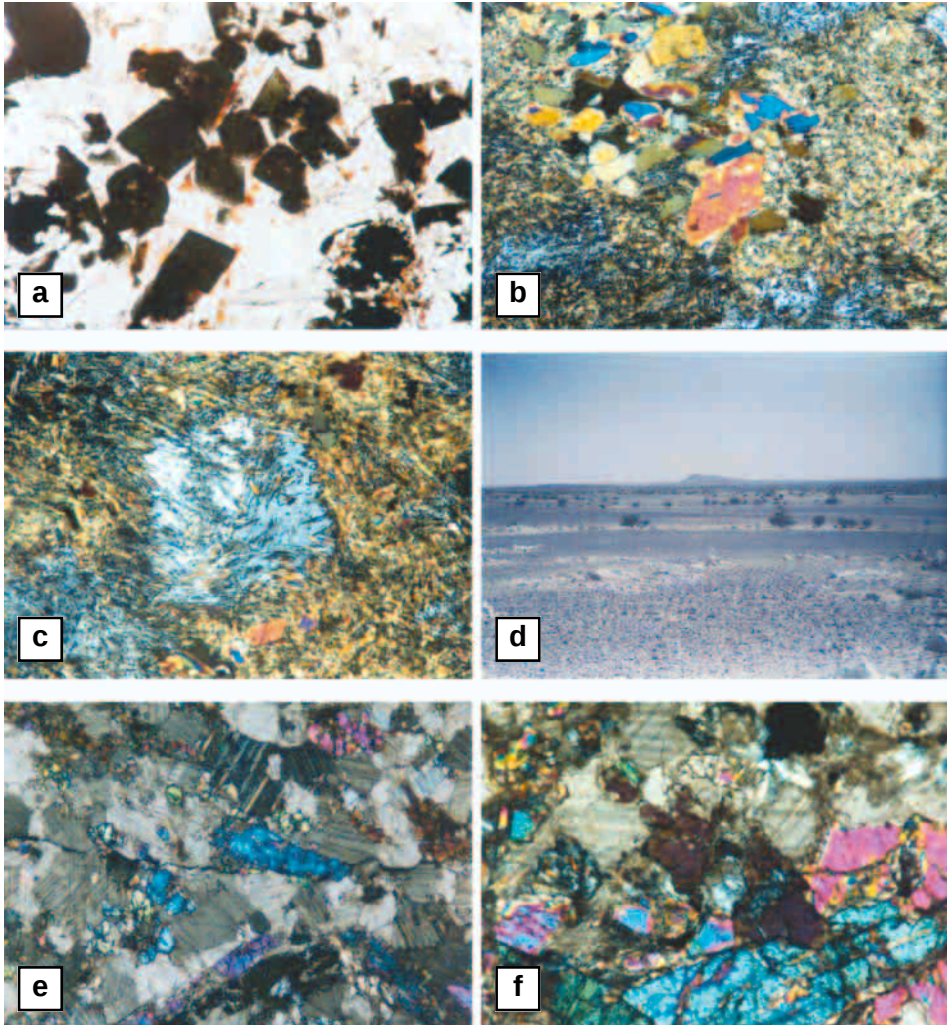
The spinel-bearing amphibolite, which is believed to be derived from ultramafic rocks (pyroxenite), is mainly made up of actinolite, relict pyroxene and spinel together with accessory opaque minerals (Plate 3d and e). Spinel occurs as coarse anhedral to subhedral aggregated grains and show a distinct green color, isotropic and high relief. Sometime, clusters of spinel aggregates are commonly associated with opaque minerals (magnetite) (Plate 3f and Plate 4a).

Takla and Noweir (1980) recorded the presence of green pleonastic spinel in pyroxenite from ophiolitic ultramafic mass of Jabal El-Rubshi. Also, spinel-bearing amphibolites have been recorded from the area around Zalim (Leistel *et al.*, 1999).

The spinel-free amphibolite, which is believed to be derived from mafic rocks (gabbros), is generally fine grained, greenish to black in color and massive. Under the microscope, these rocks are made up of amphiboles (actinolitic hornblende), plagioclase and accessory opaque minerals. Actinolite is the main constituent of the rock and occurs as fibrous and bladed crystals. Sometimes, actinolitic hornblende forms subidiomorphic to rhombic crystals (Plate 4b). Plagioclase is common and occurs as coarse corroded prismatic crystals partly replaced by acicular actinolite crystals (Plate 4c). Albite twining is still preserved in some plagioclase crystals (Plate 4c).

### ***Marbles***

Marbles are recorded at the north central and northeastern part of the study area. They occur as lenses or blocks ranging in size from 0.5-15 m in length and few meters across embedded in serpentinite matrix. The marble lenses are massive to highly fractured and form isolated blocks. They are white to grayish in color and contain black and reddish staining on the weathered surfaces. Mostly, the marble lenses occur as large rock fragments within the serpentinite country



- a) Aggregates of euhedral spinel in spinel-bearing amphibolite. T.S., P.P.L.,  $\times 200$ .  
 b) Amphibolite showing euhedral to subhedral actinolite hornblende crystals (central part of the photo) in a fine actinolite groundmass. T.S., C.N.,  $\times 100$ .  
 c) Subhedral plagioclase crystals replaced by actinolite. T.S., C.N.,  $\times 200$ .  
 d) White marble lenses incorporated within serpentinite host rock.  
 e) Elongated fractured crystals of diopside and rounded to sub-rounded grains of olivine in coarse mosaic aggregates of calcite. Marble. T.S., C.N.,  $\times 25$ .  
 f) Serpentinized olivine and prismatic diopside crystals in mosaic aggregates of calcite. Marble. T.S., C.N.,  $\times 63$ .

(host) rock (Plate 4d). Microscopically, these rocks consist mainly of calcite with subordinate olivine and diopside. Olivine and diopside appear in marbles, which are thermally affected by the granitic intrusions in the area. Calcite and dolomite are the main constituents of these rocks, and account for more than 70% of the volume of the rock. They occur as mosaic aggregates or clusters of coarse xenomorphic grains (up to 1mm across). They are colorless with rhombohedral cleavage and characteristic low birefringence (Plate 4e). Olivine occurs as fine rounded to subrounded grains ranging in size from 0.1 to 1.7 mm enclosed and interstitial to calcite. Locally olivine is altered to serpentine minerals. Diopside occurs as large, randomly oriented prismatic crystals. They range from 1 to 2.5 mm in length and are commonly cracked (Plate 4f).

### Geochemistry of Ophiolitic Mélange Rock Fragments

This section deals with the geochemistry of the metagabbroic, metabasaltic, and amphibolite fragments encountered in the ophiolitic mélange in order to identify their petrochemical character, magma type, and tectonic setting. To achieve this goal, representative samples from the different rock types were analyzed for major oxides and trace elements.

### Geochemistry of Metagabbros

The metagabbroic rocks, encountered within the ophiolitic mélange in the studied area have been sampled and analyzed for major oxides and trace elements, and were subjected for detailed petrographic investigation. The results of the major oxides and trace elements analyses of fourteen metagabbroic rock samples are listed in Table 1.

**Table 1. Chemical analyses of metagabbros.**

| Sample                         | JGN 3A | JGN 3B | JGN 4B | JGN 4D | JGN 26 | JGN 30 |
|--------------------------------|--------|--------|--------|--------|--------|--------|
| SiO <sub>2</sub>               | 47.40  | 49.70  | 43.35  | 45.25  | 51.60  | 47.35  |
| TiO <sub>2</sub>               | 0.15   | 0.26   | 0.03   | 0.27   | 1.65   | 1.26   |
| Al <sub>2</sub> O <sub>3</sub> | 15.62  | 13.55  | 16.52  | 16.60  | 15.85  | 14.30  |
| Fe <sub>2</sub> O <sub>3</sub> | 6.98   | 9.73   | 3.81   | 12.97  | 8.80   | 7.76   |
| MnO                            | 0.23   | 0.29   | 0.16   | 0.22   | 0.15   | 0.13   |
| MgO                            | 13.60  | 10.60  | 10.10  | 7.92   | 3.56   | 5.06   |
| CaO                            | 12.80  | 11.65  | 20.50  | 12.50  | 6.20   | 6.90   |
| Na <sub>2</sub> O              | 0.82   | 2.01   | 0.96   | 1.58   | 2.90   | 2.82   |
| K <sub>2</sub> O               | 0.29   | 0.49   | 0.30   | 0.56   | 1.36   | 5.15   |
| P <sub>2</sub> O <sub>5</sub>  | 0.02   | 0.06   | 0.02   | 0.04   | 0.26   | 0.44   |
| SO <sub>3</sub>                | 0.05   | 0.05   | 0.06   | 0.05   | 0.06   | 0.03   |
| L.O.I                          | 1.64   | 1.43   | 4.26   | 2.20   | 7.01   | 9.00   |
| SUM                            | 99.60  | 99.82  | 100.07 | 100.16 | 99.40  | 100.20 |

Table 1. Contd.

| Sample    | JGN 3A | JGN 3B | JGN 4B | JGN 4D | JGN 26 | JGN 30 |
|-----------|--------|--------|--------|--------|--------|--------|
|           | ppm    |        |        |        |        |        |
| Cr (10)*  | 647    | 955    | 590    | 136    | 9      | 233    |
| Ni (10)   | 222    | 299    | 162    | 149    | 42     | 101    |
| Co (5)    | 32     | 54     | 30     | 48     | 32     | 29     |
| V (10)    | 73     | 176    | 66     | 527    | 196    | 185    |
| Cu (5)    | 33     | 25     | 7      | 43     | 15     | 38     |
| Pb (10)   | 6      | 5      | 1      | —      | 1      | 10     |
| Zn (5)    | 51     | 79     | 28     | 63     | 91     | 83     |
| Bi (10)   | —      | —      | —      | 1      | 1      | 1      |
| Cd (5)    | 4      | 4      | 2      | 5      | 3      | 3      |
| Sn (50)   | 11     | 11     | 8      | 12     | 4      | 4      |
| W (10)    | —      | —      | —      | —      | 6      | 13     |
| Mo (5)    | 6      | 7      | 4      | 5      | 4      | 6      |
| As (50)   | 21     | 39     | 9      | 47     | 108    | 234    |
| Sb (10)   | —      | 2      | —      | 4      | 5      | 4      |
| Ag (1.0)  | —      | —      | —      | —      | —      | 0.7    |
| Au (0.01) | —      | —      | 0.01   | 0.01   | —      | 0.02   |
| Ba (10)   | 73     | 93     | 56     | 98     | 48     | 322    |
| Sr (5)    | 200    | 42     | 233    | 207    | 142    | 156    |
| Li (10)   | 11     | —      | 23     | 21     | —      | 39     |
| Nb (20)   | 5      | 8      | 3      | 5      | 1      | 10     |
| Zr (250)  | 10     | 59     | 6      | 20     | 5      | 94     |
| Y (20)    | 3      | 12     | 2      | 3      | 1      | 18     |
| La (20)   | —      | 4      | —      | —      | —      | 9      |
| Ce (10)   | 2      | 2      | —      | 1      | 6      | 20     |
| B (10)    | 21     | 31     | 27     | 33     | 18     | 29     |
| Be (2)    | —      | —      | —      | —      | —      | —      |

\*Detection limit. (—) Below detection limit.

Table 1. Contd.

| Sample                         | JGN 74 | JGN 101B | JGN 102 | JGN 103 | JGN 105 | JGN 107 |
|--------------------------------|--------|----------|---------|---------|---------|---------|
| SiO <sub>2</sub>               | 52.90  | 48.2     | 48.5    | 29.7    | 48.2    | 56.5    |
| TiO <sub>2</sub>               | 0.08   | 1.55     | 0.57    | 0.53    | 0.57    | 0.09    |
| Al <sub>2</sub> O <sub>3</sub> | 5.15   | 15.3     | 6.9     | 18.5    | 7.3     | 5.5     |
| Fe <sub>2</sub> O <sub>3</sub> | 9.43   | 12.3     | 9.6     | 12.4    | 9.2     | 11.3    |
| MnO                            | 0.22   | 0.21     | 0.16    | 0.28    | 0.16    | 0.18    |
| MgO                            | 21.20  | 5.5      | 20.4    | 24.3    | 19.6    | 18.8    |
| CaO                            | 7.28   | 12.8     | 8.2     | 1.6     | 8.5     | 4.8     |
| Na <sub>2</sub> O              | 0.20   | 2.23     | 0.62    | 0.14    | 0.51    | 0.51    |
| K <sub>2</sub> O               | 0.08   | 0.3      | 0       | 0       | 0       | 0.1     |
| P <sub>2</sub> O <sub>2</sub>  | 0.03   | 0.2216   | 0.1069  | 0.3378  | 0.1033  | 0.0385  |

Table 1. Contd.

| Sample          | JGN 74 | JGN 101B | JGN 102 | JGN 103 | JGN 105 | JGN 107 |
|-----------------|--------|----------|---------|---------|---------|---------|
| SO <sub>3</sub> | 0.06   | 0.04     | 0.05    | 0.06    | 0.03    | 0.06    |
| L.O.I           | 3.64   | 0.83     | 4.43    | 11.86   | 4.82    | 1.55    |
| SUM             | 100.27 | 99.4816  | 99.5369 | 99.7078 | 98.9933 | 99.4285 |
| ppm             |        |          |         |         |         |         |
| Cr              | 2751   | 806      | 2002    | 210     | 2202    | 3033    |
| Ni              | 648    | 309      | 869     | 235     | 1206    | 636     |
| Co              | 71     | 61       | 68      | 44      | 73      | 69      |
| V               | 103    | 355      | 139     | 343     | 149     | 118     |
| Cu              | 9      | 91       | 13      | 61      | 37      | 9       |
| Pb              | –      | –        | –       | –       | –       | –       |
| Zn              | 77     | 89       | 64      | 106     | 70      | 85      |
| Bi              | –      | 4        | –       | –       | –       | –       |
| Cd              | 2      | 5        | 5       | 4       | 5       | 5       |
| Sn              | 11     | 7        | 16      | 14      | 19      | 21      |
| W               | –      | –        | –       | –       | –       | –       |
| Mo              | 6      | 6        | 5       | 6       | 5       | 5       |
| As              | 168    | 21       | 52      | 57      | 25      | 53      |
| Sb              | 2      | 2        | 2       | –       | –       | –       |
| Ag              | –      | –        | –       | –       | –       | –       |
| Au              | –      | –        | –       | –       | –       | –       |
| Ba              | 421    | 223      | 39      | 295     | 24      | 62      |
| Sr              | 727    | 162      | 44      | 99      | 59      | 45      |
| Li              | 15     | 4        | –       | –       | –       | 7       |
| Nb              | 5      | 17       | 14      | 8       | 15      | 6       |
| Zr              | 101    | 99       | 61      | 47      | 64      | 31      |
| Y               | 20     | 27       | 11      | 9       | 12      | 2       |
| La              | 14     | 6        | 4       | 3       | 5       | –       |
| Ce              | 30     | 13       | 9       | 8       | 11      | 1       |
| B               | 18     | 6        | 15      | 14      | 14      | 11      |
| Be              | –      | –        | –       | –       | –       | –       |

It is well known that, recognition of magma type, its chemical nature and its behavior on differentiation, aptly help to decipher the tectonic setting of the rocks. The magma type of the concerned metagabbroic rocks is clarified through the following relationships (Fig. 3a, b and c):

a. SiO<sub>2</sub> vs. (Na<sub>2</sub>O+K<sub>2</sub>O) diagram (Fig. 3a) of Mac Donalds and Katsura (1964) shows that the metagabbros fall within the field of tholeiitic suite.

b. SiO<sub>2</sub> vs. (Na<sub>2</sub>O+K<sub>2</sub>O) diagram (Fig. 3b) of Irvine and Baragar (1971), reveals that the metagabbroic samples are plotted within the field of subalkaline magma.

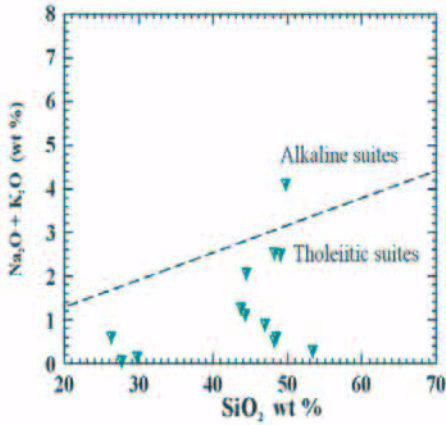


Fig. 3(a).  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  vs.  $\text{SiO}_2$  diagram for metagabbroic rocks (Mac Donalds and Katsura, 1964).

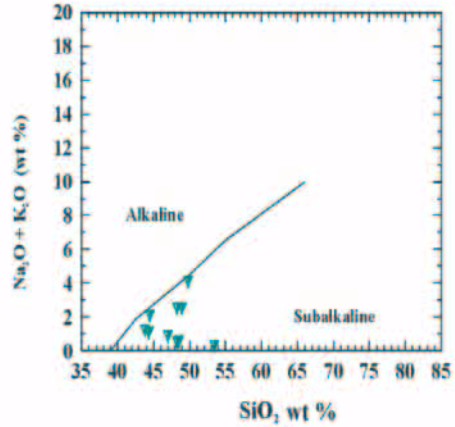


Fig. 3(b).  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  vs.  $\text{SiO}_2$  diagram for metagabbroic rocks (Irvine and Baragar, 1964).

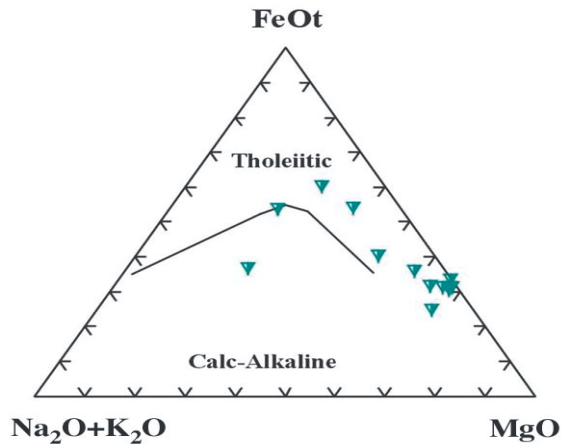


Fig. 3(c). AFM ternary diagram for the metagabbroic rocks (Irvine and Baragar, 1971).

c. On the AFM diagram (Fig. 3c) of Irvine and Baragar (*op. cit.*), the metagabbroic samples show a tholeiitic trend.

The ocean floor affinity of the metagabbros is not fully revealed by the  $\text{Ti}/100\text{-Zr-Sr}/2$  (Pearce and Cann, 1973) (Fig. 4). The scatter of the data can be explained in term of metamorphism and alteration. Also, the scatter can be attributed to the coarse grained nature of the rocks (cumulates) and the chemistry of metagabbros does not represent the original composition of the magma.

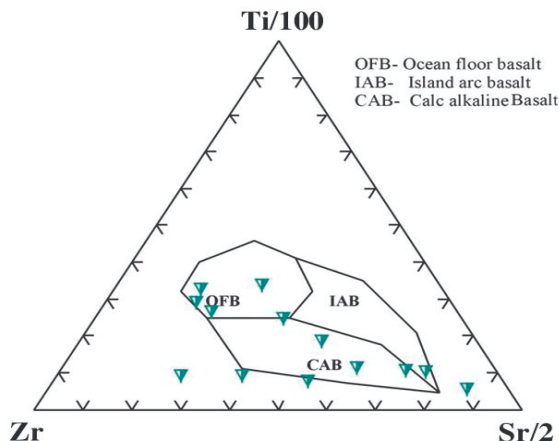


Fig. 4. Ti/100-Zr-Sr/2 ternary diagram for the metagabbroic rocks (Pearce and Cann, 1973).

### Geochemistry of Metabasalts

The metabasaltic rocks present in the study area are considered as a component of the ophiolitic *mélange* rocks. Eight samples, were analysed for major oxides and trace elements and the results are given in Table 2.

The metabasaltic rocks are chemically classified using the  $\text{SiO}_2$  vs.  $\text{Na}_2\text{O}+\text{K}_2\text{O}$  (total alkalis) and  $\text{K}_2\text{O}$  vs.  $\text{SiO}_2$  diagrams. The plotting of the data coincides completely with the microscopic identification.

Total alkalis vs.  $\text{SiO}_2$  diagram (Le Maitre *et al.*, 1989) is used to differentiate between the different types of volcanic rocks. Most of the metabasalt samples are plotted in the basalt field (Fig. 5).

Irvine and Baragar (1971) used the relationship between  $\text{SiO}_2$  and total alkalis for the distinction between the alkalic and subalkalic magma (Fig. 6). The majority of the metabasalt samples are plotted in the subalkaline field, while two samples are within alkaline field close to the subalkaline field.

Irvine and Baragar (*op. cit.*) used the AFM ternary diagram in order to discriminate between calc alkaline magma (CA) and the tholeiitic magma (TH) (Fig. 7). The majority of the metabasalt samples show Fe enrichment indicative of a tholeiitic trend.

On  $\text{SiO}_2$  vs.  $\text{FeOt/MgO}$  diagram (Miyashiro, 1974) the majority of the analyzed metabasalt samples are plotted in the tholeiite field (Fig. 8).

Pearce (1975) used the Cr against Ti diagram (Fig. 9), to differentiate between the Ocean floor basalt (OFB) and the low potassium tholeiite (LKT). The

Table 2. Chemical analyses of metabasalts.

| Sample                             | JGN 37 | JGN 47 | JGN 50A | JGN 58 | JGN 64 | JGN 76 | JGN 114 | JGN 116 |
|------------------------------------|--------|--------|---------|--------|--------|--------|---------|---------|
| <b>SiO<sub>2</sub></b>             | 47.86  | 49.00  | 50.25   | 52.50  | 49.00  | 44.75  | 52.60   | 49.80   |
| <b>TiO<sub>2</sub></b>             | 1.22   | 1.15   | 1.80    | 1.10   | 1.00   | 1.60   | 2.30    | 0.60    |
| <b>Al<sub>2</sub>O<sub>3</sub></b> | 14.40  | 13.62  | 12.70   | 17.44  | 14.23  | 14.97  | 14.90   | 16.20   |
| <b>Fe<sub>2</sub>O<sub>3</sub></b> | 8.60   | 9.98   | 11.15   | 9.65   | 10.87  | 12.22  | 9.50    | 11.30   |
| <b>MnO</b>                         | 0.14   | 0.18   | 0.21    | 0.17   | 0.27   | 0.22   | 0.10    | 0.30    |
| <b>MgO</b>                         | 5.98   | 4.60   | 5.65    | 4.90   | 7.40   | 7.60   | 3.40    | 5.70    |
| <b>CaO</b>                         | 7.30   | 10.48  | 7.84    | 6.44   | 12.34  | 14.10  | 6.30    | 11.80   |
| <b>Na<sub>2</sub>O</b>             | 2.97   | 1.16   | 3.32    | 3.89   | 2.86   | 1.31   | 3.59    | 3.24    |
| <b>K<sub>2</sub>O</b>              | 1.05   | 1.15   | 0.47    | 0.12   | 0.31   | 0.69   | 2.50    | 0.40    |
| <b>P<sub>2</sub>O<sub>5</sub></b>  | 0.35   | 0.13   | 0.16    | 0.30   | 0.09   | 0.15   | 0.97    | 0.06    |
| <b>SO<sub>3</sub></b>              | 0.08   | 0.08   | 0.06    | 0.09   | 0.08   | 0.06   | 0.06    | 0.05    |
| <b>L.O.I</b>                       | 9.38   | 8.67   | 6.71    | 3.50   | 1.43   | 1.48   | 4.45    | 0.66    |
| <b>SUM</b>                         | 99.33  | 100.20 | 100.32  | 100.10 | 99.88  | 99.15  | 100.61  | 100.06  |
| <b>ppm</b>                         |        |        |         |        |        |        |         |         |
| <b>Cr</b>                          | 387    | 193    | 40      | 50     | 306    | 317    | 212     | 632     |
| <b>Ni</b>                          | 130    | 77     | 65      | 56     | 99     | 119    | 56      | 97      |
| <b>Co</b>                          | 32     | 41     | 41      | 37     | 47     | 50     | 31      | 42      |
| <b>V</b>                           | 197    | 281    | 340     | 279    | 320    | 360    | 192     | 248     |
| <b>Cu</b>                          | 28     | 78     | 92      | 47     | 126    | 139    | 42      | 118     |
| <b>Pb</b>                          | 12     | 4      | 5       | 14     | —      | —      | 5       | —       |
| <b>Zn</b>                          | 77     | 75     | 86      | 92     | 75     | 100    | 129     | 60      |
| <b>Bi</b>                          | 3      | 4      | 4       | 5      | 2      | 5      | 2       | 6       |
| <b>Cd</b>                          | 3      | 3      | 5       | 4      | 1      | 1      | 4       | 5       |
| <b>Sn</b>                          | 13     | 14     | 13      | 13     | —      | —      | 20      | 22      |
| <b>W</b>                           | —      | 10     | 6       | 8      | —      | —      | —       | —       |
| <b>Mo</b>                          | 6      | 6      | 8       | 7      | —      | —      | 4       | 7       |
| <b>As</b>                          | 85     | 86     | 75      | 68     | 41     | 81     | 21      | 32      |
| <b>Sb</b>                          | 9      | 18     | 10      | 24     | —      | —      | —       | —       |
| <b>Ag</b>                          | —      | 0.7    | 0.2     | 0.9    | —      | —      | —       | —       |
| <b>Au</b>                          | —      | —      | —       | —      | —      | —      | —       | —       |
| <b>Ba</b>                          | 981    | 275    | 296     | 209    | 139    | 312    | 1776    | 323     |
| <b>Sr</b>                          | 609    | 159    | 212     | 1018   | 225    | 290    | 1164    | 163     |
| <b>Li</b>                          | 42     | 32     | 16      | 21     | 4      | 11     | 37      | 11      |
| <b>Nb</b>                          | 9      | 3      | 6       | 9      | 9      | 4      | 19      | 11      |
| <b>Zr</b>                          | 158    | 65     | 203     | 108    | 54     | 88     | 76      | 30      |
| <b>Y</b>                           | 18     | 20     | 25      | 20     | 18     | 22     | 17      | 15      |
| <b>La</b>                          | 15     | 2      | 4       | 15     | —      | 4      | 37      | —       |
| <b>Ce</b>                          | 34     | 3      | 9       | 34     | 5      | 9      | 79      | 1       |
| <b>B</b>                           | 22     | 29     | 21      | 24     | 17     | 19     | 4       | 13      |
| <b>Be</b>                          | —      | —      | —       | —      | —      | —      | —       | —       |

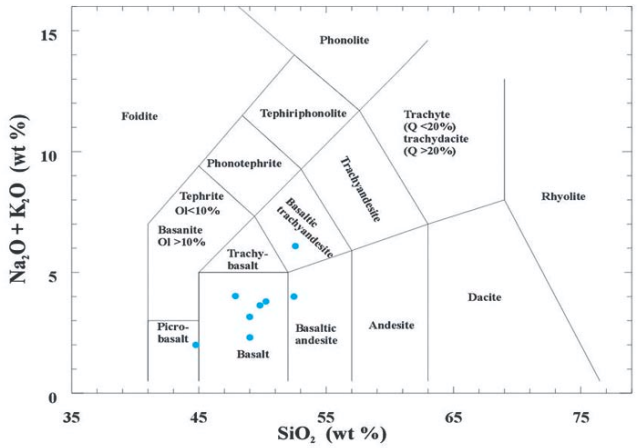


Fig. 5. Na<sub>2</sub>O+K<sub>2</sub>O vs. SiO<sub>2</sub> diagram for the metabasaltic rocks (Le Maitre *et al.*, 1989).

studied metabasalt samples are plotted within the OFB except one sample, which is plotted in LKT field close to the OFB filed.

Shervais (1982) used the V vs. Ti/1000 binary diagram to distinguish between the Ocean floor (OFB) and the Island arc (ARC) basalt. Accordingly, most of metabasalt samples are plotted within the OFB field, while two samples are plotted within the Island arc field close to the OFB field (Fig. 10).

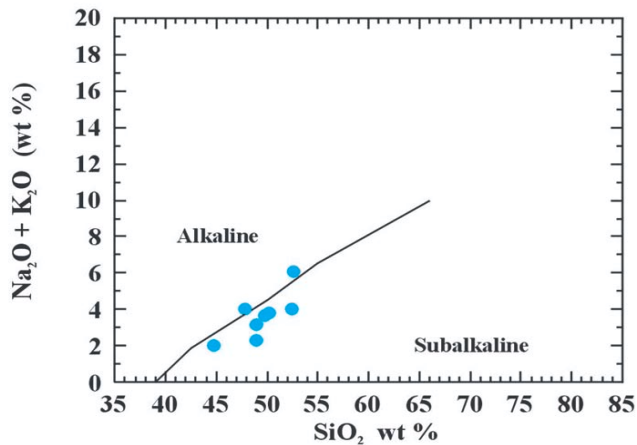


Fig. 6. Na<sub>2</sub>O+K<sub>2</sub>O vs. SiO<sub>2</sub> diagram for the metabasaltic rocks (Irvin and Baragar, 1971).

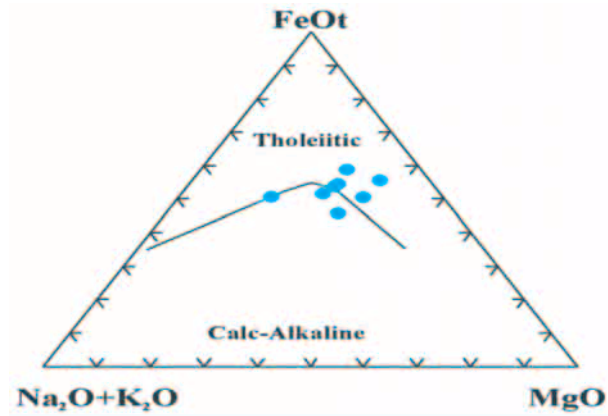


Fig. 7. AFM ternary diagram for the metabasaltic rocks (Irvine and Baragar, 1971).

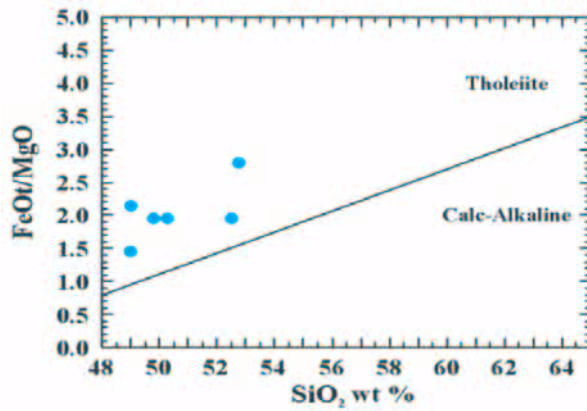


Fig. 8. FeOt/MgO vs. SiO<sub>2</sub> diagram for metabasaltic rocks (Miyashiro, 1974).

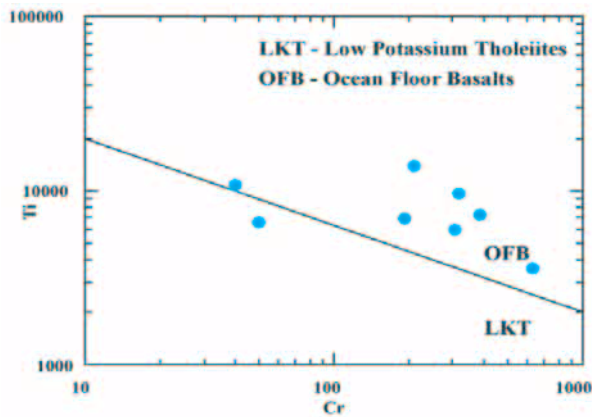


Fig. 9. Ti vs. Cr diagram for the metabasaltic rocks (Pearce, 1975).

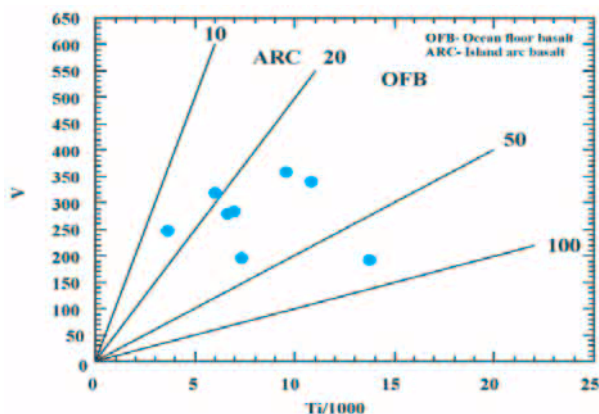


Fig. 10. V vs. Ti/1000 diagram for the metabasaltic rocks (Shervais, 1982).

### Geochemistry of the Amphibolites

The amphibolites, which are encountered in the ophiolitic *mélange* in the study area have been sampled for detailed petrography and geochemical studies to clarify their nature and parent rocks. Eight representative rock samples were analysed for the major and trace elements. The results are tabulated in Table 3.

Table 3. Chemical analyses of amphibolites.

| Sample                         | JGN 46 | JGN 78 | JGN 79 | JGN 80 | JGN 81 | JGN 121 | JGN 122C | 120A  |
|--------------------------------|--------|--------|--------|--------|--------|---------|----------|-------|
| SiO <sub>2</sub>               | 48.80  | 51.30  | 49.60  | 43.70  | 47.00  | 51.60   | 27.60    | 36.50 |
| TiO <sub>2</sub>               | 1.34   | 1.26   | 1.08   | 1.55   | 1.63   | 1.33    | 3.07     | 0.88  |
| Al <sub>2</sub> O <sub>3</sub> | 12.62  | 13.51  | 8.95   | 13.25  | 16.00  | 11.80   | 19.30    | 15.70 |
| Fe <sub>2</sub> O <sub>3</sub> | 15.15  | 10.22  | 10.42  | 12.95  | 12.70  | 12.30   | 17.50    | 13.00 |
| MnO                            | 0.31   | 0.22   | 0.18   | 0.22   | 0.20   | 0.18    | 0.30     | 0.14  |
| MgO                            | 7.46   | 7.45   | 18.90  | 19.40  | 5.35   | 12.90   | 20.50    | 24.20 |
| CaO                            | 7.14   | 8.92   | 7.40   | 4.48   | 14.40  | 6.20    | 1.10     | 1.60  |
| Na <sub>2</sub> O              | 2.89   | 5.37   | 0.32   | 0.32   | 1.32   | 1.82    | 0.09     | 0.16  |
| K <sub>2</sub> O               | 1.18   | 0.27   | 0.07   | 0.09   | 0.35   | 0.10    | 0.00     | 0.00  |
| P <sub>2</sub> O <sub>5</sub>  | 0.14   | 0.12   | 0.20   | 0.17   | 0.22   | 0.20    | 0.34     | 0.18  |
| SO <sub>3</sub>                | 0.06   | 0.07   | 0.08   | 0.04   | 0.04   | 0.05    | 0.05     | 0.05  |
| L.O.I                          | 2.82   | 1.06   | 2.14   | 2.88   | 0.72   | 1.52    | 9.82     | 7.07  |
| SUM                            | 99.91  | 99.77  | 99.34  | 99.05  | 99.93  | 100.00  | 99.67    | 99.48 |
| <b>ppm</b>                     |        |        |        |        |        |         |          |       |
| Cr                             | 95     | 420    | 1387   | 535    | 848    | 1065    | 370      | 121   |
| Ni                             | 79     | 203    | 996    | 237    | 322    | 823     | 311      | 150   |
| Co                             | 52     | 51     | 59     | 44     | 64     | 61      | 65       | 45    |
| V                              | 426    | 366    | 194    | 308    | 395    | 260     | 471      | 92    |
| Cu                             | 95     | 53     | 62     | 10     | 96     | 155     | 16       | 9     |
| Pb                             | 8      | —      | —      | —      | —      | —       | —        | —     |

Table 3. Contd.

| Sample    | JGN 46 | JGN 78 | JGN 79 | JGN 80 | JGN 81 | JGN 121 | JGN 122C | 120A |
|-----------|--------|--------|--------|--------|--------|---------|----------|------|
| <b>Zn</b> | 109    | 84     | 57     | 56     | 94     | 89      | 117      | 82   |
| <b>Bi</b> | 2      | 8      | —      | 2      | 7      | 1       | —        | —    |
| <b>Cd</b> | 4      | 1      | 2      | 1      | 1      | 6       | 7        | 5    |
| <b>Sn</b> | 20     | —      | 3      | —      | —      | 27      | 25       | 18   |
| <b>W</b>  | 13     | —      | —      | —      | —      | —       | —        | —    |
| <b>Mo</b> | 8      | 2      | 5      | 4      | 2      | 6       | 5        | 5    |
| <b>As</b> | 92     | 67     | 109    | 102    | 69     | 57      | 52       | 21   |
| <b>Sb</b> | 11     | 7      | —      | 17     | 4      | —       | —        | —    |
| <b>Ag</b> | 0.8    | —      | —      | —      | 0.5    | —       | —        | —    |
| <b>Au</b> | —      | —      | —      | —      | —      | —       | —        | —    |
| <b>Ba</b> | 355    | 178    | 109    | 80     | 164    | 170     | 152      | 24   |
| <b>Sr</b> | 423    | 213    | 55     | 65     | 196    | 184     | 106      | 36   |
| <b>Li</b> | 11     | 4      | 6      | 20     | 8      | 3       | 4        | 8    |
| <b>Nb</b> | 5      | 5      | 11     | 2      | 12     | 16      | 17       | 14   |
| <b>Zr</b> | 81     | 65     | 97     | 102    | 92     | 95      | 204      | 265  |
| <b>Y</b>  | 33     | 25     | 19     | 25     | 28     | 24      | 58       | 34   |
| <b>La</b> | 1      | —      | 9      | 6      | 6      | 6       | 9        | 26   |
| <b>Ce</b> | 1      | 6      | 20     | 13     | 13     | 13      | 19       | 55   |
| <b>B</b>  | 15     | 12     | 14     | 18     | 15     | 11      | 12       | 16   |
| <b>Be</b> | —      | —      | —      | —      | —      | —       | —        | —    |

The studied amphibolites are remarkably of mafic characters as evident from their low contents of  $\text{SiO}_2$  and alkalies, and high contents of  $\text{Fe}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{CaO}$  and  $\text{TiO}_2$ . These chemical characteristics also point out the mafic nature of their parent rocks. The petrographic study reveals the presence of two types; 1) Spinel-amphibolite and 2) Spinel-free amphibolite. The relatively high content of the  $\text{TiO}_2$  (ranging between 1 and 3.07%) collaborates the ore microscopic study, which indicates the dominance of ilmenite. The results of chemical analyses were plotted on  $\text{SiO}_2$ - $\text{CaO}$ - $\text{MgO}$  and  $\text{Al}_2\text{O}_3$ - $\text{CaO}$ - $\text{MgO}$  ternary diagrams (Fig.11a and b). From these diagrams, two groups can be distinguished. The 1<sup>st</sup> group is characterized by higher  $\text{MgO}$  and low  $\text{CaO}$  and  $\text{SiO}_2$ . The 2<sup>nd</sup> group shows higher  $\text{SiO}_2$  and  $\text{CaO}$  and lower  $\text{MgO}$ . Such grouping is confirmed petrographically where the 1<sup>st</sup> group was found to be spinel-bearing and believed to be formed after ultramafic (pyroxenites) protolith, while the 2<sup>nd</sup> group was formed after a mafic (metagabbros) protolith.

Furthermore, the  $\text{Zr/Ti}$  versus  $\text{Ni}$  and  $\text{P}_2\text{O}_5/\text{TiO}_2$  versus  $\text{MgO/CaO}$  relationships, which were used by many authors (e.g., Miller and Barr, 2000) to distinguish between ortho (igneous) and para (sedimentary) amphibolites indicate that the studied amphibolites are of igneous protolith (Fig.12a and b).

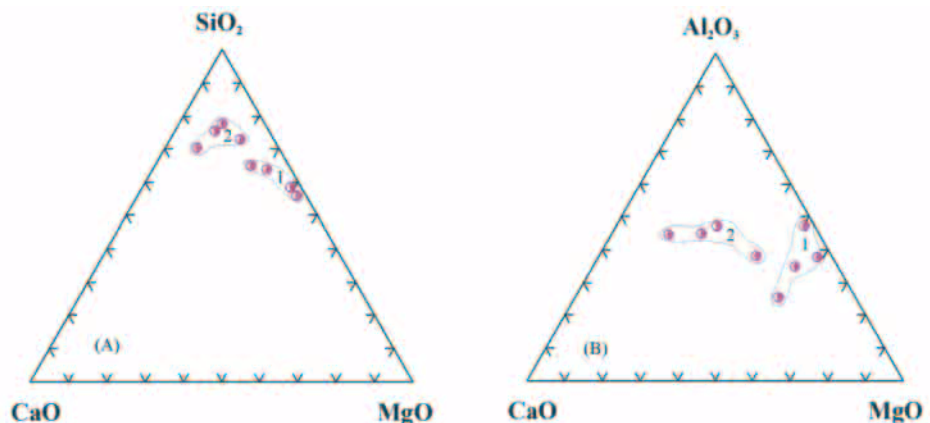


Fig. 11.  $\text{SiO}_2$ -CaO-MgO (A) and  $\text{Al}_2\text{O}_3$ -CaO-MgO (B) ternary diagrams for spinel-bearing (1) and spinel free (2) amphibolites.

The Zr versus  $\text{TiO}_2$  diagram was used by Hallberg (1985) to distinguish between the different types of plutonic rocks. The majority of amphibolite samples were plotted within the field of mafic-ultramafic rocks, (Fig. 13).

The magma type of the amphibolite protolith can be clarified from the relation between the total alkalis and  $\text{SiO}_2$  (Irvine and Baragar, 1971) for the distinction between the alkaline and subalkaline magmas. Most of the amphibolite samples are plotted within or close to the field of subalkaline magma (Fig. 14).

Irvine and Baragar (*op. cit.*) used the AFM ternary diagram in order to discriminate between the calc-alkaline magma (CA) and the tholeiitic (TH) one. The majority of the amphibolite samples show tholeiitic trend (Fig. 15).

The tectonic setting of the protolith of the amphibolites is defined through the V versus  $\text{Ti}/1000$  binary diagram, which distinguishes between the ocean floor basalt (OFB) and the island arc (ARC) basalt (Shervais, 1982). Accordingly, most of the amphibolite samples plot within the OFB field (Fig. 16).

Pearce and Cann (1973) used the  $\text{Ti}/100$ -Zr- $\text{Y}^*3$  ternary diagram to identify the different tectonic setting of basaltic magma. The majority (6 samples) of studied amphibolite samples plot within the field of the ocean floor (Fig.17).

In conclusion, based on the mineralogical composition as well as geochemical characters, the studied amphibolites were derived by metamorphism of mafic (metagabbro)-ultramafic (pyroxenite) protolith and can be considered as the metamorphic sole or subophiolitic amphibolites similar to those described from Oman (Lippard *et al.*, 1986), Egypt (Abd El-Naby *et al.*, 2000) and Newfoundland (Williams and Smythe, 1973).

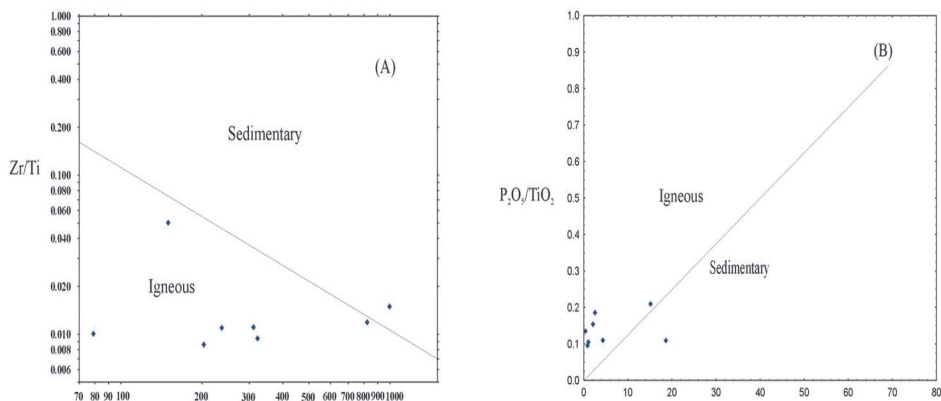


Fig. 12. Zr/Ti vs. Ni (A) and  $P_2O_5$  vs. MgO/CaO (B) for amphibolites. Dividing lines in A and B (after Wernner, 1987).

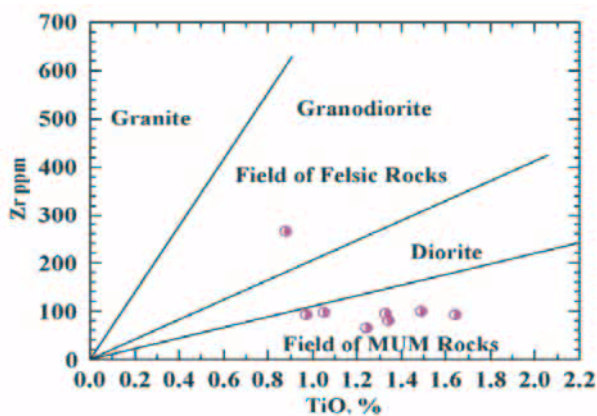


Fig. 13. Zr vs.  $TiO_2$  diagram for amphibolites (Hallberg, 1985).

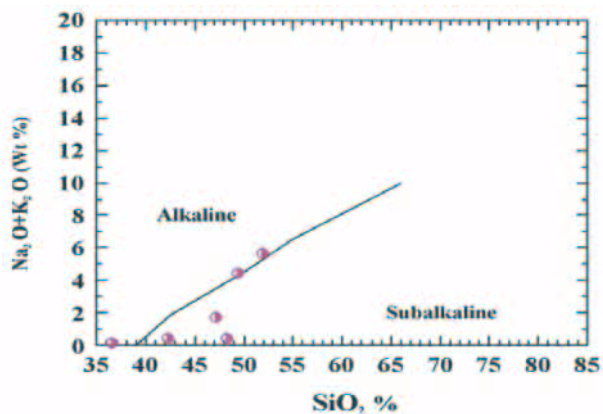


Fig. 14.  $Na_2O+K_2O$  vs.  $SiO_2$  diagram for the amphibolites (Irvine and Baragar, 1971).

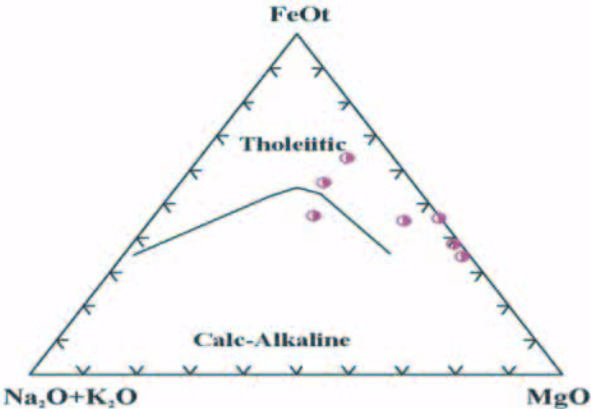


Fig. 15. AFM ternary diagram for the amphibolite rocks (Irvine and Baragar, 1971).

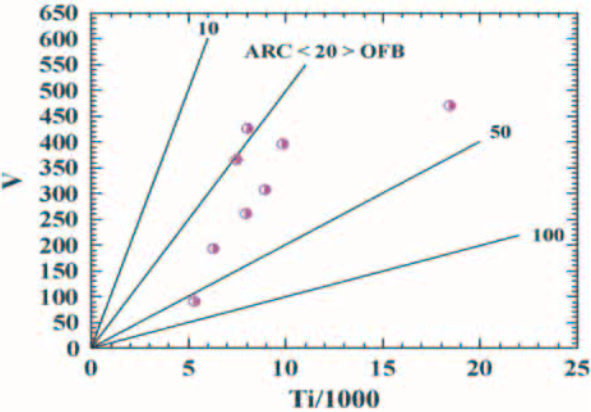


Fig. 16. V vs. Vi/1000 diagram for the amphibolites (Shervais, 1982).



Fig. 17. Ti/100-Zr-Y\*3 ternary diagram for the amphibolites (Pearce and Cann, 1973).

### Geochemistry of Chromite

The petrographic studies of the metaultramafites and associated rock fragments revealed that the area was subjected to green schist- amphibolite facies metamorphism. Such a metamorphism obliterated the primary minerals of the ultramafic protolith, however, chromite survived metamorphism and can be used as a petrogenetic indicator (Irvine, 1965, 1967 and 1976; Dick, 1977; Evans and Frost, 1975; Fisk and Bence, 1980; Dick and Bullen, 1984 & Ahmed *et al.*, 2001).

The studied serpentinites and listvanites contain chromite as disseminations as well as massive lensoid aggregates (chromitites). Chromite crystals are highly fractured, brecciated and altered along the crystal boundaries and fractures into magnetite with fresh remnants at the core displaying the characteristic brown color.

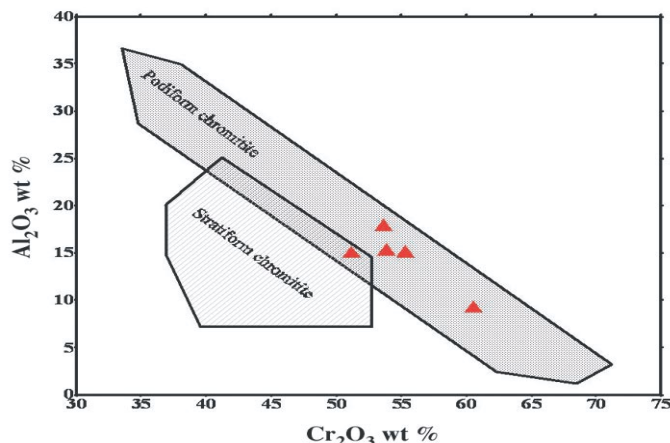
Representative crystals were analyzed for major oxides by SEM-EDX and the results are listed in Table 4. Chromite shows a wide compositional range where Cr<sub>2</sub>O<sub>3</sub>% ranges from 51.18 to 60.58 and Al<sub>2</sub>O<sub>3</sub> content from 2.20 to 17.73 % and is comparable to chromite from podiform chromitites (Fig. 18). The Cr# varies from 0.67 to 0.82 (Table 4) and is comparable to those reported by Ahmed *et al.* (2001) from Proterozoic ophiolites from Egypt. The Mg# is generally variable and ranges from 0.12 to 0.94.

**Table 4. Chromite major oxides content.**

| Wt %                           | 1      | 2      | 3     | 4     | 5      |
|--------------------------------|--------|--------|-------|-------|--------|
| Cr <sub>2</sub> O <sub>3</sub> | 60.58  | 55.27  | 53.89 | 51.18 | 53.26  |
| Fe <sub>2</sub> O <sub>3</sub> | 22.88  | 20.38  | 22.11 | 31.71 | 18.52  |
| Al <sub>2</sub> O <sub>3</sub> | 9.12   | 14.93  | 15.18 | 14.90 | 17.73  |
| MgO                            | 7.42   | 8.97   | 9.25  | 2.20  | 10.14  |
| Total                          | 100.00 | 100.00 | 99.43 | 99.99 | 100.01 |
| Cr#                            | 0.82   | 0.71   | 0.70  | 0.70  | 0.67   |
| Mg#                            | 0.94   | 0.46   | 0.47  | 0.12  | 0.36   |

The close similarity of Pan-African (Upper Proterozoic) peridotites to Phanerozoic peridotites from present day fast-spreading ridges suggests that the geothermal gradients, which control the genesis of the crust-mantle rocks, have not significantly changed since the late Proterozoic era (Brown, 1979 and Ahmed *et al.*, 2001).

Dick and Bullen (1984) classified peridotites from ophiolitic complexes, based on chromite chemistry, as type I where the chromite composition is com-



**Fig. 18.** Variation of  $\text{Cr}_2\text{O}_3$  vs.  $\text{Al}_2\text{O}_3$  of chromite in Ghadarah peridotites. Compositional fields of podiform and stratiform chromitites after Bonavia *et al.* (1993).

parable to chromite from peridotites dredged from the present day mid-ocean ridge rocks ( $\text{Cr}\# > 0.6$ ), type III where the chromite composition ( $\text{Cr}\# < 0.6$ ) is different from type I and resembles peridotites from island-arc terranes, and as type III where the chromite composition overlaps type I and III and is of composite origin (island arc on oceanic crust).

On the  $\text{Cr}\#$  ( $\text{Cr} \times 100 / (\text{Cr} + \text{Al})$ ) vs.  $\text{Mg}\#$  ( $\text{Mg} \times 100 / (\text{Mg} + \text{Fe}^{2+})$ ) diagram (Fig. 19), the chromite from the study area is similar to chromite of the type-III peridotites suggesting the formation of the peridotites in an arc-related setting.

The proterozoic ophiolitic rocks of the Arabian Shield were studied by Al Shanti and El-Mahdy (2001) and five terranes sutured by ophiolitic rocks were recognized, and three types of collision between these terranes were suggested: 1) Island arc – Island arc (*e.g.*, Bir Umq – Jabal Thurwah), 2) Island arc – Continental margin (*e.g.*, Bir Tuluha-Hamdah), and 3) Collision between two continental blocks. In the first two types of collision arc volcanics and ophiolitic rocks are juxtaposed along the sutures, while in the latter the ophiolitic rocks are not associated with arc volcanics. The ophiolitic rocks in the 3<sup>rd</sup> type were interpreted as a squeezed oceanic crust formed in a rift zone between two continental blocks. Johnson *et al.* (2003) mapped arc related volcanics and intrusive rocks in association with Halaban ophiolitic complex (Fig. 11), thus, it resembles the other sutures. Moreover, chromite from Halaban ophiolitic complex plot close to the fields of chromian spinels from bonatites and forearc ophiolites (Johnson *et al.*, 2003)

The chromites from the Arabian Shield ophiolitic rocks show a high variation in Cr and Al ( $\text{Cr}\#$  for the majority of samples ranges between 0.6 and 0.8)

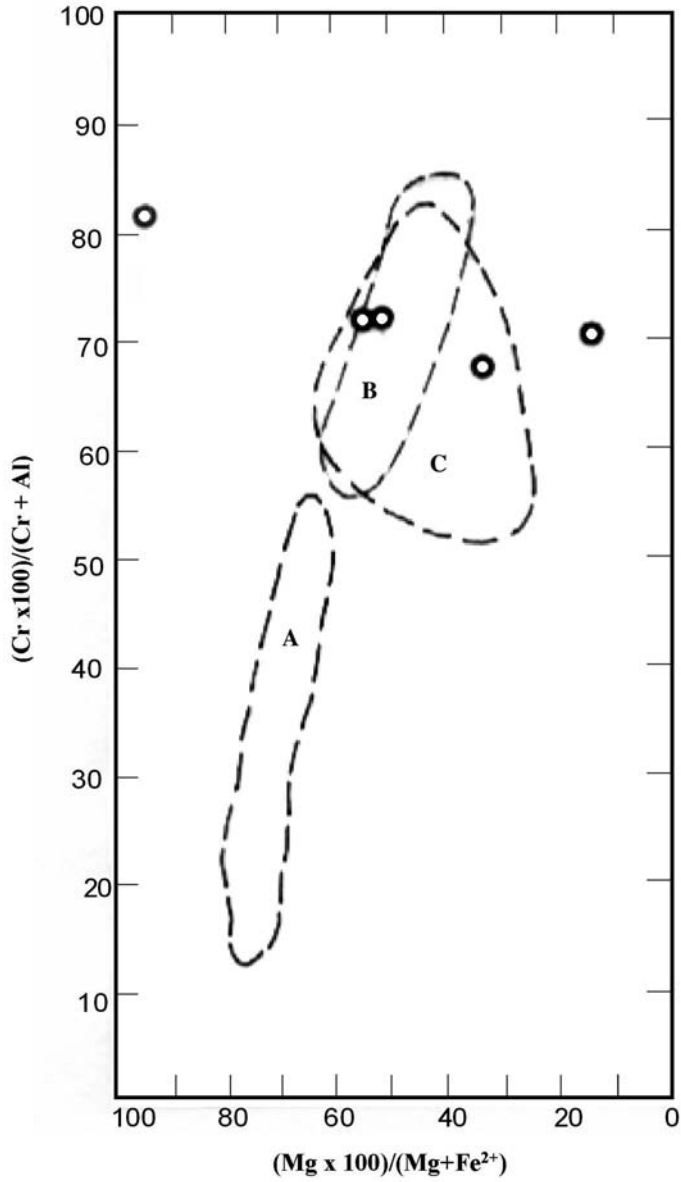


Fig. 19. Composition of the chromite from the study area. Fields A, B and C after Dick and Bullen (1984). Field A for mid-ocean ridge peridotites, fields B and C for type III Alpine peridotites (Field B for peridotites from Twin Sisters, and C for peridotites from Troodos Complex).

and are similar to chromites of the podiform (Alpine) type (El-Mahdy and Al Shanti, 2001). Also, on the basis of chromite chemistry, forearc-setting has been suggested for Jabal Ess and Bir Tuluha ophiolites (Johnson *et al.*, 2003), and Jabal Thurwah ophiolite complex (Nassief *et al.*, 1984).

Bakor *et al.* (1976) studied the mafic-ultramafic complex from Jabal Al Wask (Saudi Arabia) and was considered as an ophiolite possibly formed in a back arc environment and the ultramafic zones are sutures between island arcs during the cratonization of the Arabian Shield.

Based on chromite chemistry and petrological data, Azer and Khalil (2006) suggested an environment akin to a suprasubduction zone in a back arc basin for serpentinites and associated chromitite lenses from Wadi Sodmein area, Nubian shield, Egypt.

### Summary and Conclusions

The study area comprises the following rock units (from the oldest to the youngest): the ophiolitic *mélange* rocks, the early Hulyfah volcanosedimentary rocks, the late Hulyfah volcanosedimentary rocks, the syn- to late-orogenic intrusive rocks, the Murdamah volcano-sedimentary rocks, the post orogenic intrusive rocks and dikes.

The term ophiolitic *mélange* is introduced for the first time to describe the geology of the study area. It consists of ultramafic rocks (serpentinites and listvenite), metagabbros, metabasalts, marble lenses and amphibolites. The described ophiolitic *mélange* occupies the hanging wall of the major Bir Tawilah thrust fault. The footwall is occupied by the late Hulyfah volcanosedimentary rocks. The zone of the listvenite along the Bir Tawilah major thrust fault marks the contact between the late Hulyfah volcanosedimentary rocks and the ophiolitic *mélange*. The sheared serpentinites host the components of the ophiolitic *mélange*. Based on their major and trace element compositions, the metagabbro and metabasalt rock fragments, are tholeiitic in character and of ocean floor-affinity. The amphibolites are found to be orthoamphibolites of igneous protolith. The protolith of these amphibolites is tholeiitic in character and of ocean-floor affinity and was derived by metamorphism of mafic (metagabbro)-ultramafic (pyroxenite) protolith.

The chemistry of chromite from Jabal Ghadarah area is similar to podiform chromitites, to chromite from Proterozoic ophiolite peridotites and can be grouped with chromite from type III peridotites formed in an arc-related setting.

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## جيولوجية وجيوكيميائية الميلانج الأفيوليتي في منطقة جبل غدارة، مربع ظلم، وسط المملكة العربية السعودية

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المستخلص. يمكن تقسيم صخور ما قبل الكامبري الموجودة في منطقة جبل غدارة إلى صخور فوق مافية متحولة، وصخور بركانية رسوبية متحولة (قوسية)، وجرانيتات متزامنة ومتأخرة النشأة التجبلية، ورواسب المولاس، ومونوزوجرانيت ما بعد التجبل. وتظهر الصخور فوق المافية المتحولة ويصاحبها انكشاف اللستفينيت على امتداد طول صدع اندفاعي يأخذ اتجاه شمال شمال شرق ويميل باتجاه الشرق، متلامسة مع الصخور البركانية الرسوبية المتحولة. وتتميز الصخور فوق المافية المتحولة بوجود قطع مختلفة الأحجام من الجابرو المتحول، والبازلت المتحول، والشيس، والامفيبوليت، والرخام. ويشير توزيع العناصر الرئيسة والشحيحة إلى أن الجابرو المتحول، والبازلت المتحول، والامفيبوليت إلى أنها ثولييتية تنسب إلى قاع المحيط. وقد اشتقت صخور الأمفيبوليت من صخر أولي مافي أو فوق مافي. وأوضح الكروميت الموجود في صخور السربنتين والستفينيت مدى واسع في محتواه من أكاسيد العناصر الرئيسة مشابهاً في ذلك الكروميت من النوع اللائي. وقد فسر تلازم القطع الصخرية مختلفة الأحجام مع الصخور فوق المافية المتحولة على أنها ميلانج أفيوليتي تراكب مع تتابع الصخور البركانية الرسوبية المتحولة أثناء الحركات التكتونية المصاحبة لعمليات تجبل الدرع العربي مختلفاً في ذلك مع ما اقترح سابقاً بأنها صخور متداخلة.