GEOLOGY AND MINERALIZATION OF WADI AL HWANET AREA, NORTH-WESTERN SAUDI ARABIA: WITH SPECIAL REFERENCE TO ULTRAMAFIC ROCKS

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Abstract

Wadi Al Hwanet and Jabal Al Wasq, parts of Al’Ays belt, represent one of the most important ophiolitic rocks of Proterozoic age in the Arabian Shield. The mantle section is dominated by harzburgite with abundant dunite. Most of the primary silicates in the Proterozoic ophiolitic mantle rocks were converted into secondary minerals. Although intense alteration and serpentinization, primary silicate minerals like olivine, orthopyroxene and clinopyroxene are still preserved, especially in Wadi Al Hwanet area. Primary chromian spinel in the studied areas is also survived alteration and is used as a petrogenetic indicator of the tectonic setting at which the podiform chromitites are formed.

The podiform chromitite deposits in Wadi Al Hwanet are common as lenses and micropods. The lenses differ in shape from elliptical to lenticular, but some occur as elongated discontinuous bodies of chromite lenses. The lenses are 1to more than 20 m long and up to 2m wide and consist of fine- to medium-grained, massive and fractured chromite with few interstitial serpentine gangue minerals. The Cr# (Cr# = Cr/(Cr + Al) atomic ratios) exhibits a wide compositional variation from lens to lens. It varies from intermediate 0.62 to high 0.81 in chromitites, from 0.56 to 0.60 in dunite envelope, from 0.54 to 0.57 in dunite mass and from 0.46 to 0.57 in harzburgites.

The podiform chromitite deposits in Jabal Al Wasq occur mainly as lensoidal bodies; the size of the studied lens is about 30 m in dimensions. It is massive to submassive and surrounded by a thin veneer of intensely altered and sheared serpentinitized dunite envelope. The chromian spinel of Jabal Al Wasq chromitite usually has high and restricted Cr#, usually ≥ 0.80. The Cr# of the spinel in dunites and harzburgites of Jabal Al Wasq are also very high; it varies from 0.75 to 0.80 in dunites, and from 0.77 to 0.80 in harzburgites. The total PGE content of Wadi Al Hwanet chromitites ranges from 351 to 967 ppb, and display two distribution patterns: (1) negatively sloped PGE patterns where the IPGE is highly enriched compared with PPGE (Pd/Ir ratio = 0.21 on average), (2) positively sloped PGE patterns where the PPGE is much more enriched compared with IPGE (Pd/Ir ratio = 5 on average). In Jabal Al Wasq chromitites, almost all samples show a negatively sloped PGE patterns, but some samples show relative enrichment in both IPGE and PPGE contents. The total PGE contents of Jabal Al Wasq chromitites ranges from 139 to 355 ppb. The most common platinum-group minerals (PGE) in Wadi Al Hwanet chromitites are Ir–rich laurite (RuS2) as solitary inclusions within chromian spinel, while in Jabal Al Wasq chromitites the most common PGM species are the Os- Ir- Ru alloys.

The intermediate Cr# (~ 0.6) and PPGE- enrichment in Wadi Al Hwanet area, may suggest partly, low to intermediate degrees of partial melting for these chromitite deposits during the first stage melting at a MORB setting. The high Cr# of spinel ( ≥0.8) and IPGE in Wadi Al Hwanet area enrichment and some extent, in Jabal Al Wasq area with low TiO2 content of chromite (0.01- 0.35 wt%) suggest
second stage melting in a supra-subduction zone setting, and involvement of boninite or high-Mg arc tholeiitic magma in the formation of these high Cr- chromitites.

The primary compositions of chromian spinel have been used to calculate the composition of parental melt involved in formation of the podiform chromitites of the studied areas. The parental melt calculations indicate derivation from a high-Mg tholeiites or boninitic magmas that is similar to the composition of parental melts in equilibrium with Proterozoic chromitites of other complexes such as those of Eastern Desert of Egypt, and Bou Azzer, Morocco, and slightly different from those of Phanerozoic ophiolites, e.g. Oman ophiolite. Tectonic discrimination diagrams using the spinel primary composition indicate a supra- subduction zone setting that modify the initial MORB setting.
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Chapter I

Introduction

1.1 Ophiolite Complex

Many geoscientists have attempted to define what makes up an ophiolite. For simplicity, the definition presented here is the most common and widely accepted description of an ophiolite. At the Penrose conference in 1972, a definition of a seven-part ophiolite complex was prepared. An ophiolite is a vertical cross section of oceanic crust that has been removed or obducted during a tectonic event (Fig 1.1.). The typical layers include from bottom to top: 1) mantle-ultramafic cumulates with harzburgite, lherzolite, and/or dunite with a metamorphic tectonic fabric, 2) moho-seismic rocks, 3) mafic cumulates consisting of peridotites and pyroxenites, 4) a gabbroic complex with cumulate textures 5) mafic sheeted dike complex, 6) pillow basalts, and 7) pelagic/abyssal cherty sediments. It is noteworthy that there are some slight variations from the Penrose definition; however, the definition is still a general synthesis.

Ophiolite complexes are major hosts of chromite ore. The more important igneous layered complexes harzburgite-type peridotites are the main carrier of chromite in ophiolitic rocks, whereas the lherzolite-type peridotites have almost no chromite.
1.2 Geology of the Arabian Shield

The Arabian Shield is exposed in the western and southwestern parts of the Arabian Peninsula and covers about 25% of the area of Saudi Arabia. It is bordered to the north, east, and south by Phanerozoic sedimentary successions and is separated from the Nubian part of the African Shield by the Red Sea rift (Fig. 1. 2). The Arabian Shield consists predominantly of thick sequences of volcano-sedimentary successions and associated plutonic complexes that have been deformed, metamorphosed and intruded by numerous gabbro-diotite- granodiorite plutons that have been affected by multiple subsequent events of deformation, regional metamorphism, and post-tectonic plutonism. Age determinations of these rocks give Late Neoproterozoic ages (950-550 Ma; Greenwood et al., 1980). Local Archean to Paleoproterozoic ages are recorded in same terranes in Yemen and western Saudi
Arabian (Al-Shanti, 1993). The Neoproterozoic sequences contain volcanic and some plutonic rocks, whose chemical character appear to have changed gradually with thickening of the crust from an earlier tholeiitic affinity to later calc–alkaline and alkaline character (Stoeser and Camp, 1985).

Stoeser and Camp (1984) proposed a microplate accretion model for the Late Neoproterozoic crustal evolution of the Arabian Shield. In this model, they divided the Arabian Shield into five terranes that are separated by four ophiolite-bearing suture zones (Fig 1.2). The western part of the Shield is comprises at least three intraoceanic island arc terranes (Asir, Hijaz, Midyan), whereas the eastern part contains one terrain of continental affinity (Afif) and one terrain of probable continental affinity (Ar Rayn). The four suture zones separating these terranes are genetically categorized into three types: (1) the Bir Umq and Yanbu sutures, formed by island arc-island arc collision; (2) the Nabitah suture, formed by arc-continent collision; and (3) the Al-Amar suture, formed by continent-continent collision. Stoeser and Camp (1984) proposed that the evolution of the Arabian Shield could be divided into five main phases: (1) Rifting of the African craton (1200-950 Ma); (2) ensimatic island arc development (950-715 Ma); (3) formation of the Arabian-Nubian neocraton by microplate accretion and continental collision (715-640 Ma); (4) collision related intracratonic magmatism and tectonism (630-550 Ma); and (5) epicontinental subsidence (550 Ma).

The abundance of plutonic mafic-ultramafic complexes within the Arabian Shield, and their potential as sources for Fe, Ti, V, Cr, Ni, Au and PGE mineralization have led to detailed examinations of these complexes over the past 20 years by (Chevremont and Vaillant, 1983).
1.3 Arabian Shield Ophiolites

Neoproterozoic mafic-ultramafic complexes make up less than 1% of the surface area of the Arabian Shield but their study starting with the pioneering work of Al-Shanti and Mitchell, (1976).

Ophiolites occupy small, but tectonically important parts of the Arabian Shield (Al-Shanti, 1993). Where most complete, they consist of serpentinized peridotite, mostly harzburgitic, containing magnesian olivines and spinels that have compositions consistent with extensive melting. However, because of folding and shearing, the majority of the ophiolites lack one or more of these diagnostic lithologies. 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 (Greenwood et al., 1980). 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 along 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. Some less altered and deformed ophiolitic rocks contain relics of primary textures and minerals. Ophiolites are considered as primary indicators of suturest between terranes of different lithostratigraphy.

Previous studies (Gass, 1984; Bakor et al., 1976) have recognized that ophiolites in Saudi Arabia occur alongside certain curvilinear belts that trend in a NE–SW direction as well as in a NNW–SSE direction (Gass, 1984; Bakor et al., 1976).
The mafic and ultramafic belts (ophiolites) in Arabian Shield have been affected by the Najd Fault System which is a NW- taranccurrent fault (Moor,1979) that have been interpreted to reflect E-W compression and north directed tectonic escape (Stern,1994). They are dissected and dismembered that no complete sequence has to be found in anyone locality. For example, in a particular belt, serpentinite may be associated only with gabbro and both completely disappear along the strike of the belt, and farther on, serpentinite with basalt would crop out, and so forth. Diabase or doleritic sheeted dikes are extremely difficult to recognize in these sequences due to their close mineralogic and textural similarity to basalt and the extensive alteration and deformation that affected these belts since Precambrian time. Nonetheless, it was possible to recognize sheeted dikes in three belts: at Jabal Saleeb (Al-Amar - Idsas belt), Jabal Thurwah (Bir Umq - Jabal Thurwah belt), and at Jabal Ess (Jabal Al-Wasq - Jabal Ess belt (Al-Shanti and El-Mahdy, 1989).

The ophiolite sequences form elongated dissected and widely spaced exposures within the Shield. According to Al-Shanti and El-Mahdy (1989), the ophiolite sequences have been divided into six belts (Fig 1. 2.). The following are brief accounts on these belts; starting from east to west:

1.3.1 Al Amar- Idsas Belt

This belt is located in the eastern part of the Arabian Shield trending N –S. and associated with a profound suture zone known as Al Amar - Idsas Fault. It is estimated to be extended for about 200 km and ranges in width from half a kilometer to six kilometers. Along the fault zone this belt is characterized by the predominance of Mafic and ultramafic rock types. The Al Amar - Idsas Fault zone is a suture
between two terranes, the eastern is possibly an island arc made up of a volcanic succession of the Halaban Group (Al-Amar) and is called Ar Rayn Province.

1.3.2 Humayyan Sabhah Belt

This belt appears to be parallel to Al Amar-Idsas belt (Fig 1. 2), in the Abt schist rock formation. The belt is dismembered and discontinuous along its length, which extends from the east edge of Ad Dawadimi granite batholith and west of Abt schist basin of deposition. Al-Shanti (1993) mentioned that the belt is 75 km long, where Jabal Sabha marks its southern exposed rocks. It appears that the Humayyan - Sabha belt joins another western belt, Al Bijadiyah - Halaban. Al-Shanti (1993) related the junction of both belts due to left lateral dislocation movements caused by the Najd Fault System.

1.3.3 Al Bijadiyah – Halaban Belt

This belt is situated at the eastern margin of Afif Terrain, and extends in a north - northwest direction for about 170 km long. It is bounded from the east by Ad- Dawadimi batholith and from the west by Afif Terrain, which contains Murdamah clastic group, Jibalah Group and old basement gneisses with its intruding reactivated granite plutons. Al-Shanti (1993) divided this belt into three parts, as follows:

- North Area, north of Afif - Ar Riyad road.
- Central Area, in between the two roads to Ar Riyad.
- Southern Area, south of Ar Riyad - Taif road.

1.3.4 Al Hulayfa - Hamada (Nabitah) Belt

The Al Hulayfa - Hamada belt is a N-S sutur located in the central part of the
Arabian Shield within Najd Plateau. It is the longest belt of mafic and ultramafic rocks in the Arabian Shield; its apparent length is about 800 km. This belt seems to be the most affected by dislocations caused by the Najd Fault System hence it was used to measure the total and individual amounts of displacements on the Najd Faults. Brown et al., (1989) estimated the total dislocation of this belt to be about 250 km.

The geologic and tectonic characteristics of this ophiolitic belt were identified by Al-Shanti (1993) through investigating some of its important parts such as Bir Tuluahah and Arja, Jabal Ghurrab, Jabal Nabita, Jabal Al Wudaihi, Tathlith and Hamdah.

The ophiolite rocks disappear in the north, in Wadi Ar Rimmah, east of Hulayfah Town on the Al Madinah Al Munawarah - Hail road. In the south they disappear under the Phanerozoic cover rocks.

This ophiolite belt lies on a suture between continental Afif Terrain to the east and the Island Arc terrains of Madyan, Al Hijaz and Asir to the west. The belt is also called the Nabita belt, after a mountain in the southern Arabian Shield along the suture containing ophiolitic rocks. It lies about 110 km north of Bishah Town. Some of the sections of this ophiolite belt are well exposed for long distances, as in the case at Bir Tuluahah, or by their disappearance under a sand cover for longer distances, as in the case of the central part that caused by dislocation along Najd Faults.

1.3.5 Bir Umq - Jabal Thurwah Belt

The location of this ophiolite belt is clearly observed on a tectonic suture between Al - Hijaz Terrain in the north and Jeddah terrain in the south (Fig 1. 2.)
This belt is extending for about 250 km in a NE direction and continues in the Nubian Shield in Sudan, south of Port Sudan area. It is characterized by the presence of two important ophiolitic occurrences which are Bir Umq in the northeast and Jabal Thurwah in the southwest. The two occurrences are separated by the Tertiary and Quaternary lava fields of Harrat Rahat and Recent Wadi sediments. Bir Umq ophiolite is bounded from south and north by Hulayfah Group rocks where the contact is always a thrust plane. The ophiolitic rocks were tectonically emplaced unconformably over Hulayfah rocks, which constitute part of Al - Hijaz Island Arc.

On the other hand, the Jabal Thurwah ophiolite is bounded from the north by the volcanic sedimentary rocks of Al - Birak Group that belongs to Al Hijaz arc terrane and from the south by volcano-sedimentary rocks of the Samran Group of the Assir arc terrane. The contact is always a thrust fault that exposed in many locations. Al-Shanti (1993) indicated that, the lower parts of the ophiolite succession contain melange zones, where the serpentinite engulfs foreign allochthonous rock bodies. These rocks are generally intensely deformed.

1.3.6 Jabal Al-Wasq - Jabal Ess (Al'Ays Belts)

Jabal Al Wasq - Jabal Ess belt lies in the northwestern part of the Arabian Shield between Yanbu City and Al Ula Town. It separates Madyan Terrain in the north from Al Hijaz Terrain in the south. It is called sometimes Al’Ays - Jabal Al Hwanet Belt that spreads across the Red Sea into the Nubian Shield of Sudan in Sol Hamid towards the southwestern areas.

In general, Jabal Al Wasq - Jabal Ess and the Thurwah - Bir Umq Belts are characterized by their location along NE trending tectonic sutures, a trend different from the NS trend of the other four belts. It is also characterized by its dissected and
dislocated ophiolitic parts towards the east for variable, distances particularly, in the middle, by the left lateral faults of the Najd System. The Najd faults dislocated Jabal Ess and Jabal Al Hwanet towards the northwest for more than 50 km. The other parts of the ophiolite belt are distributed in the region separating Jabal Ess from Jabal Al Wasq.

The Jabal Ess - Wadi Al Hwanet and the Jabal Al Wasq – Al’Ays belts represent the most important and widespread ophiolitic rock areas in the Arabian Shield. Anonymous (1972) concluded that the Jabal Ess - Al Hwanet and Jabal Al Wasq – Al’ Ays belts contain the complete ophiolitic successions particularly at Jabal Ess (Al-Shanti and Roobol, 1979; Al-Shanti, 1982, and Al-Shanti, 1983). The two areas contain the largest number of chromite lenses as compared with other belts. They are the most important physiographic landforms of this area where both are made up of ophiolitic allochthonous rocks emplaced unconformably over a tectonic thrust contact over metavolcanosedimentary rocks and their intruding plutons (Al-Shanti, 1993).
Fig. 1. 2. Map of the Arabian Shield showing the ophiolitic belts (after Nehling et al., 2002) and the locations of the studied areas; (red rectangles), the upper rectangle is Wadi Al Hwanet, and the lower rectangle is Jabal Al Wasq
1.4 Chromite Mineralization

Spinel-group minerals occur as common accessory minerals in peridotites of the ophiolite complexes. They display a wide range in composition reflecting their primary magmatic or secondary origin. Unaltered, primary spinel, particularly chromite, are highly susceptible to chemical modification during hydrous alteration and metamorphism at low grades, and can be used as a petrogenetic indicator.

Chromian spinel in chromitites and peridotites occasionally survives alteration and can be used as a reliable petrogenetic indicator to determine the primary mantle lithology, even in highly serpentinized ultramafic rocks (Ahmed et al., 2005a).

Chromite is the only chromium-bearing ore mineral. The majority of chromite is converted to ferrochrome, of which about 70 % is used in the manufacture of stainless steel. Chromium, therefore, plays a significant role in modern industrial societies, with both civilian and military applications. About 95% of chromium resources are geographically concentrated in southern Africa. Reserves and reserve base are geographically concentrated in southern Africa and Kazakhstan.

As a consequence of its industrial importance and limited geographical distribution, chromite is classed as a strategic mineral.

Chromitite ores are usually assigned to one of the following two classes on the basis of mode of occurrences, petrologic character and tectonic setting of their host rocks (Thayer, 1960).

1) **Stratiform deposits:** are sheet-like accumulations of chromite that occur in layered ultramafic to mafic igneous intrusions, such as the Bushveld and Stillwater complexes. In this type, chromitite forms layers, up to 1.5 m thick
extending over a few tens of kilometres, parallel to the igneous layering. They display clear sedimentary magmatic structures. Each chromitite band corresponds to the lower part of a cumulative stratigraphic unit. The layers are not deformed and composed mainly of small euhedral chromite crystals. They do not exhibit nodular or orbicular textures.

(2) *Podiform deposits*: are irregular but fundamentally lenticular, pod-like and tabular chromite-rich bodies that occur mainly in tectonic peridotites and basal dunite cumulates of ophiolites and Alpine-type peridotites. The association of podiform deposits with ophiolites restricts their occurrence to island arcs and mobile orogenic belts of Palaeozoic or younger ages (Thayer 1970), although upper Proterozoic ophiolite podiform chromitite have been described (e.g., Neary, 1974; Ahmed *et al.*, 2001, 2005, 2009). Thayer (1970) noted that all economically important stratiform type chromitites are relatively undeformed and occur in stable shield areas of Precambrian age. The Podiform chromitites are invariably surrounded by a sheath or halo of dunite regardless of its size and shape (e.g., Thayer, 1964; Dickey, 1975; Arai and Yurimoto, 1994; Ahmed and Arai, 2002). The dunite bodies contain disseminated and schlieren textured chromite.

Podiform chromitites are texturally distinct from stratiform ones; the former are commonly consist of coarse anhedral interlocking grains and can display nodular and orbicular textures. The latter commonly have smaller euhedral grains and lack these textures. Podiform chromitites are also chemically distinct from stratiform ones; the former chromite (spinel) has very low Fe$^{3+}$ ratios and less than 0.3 wt % of TiO$_2$, whilst the latter chromite has a greater amounts of Fe$^{3+}$ and TiO$_2$. 
Formation of podiform chromitite is one of the important mantle processes that gives constraints on the physico-chemical conditions and evolution of mantle lithosphere (e.g. Lago et al., 1982; Leblanc and Ceuleneer, 1992).

1.5 Chromite Mineralization in Saudi Arabia

Chromite Mineralization in Saudi Arabia is restricted to Neoproterozoic ophiolitic mafic-ultramafic rocks of the Arabian Shield (850 -700 Ma) (Al-Shanti and El-Mahdy, 1989). Not all ophiolitic rocks of the Shield are chromite-bearing. It was found that chromite only occurs in certain favorable horizons of ultramafic rocks.

Chromite occurs in serpentinites derived from harzburgite and to a lesser extent dunite. Chromite mineralization in the shield could be divided into the following types:

1- Massive lenses and lensoid pods with chromite forming more than 80 % of the rock. They range in length from less than a meter to 10 meters, and are 1/2 to 2 meters wide. An exception is the large lenses at Al'Ays area (22 x 10 and 32 x 12 m).

2- Leopard type, where chromite occurs as discrete grains or aggregates disseminated within gangue serpentine minerals and forms about 40 to 50 % of the rock.

3- Nodular type where aggregates of fine- to medium-grained chromite are found as nodules cemented by internodular serpentine minerals.

4- Schlieren (banded) type, where chromite grains form thin parallel bands constituting 25 to 50% of the rock.
5- Disseminated type, where chromite occurs as random disseminations in serpentinized host rocks.

Mechanically transported floats of the various types of chromite are common along wadis and slopes draining chromite-bearing areas. These range in size from few cm to a maximum of one meter.

1.6 Platinum-Group Elements (PGE)

Platinum-group metals are of great strategic importance to the industrialized World. There is a vital need for platinum in many of the processes upon which we depend for our standard of living. These processes range from the production of basic fuels, chemicals and materials to high-technology applications in the protection of the environment and the treatment of pernicious disease.

The economic interest of PGE in the international market did not undergo any downward trend, as it happened for a number of other metals (e.g., Au). The demand for PGE has constantly increased since the 1970 because of the increased use of these metals in the technology of environmental protection (autocatalyst) and clean energy production (fuelcell). This increment of interest has promoted a worldwide geological investigation and development of metallogenic models with the aim to formulate criteria, which can be used to target further PGE deposits in traditional or completely new geological environments.

The six platinum-group elements (PGE), ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt), have long been grouped with gold and silver as the “precious metals” or “noble metals”. These elements are said to be “noble” because they are relatively inert to corrosion and are not easily
oxidized in the metallic state. They are currently receiving worldwide attention as an attractive exploration target because the PGE offer the dual attraction of rare and high value precious metals as well as major industrial uses. Platinum has aesthetic qualities combined with a permanent luster, which encourages its use in the manufacture of jewellery. Platinum, palladium, and rhodium have important applications as catalysts, enabling petroleum and other fuels and chemicals to be produced efficiently from crude oil. Substitution by other metals in this strategically important function is difficult. PGE are also used as catalysts to produce sulfuric, acetic and nitric acids. They are used in the manufacture of artificial teeth, surgical tools and unmagnetic watches. Platinum alloys with iridium are very hard and resistant to corrosion and are used for electrical connections in jet planes, rockets, and space crafts. Platinum is also alloyed with Cu, Fe, Ni, Zn, Pb, Sn, Bi, and As. These are used in the manufacture of several components for sophisticated mechanical and electrical industries. Pt-Rh thermocouples are extensively used in the measurement of high temperatures in furnaces.

PGE occur at the ppb level in ultramafic igneous rocks and may be concentrated in the associated chromitites during mantle melting. They tend to be concentrated in the early magmatic precipitates in ophiolitic chromitites. The distribution of PGE in chromitites and associated ultramafic rocks gives constraints on the petrological nature and evolution of the mantle source from which they were derived. (Ahmed et al., 2007)

Geochemically, the noble metals have been considered to be siderophilic, and to a lesser extent, chalcophilic. Rhenium (Re) is considered to be one of noble metals by some cosmochemists (e.g., Chou 1978); however, Re differs from the noble
metals in forming stable oxyanions at relatively low oxygen activities, and Re shows little coherence with the noble metals in terrestrial environments.

Due to the compatibility of Ir-subgroup (IPGE = Os, Ir and Ru) of platinum-group elements (PGE) during mantle melting, they tend to be concentrated in the early magmatic precipitates and associated with chromitite as alloys and sulphides. The geochemical behavior of IPGE in the mafic and ultramafic systems is very different from those of the Pd-subgroup (PPGE = Rh, Pt and Pd), which are incompatible during mantle melting and tend to be retained in the residual melt (e.g., Crocket, 1981; Barnes et al., 1985). The PPGE and Au are often associated with sulfides of Fe, Ni and Cu and are found in gabbros and dunites (Barnes et al., 1985). The common association of platinum-group minerals (PGM) and chromitite in mafic and ultramafic intrusions has received much attention in recent years. This association is well known in ophiolites, Alpine-type peridotites, Alaskan-type complexes, and stratiform intrusions (e.g. Talkington et al., 1984).

Cabri (1984) proposed a classification based on the regional tectonic setting of the PGE deposits and suggested the following three classes:

1- Deposits associated with large layered anorogenic complexes with tholeiitic affinity and specifically of Archean age: Bushveld, South Africa, and Stillwater, USA.

2- Deposits associated with small to medium anorogenic complexes with an age that is not exclusively Archean.

3- Deposits associated with orogenic complexes:
   i- Komatiitic Suites where sulfides are characterized by relatively low:
(Pt+Pd)/(Ru+Ir+Os) ratios compared with those from gabbro/flood basalt magmas.

ii- Alaskan-type complexes characterized by high (Pt+Pd)/(Ru+Ir+Os) ratios.

iii- Alpine-type complexes characterized by high Ru-Os-Ir ratios with respect to Pt, Rh and Pd.

The economically most important PGE deposits are hosted by stratiform mafic-ultramafic complexes, such as Bushveld and Stillwater, and by magmatic sulfide deposits. Almost all reported PGE concentrations in ophiolites are associated with the chromitite pods. Ophiolitic chromitites are almost characterized by enrichment in Os, Ir and Ru relative to Pt and Pd and display negatively sloped PGE patterns (Page and Talkington 1984; Barnes et al., 1985; Leblanc 1991).

1.7 PGE Mineralization in Saudi Arabia

The abundance of mafic/ultramafic complexes (ophiolitic belts) in the Arabian Shied (Figure 1.2) and their potentiality as hosts for ores of several metals including PGE has led to detailed examinations of these complexes over the last 20 years. Bibliographic review of known PGE mineralization in the world (Chevremont and Vaillant, 1983) have led to the conclusion that within the Precambrian mafic/ultramafic complexes of the Arabian Shield, the most potential host rocks for PGE mineralization are:

1- Massive to submassive Cu-Ni sulfide mineralization associated with tholeiitic to subalkaline complexes.
2- Dunite, or serpentinized dunite containing hypermagnesian olivine (Fo > 90) and chromiferous spinel in orogenic complexes displaying similarities to Alaska-type alkalic complexes.

3- Massive chromite lenses enclosed in serpentinite and belonging to the Alpine-type complexes, a type that includes ophiolites. To a lesser extent, massive magnetite-ilmenite mineralization is also a potential PGE host rock.

Prichard et al. (2008), studied the podiform chromitites in Al 'Ays ophiolite complex, Saudi Arabia and found to be contains anomalous concentrations of all six platinum group elements (PGE) in podiform chromitite with maximum values of 2,570 ppb Pt, 6,870 ppb Pd, 840 ppb Rh, 5,800 ppb Ru, 6,200 ppb Ir, and 3,300 ppb Os.

1.8 The Study Area

The main area of this study is Wadi Al Hwanet, which lies approximately 200 km northwest of Al Madinah Al Monawwarh and bounded by Long. 37° 27' and 37° 25' E and Lat. 26° 17' E and 26° 25' N and 15 km south of the Ashizm prospect (Fig 1.2). This area will be compared with Jabal Al Wasq area, which occupies over 500 km² in the northern Hijaz Terrain, between latitudes 25°00' to 25°27'N and longitudes 37°46' to 38°12'E.

1.9 Aim of Study

This study concerns mainly with the geology and mineralization of the upper mantle sequence (mafic-ultramafic associations) at Wadi Al Hwanet area, northwestern Saudi Arabia. It aims to specify the geology and tectonic setting of the upper
mantle members based on their chromian spinel characteristics of chromitite ores and their PGE concentrations and distribution, as well as any other mineralization in the area like Cu-Ni-Co sulfides, if any.

Many trials have been made for the search of gold in Saudi Arabia for a long time, but very few trials were recorded for the search of PGE. Numerous podiform chromite lenses occur in serpentinite close to the contact between the serpentinite and volcano-sedimentary rocks at Wadi Al Hwanet area. The chromitite lenses are small, average 5 m long and up to 2 m wide, and mainly massive and fractured chromite. These chromitite deposits might represent a potential source of PGE because of the common association of PGE and chromitite in ultramafic rocks.

One of the general aims of this study is to improve our knowledge of natural processes, which lead to formation of chromitites and associated PGE concentrations in upper mantle rocks. The scientific purpose of this work is to study the distribution of PGE in the chromitite ore deposits and associated rocks located in the upper mantle section of the Wadi Al Hwanet area and compare that with other available studies locally and worldwide. The main goal of this study is to check the petrological characteristics of podiform chromitites and associated ultramafic rocks, and the existence of geochemical and mineralogical anomalies of the noble metals in these specific areas. The finding of these anomalies will constitute the base for further development of metallogenic models necessary to mining prospection and evaluation of the ore deposits in study area and other comparable areas in the Kingdom.

The results expected from the study will constitute a set of new information that may potentially reevaluate the economical interest of these ore resources. They
will also provide a unique opportunity to widen our knowledge of metallogenic processes for noble metal concentration in nature.

The main principal objectives of this study can be summarized below:

- To describe in details the geology and field relationships of all the rock unites in the study area, with special concern with mafic and ultramafic rocks.

- Collect representative samples from mafic-ultramafic rocks, especially chromitite deposits and associated ultramafic rocks in the study area to be carefully studied in the laboratory.

- To evaluate the tectonic setting.

- To evaluate the magma source and composition of the studied rocks.

- Check the existence of geochemical and mineralogical anomalies of PGE in chromitite ore deposits and associated ultramafic rocks.

- Determine the origin of chromite – bearing ultramafic complex.

- The data of Wadi Al Hwanet area will be compared with a famous area in Arabian Shied that is Jabal Al Wasq area.

1.10 Methodology

**Geology:** Field trips to the study area to collect samples of chromitite ores and associated ultramafic rocks. Geological map will be prepared using combined field observations and digitized satellite images (scale 1:100,000). This will be assessed
by detailed field work for the lithological units exposed in the area and their mutual relationships, in addition to the major structural features.

**Petrography:** Petrographical and mineralogical studies will be done to determine the mineralogy and textures of the mafic and ultramafic rocks. This will be done by using Polarizing microscope and thin sections of representative samples. A number of polished sections will be studied using Ore Microscope in order to study the opaque minerals such as oxides (e.g. chromite) and sulfides to identify the possible mineral species and paragenesis.

**Geochemistry:** Geochemical analysis of major oxides, trace elements and rare-earth elements (REE) will be done on representative samples from the mafic-ultramafic associations using X-ray florescence and inductively coupled plasma-mass spectroscopy (ICP-MS). Multi-element analytical instruments are available for the rock samples in most of the laboratories of the world. All REE can be determined down to approximate chondritic abundance level. We planned to analyze all trace elements including rare earth elements (REE) by inductively coupled plasma mass spectrometry (ICP-MS).

Selected samples from the collected mafic-ultramafic lithologies will be analyzed for their PGE and Au in addition to Ni and Cu. PGE analysis will be performed by Ultratrace using Ni-sulfide fire assay, and the samples will be digested and refluxed with a mixture of hydrofluoric, nitric, hydrochloric, and perchloric acids. The analyses will be performed using an ICP-MS. Cu and Ni will be obtained using XRF or ICP-MS analysis. Individual chromite grains and silicate minerals as well as PGM, if any, and sulfide grains will be analyzed using an Electron Probe Micro Analyzer (EPMA).
المستخلص

تمثل منطقة وادي الحوانيت وجبل الوسق أحد الأجزاء المهمة في حزام العيالي، شرقي الجزء الرئيسي من حزام العيالي في شمال الدرع العربي، وتكون من عروق الهاريزيت مع أنواع مختلفة من صخور الدونيت. وقد أوضح أن الدراسات البيولوجية عن إدراك المعادن الأساسية لهذه الصخور قد تطورت إلى معادن ثانوية ممثلة بمعدن السربنتين وتكون ممثلة بمعدن الأولي، بما في ذلك سيرفيت وبيروكسين، خصوصا في منطقة وادي الحوانيت.

يعتبر معدن الكروم من المعادن القائمة لعمليات التآكل والتغبير، ويعتبر من المعادن الهامة الدائرة على الوضع التكتوني السائد الذي تكونت عنه تلك الصخور. توجد العديد من عناصر الكروم المختلفة وحجم في وادي الحوانيت التي يصل طولها إلى أكثر من 20 مترا وتختلف هذه العناصر في تركيبها الكيميائي حيث يتراوح أكسيد الكروم فيها من 0.2 إلى 20%، كما يحتوي جبل الوسق على عناصر الكروم وهي يتمطل طولا في بعض المناطق إلى 7 مترا وتحاط هذه العناصر بالصخور اللامتحولة، وتعود وجود صخور الدونيت والهارزبرجيت المتحولة إلى سربنتينت، حيث يتم طلب أكسيد الكروم فيها إلى أكثر من 20%.

يسجل المجموع الكلي لعناصر البلاتين في وادي الحوانيت إلى حوالي 257 جزء من البلين Prints، وتعطي نوعين من التمددات: عنصر غني بعناصر الأوزميوم والأبريديوم، والروثينيوم بينما النطاق الثاني غني بعناصر البلاتين والبراديوم والروثينيوم، وفي جبال الوسق فإن معظم العناصر غنية بالمغلفات. تتمثل معادن مجموعة عناصر البلاتين أساسا بعدن اللورايت الغني بعناصر الأوزميوم في نواحي كروميت وادي الحوانيت، بينما تتمثل بخلط من عناصر الأوزميوم-الروثينيوم-الأبريديوم في نواحي كروميت جبل الوسق.

إن اختلاف معامل الكروم في صخور الكروميت في هذه المناطق مع انخفاض نسبة أكسيد التيتانيوم يعطي دلالة على أن هذا النبات الأفليتي تكون في مرحلتين: المرحلة الأولى تكون خلالها خامات الكروميت ذات القيم المتوسطة في معامل الكروم في بيئة آباء منتصف المحيطات، حيث تكون درجة الانصهار الجزئي منخفضة إلى متوسطة، أما المرحلة الثانية فقد تكون خامات الكروميت ذات القيم العالية في معامل الكروم في مناطق الابنكا، حيث كانت درجات الانصهار الجزئي مرتفعة.

تم حساب التركيب الكيميائي للصغير المسنود عن تكوين خامات الكروميت، وذلك باستخدام معدن الكروميت غير المتحول، وتم استنتاج أن الماجما الأصلية التي تكونت هذه الصخور هي من النوع الثيوليتي أو من النوع البليديتي. وهذه الماجما مشابهة للتركيب الكيميائي للماجما التي تكونت صخور الكروميت في حقب الحياة القديمة في جبال بو عازر بالمغرب، وكذلك المتواجدة في الصحراء الشرقية في مصر، ولكنها تختلف عن تركيب الماجما المكونة لعناصر الكروميت في حقب الحياة الحديثة المتواجدة في أفليالي سلطنة عمان.