DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Precambrian ophiolites of Arabia: A summary of geologic settings U-Pb geochronology, lead isotope characteristics, and implications for microplate accretion, kingdom of Saudi Arabia

by

J. S. Pallister1/, J. S. Stacey2/, L. B. Fischer and W. R. Premo

Open-File Report 88-606

Report prepared by the U.S. Geological Survey in cooperation with the Deputy Ministry for Mineral Resources, Saudi Arabia

1/ U.S. Geological Survey, Denver, CO
2/ U.S. Geological Survey, Menlo Park, CA

1988

CONTENTS

ILLUSTRATIONS

TABLES

PRECAMBRIAN OPHIOLITES OF ARABIA: A SUMMARY OF GEOLOGIC SETTINGS, U-PB GEOCHRONOLOGY, LEAD ISOTOPE CHARACTERISTICS, AND IMPLICATIONS FOR MICROPLATE ACCRETION

by

John S. Pallister, John S. Stacey, Lynn B. Fischer
and Wayne R. Premo

ABSTRACT

Disrupted ophiolites occur in linear belts as much as 900 km long between microplates that collided during the late Proterozoic to form the Arabian Shield. The U-Pb zircon ages and lead-isotope data from these ophiolitic rocks help constrain the history of accretion of the Arabian Shield and thereby contribute to the definition of its microplates and terranes. Microplates of the central and western Arabian Shield are generally thought to represent intra-oceanic island arcs that range in age from about 900 Ma to 640 Ma; however, a region of the eastern Arabian Shield contains rocks of early Proterozoic age and may represent an exotic continental fragment entrained between the arc complexes.

The Ophiolites of the Yanbu suture (northwestern Arabian Shield), dated by U-Pb (zircon) and Sm-Nd (mineral isochron) methods, yield model ages of 740-780 Ma. These are the among the oldest well-dated rocks in the northwestern Arabian Shield. Ages from the Jabal al Wask complex overlap with ages of adjacent arc rocks. This overlap in age supports geologic and geochemical evidence that the complex represents a fragment of back-arc oceanic lithosphere formed during arc magmatism. Older dates of about 780 Ma for gabbro from the Jabal Ess ophiolite suggest that these gabbros are either fore-arc oceanic crust or fragments of oceanic crust on which an arc was built.

Gabbro samples from ophiolites of the Bir Umq-Port Sudan suture (west-central Arabian Shield) yield zircons with ages of 820-870 Ma and ≥1,250 Ma. The 820-870 Ma dates overlap with ages of the oldest nearby arc rocks; this favors an intra-arc or near-arc setting for the ophiolites. The older zircons suggest that middle or early Proterozoic crustal material, possibly derived from the Mozambique belt of Africa, was present during back- or intra-arc magmatism.

Plagiogranite from the Bir Tuluhah ophiolitic complex at the northern end of the 900-km-long Nabitah mobile belt was dated by the zircon U-Pb method at approximately 830 Ma. This date is within the range of the oldest dated arc rocks along the northern and central parts of the Nabitah suture zone, but is approximately 100 million years older than the oldest arc plutons (tonalites) associated with the southern part of the belt. These age relations suggest that the northern part of the Nabitah belt contains an extension of the Bir Umq-Port Sudan suture that was rotated parallel to the Nabitah trend during collision of the arc terranes of the northwest Arabian Shield with the Afif plate to the east.

Feldspar lead-isotope data are of three types: 1) lead from the ophiolitic rocks and arc tonalites of the northwestern Arabian Shield and ophiolitic rocks of the Nabitah suture zone is similar to lead in present midocean ridge basalt, 2) anomalous radiogenic data from the Thurwah ophiolite are from rocks that contain zircons from pre-late Proterozoic continental crust, and 3) feldspar from the Urd ophiolite shows retarded uranogenic lead growth and is related either to an anomalous oceanic mantle source, or in an unknown manner to ancient continental mantle or lower crust of the eastern Arabian Shield.

INTRODUCTION

OPHIOLITES AND THE ARABIAN SHIELD

The Arabian Shield is generally regarded as being made up of a series of late Proterozoic intra-oceanic island arcs that were accreted between about 630 and 715 Ma, along with their sedimentary aprons and occasional slivers of oceanic lithosphere (ophiolites) (see reviews by Greenwood and others, 1976, 1980, 1982; Schmidt and others, 1979; Gass, 1981; Stoeser and Camp, 1985; Kröner, 1985). Several of the arc complexes are separated by sutures (first recognized by Brown and Coleman, 1972) that contain ophiolites or fragments of ophiolite suites (fig. 1). The process of arc accretion resulted in the growth of at least 1 x 10^6 km^2 of new continental crust with an average thickness of about 40 km (Mooney and others, 1985) adjacent to the Archean Congo Craton and early Proterozoic Mozambique belt. This series of events was probably a key element in the formation of a proto-Gondwana supercontinent by the end of the Precambrian (Kröner, 1980).

A number of geologic factors have resulted in superb exposure of the Proterozoic accreted-arc terranes in Arabia. Many of the rocks are metamorphosed to only greenschist or lower facies, are exposed at relatively shallow crustal levels, and have been buried under the deposits of epicontinental seas since the close of the Precambrian. A peneplain developed at the end of the Proterozoic (or during the earliest Paleozoic) providing a natural plan section of the Arabian Shield (Powers and others, 1966). Much of the Shield is now exposed at about the level of this old peneplain surface due to broad upwarping and erosion occurring after Tertiary Red Sea rifting (Schmidt and others, 1982). There has been little penetrative deformation during the Phanerozoic.

The ophiolitic suites described in this report are among the oldest known. As such, they provide some of the first direct geologic evidence of modern-style plate tectonics. In addition to providing *prima facie* evidence of the formation of oceanic lithosphere during the late Proterozoic, the ophiolites of the Arabian-Nubian Shield yield direct chemical, isotopic, and structural information on the evolution of the mantle — data that cannot be reliably obtained from continental rocks.

The earliest fragmentary ophiolites (representing oceanic crust and mantle) are found in the late Proterozoic rocks of Newfoundland (Strong, 1979), Wales (Thorpe, 1978), North Africa (Leblanc, 1981; Boudinier and others, 1984), possibly in the southwest United States (Garrison, 1980), and in the Arabian-Nubian Shield (Bakor, 1973; Bakor and others, 1976; Frisch and Al-Shanti, 1977; Delfour, 1977; Al-Rehaili and Warden, 1980; Kazmin, 1978; Shanti and Roobol, 1979; El Bayoumi, 1980; Nassief, 1981; Chevremont and Johan, 1982a, 1982b; Fitches and

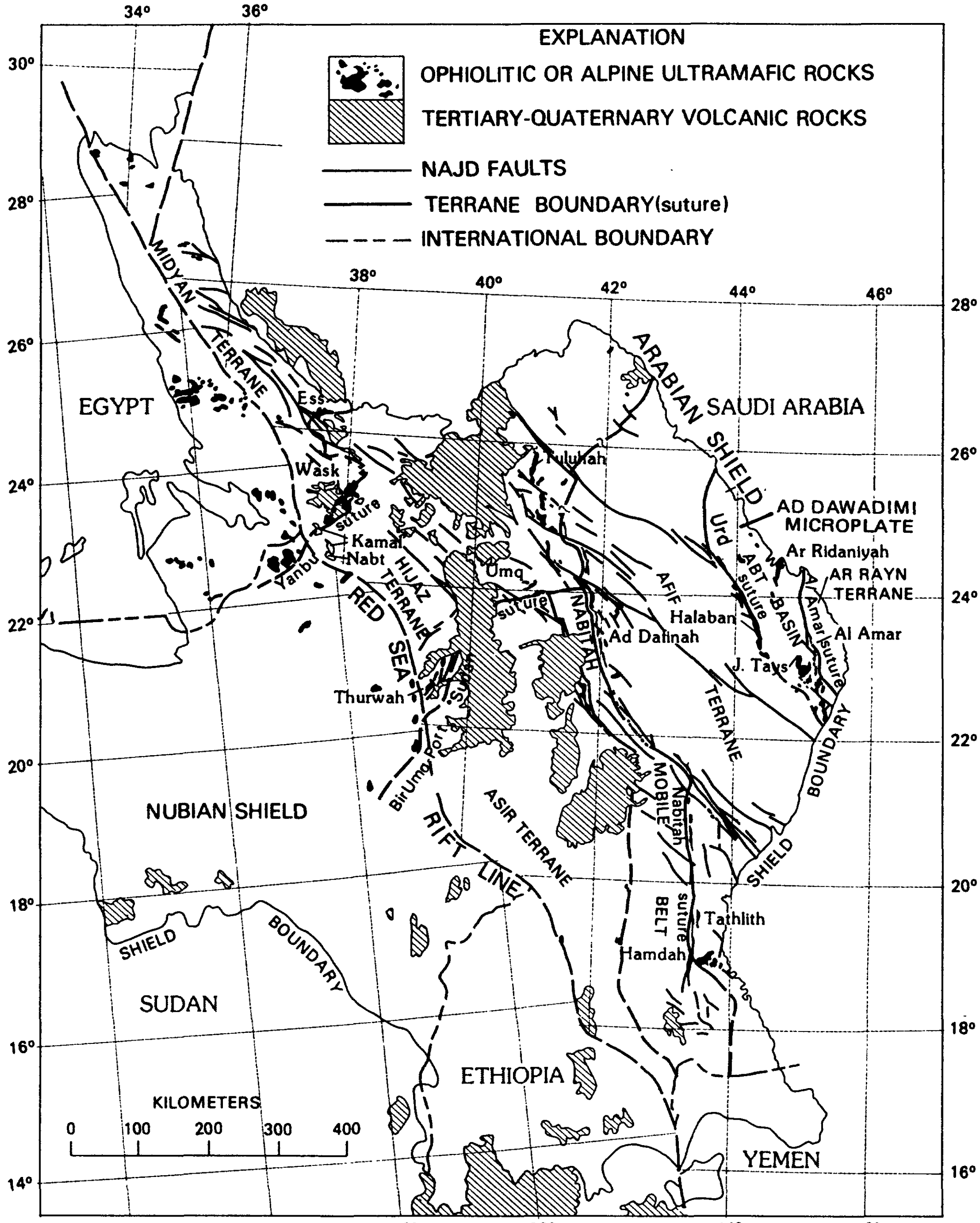


Figure 1.--Index map of the Arabian-Nubian Shield prior to Red Sea rifting showing the location of ophiolitic rocks and other prominent geologic features. Based on maps by the U.S. Geological Survey and Arabian American Oil Company (1963), Baubron and others (1976), Frisch and Al-Shanti (1977), Greenwood and Anderson (1977), Schmidt and others (1979), Dixon (1981), Egyptian Geological Survey and Mining Authority (1981), Stacey and Stoeser (1983), Fitches and others (1983), Camp (1984), Stoeser and Camp (1985), and Stoeser (unpublished compilation, 1985).

others, 1983; Ries and others, 1983; Claesson and others, 1984; Shimron, 1984). The first reference to ophiolitic rocks in the Arabian Shield was apparently made by Victor Kahr (1961).

Geochronologic studies have been instrumental in the understanding of the tectonic history of the Arabian-Nubian Shield. Kennedy (1964) defined the "Pan African tectonic episode" as one during which a preexisting shield was differentiated into cratons and orogenic belts. This was done on the basis of a K-Ar age peak at 500±50 Ma. For the Arabian Shield, this interval is now thought to represent a final period of consolidation (Schmidt and others, 1979; Schmidt and Brown, 1982; Jackson and Ramsey, 1980). Geochronologic work, using U-Pb and Rb-Sr methods, has shown that cratonization consisted of a number of individual episodes of arc magmatism and microplate accretion that began in Arabia at about 900-950 Ma and culminated with final post-orogenic intrusion, uplift and cooling about 570-500 Ma. The entire cratonization process may be regarded as "Pan-African" in the broad sense advocated by Kröner (1980; 1984).

The K-Ar studies of the 1960's and early 1970's (Fleck and others, 1976; Baubron and others, 1976) verified the Proterozoic age of the Arabian Shield; however, these authors noted that the thermal effects of final Shield consolidation had reset many of the ages of the igneous rocks to produce metamorphic ages of between 510 and 610 Ma. The Rb-Sr isochron method was used extensively during the 1970's and 1980's and has extended the record of arc magmatism to more than 900 Ma (Fleck and others, 1980); however, the results of Rb-Sr age determinations have often been equivocal, due both to geologic uncertainty that sample suites are comagmatic, and to metamorphic redistribution of rubidium and strontium.

The introduction of U-Pb zircon geochronology to studies of the Arabian Shield (Cooper and others, 1979) has provided the necessary age discrimination to allow detailed correlation of rock units. The combination of U-Pb and Rb-Sr geochronology with lead-, strontium-, and neodymium-isotope studies has been critical in formulating and testing tectonic models of Arabian Shield formation (Kemp and others, 1980; Stoeser and others, 1982, 1984; Duyverman and others, 1982; Calvez and others, 1984; Camp, 1984; Stacey and Hedge, 1984; Stoeser and Camp, 1985; Stacey and others, 1984; Claesson and others, 1984).

Recent isotopic and geochronologic work indicates that an early Proterozoic continental fragment was entrained between the accreted arc complexes (Stacey and Stoeser, 1983; Stacey and Hedge, 1984; Stacey and Agar, 1985) and suggests that older rocks in the eastern Arabian Shield may represent a rifted fragment of the early-Proterozoic Mozambique belt of southeast Africa (Stoeser and Camp, 1985). Exotic and ancient continental fragments are also found in extensive Phanerozoic accreted-arc terranes such as in Indonesia and Alaska (Hamilton, 1979, 1981; Jones and others, 1982, 1984). However, it is ironic that the apparent absence of older continental crust within the Arabian Shield is the factor that initially convinced most workers of its accreted-arc ancestry.

The ophiolites of the Arabian Shield are a key element in most tectonic models, yet they are among the most difficult rocks in the Shield to date radiometrically. Attempts to use the zircon U-Pb method have been plagued both by the scarcity of suitable felsic differentiates that are demonstrably comagmatic with the suites, and by analytical uncertainties related to low uranium and lead concentrations in the few zircons obtained (Calvez and others, 1984; Claesson and others, 1984). Several years ago we concluded that the importance of these rocks warrented the additional effort in obtaining geochronologic data. The ophiolitic rocks are commonly in fault contact with adjacent rocks and therefore could be much older, coeval, or younger than the surrounding arc rocks. An individual ophiolite could represent a fragment of ocean lithosphere formed much earlier at a spreading ridge far from the now adjacent arc rocks. In contrast, it could be roughly coeval, the product of back-arc spreading; or alternatively, it might be younger, produced in an intra-arc basin after cessation of adjacent arc magmatism.

By determining the igneous ages and lead-isotopic characteristics of fragments of ocean crust caught up in sutures between the arc complexes, we are attempting to unravel part of the arc-accretion history of the Shield. This study parallels those of Stacey and Stoeser (1983), Stacey and others (1984), Stoeser and others (1984), and Stoeser and Camp (1985). However, rather than relying primarily on data from the arc rocks themselves, we also consider the age and characteristics of intervening ocean-crust fragments.

A NOTE ON STRATIGRAPHIC NOMENCLATURE

Originally, Brown and Jackson (1960; U.S. Geological Survey and ARAMCO, 1963) divided the late Proterozoic metavolcanic and metasedimentary rocks of the Arabian Shield into a series of informal groups based on lithologic similarity and apparent relative ages. This early classification laid the foundation for the increasingly complex (and sometimes contradictory) nomenclature that has developed during geologic mapping of the Arabian Shield at 1:100,000 and 1:250,000, a project now nearing completion through a cooperative effort by U.S. Geological Survey (USGS), Bureau de Recherches Geologiques et Minieres (BRGM), and Saudi Arabian Directorate General for Mineral Resources (DGMR).

In recent years, the early lithologic correlations have been widely revised as the concepts of island-arc and exotic-terrane accretion have been applied to the Arabian Shield, and as isotopic, geochemical, and precise geochronologic methods have been used to characterize various terranes. It is now recognized that methods of classical regional-stratigraphic nomenclature are difficult to apply to the mosaic of accreted terranes that make up the Arabian Shield. The task may be compared to the production of a terrane map of Alaska (e.g., Jones and others, 1984) without the aid of paleontology. A recent attempt at chronologic correlation of major lithostratigraphic units is shown in Stoeser and Camp (1985) and the distribution of various units within proposed terranes is shown on 1:1,000,000-scale maps of the Shield by Johnson and Vranas (1984) and Johnson and others (1986).

Brown and Jackson (1960) classified most of the bedded rocks of the Arabian Shield into 1) the early, compositionally primitive (basalt and soda rhyolite) Baish group, 2) the intermediate age and compositionally mature (andesite and graywacke dominated) Halaban andesite and Murdamah formation, and 3) the late, compositionally evolved Shammar rhyolite. This broad threefold division has survived in the "sequence C, B, and A" terminology of Jackson and Ramsay (1980). Although simplified, this threefold division is generally regarded as distinguishing the products of immature intra-oceanic island arcs, more mature intra-oceanic or marginal arcs, and the products of syn- and post-accretion crustal melting.

Rocks known variously as Halaban group, Hulayfah group, or as local lithostratigraphic divisions of these units are of particular importance in this report because they host most of the ophiolites. The Hulayfah group is roughly equivalent to (or is a subgroup of) the Halaban group of Brown and Jackson (1960) and consists of calc-alkaline island-arc volcanic rocks and volcaniclastic sediments. Most Hulayfah rocks were derived from arcs that reached maturity during the intermediate period (~715-780 Ma) of Arabian Shield development (Stoeser and Camp, 1985). Rocks formerly assigned to the Halaban group are now generally referred to as Hulayfah group (or have been reassigned to lower-rank local units) because of stratigraphic and chronologic inconsistencies, including problems with the type Halaban area (for example, Defour, 1979b; Stoeser and others, 1984).

ACKNOWLEDGMENTS

We would like to acknowledge many helpful discussions and, in several instances, field excursions with the following individuals: Mohammad Nassief, John Roobol, and Mohammed Shanti of King Abdulaziz University; Jean-Yves Calvez and John Kemp of the BRGM, Colin Ramsay of the DGMR; and Glen Brown, James Cole, Warren Hamilton, James Quick, and Douglas Stoeser of the USGS. We especially appreciate the use of low-level-Pb laboratory facilities provided by Mitsunobu Tatsumoto for the analysis of single crystals and very small zircon fractions. Mineral separations were carried out by Ghalib Hasan Abubaker, Mir Amjad Hussain, Randolph Ogg, and David Plume of the USGS. Field work was facilitated by Paul Togans and Yousif al Somali of the USGS and their field-support staff. Field assistance and philosophical discussions with Omar Noor of the USGS added greatly to our experiences in Saudi Arabia.

We would also like to thank Wayne Hawkins of the USGS for patient and meticulous drafting assistance. The manuscript was improved through constructive review by James Quick, Douglas Stoeser, and Robert Zartman of the USGS.

GEOLOGIC AND TECTONIC SETTINGS, SAMPLE DESCRIPTIONS

The ultramafic and mafic rock complexes within the Arabian Shield can be divided into two genetic types: *in situ* intrusions and ophiolitic complexes. This distinction was used by BRGM to classify the major occurrences of the Arabian Shield into either "ophiolitic" or "basic intrusive" categories (Sustrac, 1980). The "basic intrusive" type forms both discreet (commonly layered) plutons and the mafic cumulates of composite plutons and batholiths. This type differs from the "ophiolitic" type by having more gabbro and diorite than peridotite or serpentinite, cumulus textures in peridotite, locally alkaline compositions, and less alteration. It is also generally less serpentinized and deformed and lacks nonplutonic members of the ophiolite suite (pillow lavas, sheeted dikes, peridotite tectonites, and associated sedimentary rocks). In contrast, the ophiolitic type is characterized by the presence of serpentinized peridotite with relict tectonite fabrics (the "alpine-type" peridotite of Jackson and Thayer, 1972), and by the association of various members of the classic ophiolite suite as defined by the Penrose Ophiolite Manifesto (Anonymous, 1972). The ophiolitic-type ultramafic rocks have commonly undergone hydrothermal alteration to produce listwänite or bibirite (the carbonated or silicified serpentinite of Duparc and others, 1927). In addition, the ophiolitic rocks occur in linear belts marking sutures that separate rocks of different provenance, age, geochemical affinity, or structural and metamorphic character (fig. 1).

Several of the ophiolitic complexes in the Arabian Shield have been mapped and studied in detail (Bakor, 1973; Bakor and others, 1976; Shanti and Roobol, 1979; Nassief, 1981; Chevremont and Johan, 1982a, 1982b; Al-Shanti and Gass, 1983; Nassief and others, 1984) and most of the complexes have been included in regional geologic mapping at scales of 1:100,000 and 1:250,000 by BRGM, USGS, and DGMR. Using these sources for guidance, we visited most of the reported ophiolitic occurrences of the Arabian Shield during 1981-1983, examined geologic field relations, and collected samples for petrographic, geochemical, and geochronologic studies. Sample-locality coordinates and petrographic descriptions are given in table 1. The first results of our reconnaissance study (Sm-Nd data for ophiolitic rocks of the northwest Arabian Shield) were reported by Claesson and others (1984). In this second report, we review geologic relations and present U-Pb zircon dates and lead-isotopic characteristics of ophiolitic rocks from all parts of the Shield.

Samples were selected according to the following guidelines: 1) evidence of comagmatism with other ophiolitic rocks in the area, 2) presence of modal zircon, and 3) relative lack of alteration. Plagiogranite (Coleman and Peterman, 1975; Coleman, 1977) is present as small intrusions or pods within several of the ophiolites and was collected where possible because zircon tends to be concentrated in this ophiolitic rock type (Tilton and others, 1981); however, in many of the ophiolitic melanges of the Arabian Shield, small bodies of albitized trondhjemite or tonolite have intruded or are faulted against gabbro or serpentinite. Although these felsic rocks resemble oceanic plagiogranite in the field, they are actually comagmatic with the adjacent arc plutonic rocks. Therefore, we also collected gabbro or hornblende diorite that could be assigned to ophiolitic suites more directly. This necessitated collecting large samples (approximately 80-100 kg, table 1). Fractions of the same samples were reserved for Sm-Nd and geochemical studies (Claesson and others, 1984; Pallister, unpublished data), and lead-isotope ratios were measured on feldspars separated from many of the samples.

NORTHWEST AND WEST-CENTRAL ARABIAN SHIELD

North of about lat 21^{o} N. and west of the Nabitah suture, the Arabian Shield is dominated by northeast-trending structural and lithologic belts (Johnson, 1983). These have been offset along northwest-trending latest Proterozoic (580-530 Ma) strike-slip faults (the "Najd faults" described by Brown and Jackson, 1960; Moore and Al-Shanti, 1979; Moore, 1979; and Davies, 1984). The Jabal Ess and Jabal al Wask ophiolites define the Yanbu suture, which separates the Hijaz and Midyan microplates. To the south, the Bir Umq-Port Sudan suture is defined by the Thurwah ophiolite and the Bir Umq ophiolitic complex. This suture separates the Asir microplate of southwestern Arabia from the Hijaz microplate (Stoeser and Camp, 1985) (fig. 1).

Jabal Ess Ophiolite

The Jabal Ess ophiolite, also known as the Wadi al Houanet ophiolite (Sustrac, 1980) and as the Wadi al Hwanet-Jabal Iss ophiolitic complex (Chevremont and Johan, 1982a), is the best-preserved ophiolite yet described in the Arabian Shield.

It contains all the components of the classic ophiolite pseudostratigraphy, but has faulted contacts between many of the members and lacks parts of individual sections. The following description is based on work by Shanti and Roobol (1979, 1982), Chevermont and Johan (1982a), and on observations by the senior author.

The ophiolite is a folded allochthonous thrust sheet contained within metasedimentary and metavolcanic host rocks. The host rocks were first assigned to the Halaban (Hulayfah) group by Pellaton (1976), but were later correlated with the Farri group of the Jabal al Wask region, as defined by Kemp (1981; see also Chevremont and Johan, 1982a).

The ophiolite and its host rocks are faulted against and locally unconformably overlain by a thick (~3.5 km) metavolcanic sequence consisting of a basal section of subaqueous lava flows and volcaniclastic rocks that grades upward into a subaerial section of ignimbrites. Because most of the contacts within the ophiolite are faults or are intrusive, it is not possible to demonstrate an internal stratigraphic sequence; however, the outcrop pattern of various units in the northeastern part of the complex suggests a faulted and possibly refolded synform. Pillow lavas (fig. 3a) and pelagic metasedimentary rocks occur in a northwest-trending belt, bounded on the southwest and northeast by sheeted dikes, gabbro, and serpentinized peridotite (fig. 2).

Serpentinized peridotite crops out over an area of about 20-30 km^2 in the Wadi al Houanet-Jabal Ess area (fig. 2). The peridotite appears to be part of a larger gabbro-diabase complex within a synclinal structure in the late Proterozoic metasedimentary and metavolcanic host rocks. The peridotite is composed of serpentinized harzburgite and dunite tectonites that are locally interlayered and infolded. The harzburgite contains deformed enstatite porphyroclasts, and both the harzburgite and dunite have metamorphic foliations and lineations defined either by enstatite banding or by trains of ovoid (stretched) chromite grains (fig. 4a). Although olivine fabrics have not been measured, the enstatite foliations and spinel lineations suggest tectonite fabrics consistent with high-temperature subsolidus deformation of the type associated with plastic mantle flow below oceanic spreading ridges (Nicolas and others, 1980). Small podiform chromitite bodies occur within the peridotite and are shown on the compilation map of Sustrac (1980). The rock types, fabrics, compositions, and limited compositional variations of olivine, orthopyroxene, and minor clinopyroxene ($Fo_{\sim 91}$, $En_{\sim 90-91}$, $En_{\sim 49-50}$ $Fs_{\sim 2-3}$ $Wo_{\sim 47-50}$; Chevremont and Johan, 1982a), and the presence of podiform bodies of chromitite are all characteristic of the alpine-type harzburgitic peridotites (Jackson and Thayer, 1972) that form the basal section of Phanerozoic ophiolites (Coleman, 1977). The chrome-spinel from the peridotite and chromitite shows a wide compositional range (fig. 5), characteristic of "Type II" alpine-type peridotites. Dick and Bullen (1984) state that such peridotites formed in a composite environment, such as an island arc on oceanic crust.

The peridotite is laced with lizardite-chrisotile and magnesite veins only a few millimeters or centimeters wide. The degree of serpentinization varies locally. The least- serpentinized peridotite is found in the more incised wadi channels, suggesting that low-temperature serpentinization is ongoing, as has been demonstrated at other ophiolites (Hopson and others, 1981). The serpentinite is carbonated or silicified along major fault zones. Jabal Ess is capped by a zone of biberite (ferruginous chert derived from serpentinite) 50-100 m thick (fig. 3b) that contains goethite clasts and relict chromite grains.

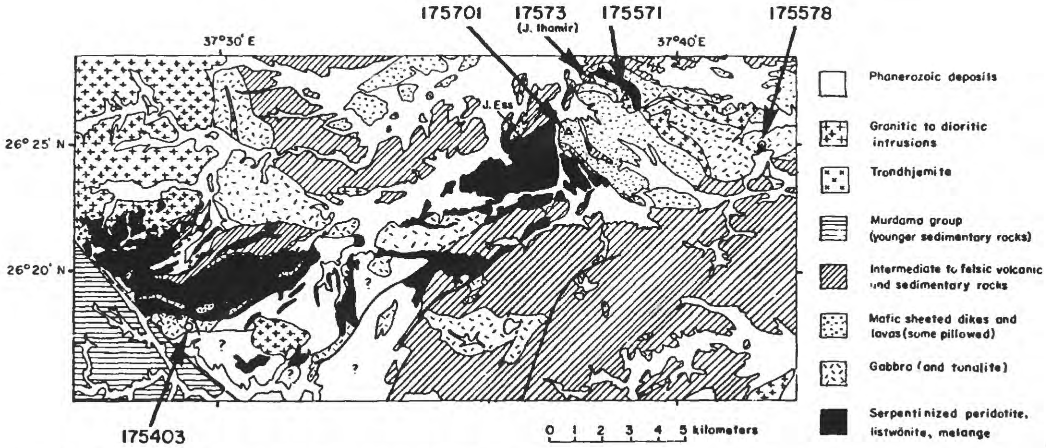


Figure 2.--Geologic map showing sample localities at the Jabal Ess ophiolite. Map simplified from Shanti and Roobol (1982) and Chevremont and Johan (1982a). Solid and dashed lines indicate mapped faults. Areas labeled with question marks are unmapped. Circles indicate Sm-Nd samples from Claesson and others (1984); triangles indicate sample localities for this study.

A small zone of cumulus wehrlite was mapped by Shanti and Roobol (1979, 1982) within a northwest-trending fault zone that separates serpentinized harzburgite and dunite tectonite from gabbro and a sheeted-dike complex. Layered cumulus gabbro and noncumulus hypidiomorphic gabbro are present in the Jabal Ess area. The gabbro crops out as a thin (<100 m) septum separated from the peridotite by the fault zone, and as several larger plutons that either intrude or are faulted against peridotite (fig. 2). The gabbro locally intrudes the sheeted-dike complex along an abrupt contact; however, septa and inclusions of gabbro are present within the dike complex close to the contact (Shanti and Roobol, 1982).

An arcuate pluton intrudes the metagabbro of the ophiolite and contains inclusions of pelagic metasedimentary rocks that elsewhere overlie pillow lavas of the complex. The pluton is considered to be the youngest component of the ophiolite and was mapped as plagiogranite by Shanti and Roobol (1982); however, the rock contains minor microcline and biotite (table 1) and about 2 percent K_2O (Pallister, unpublished data). Oceanic plagiogranite is characterized by very low (<1 percent) K_2O content (Coleman and Peterman, 1975), therefore the pluton is classified here as trondhjemite following the criteria of Barker (1979). The K_2O content of the pluton and its geologic setting suggest that it is not part of the ophiolite, but is the product of subsequent arc magmatism.

Sheeted dike complex crops out in the northeastern part of the complex and transitional or intrusive contacts with both gabbro and pillow lava are locally preserved. The dikes are so altered and fractured that chill margins are indistinct; however, in several outcrops east of Jabal Ess, close inspection reveals a transition from approximately 100 percent dike rock into a zone of dikes intruding pillow lavas and pillow breccia (Shanti and Roobol, 1982).

The pillow-lava section of the ophiolite is best exposed in a syncline east of Jabal Ess (fig. 2). Pillow forms are very well preserved locally (fig. 3a) and are compositionally similar to abyssal tholeiite (Shanti and Roobol, 1982). The pillow lavas are intercalated with banded chert and shale.

A

Figure 3.--Photographs showing field characteristics of Arabian Shield ophiolites: a) tubular pillow lava of the Jabal Ess ophiolite; b) Jabal Ess showing prominant biberite- and listwaenite-veined fault zone. P = serpentinized peridotite, L = listwänite and bibirite; c) listwänite-serpentine matrix melange at southern edge of Jabal al Wask ophiolitic complex, dark lenses are metagabbro; d) metavolcanic and metasedimentary rocks of the Farri group (V) thrust over serpentinized peridotite (P), southern Jabal al Wask complex; e) oblique aerial view (to west) of thrust fault contact between harzburgite and dunite tectonite (P, on left) and layered gabbro (G, on right) at the Thurwah ophiolite, abundant dunite (D, light weathering) present near contact; f) ribbon chert from the Bir Umq complex, g) spinel trains in serpentinized dunite from central Hamdah complex (pen length = 10 cm); h) interlayered (isoclinally folded) dunite and harzburgite serpentinite in the western Hamdah complex (frame width represents about 3/4 km in the foreground, symbol indicates layering attitude); i) interlayered dunite (D on left) and harzburgite (H on right) serpentinite with strong enstatite (bastite) foliation parallel to 10-cm-long pen; j) isoclinally folded dunite dike in serpentinized harzburgite tectonite from western Hamdah complex (dike boundaries and pyroxene foliation highlighted with marker lines) (pen length = 10 cm).

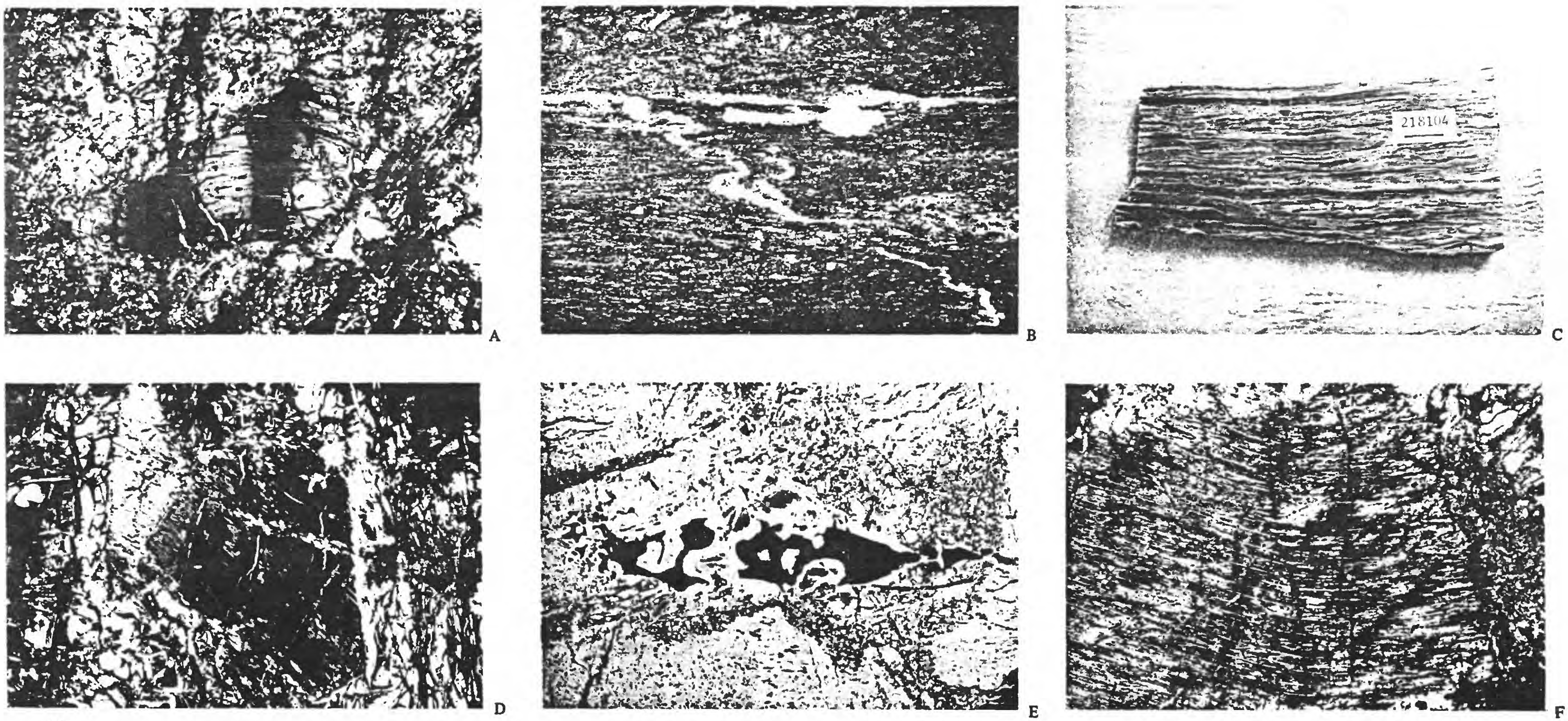
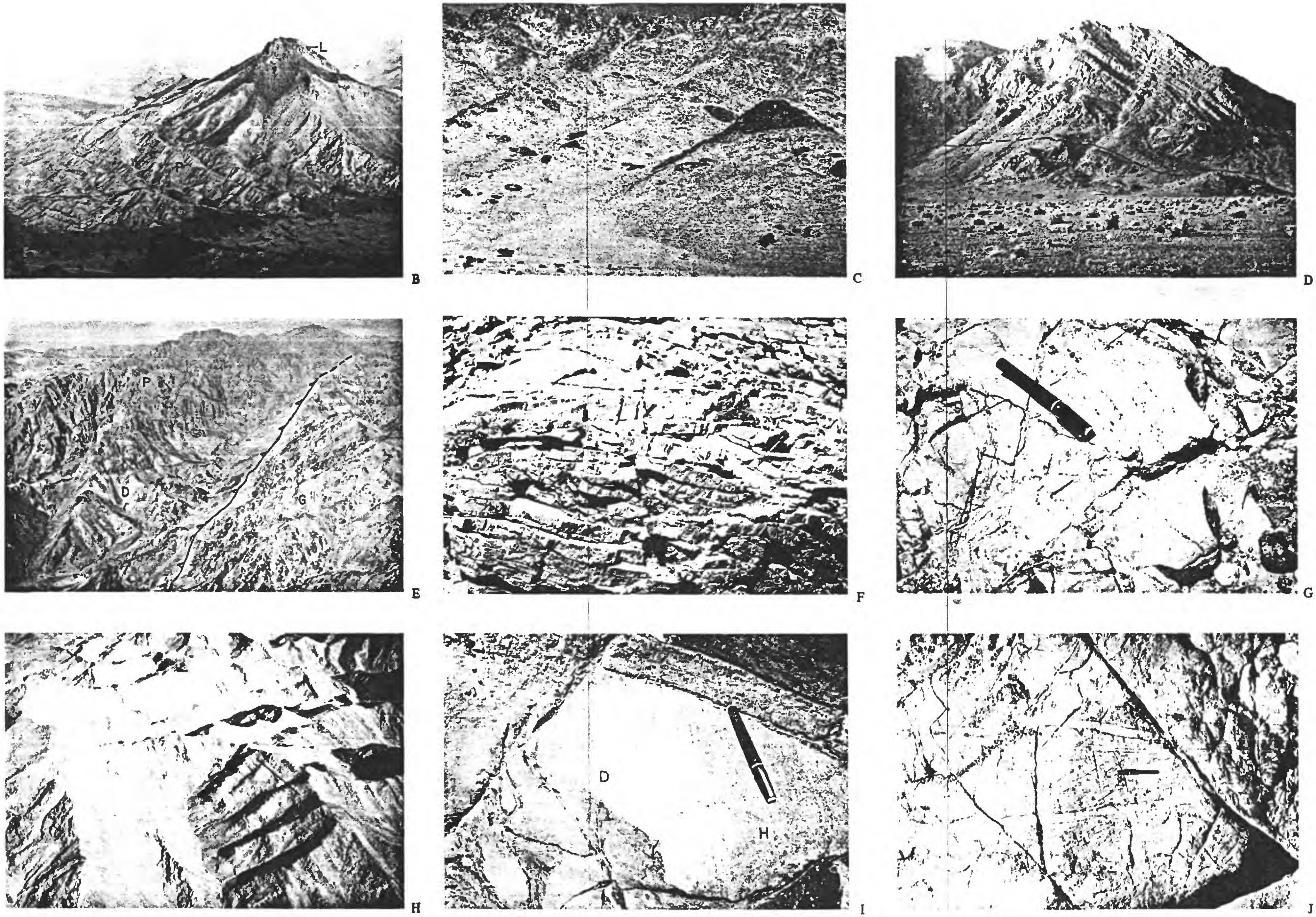


Figure 4.--Photomicrographs (cross-polarized light, frame width 2.4 X 3.6 mm, except as noted) of a) harzgurgite tectonite from the Jabal Ess ophiolite showing deformed enstatite porphyroclast, b) basaltic mylonite from contact between ophiolitic basalt and Farri group metasedimentary rocks (note ptygmatically folded quartz-albite vein), c) polished slab of basaltic mylonite from same area as (b) (bar = 1 cm), d) deformed enstatite in harzburgite tectonite from the Bir Tuluhah ophiolitic complex (note undulatory extinction), e) irregular lensoidal spinel grain in train of grains within serpentinized harzburgite from the Hamdah complex (plane light), f) bastite pseudomorph after deformed enstatite porphyroclast in serpentinized harzburgite from the Hamdah complex (plane light, 4.5 X 7.0 mm field).



10b

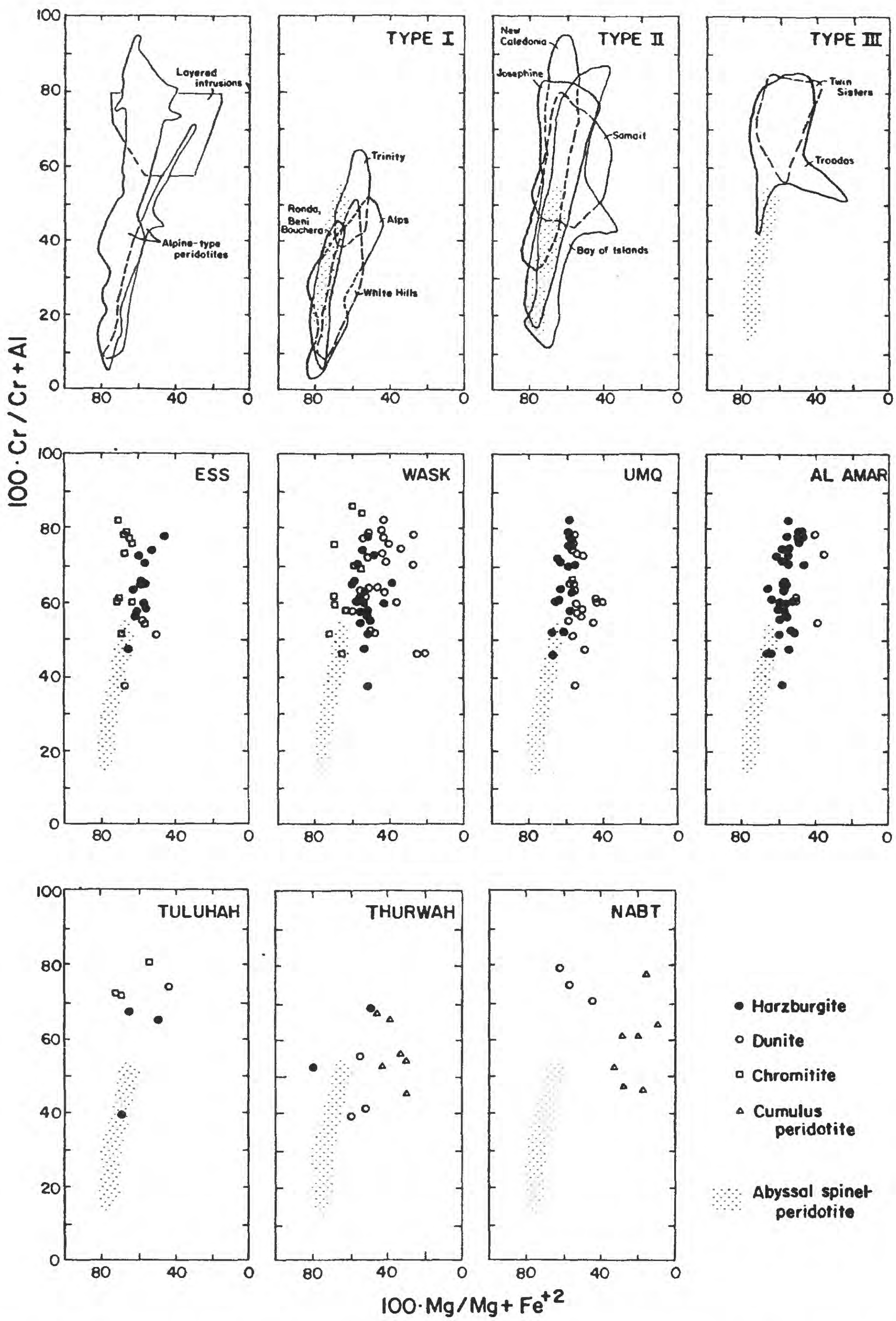


Figure 5.--Cr/Cr+Al and Mg/Mg+Fe^{+2} variation in chromite. Fields for layered intrusions, abyssal spinel-peridotite, and alpine-type peridotites from a compilation by Dick and Bullen (1984). Types I, II, and III are categories defined by Dick and Bullen for alpine-type peridotites formed at mid-ocean ridges (Type I), island arcs (Type III) and composite settings (Type II) (e.g., arc built on mid-ocean ridge lithosphere). Data from Arabian Shield ophiolitic rocks indicated by abbreviated complex names and compiled from Chevremont and Johan (1981, 1982a,b), Nassief (1981), Le Metour and others (1982, 1983), and Ledru and Auge (1984).

Several samples were collected from the Jabal Ess ophiolite for radiometric dating (fig. 2, table 1). A large sample of noncumulus hornblende-clinopyroxene gabbro was collected from the northeast part of the complex for Sm-Nd (Claesson and others, 1984) and U-Pb geochronology. A sample from a discontinuous metadiorite dike within the dike complex was collected for U-Pb zircon dating. In addition, samples were collected from the northwestern and southern parts of the trondhjemite pluton (the "plagiogranite" of Shanti and Roobol) to determine if it is appreciably younger than the ophiolite.

Jabal al Wask Complex

The Jabal al Wask complex is the largest (~1,000 km^2) ophiolitic ultramafic-mafic suite in the Arabian Shield (fig. 6). The complex consists of structurally interleaved serpentinized peridotite, gabbro, diabase, and pillow lavas, as well as intrusive gabbro plutons and sills within the peridotite. The complex is probably best described as a huge serpentine-matrix tectonic and intrusive melange. Sheeted dikes have not been recognized in the region. Rocks of the complex crop out in a northeast-trending belt that is offset from the Jabal Ess ophiolite by about 50 km along a left-lateral strike-slip Najd fault (figs. 1 and 6). The complex is the subject of a Ph.D. dissertation by Bakor (1973) and a summary paper by Bakor and others (1976). The ultramafic and mafic rocks are called the Haja complex (Kemp, 1981) or the Al 'Ays ophiolitic complex (Chevremont and Johan, 1982b; Ledru and Auge, 1984). The southern part of the complex is also known as the Wadi Malahat suite (Sustrac, 1980). In this report, we follow the usage of Bakor (1973) and Bakor and others (1976), and use the name Jabal al Wask for the entire complex.

The ultramafic rocks of the complex are mostly serpentinized harzburgite and dunite. As at Jabal Ess, the serpentinite is locally converted to listwänite and bibirite along fault zones. Olivine and pyroxene from the harzburgite are highly magnesian and show little chemical variation (Fo_{91-93}, En_{89-91}). However, dunites and wehrlites with less magnesian and more variable olivine and pyroxene compositions also occur (olivine variation: Fo_{85-91}). These data suggest the presence of both residual mantle tectonites and more evolved cumulates (Chevremont and Johan, 1982b; Ledru and Auge, 1984). Chrome spinel shows a wide compositional range, characteristic of "Type II" alpine peridotites (fig. 5). There is a general trend of decreasing $Mg/Mg+Fe^{+2}$ from chromitite to harzburgite and dunite in each of the Arabian Shield ophiolites. We attribute this trend to low-temperature reequilibration with olivine accompanying a decrease in modal chromite/olivine ratios (Irvine, 1967; Dick, 1977). However, the lower $Mg/Mg+Fe^{+2}$ chromite grains in dunites with $<Fo_{90}$ olivine are probably cumulus grains that originated in relatively evolved basaltic magmas.

As noted at Jabal Ess, some of the serpentinized peridotites have relict porphyroclastic or porphyroblastic textures, deformed enstatite (bastite) grains, and ovoid chrome spinel in trains; these features may be the result of the high-temperature plastic deformation typical of mantle peridotites (Nicolas and others, 1980). Podiform bodies of chromitite (characteristic of ophiolitic occurrences) are common within the serpentinized peridotite; the largest known chromitite lens, the "JL1" body (Sustrac, 1980) is about 20 by 40 m in outcrop area.

Bakor and others (1976) describe the Jabal al Wask complex as an Eocambrian back-arc ophiolite that is unconformably overlain by a thick sequence of rhyodacitic pyroclastic deposits. The upper parts of the ophiolite are reported to

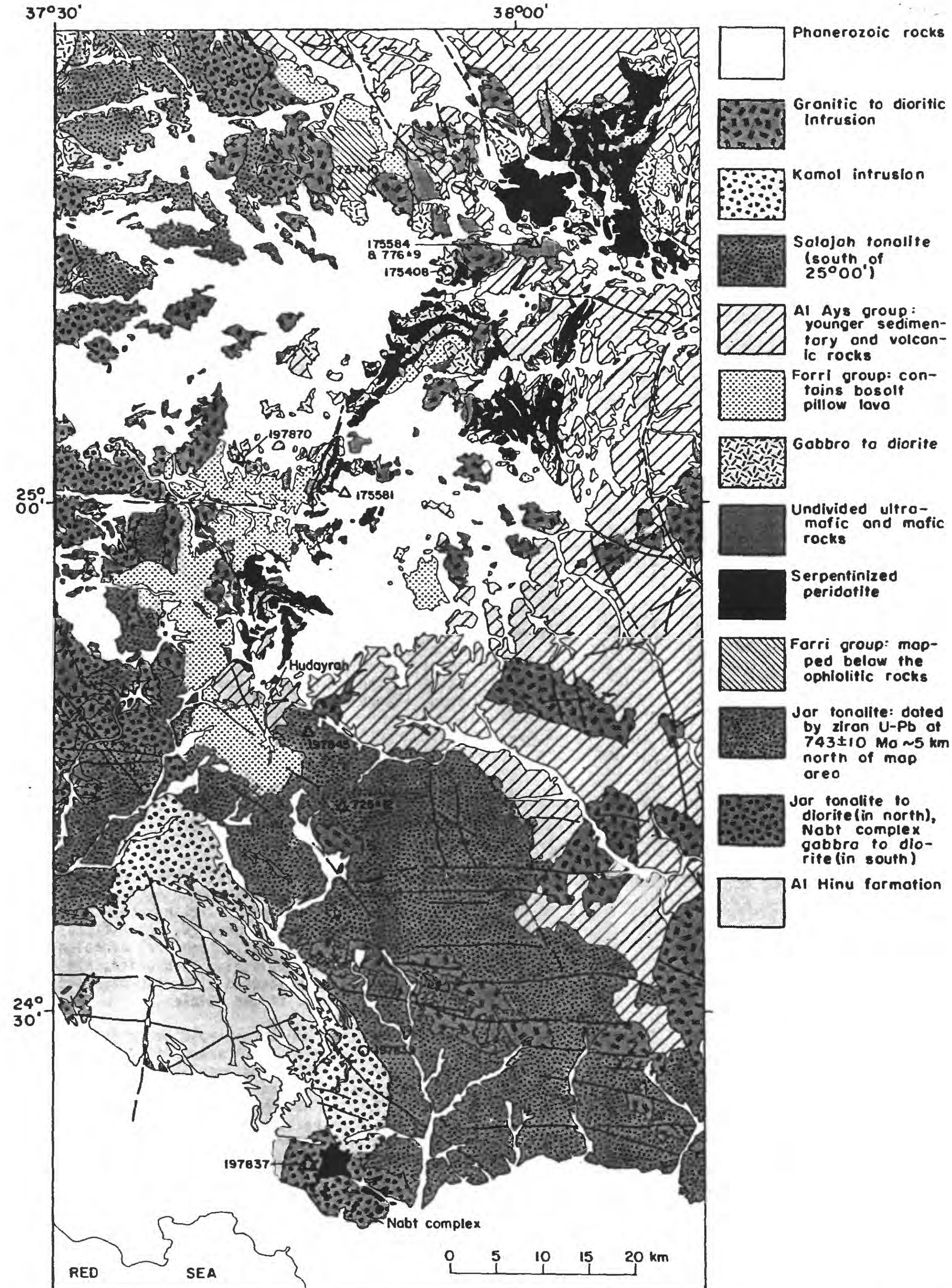


Figure 6.--Geologic map showing sample localities at the Jabal al Wask ophiolitic complex, the Nabt complex, and the Kamal intrusion. Map simplified from Kemp (1982), Pellaton (1979), Chevremont and Johan (1981). Solid and dashed lines indicate mapped faults. Circles indicate Sm-Nd samples from Claesson and others (1984); triangles with dates indicate U-Pb zircon samples from Kemp and others (1980) and Calvez and others (1984); triangles with sample numbers indicate U-Pb zircon samples for this study. Date shown as 725±12 Ma revised to 720±5 Ma (Ledru and Auge, 1984).

Table 1.--Sample Descriptions.

Complex Name	Sample No.	Latitude (North)	Longitude (East)	Rock Type	Sample Weight	Petrographic/sample description
Jabal Ess	175571	26°23.4'	37°38.7'	Trond-hjemite	~50 kg	(Biotite)-bearing trondhjemite; allotriomorphic granular, medium grained. ~65% oligoclase, moderately altered, rimmed by microcline; ~25% quartz, strained, anhedral; 8% microcline microperthite, anhedral, interstitial; ~1% chlorite, interstitial, pseudomorphs after biotite(?), ~1% titanomagnetite, exsolved and partly replaced by leucoxene, trace apatite and zircon. Sample from southern part of 1/2 X 3 km intrusion that cuts ophiolite metagabbro and includes pelagic metasediments
	175573	26°23.8'	37°38.1'	Trond-hjemite	~50 kg	(Biotite)-bearing trondhjemite; hypidiomorphic granular, medium grained. ~70% oligoclase, slightly altered, rimmed by microcline; ~20% quartz, strained, anhedral; ~7% microcline perthite, anhedral, interstitial; ~1% chlorite and smectite, interstitial, pseudomorphs after biotite(?), <1% hematite, pseudomorphs after Fe-Ti oxides, trace zircon and apatite. Sample from northwest end of 1/2 X 3 km intrusion that cuts ophiolite metagabbro and includes pelagic metasediments
	175578	26°22.4'	37°41.8'	Gabbro	~80 kg	Hornblende-clinopyroxene gabbro; hypidiomorphic granular, medium grained. ~65% oligoclase-andesine, moderately to highly saussuritic; ~20% clinopyroxene, partly replaced by hornblende or uralite; ~15% hornblende, uralitic or chloritic; ~1% titanomagnetite, hematitic; trace biotite, apatite, and zircon. Forms main body of non-layered gabbro in the eastern part of the complex
	175701	26°22.8'	37°37.7'	Meta-diorite	~100 kg	Epidote metadiorite; granoblastic to weakly nematoblastic, very-fine grained. ~90% albite-oligoclase, albitized; ~5% epidote, ~3% titanite, ~2% calcite. Forms thin (0-1 m) dike within diabase sheeted dike complex
Jabal al Wask	175581	25°01.2'	37°47.4'	Gabbro	~80 kg	Clinopyroxene gabbro; hypidiomorphic granular, fine grained. ~60% andesine-labradorite, highly saussuritic; ~35% clinopyroxene, partly replaced by uralite; ~5% epidote; veined by calcite and zeolites. Forms large (20 to 100 m-thick sill within serpentine
	175584	25°15.2'	38°01.8'	Trond-hjemite	~60 kg	Biotite-hornblende trondhjemite; allotriomorphic granular, medium-fine grained. ~60% plagioclase, almost entirely replaced by saussurite and epidote; ~30% quartz, anhedral, some intergrown with plagioclase; ~7% hornblende, pleochroic olive to bluish-green, partly uralitic, ~3% biotite, chloritic, interstitial. From boudinaged, m-scale dike within serpentine-matrix melange
Nabt	197837	24°21.3'	37°46.6'	Gabbro	~10 kg	Hornblende gabbro; mesocumulus; medium grained. ~65% labradorite to andesine (broadly or edge-zoned), subhedral laths, slightly saussuritic; ~32% hornblende, pleochroic olive to tan- or blue-green; ~1% biotite, interstitial, <1% clinopyroxene, relict cores to anhedral hornblende grains, <1% titanomagnetite, interstitial with biotite, <1% apatite, large euhedral grains. Interlayered with serpentinized peridotite in the west-central part of the complex
Salajah	197845	24°46.3'	37°46.1'	Tonalite	~50 kg	Biotite-hornblende tonalite; hypidiomorphic granular; medium grained. ~65% andesine with saussuritic cores; ~20% anhedral strained quartz; ~10% hornblende, partly uralitic, ~5% biotite, partly replaced by chlorite and epidote, ~2% K-feldspar, interstitial; <1% magnetite; also contains mm-scale fine-grained biotite tonalite inclusions. From north-central part of batholith ("agl" unit on Yanbu' al Bahr map (Pellaton, 1979) where tonalite intrudes Farri and Al Ays groups.
Jar	197870	25°02.5'	37°42.0'	Tonalite	~50 kg	Hornblende tonalite; plagioclase porphyritic; medium grained groundmass; weakly foliated. ~45% subhedral zoned plagioclase (andesine-oligoclase) in allotriomorphic granular to granoblastic groundmass and as 5-10 mm phenocrysts, saussuritic cores; ~30% quartz, anhedral mosaic-recrystallized grains; ~25% subhedral hornblende, pleochroic and zoned from tan to pale olive; <1% biotite, chloritized; <1% titanomagnetite. From dike swarm that intrudes upper Farri group along Wadi as Sahafa; shown as "tnl" on the Wadi Al Ays map (Kemp, 1981)
Thurwah	175925	22°38.2'	39°23.8'	Meta-gabbro	~100 kg	Hornblende-clinopyroxene gabbro (metagabbro); hypidiomorphic granular, coarse grained. ~60% plagioclase, completely replaced by saussurite and clinozoisite; ~30% clinopyroxene, partly replaced by hornblende or uralite; ~10% hornblende, pleochroic in pale browns, rims and replaces clinopyroxene. Coarse-grained, leucocratic zone within section of deformed cumulus layered gabbro, pyroxenite, and wehrlite; within gabbroic section in northern part of complex

Table 1.--Sample Descriptions--Continued

Complex Name	Sample No.	Latitude (North)	Longitude (East)	Rock Type	Sample Weight	Petrographic/sample description
Thurwah (continued)	175937	22°35.8'	39°24.7'	Meta-gabbro	~100 kg	Hornblende gabbro (metagabbro); hypidiomorphic granular, medium-coarse grained. ~65% plagioclase, completely replaced by saussurite and clinozoisite; ~35% hornblende, pleochroic tan to green-brown. From coarse-grained pods and discontinuous (filter-pressed?) dikes and sills within imbricate section of gabbro in southern part of complex
	197601	22°37.8'	39°24.7'	Meta-gabbro	~100 kg	Clinopyroxene gabbro (metagabbro); adcumulus, medium grained. ~65% plagioclase, entirely replaced by saussurite (chiefly zoisite), ~35% clinopyroxene partly replaced by fibrous amphibole. Forms outcrops of cumulus ratio-layered (cm-thick layering) gabbro in central part of complex
Bir Umq	175471	23°54.8'	40°52.9'	Meta-diorite	~100 kg	Composite sample of variably layered hornblende diorite, hornblende gabbro and gabbro pegmatite that forms poorly exposed and fault-bounded gabbro-diorite transition zone in estern part of complex. Most of sample consists of medium grained, hypidiomorphic granular hornblende diorite made up of 30-40% brown hornblende, partly converted to fibrous amphibole (uralite), and highly saussuritic plagioclase
	175592	23°55.7'	40°55.5'	Kerato-phyre	~80 kg	Quartz keratophyre; plagioclase porphyritic, fine grained. 50% plagioclase phenocrysts (<0.5 mm diameter, equant), albitized; very-fine grained felsophyric groundmass of plagioclase (albitized) and quartz; minor chlorite, Fe-Ti oxides, epidote, and calcite. Small aplitic intrusion (dikes and sill?) within serpentinite, listwaenite, and bibirite; intruded by sparse diabase dikes and common bull quartz dikes and veins
	175602	23°57.6'	40°59.3'	Meta-gabbro	~80 kg	Hornblende-clinopyroxene gabbro (clinopyroxene-plagioclase mesocumulate); planar laminated, fine grained. ~65% plagioclase, completely replaced by saussurite; ~35% clinopyroxene, partly replaced by chlorite; ~5% hornblende, pleochroic pale tan to brown, interstitial and rimming clinopyroxene. Irregular fault-bounded body (50 X 150 m) of gabbro within serpentine; contains cm-thick, coarse grained hornblende gabbro veins
Tuluhah	175585	25°40.5'	40°48.3'	Plagio-granite	~60 kg	Leuco-plagiogranite, relict hypidiomorphic granular, fine grained. ~60% albite, zoned, with altered more calcic cores; ~40% quartz, interstitial, mosaic recrystallization; <1% Fe-Ti oxides and epidote. Forms dikes and pods cutting serpentinite; rodingitized at contacts with serpentine
	175588	25°40.7'	40°48.4'	Plagio-granite	~60 kg	Epidote leuco-plagiogranite, relict hypidiomorphic granular, medium-fine grained. ~65% albite, zoned, with altered more calcic cores; ~40% quartz, interstitial, mosaic recrystallization; ~4% epidote; <1% Fe-Ti oxides. Forms dikes and pods within serpentinite; continuation of 175585 zone
Ad Dafinah	175595	23°25.6'	41°56.5'	Quartz diorite	~80 kg	Hornblende quartz diorite, hypidiomorphic granular, medium grained. ~50% plagioclase, completely replaced by saussurite; ~40% hornblende, pleochroic pale to olive green; ~10% quartz, interstitial; ~1% Fe-Ti oxides. Poorly exposed outcrops in north-trending belt along Nabitah suture, cut by numerous m-thick bull-quartz veins; contains metabasalt inclusions
Tathlith	197642	19°34.9'	43°34.4'	Gabbro	~100 kg	Hornblende-bearing clinopyroxene gabbro, hypidiomorphic granular, medium grained. ~55% labradorite, locally altered to zoisite; ~40% pale green to tan, weakly pleochroic fibrous amphibole as uralitic replacement of clinopyroxene; ~5% clinopyroxene, as relict cores of uralite grains; ~1% magmatic hornblende, pleochroic tan to red-brown, interstitial; <1% titanomagnetite. Faulted against metadiabase northeast of Tathlith village, possibly younger than ophiolitic serpentinite and diabase in area
Al Amar	175610	22°24.6'	45°18.3'	Meta-gabbro	~80 kg	Hornblende-(clinopyroxene) gabbro (clinopyroxene-plagioclase mesocumulate), planar laminated, medium-fine grained. ~65% plagioclase, completely replaced by saussurite (zoisite rich); ~30% clinopyroxene, completely replaced by uralite; ~5% hornblende, pleochroic pale brown to brown, relict interstitial grains. Fault-lens of layered gabbro within serpentinite
	175613	23°24.8'	45°05.4'	Meta-gabbro	~80 kg	(Pyroxene) leuco-metagabbro or metadiorite, granoblastic, medium grained. Primary mineralogy: ~90% plagioclase, ~10% pyroxene; plagioclase mostly replaced by saussurite and albite, pyroxene completely replaced by actinolite-tremolite. Micro-veined by secondary quartz, albite, and minor potassium feldspar. Forms 10 X 20 m knocker in serpentine-matrix melange
Ar Ridaniyah	175606	24°20.7'	44°38.9'	Meta-dacite	~60 kg	Biotite granite aplite, allotriomorphic granular, fine grained. ~40% oligoclase (zoned); ~25% microcline; ~30% quartz; ~4% biotite; <1% white mica. Forms north-trending dike cutting serpentinite belt

be overlain by shallow-water pyroclastic rocks. These are interbedded first with limestones and cherts, then with argillaceous distal turbidites, and finally overlain by graywackes. This is cited as evidence of formation in a shallow basin (such as a back-arc basin) close to a volcanic landmass.

Delfour (1979a) described the Jabal al Wask complex as the lower part of an ophiolite suite associated with the base of the Hulayfah group. When Kemp (1981) revised the stratigraphy of the region, he replaced the broad Hulayfah group with two new informal ones: the older Farri group and the younger Al Ays group. According to Kemp (1981) and Kemp and others (1982a), the ultramafic and mafic-plutonic rocks of the Jabal al Wask complex intrude the upper formation of the newly defined Farri group, a volcanic unit dominated by pillow basalt and breccia. The middle and lower formations of the Farri group consist of welded and unwelded silicic tuff, volcanic breccia and conglomerate, and lesser amounts of limestone. The Farri group is unconformably overlain by the volcanosedimentary Al Ays group (fig. 6).

As at the Jabal Ess complex, the overlying volcanosedimentary section (Al Ays group) contains a local basal conglomerate (Shanti and Roobol, 1982; Kemp, 1981). This conglomerate contains some blocks of ophiolitic rocks as well as much more abundant felsic volcanic clasts. A few serpentine, gabbro, and basalt cobbles were noted by the senior author in outcrops north of Hudayrah; therefore, most Al Ays group rocks postdate emplacement of the ophiolitic complex. This is consistent with observations that the Al Ays group has undergone fewer stages of deformation than has the Farri group (Kemp, 1981).

Plagiogranite from the Jabal al Wask complex (De La Boisse and others, 1980; Kemp and others, 1980; Calvez and others, 1984) was originally dated at 882±12 Ma; this would have been the oldest zircon date reported from the oceanic part of the central and western Arabian Shield. However, reevaluation of this initial date and more recent geochronology indicate that the ophiolitic rocks are ~740--~780 Ma and the plagiogranite is 776±9 Ma (Claesson and others, 1984; Ledru and Auge, 1984). The upper formation of the Farri group (mostly ophiolitic pillow basalt) was intruded by the Jar tonolite (Kemp, 1981). This tonalite was initially dated at 796± 23 Ma (De La Boisse and others, 1980; Calvez and others, 1984), but this date has now been revised to 743±10 Ma (Ledru and Auge, 1984). Zircon dates of 737±10 Ma (or 733±8 Ma) and 742±6 Ma from rhyolite in the lower formation of the Farri group (Calvez and others, 1984; Ledru and Auge, 1984) overlap the age of the ophiolitic plutonic rocks, and therefore do not preclude an intrusive origin for the ophiolitic rocks as proposed by Kemp (1981). The mean dates of the ophiolite are older than the Farri rhyolite dates, however, and this suggests that the ophiolitic rocks are allochthonous.

Other geologic and mineralogic facts indicate an allochthonous setting for the ophiolitic rocks. Serpentine-matrix melange zones are developed at contacts between the ophiolitic rocks and the adjacent Farri and Al Ays group rocks. A thick (>1 km) zone of serpentine-matrix melange containing blocks (from a few meters to a few kilometers in size) of gabbro, basalt, and subordinate graywacke crops out with Farri and Al Ays-group metasedimentary rocks along the southern contact of the complex (fig. 3c). Another melange zone was observed near the northern part of the complex by Ledru and Auge (1984). Contact relations suggest that not only is the ophiolite allochthonous (and internally disrupted), but that the adjacent Farri-group rocks are also part of a thrust complex. Farri-group rocks are thrust either over serpentinized peridotite or serpentinite-matrix melange in the southern part of complex (fig. 3d).

Mylonite zones border some ultramafic and mafic plutonic rocks mapped as intrusive into Farri group volcanic rocks by Kemp (1981) (fig. 4b and 4c). Metamorphic aureoles are not developed at the contacts between the ultramafic-mafic plutonic rocks and the adjacent volcanic and sedimentary rocks. This lack of contact metamorphism supports the theory of an allochthonous origin, as the high liquidus temperatures that would have existed if these rocks were intrusive would have resulted in a contact aureole. As noted earlier, the peridotite rock types and mineral compositions show limited variations, which suggests mantle origins. In addition, fluid-inclusion studies indicate equilibrium pressures of approximately 7kb (equivalent to >20 km depth) for ultramafic rocks and chromitite from the ophiolite (Chevremont and Johan, 1982b).

Ledru and Auge (1984) relate the present outcrop patterns and structural relations of the various units of the ophiolitic complex to strike-slip and vertical movements along steeply dipping shear zones, and accordingly reject an obduction process for the observed tectonic interleaving of the units. However, much of the layering in the adjacent Farri and Al Ays sedimentary and volcanic rocks is also steep and, as Ledru and Auge note, the primary emplacement mechanism for the ophiolitic rocks has not yet been discovered.

A large sample of clinopyroxene gabbro was collected for U-Pb zircon geochronology analysis from a thick sill within the ophiolitic peridotite. A sample of trondhjemite was collected from a zone of blocks within serpentine-matrix melange (possibly a boudinaged and disrupted dike) in the central part of the complex (fig. 6, table 1). This trondhjemite is from the same area that yielded the plagiogranite initially dated at 882±12 Ma by De La Boisse and others (1982), but was revised to 776±9 Ma, as reported by Ledru and Auge (1984).

Nabt Complex and the Kamal Intrusion

Two mafic-ultramafic rock suites of uncertain affinity are found on the coastal plain south of the Jabal al Wask complex (fig. 6). The Nabt complex consists of several bodies of amphibolite, layered and nonlayered gabbro, diorite, pyroxenite, and dunite that intrude the high-grade metamorphic rocks of the Al Hinu formation (amphibolite, quartzite, leptite, gneiss, and migmatite). The Nabt complex and the metamorphic rocks are intruded by the Salajah tonalite (Pellaton, 1979). The age of the Al Hinu formation is unknown; the Salajah tonalite is dated at 725±12 Ma (Calvez and others, 1984).

Pellaton (1979) mapped the Kamal pluton as a zoned mafic pluton that intrudes both the Nabt complex and the Salajah tonalite (fig. 6). The Kamal intrusion has a fine-grained norite and gabbronorite margin that envelops the southern end of the intrusion. The pluton is zoned from norite at the margin to an annular main-zone of cumulus anorthosite or leucogabbro. These rocks are intruded by a late magmatic core phase composed of olivine and pigeonite gabbro (Pellaton, 1979; Chevremont and Johan, 1981).

Chevremont and Johan (1981) agree with the intrusive relations shown by Pellaton (1979), but place both the Nabt and Kamal complexes into a single "Kamal ultramafic/mafic layered complex". They consider the upper part of this complex (the Kamal pluton, as defined by Pellaton) to be bracketed by the zircon dates of the Salajah tonalite and of a granodiorite pluton that intrudes the border zone of the Kamal pluton (725±12 Ma and 611±14 respectively, Kemp and others, 1980). They also include the 611-Ma granodiorite as the upper member of their

Kamal layered complex. We retain the distinction of Pellation (1979), however, because the Kamal pluton intrudes the Salajah tonalite but the Nabt complex is intruded by the Salajah (as well as the Kamal). This indicates that there was probably a significant hiatus between the magmatic ages of the mafic rocks of the Nabt and Kamal.

Chevremont and Johan (1981) analyzed minerals from the Nabt complex and found that dunite from the central part of the Nabt complex contains Fo_{92} olivine and relatively high Cr/Cr+Al and $Mg/Mg+Fe^{+2}$ spinels. These data are similar to those found in the ophiolitic peridotites at Jabal al Wask (fig. 5). However, Chevremont and Johan also noted that spinel grains from the cumulus wehrlite and lherzolite from the southern part of the complex have low $Mg/Mg+Fe^{+2}$ and relatively high TiO_2 (averaging 0.5%). This feature distinguishes these rocks from the ophiolitic peridotite tectonites thought to represent residual oceanic mantle. The ultramafic rocks of the Nabt complex occur with the amphibolites and metasedimentary rocks of the Al Hinu formation that were tentatively correlated with the Farri group by Pellaton (1979). The association of ultramafic rocks with possible Farri-group metavolcanic and metasedimentary rocks is similar to that observed in the Jabal al Wask complex. However, the Al Hinu formation contains higher grade metamorphic rocks and more quartzose rocks than is typical of the Farri; therefore, the alternative hypothesis of Pellaton (1979) that the Al Hinu formation might represent older basement material must still be considered possible.

Samples were collected from the Nabt complex and Salajah tonalite for U-Pb zircon dating (table 1). Although the Nabt complex is not clearly ophiolitic, it may represent the mafic-ultramafic basement of an early arc complex. Accordingly, its age and relationship to both the Jabal al Wask complex and to the older Al Hinu formation are important to paleotectonic models of the northwest Arabian Shield.

THURWAH OPHIOLITE

The Thurwah ophiolite is part of the Bir Umq-Port Sudan suture of Camp (1984) and Stoeser and Camp (1985) (fig. 1). Ultramafic rocks were first recognized at Jabal Thurwah by Abo Rashid (1973). The complex was mapped at a scale of 1:100,000 by Gilboy and Skiba (1978) as part of their map of the Rabigh 30-minute quadrangle. Gilboy and Skiba subdivided the Thurwah complex into olivinite (dunite), peridotite, pyroxenite, layered and massive gabbro, and metagabbro, and considered the complex to be intrusive into the volcanic and volcaniclastic rocks of the Samran group.

The Thurwah complex is the subject of a Ph.D. dissertation by Nassief (1981), who recognized all of the major components of an ophiolite and remapped the complex at a scale of approximately 1:26,000. A summary of this study was published by Nassief and others (1984) and the regional geology has recently been compiled and synthesized by Ramsay (1983). The description that follows draws heavily on the work of Nassief (1981), Nassief and others (1984), and Ramsay (1983). Unless noted otherwise, specific data regarding the ophiolite, such as mineral chemistry, are from Nassief (1981) or Nassief and others (1984).

The Thurwah ophiolite is exposed as a series of northeast-trending ultramafic and mafic thrust plates that dip steeply (30° to 60° to the southeast). They crop out in a 6 by 12 km area within a region of late Proterozoic, poly deformed but northeast-trending metavolcanic rock belts (fig. 7). The metavolcanic (and metavolcaniclastic) rocks on either side of the ophiolite were formerly thought to be equivalent and were assigned to the informal Samran group; however, Ramsay (1983) mapped a major northeast-trending thrust (the Labunah thrust zone) southeast of the complex. He then assigned the northwestern metamorphosed basalt, chert, and marble (structurally below or interleaved with the ophiolite) to the newly defined Birak group.

The age relations between the Samran and Birak groups are unknown, but the Birak group contains low-K_2O basalts, as well as subordinate lavas and volcaniclastic rocks that range in composition from andesite to rhyolite. The basalts have immobile trace-element abundances and ratios that overlap those of the ophiolite, but they are transitional from tholeiitic to calc-alkaline affinity. These rocks are thought to have formed in an immature arc system (Nassief and others, 1984; Ramsay, 1983), an origin also proposed for several of the older (>900 Ma) volcanic assemblages of the Arabian Shield (Roobol and others, 1983; Pallister, 1986).

The Samran group contains volcanic and volcaniclastic rocks that are similar to the Birak assemblage and are also interpreted as being the products of an immature arc (Roobol and others, 1983; Ramsay, 1983). The Samran group contains 1) a bimodal suite of tholeiitic pillow basalt and dacite-rhyolite, 2) a more potassic basalt and andesitic assemblage, 3) locally abundant graywacke, and 4) minor conglomerate. Samran-group rocks are intruded by tonalite that was dated by the Rb-Sr isochron method at 769$\pm$39 Ma (Fleck, 1981).

Ramsay (1983) points out that the Labunah thrust zone extends into the Birak group where it juxtaposes marble, cherty rocks, spilitic rocks, and serpentinite. He also suggests the "possibility of a major subduction-related structure involving oceanic crust". The Labunah thrust has these features in common with the better-known Nabitah suture of the central Arabian Shield, and in this report is interpreted to be a segment of the Bir Umq-Port Sudan suture.

Serpentinized peridotite tectonites and cumulates are the dominant rock types exposed in the Thurwah ophiolite (fig. 7). The peridotite tectonite is chiefly harzburgite, but contains minor (5 percent) dunite bodies. The harzburgite is characterized by a distinct foliation produced by the elongation and flattening of orthopyroxene and chromite grains. Nassief (1981) describes progressive stages in the development of porphyroclastic-neoblastic textures in the harzburgites, and attributes the tectonite fabrics to near-solidus deformation during flow of the mantle below an ancient spreading axis. Olivine and orthopyroxene from the harzburgite have compositions of $Fo_{89.5-93.4}$ and En_{90-92}, similar to the compositions from the inferred mantle sections of Phanerozoic ophiolites (Coleman, 1977). Chromites from harzburgite and dunite tectonites have Cr/Cr+Al ratios between 0.4 and 0.7 and $Mg/Mg+Fe^{+2}$ ratios between 0.5 and 0.8 (fig. 5); these are within the "Type II" category of Dick and Bullen (1984). Cumulus peridotites contain spinels with distinctly lower $Mg/Mg+Fe^{+2}$ (fig. 5).

The cumulus ultramafic rocks of the Thurwah complex comprise two thrust sheets northwest of a central tectonite massif. The main rock types are dunite, lherzolite, and pyroxenite that form a layered sequence. This sequence has cumulus textures and igneous planar lamination, but lacks high-temperature tectonite fabrics. The cumulus peridotites and pyroxenites show a wide range in mineral composition that are consistent with their magmatic origin; the olivine

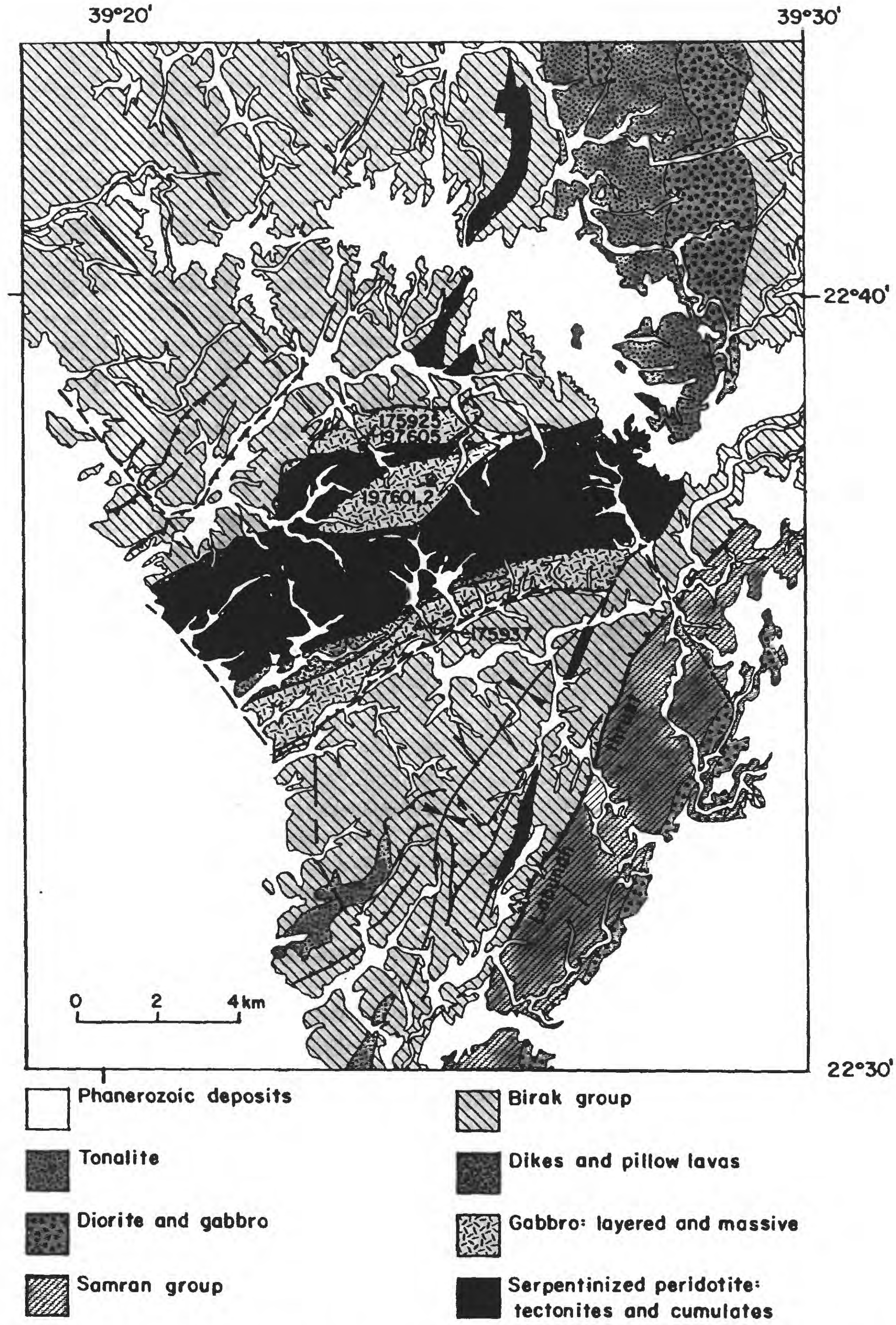


Figure 7.--Geologic map showing sample localities at the Thurwah ophiolite. Map derived from Gilboy and Skiba (1978), Nassief (1981), Nassief and others (1984), Ramsay (1983), and observations by the first author. Triangles indicate U-Pb zircon samples for this study, circles indicate Nd-Sm samples for a study in progress.

compositions overlap those of the harzburgite tectonites but range as low as Fo_{84} in some lherzolites and olivine pyroxenites. The clinopyroxene in the cumulus ultramafic rocks is calcic diopside with Al^{IV}/Si values characteristic of pyroxenes from tholeiitic rocks (Kushiro, 1960).

Layered cumulus gabbro is found in three thrust plates in the central and northern parts of the complex (fig. 7). Although faulted, the southern contact between the central layered-gabbro plate and peridotite tectonite (fig. 3e) is reminiscent of primary disruption zones along the petrologic Moho in the Oman ophiolite (Hopson and others, 1979; Pallister and Hopson, 1981). If the analogy is appropriate, it suggests an inverted pseudostratigraphy, in accord with the interpretation of Nassief (1981).

The layered gabbro grades into a 100-200-m-thick zone of massive gabbro in the northern thrust plate. A similar zone of massive gabbro crops out within a zone of imbricate thrusts along the southern boundary of the complex. The sequence of crystallization for the igneous rocks of the complex is inferred to be 1) olivine (and chromite), 2) clinopyroxene, 3) orthopyroxene, and 4) plagioclase. Gabbro pegmatite and associated leucodiorite or trondhjemite crop out as meter-long pods and smaller veins within the massive gabbro and are interpreted to be late fractionation products of the gabbroic magma by Nassief (1981).

Most of the hypabyssal and volcanic basaltic rocks at Jabal Thurwah are so deformed and recrystallized that positive identification of the protolith (intrusive or extrusive) is often impossible. Nassief (1981), however, identified a mafic-dike complex in outcrops within the fault slivers along the southern flank of the ophiolite. He also noted transitions from massive gabbro and pillow lava into sheeted dikes. Nassief also identified chilled margins and dike- against-dike chilled contacts, although they are rarely exposed. Trace-element abundances and ratios from the metabasaltic rocks of the Thurwah ophiolite suggest that the the magma originated in an island-arc ("supra-subduction zone") tectonic setting (Nassief, 1981; Nassief and others, 1984). In particular, the Thurwah samples have low titanium contents, but a wide range in zirconium and yttrium contents. These data overlap island-arc tholeiite and midocean ridge basalt fields in various discrimination diagrams. The wide range in high field-strength element abundances and the relative enrichment in large-ion lithophile elements are taken as indications of formation in a subduction-related setting. The basaltic rocks in the Birak group have similar trace-element abundances and are thought to have formed in the same subduction realm as the ophiolite.

Samples of gabbro were collected for U-Pb zircon dating from the northern and central thrust plates and from the southern imbricate zone of the ophiolite. (fig. 7). Samples from the northern and southern areas are of coarse-grained gabbro from gabbro pegmatite pods.

Bir Umq Complex

The Bir Umq mafic-ultramafic complex is an east- to northeast-trending allochthonous thrust sheet of serpentinized peridotite and associated mafic rocks. It is exposed over an area of about 15 by 60 km in the central Arabian Shield near the intersection of the Bir Umq-Port Sudan and Nabitah sutures (figs. 1 and 8). The rocks were recognized as possibly ophiolitic and the complex was named after the village of Bir Umq by Aguttes and Duhamel (1971). The complex is the subject of a M.Sc. thesis by M. H. Al-Rehaili (1980) and is described in

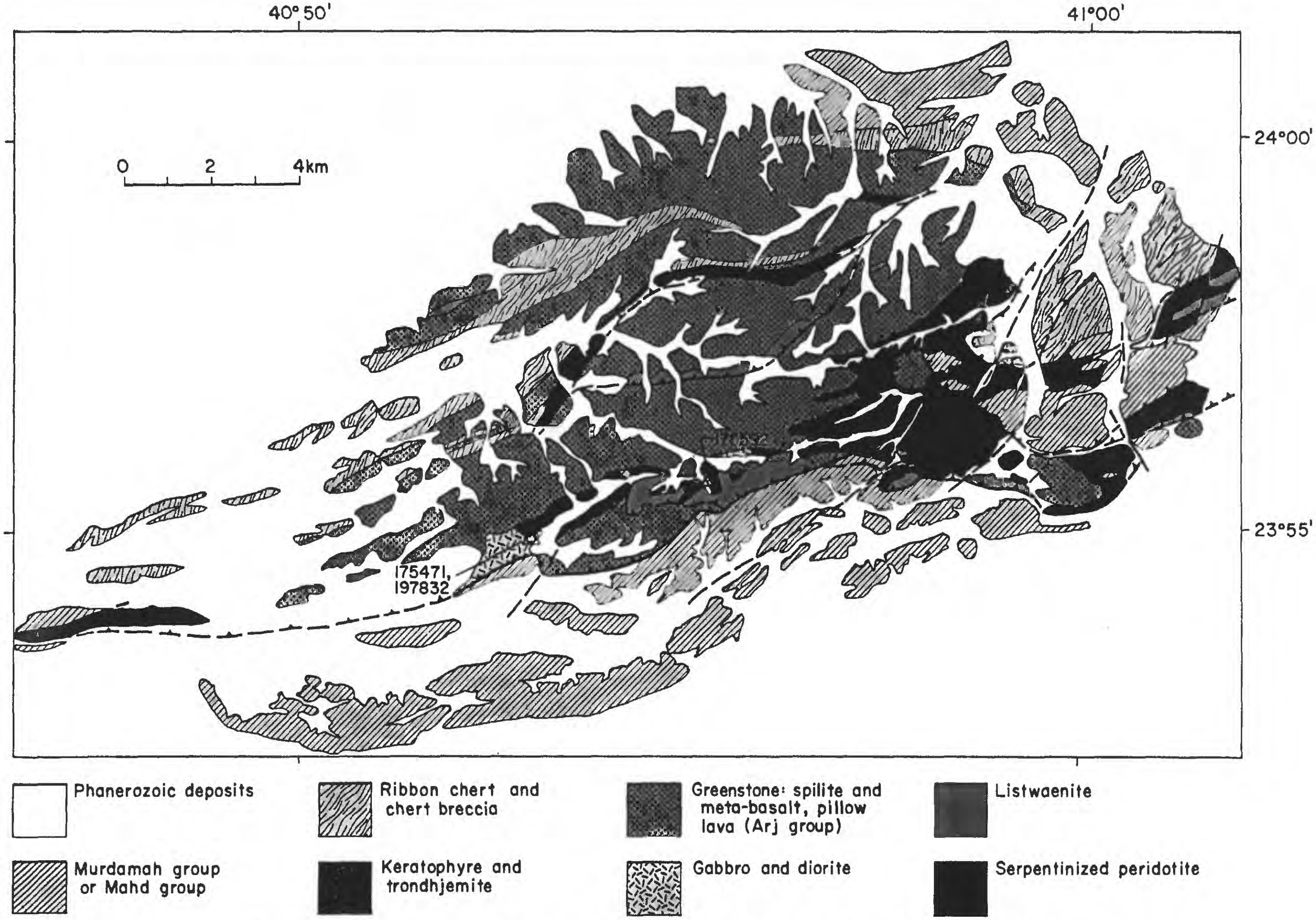


Figure 8.--Geologic map showing sample localities at the Bir Umq complex. Map simplified from Al-Rehaili and others (1978), Bowden and others (1981), Le Metour and others (1982), and Kemp and others (1982b). Triangles indicate U-Pb zircon samples collected for this study, circle indicates Nd-Sm sample for a study in progress

publications by Al-Rehaili and others (1978) and Al-Rehaili and Warden (1980). More recent work by the BRGM is summarized by Le Metour and others (1982), Aslac and others (1982), and Kemp and others (1982b). The references cited above and field excursions conducted by the senior author form the basis of the description that follows.

Al-Rehaili and Warden (1980) noted that serpentinized dunite is the most abundant ultramafic rock present in the complex. They note that the peridotite is generally highly serpentinized and is pervasively carbonated and silicified in irregular zones above a basal thrust fault. Le Metour and others (1982) describe both serpentinized dunite and harzburgite and classify most of the harzburgite as cumulus. Some of the peridotite shows evidence of high-temperature plastic deformation; however, most of the deformation is attributed by these authors to shearing during emplacement. The chrome-spinel compositions reported by Le Metour and others (1982) for harzburgite and dunite are TiO_2-poor ($\leq$0.25 percent) and show a wide range in Cr/Cr+Al at relatively high Mg/Mg+Fe^{+2} (fig. 5). These features are characteristic of the "Type II" field of Dick and Bullen (1984).

Le Metour and others (1982) also describe a cumulus layered complex consisting of several sequences of dunite, plagioclase lherzolite, plagioclase wehrlite, gabbronorite, gabbro, and hornblende gabbro. This layered sequence is exposed in a fault-disrupted area north of Bir Umq that is shown as a higher thrust plate within the complex by Le Metour (fig. 8). The layered complex is reported to have intruded basalt, chert, and younger detrital sedimentary rocks. Primary minerals in the layered complex are mostly replaced by deuteric or metamorphic minerals; however, the chemistry of relict clinopyroxene grains and the presence of minor orthopyroxene in these rocks indicate a tholeiitic parent magma. The presence of brown hornblende as an intercumulus phase in the lherzolite and wehrlite, and brown to green magmatic hornblende in the gabbro attest to the hydrous character of the parent magma.

Hornblende gabbro and diorite are poorly exposed in a wadi floor near the southwestern thrust contact of the complex. These rocks were included in the ophiolitic suite by Al-Rehaili, but were assigned to an autochthonous basaltic series below the ophiolitic nappe by Le Metour. The diorite includes small blocks of metadiabase and basalt, and is similar to the high-level leucocratic phases of Phanerozoic ophiolites that commonly have intruded overlying diabase dike complex. A small (<1 km^2) hypabyssal body of keratophyre and trondhjemite intrudes serpentinized and carbonated peridotite near the southern (basal) thrust contact of the complex and appears to post-date carbonate alteration of the peridotite. The keratophyre and trondhjemite were included within the Bir Umq thrust plate by Al-Rehaili (1980), but they are mapped as intruding the basal thrust by Le Metour.

Pillow basalt, although spilitic, is locally well exposed in the Bir Umq complex. Al-Rehaili determined upright-facing directions in several localities and suggested that massive and schistose zones in more deformed areas might represent interlayered flows and basaltic tuffs. Late, cross-cutting mafic dikes have intruded various rocks of the complex, but a sheeted dike complex has not been recognized within the complex. Beds of chert and metatuff are found in the northern part of the complex, both interlayered with basalts and as bedded deposits (figs. 8 and 3f).

The serpentinite and associated mafic plutonic and volcanic rocks were considered to be parts of a single dismembered ophiolite complex by Al-Rehaili and others (1978). In contrast, Kemp and others (1982b) noted intrusive contacts between the serpentinite and basaltic rocks and mapped the complex as a large intrusion within a predominantly basaltic volcanic formation.

Le Metour and others (1982) suggested a back-arc tectonic setting for Bir Umq but questioned the ophiolitic character of some of the rocks within the complex. They argued that the trondjhemite and keratophyre exposed west of Bir Umq are younger than the other members of the suite and post-date thrusting. They state however, that the serpentinized peridotite is ophiolitic in character because of the similarity of the chrome-spinel compositions to those from Tethyan ophiolites (fig. 5). It is important to recognize that internal intrusive contacts between different magmatic episodes or between early and late phases of a single magmatic episode are to be expected within a broadly coeval ophiolite (George, 1978; Pallister and Hopson, 1981). The key question herein is whether the gabbro and keratophyre bodies within the serpentinite are distinctly different in age, or are part of a broadly coeval (to within a few million years) magmatic episode.

The ophiolitic rocks form the basal part of the Bir Umq thrust plate (fig. 8) that was apparently thrust from north (northwest) to south (southeast) over the volcanic and sedimentary rocks of the Murdama group (Al-Rehaili and others, 1978; Al-Rehaili and Warden, 1980). The rocks to the south of the Bir Umq complex have been redefined as part of the Mahd group by Kemp and others (1982b). Discontinuous east-northeast trending bodies of the various rock types north of the main thrust contact crop out either as fault-imbrications or as windows through folds within the basal part of the Bir Umq thrust.

The Bir Umq serpentinite is correlated with the Haja complex (serpentinized peridotite and gabbro of the Jabal al Wask ophiolitic complex), and the Mahd group is correlated with the Al Ays group of the Jabal al Wask area by Kemp and others (1982b). The metabasalts associated with the Bir Umq serpentinite are assigned to the newly defined Arj group and are correlated with the upper formation of the Farri group in the Jabal al Wask area by Kemp and others (1982b).

Recent radiometric determinations (Calvez and others, 1984) provide constraints on the age of the surrounding metavolcanic and metasedimentary rocks. The foliated Dhukhr tonalite, about 80 km southwest of Bir Umq, was dated at 816$\pm$3 Ma (zircon U-Pb). Although host-rock contacts are not exposed, Kemp and others (1982b) believe that the tonalite predates the Mahd group and probably gives an upper limit for the age of the Arj group. Rhyolite of the Mahd group is dated at 772$\pm$28 Ma (Rb-Sr), and granophyre that intrudes, but may also be coeval with, parts of the Mahd group, is dated at 769$\pm$5 Ma (zircon U-Pb). These age relations indicate that the correlation of the Mahd-group rocks with the Hulayfah by early workers in the area (Aguttes and Duhamel, 1971) was more appropriate than the Mahd group's assignment to the Murdama group by Al-Rehaili and others (1978). These radiometric age relations indicate that rocks of the Mahd group, over which the ophiolitic rocks are thrust, are about 770 Ma and suggest that the oldest arc plutons in the region are about 816 Ma.

Samples of hornblende-clinopyroxene gabbro, hornblende diorite, and keratophyre were collected from the eastern, western, and central parts of the complex, respectively, for U-Pb zircon dating (table 1). The gabbro and diorite samples provide the best means of dating ophiolitic magmatism. The keratophyre was sampled to test the hypothesis that it is a younger intrusion that postdates obduction.

NABITAH SUTURE ZONE

Brown and Coleman (1972) noted that ophiolites within the Arabian Shield occupy three north-south "cryptic sutures" that are offset by northwest-trending strike-slip faults. Schmidt and others (1979) interpreted the central ophiolite-lined belt as a suture between an older, more primitive arc complex to the west and a younger, more evolved arc complex to the east. They named the suture after the serpentinite-lined Nabitah fault zone of the Jabal Ishmas quadrangle in the central Arabian Shield (Gonzalez, 1974). Reconstructions of offset by left-lateral Najd faults (fig. 1) yield total lengths for the suture of as much as 1,200 km. Schmidt and others (1979) noted that the serpentinite and talc in the southern part of the suture are intruded and disrupted by orthogneiss. They suggested that this part of the suture may have been eroded to a deeper level than that in the north, and may represent an older subduction zone that gave rise to the 800-900-Ma arc rocks of the southwestern Arabian Shield (the Asir microplate of fig. 1).

Stoeser and others (1984) extended the suture concept to include a 100- to 200-km-wide zone that contains synorogenic plutonic complexes as well as ophiolitic rocks. They called this zone the Nabitah mobile belt, but they still regarded the zone as a broad suture between two composite allochthonous microplates: 1) the pre-accreted intraoceanic Hijaz-Asir arc province to the west and, 2) to the east, the Afif microplate with its early Proterozoic continental microplate entrained within volcanic and plutonic arc rocks similar to those of the Hijaz microplate (fig. 1).

Bir Tuluhah Complex

Delfour (1967) described an ophiolitic assemblage along the northern Nabitah suture and mapped these ophiolitic rocks as part of a newly defined Urd group ophiolitic complex in his 1:250,000-scale map of the Nuqrah quadrangle (Delfour, 1977). The ophiolitic rocks are best exposed near Bir Tuluhah, the spring for which the complex is named (fig. 9). The description that follows is based principally on the work of Delfour (1977), Le Metour and others (1983), and Chevremont (1984).

Delfour (1977) considered the Bir Tuluhah complex to be a typical alpine-type ophiolitic complex exposed in an overturned, north-trending anticline. He described the complex as consisting of (from the core of the structure outwards): a 2-km-wide zone of alternating serpentinized dunite and harzburgite, a transition zone with alternating serpentinized peridotite, anorthosite, and chromitite, a 200-m-wide zone of alternating serpentinite and metagabbro, a zone of listwänite, and a 3-km-wide zone of interlayered pillow and amygdaloidal metabasalt and meta-andesite, mafic tuff, and jasper. According to Delfour (1977), the ophiolitic rocks are faulted against steeply dipping andesitic and rhyolitic rocks of the Hulayfah group on the east; however, on the west, they are apparently unconformably overlain by a basal conglomerate of the Hulayfah group.

Le Metour and others (1983) remapped the area near the Bir Tuluhah complex in more detail (fig. 9) and shows the ultramafic rocks as a steeply dipping, fault-bounded slab within a metavolcanic and metasedimentary sequence. This sequence consists of a lower basaltic unit (locally pillowed) overlain on the west by interlayered andesite lava, breccia, tuff, conglomerate, graywacke, and rhyodacite tuff dated at about 740 Ma. They mapped conglomerate interbeds

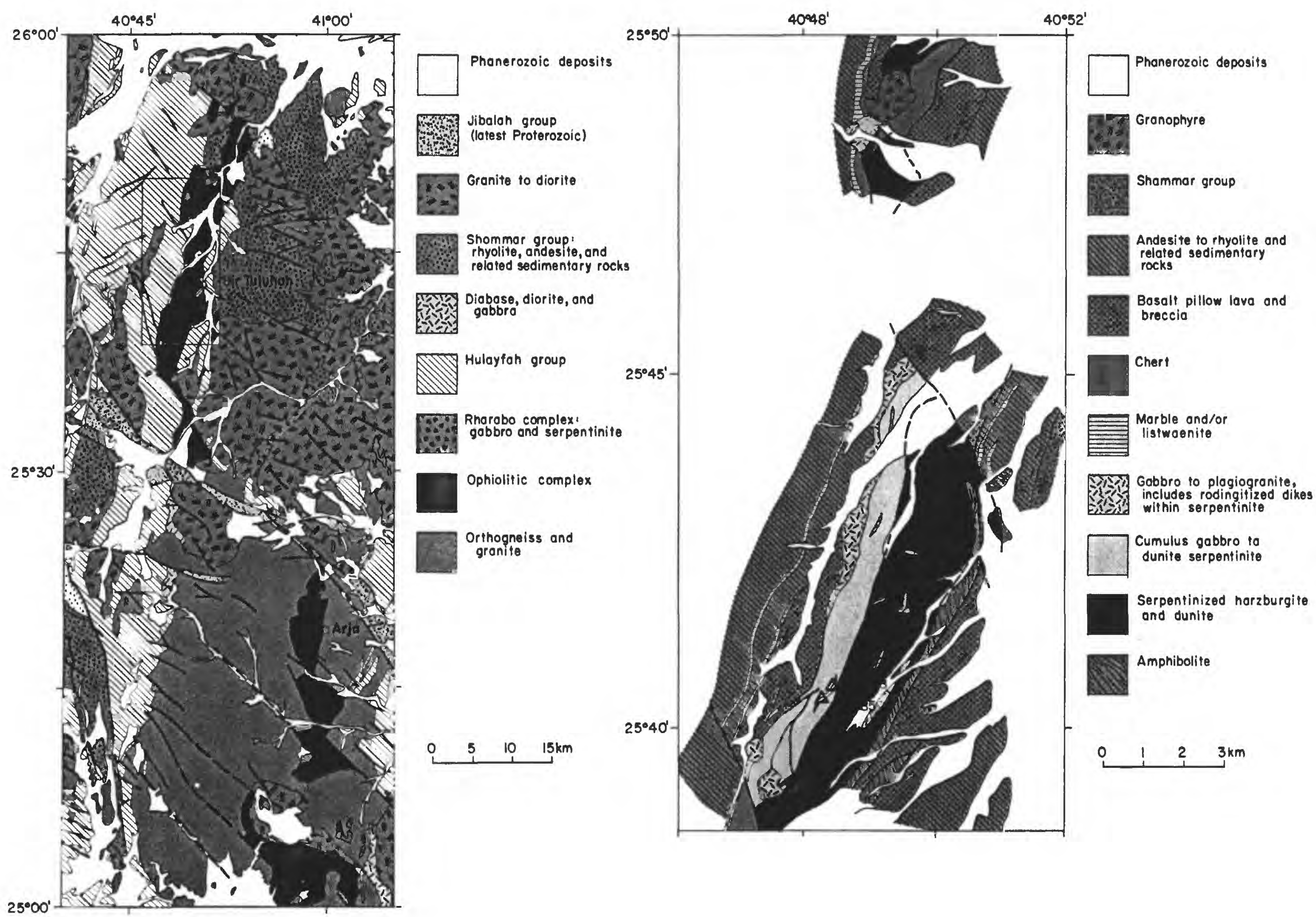


Figure 9.--Geologic map showing sample localities at the Bir Tuluhah complex. Map on left simplified from Delfour (1977). Inset rectangle indicates area of map on right, which is adapted from Le Metour and others (1983). Triangles indicate U-Pb samples collected for this study.

within the Hulayfah andesitic section and pointed out that the pillow basalts are part of a conformable volcanosedimentary sequence, not necessarily part of an older mafic (ophiolitic) assemblage.

A garnet-clinopyroxene amphibolite unit bordering the harzburgite and dunite was mapped by Le Metour and others (1983) (fig. 9). On the basis of mineral chemistry, they argue that the rock formed at upper amphibolite facies, and, by analogy to Barrovian metamorphic zones as defined for pelitic rocks, they suggest a temperature of $\geq 650^{\circ}C$ and at a pressure of $\geq$ 6 kb. They accordingly decided that the Bir Tuluhah complex represents a fragment of mantle and basal crustal rocks emplaced diapirically in an "epicontinental" setting. It is not possible to apply garnet-clinopyroxene or amphibole-clinopyroxene geobarometry or thermometry to the mineral chemistry because full probe analyses are not given; however, $^{IV}Al/^{VI}Al$ values in amphiboles as cited by Le Metour and others (1983) are mostly between 3 and 4. These ratios are within the low pressure field ($^{IV}Al/^{VI}Al > 2$) of Fleet and Barnett (1978) and represent equilibration at less than 5 kb (Raase, 1974).

Le Metour and others (1983) mapped a cumulus layered suite that ranges from dunite, wehrlite, lherzolite, websterite, and olivine clinopyroxenite in the east to gabbronorite and gabbro in the west (fig. 9). This cumulus suite is in fault contact with harzburgite and dunite tectonite on the east and is apparently intruded by noncumulus gabbro and quartz diorite on the west. Chromites from the harzburgite and dunite tectonites have a wide range in Cr/Cr+Al and $Mg/Mg+Fe^{+2}$ values, features typical of "Type II" Alpine-type peridotite as shown in figure 5.

The observed progression from east to west (amphibolite-peridotite tectonite-cumulus peridotite-cumulus gabbro-noncumulus gabbro) is identical in sequence to the metamorphic and plutonic stratigraphic progression observed in numerous Phanerozoic ophiolites. Although the relation of the igneous rocks to the pillow basalts to the west (and east) is not clear, and there is no definitive evidence for origin of the amphibolite, the field evidence strongly suggests that the ultramafic and mafic suite is part of an ophiolite complex. These rocks therefore probably represent part of the base of an ophiolite nappe that was obducted during closure of an oceanic basin. The ophiolitic nappe was apparently rotated to a steep attitude and locally overturned during formation of the Nabitah suture.

Small deformed and rodingitized gabbro and plagiogranite dikes intrude the ultramafic rocks. Similar dikes were mapped within the basaltic rocks to the west by Le Metour and others (1983) (fig. 9). Zircon samples were collected from a plagiogranite dike within serpentinized harzburgite tectonite (fig. 4d) about 5 km southwest of Bir Tuluhah. The dike has rodingite margins, indicating intrusion prior to latest serpentinization; therefore, it should provide a minimum age for the ultramafic rocks. Also, because of its typical plagiogranite composition with only 0.15 percent K_2O (Pallister, unpublished data) and its geologic setting, it was probably formed during a late phase of ophiolite magmatism.

Ad Dafinah Belt

The Bir Tuluhah complex is offset about 20 km to the southeast by a strand of the Najd fault system and continues in a southerly direction near the village of Bir Arja (fig. 9). South of lat 25° N. and through the central part of the Arabian Shield, the Nabitah suture traverses an area of low relief and poor exposure. In this region, the suture is expressed as a discontinuous belt of mafic and ultramafic regolith in a series of broad south-trending valleys that are punctuated by occasional elongate hills of listwänite and inselbergs of gabbro or postorogenic granite. Parallel exposures of ultramafic and mafic rocks occur 35 to 60 km east of the main Nabitah trend over part of this segment of the central Arabian Shield. These eastern exposures are shown on the 1:1,000,000-scale compilation of the geology of the Arabian Shield by Johnson (1983) and Johnson and others (1986), and may represent a younger strand of the Nabitah suture zone.

About 15 km north-northwest of the village of Ad Dafinah, gabbro and diorite are in fault contact with serpentinized peridotite (fig. 10). An ophiolitic association cannot be established in this area, but its location along the Nabitah suture zone is suggestive of an ophiolitic source. A sample of granular quartz diorite was collected for U-Pb zircon dating from an outcrop of quartz diorite and gabbro about 0.8 km southeast of the fault contact with the serpentinite. Kemp and others (1982b) consider the diorite and gabbro to be part of the Mughar complex, the oldest map unit in the region. This unit is composed of orthogneiss, migmatite, amphibolite and schist, in addition to variably metamorphosed gabbro and diorite. Letalenet (1979) noted that the stratigraphic positions of individual small serpentinite belts in the region are uncertain, and suggested that there may be two ages of mafic-ultramafic assemblages.

The serpentinite in the area is composed of antigorite (Letalenet, 1979). The Mughar complex locally contains sillimanite-bearing gneiss and schist, and migmatite with granitic segregations (Kemp and others, 1982b). These features indicate higher grade metamorphism, which would be consistent with exposure of deeper crustal levels to the south along the Nabitah suture zone.

Tathlith and Hamdah Complexes

Between latitudes 22°30' and 21° N., the Nabitah suture is apparently offset 220 km to the southeast along the southern strand of the Najd strike-slip fault system (fig. 1). Small, northwest-southeast-trending elongate outcrops of serpentinite or listwänite crop out sporadically along the fault trace. These probably represent disrupted ophiolitic serpentinite from the suture that has been remobilized in the Najd fault zone. Schmidt (1981) describes chromite-fuchsite silicic dolomite (listwänite) associated with the extension of the southern Najd faults near lat 20°45' N. Between latitiudes 21° and 19° N. the suture is exposed as a north-south-trending belt of steeply dipping faults, commonly lined with losenges of serpentinite, talc-actinolite schist, and listwänite (fig. 11a). These bodies of variably altered ultramafic rocks range from 1 m^2 to >5 km^2 fault slivers such as at Jabal Nabitah (lat 20°50' N.) in the northeastern Jabal Ismas quadrangle (Gonzalez, 1974). Larger areas of ultramafic and mafic rocks crop out east of the main fault belt at Tathlith and near Hamdah (figs. 11b and 11c).

The ultramafic and mafic rocks at Hamdah and Tathlith were differentiated in 1:100,000-scale regional mapping by Overstreet (1978), and part of the ultramafic complex south of Hamdah was mapped at a scale of 1:25,000 by Worl (1981). Asbestos occurrences in the Hamdah area were investigated by Rooney and Al-Koulak (1978), and numerous ancient gold mines associated with the Nabitah suture and the Hamdah mafic-ultramafic complex were investigated by Worl and Elsass (1980) and Helaby and Worl (1980). Gold was found in quartz veins within (or close to) greenstone sequences and as disseminations along an altered and veined contact between serpentinite and hornblende schist.

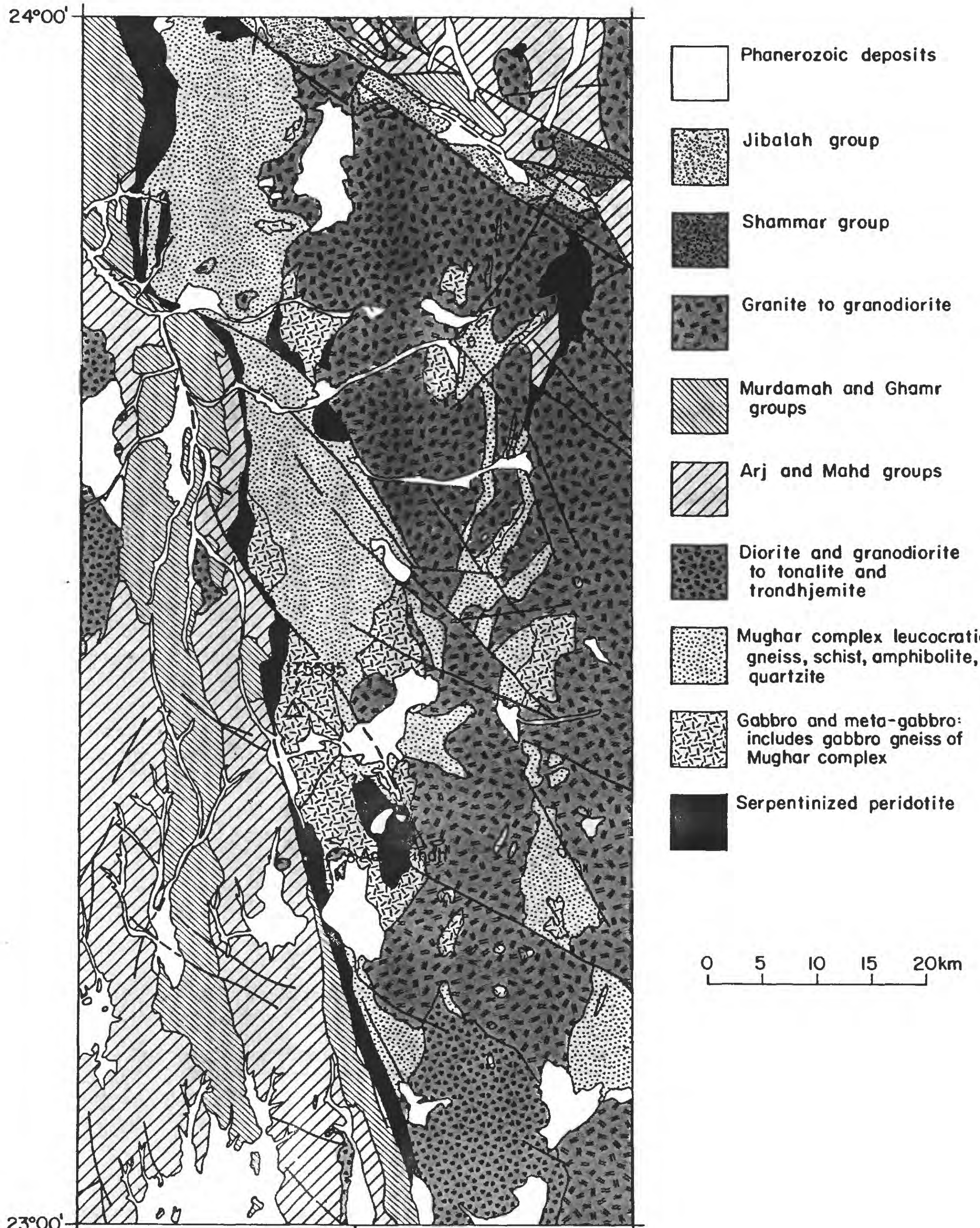


Figure 10.--Geologic map showing sample locality from the Ad Dafinah ultramafic-mafic belt. Triangle indicates U-Pb sample. Map simplified from Letalenet (1979) and Kemp and others (1982b).

A

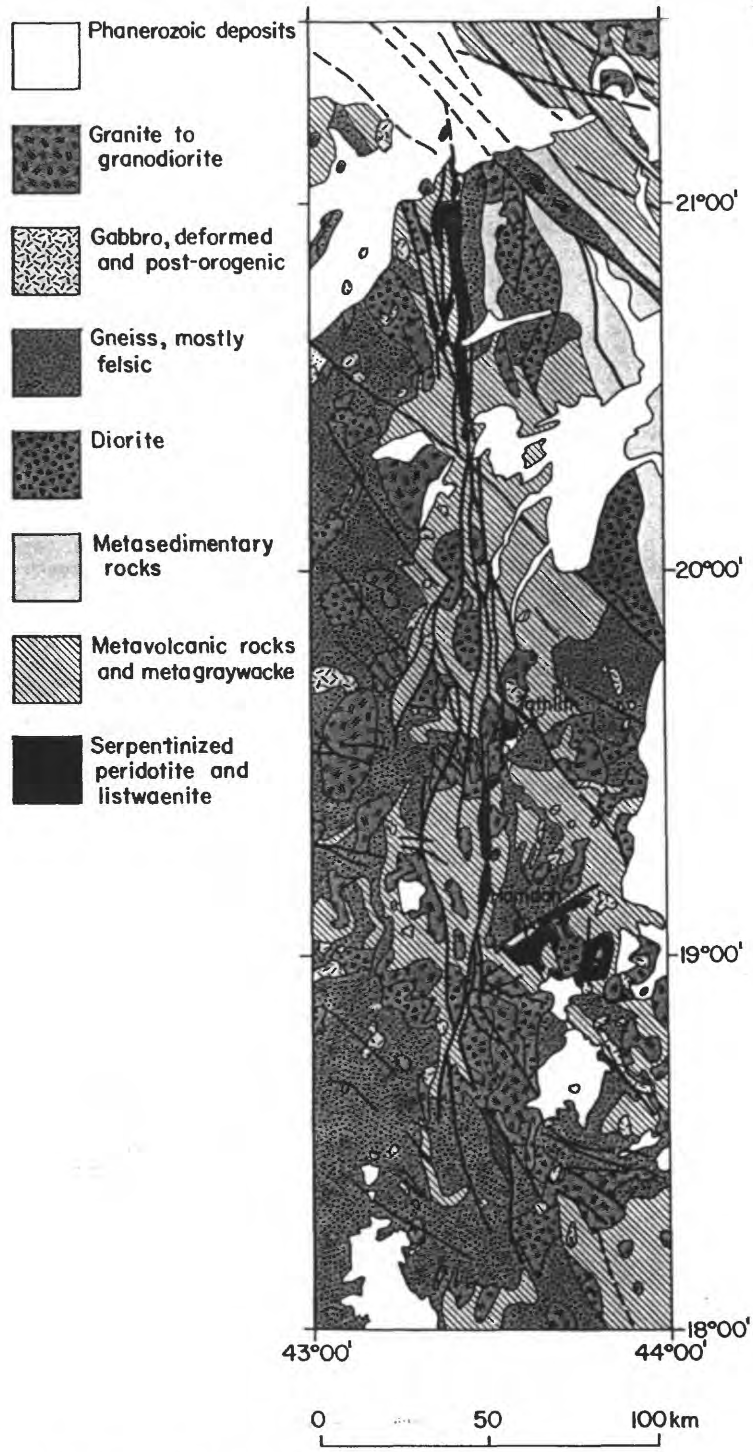
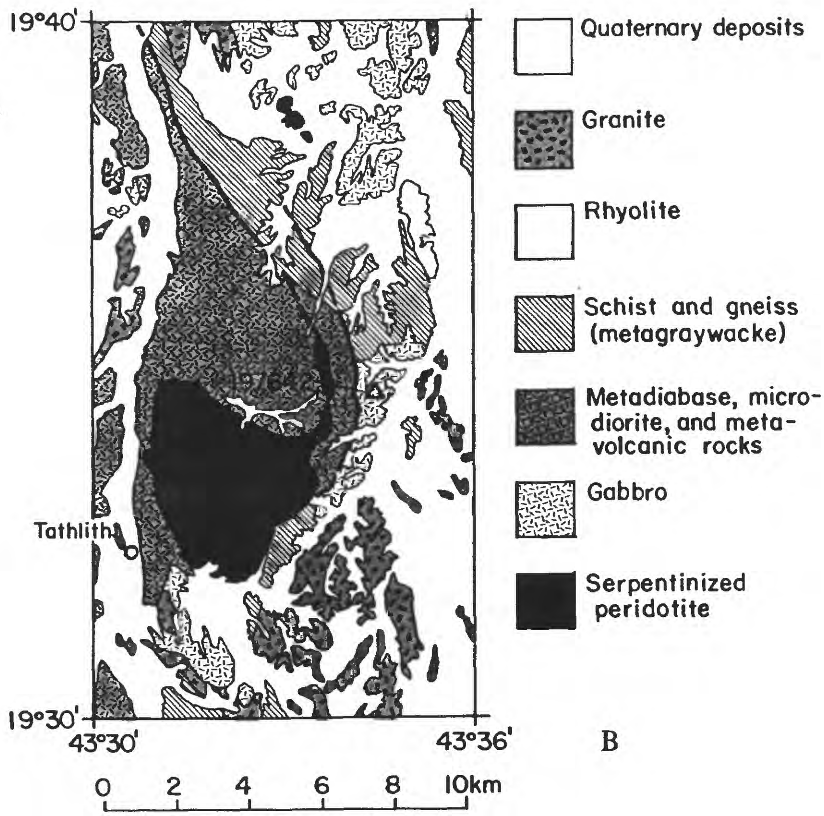
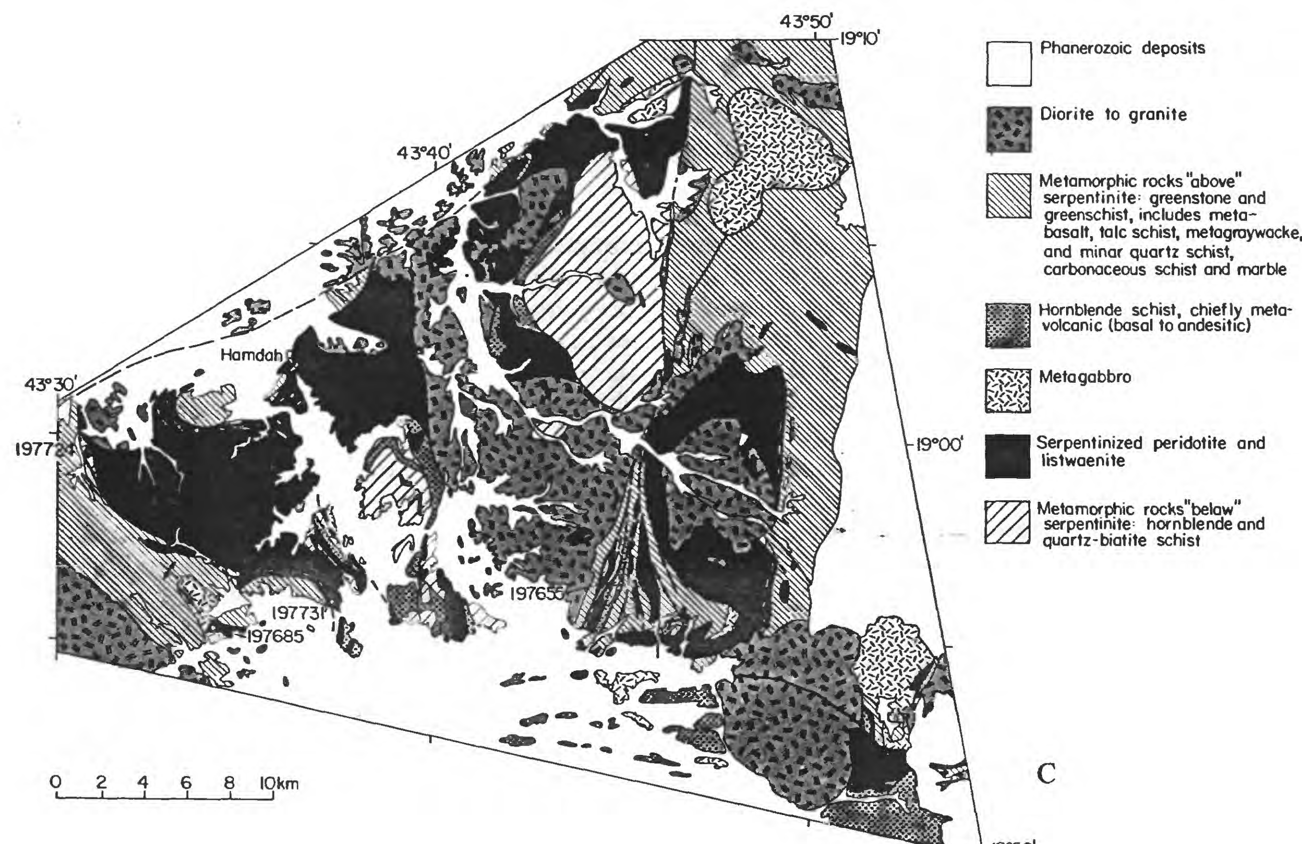


Figure 11.--Geologic maps showing sample localities at the Tathlith and Hamdah complexes. Triangles indicate U-Pb zircon samples, circles indicate Sm-Nd samples for a study in progress. Index map (a) modified from Worl (1979). Map of the Tathlith area (b) modified after Overstreet (1978) and map of the Hamdah area (c) modified after Worl and Elsass (1980) and Worl (1981) on the basis of field work by the first author.



19°40'
19°30'
43°30'
43°36'
Tathlith
0 2 4 6 8 10km
Quaternary deposits
Granite
Rhyolite
Schist and gneiss (metagraywacke)
Metadiabase, micro-diorite, and meta-volcanic rocks
Gabbro
Serpentinized peridotite

B



43°50'
19°10'
43°40'
43°30'
Hamdah
19°00'
18°50'
197731
197685
0 2 4 6 8 10km
Phanerozoic deposits
Diorite to granite
Metamorphic rocks "above" serpentinite: greenstone and greenschist, includes meta-basalt, talc schist, metagraywacke, and minor quartz schist, carbonaceous schist and marble
Hornblende schist, chiefly meta-volcanic (basal to andesitic)
Metagabbro
Serpentinized peridotite and listwaenite
Metamorphic rocks "below" serpentinite: hornblende and quartz-biotite schist

C

A zircon sample was collected from an outcrop belt of hornblende-clinopyroxene gabbro faulted against metamorphosed basaltic rocks and serpentinite northeast of the village of Tathlith (fig. 11b). As the gabbro is anomalously fresh compared to metagabbro associated with the Hamdah complex, it may not have undergone the same greenschist- and amphibolite-facies metamorphism that affected the metabasaltic rocks. To the north, the gabbro is mapped as intrusive into metagraywacke (Overstreet, 1978). Similar gabbro southeast of the village of Tathlith has undeformed cumulus layering and is clearly younger than the ophiolitic rocks.

Worl and Elsass (1980) recognized both metamorphic (tectonite) and cumulus peridotite in the Hamdah area and suggested that the serpentinite was derived from harzburgite-type alpine peridotite, possibly the ultramafic part of an ophiolite. They described the Hamdah serpentinite as consisting of flat, sheet-like bodies that extend as much as 40 km east of the Nabitah fault zone and that overlie hornblende schist, quartz-biotite schist, and carbonaceous schist, possibly in a thrust relationship. The serpentinite is overlain by a structurally complex unit containing foliated gabbro, diorite, metabasalt, diabase, meta-andesite, and metagraywacke. Amygdules and pillow structures were observed locally.

Pods, lenses, and dike-like bodies of serpentinite occur within the overlying rocks. Blocks of serpentinite are also enclosed in the underlying rocks. Worl and Elsass (1980) suggest that fragments of layered gabbro, pillow lava, and sheeted dikes might be remnants of an ophiolite that was dismembered and tectonically mixed with the overlying metasedimentary and metavolcanic rocks. They also suggest that the thin (<200 m) hornblende schist unit that generally underlies the serpentinite sheets and that grades downward into quartz-biotite and chlorite schist may represent a metamorphic sole of the type commonly developed at the bases of Phanerozoic ophiolites. Greenwood (1981) considers the all of the metavolcanic and metasedimentary rocks in the Hamdah region that contain small blocks to kilometer-sized sheets of ultramafic and mafic rocks represent an accretionary melange formed by subduction during Hulayfah (circa 750 Ma) arc magmatism.

Al-Rehaili and Warden (1980) were impressed by the degree of deformation and the lack of a coherent ophiolite stratigraphy within the Hamdah complex. They suggested that first the complex was emplaced by serpentinite diapirism and flowage into and over a variety of layered metamorphic rocks, then it was intruded by plutons ranging in composition from gabbro to granite. They interpreted trains of chromite and magnetite grains within the serpentinite as indicating intricate rheid flow patterns. We also observed trains of ovoid spinel grains in the serpentinite and relict porphyroclastic textures in serpentinized harzburgite and dunite (figs. 3g, 4e, 4f). In addition, interlayered and isoclinally folded harzburgite and dunite tectonites are preserved locally in an area southwest of Hamdah (figs. 3h, 3i, 3j, and 11c). Structures in this area are remarkably similar to those produced by high-temperature (mantle) deformation in peridotite from the Oman ophiolite (Boudier and Coleman, 1981) and indicate plastic deformation that predates serpentinization and emplacement. We suggest that relicts of mantle tectonite more than 1 km in diameter exist locally within the Hamdah complex, but that most of the rocks have undergone relatively low-temperature deformation, probably associated with emplacement and serpentine diapirism.

As in the Jabal al Wask complex, large areas of serpentinite-matrix melange are present and contain blocks of metagabbro that range from a few meters to several kilometers in length. Primary contact relations are rarely exposed, and metagabbro bodies typically have sheared contacts with adjacent serpentinite rather than intrusive contacts. Samples were collected from three such bodies in the Hamdah complex for U-Pb zircon dating (fig. 11c).

EASTERN ARABIAN SHIELD

Ophiolitic rocks in the eastern Arabian Shield occur mostly in two northwest-trending belts that appear to merge to the south, possibly due to the presence of a broad synclinorium structure (fig. 1; fig. 12a). Zircon sample localities from the ophiolitic belts are shown in figures 12a-d. The two belts of ophiolitic rocks separate the Afif microplate to the west from the Ar Rayn microplate to the east (Stoeser and Camp, 1985). The southern part of the Afif microplate contains a continental terrane composed of early to middle Proterozoic (1,600-1,900 Ma) and possibly Archean high-grade metamorphic rocks (Stacey and Hedge, 1984; Stacey and Agar, 1985). The Ar Rayn microplate contains plutons with inherited (approximately 2,000 Ma) zircons thought to have been derived either from sediments in the Abt formation that lies between the two ophiolitic belts or from an older plutonic substrate (Calvez and others, 1985a; 1985b).

The Abt formation consists of a monotonous sequence of thinly bedded, isoclinally folded and bedding-plane-faulted sericite-chlorite albite schist and quartz schist exposed between the two ophiolitic belts. The Abt schist represents a thick accumulation (now imbricated and repeated by folding) of shale, siltstone, and graywacke. Much was deposited as thinly bedded turbidites and derived from a low-potassium source (Delfour and others, 1982; Stacey and others, 1984). The Abt turbidites were derived from a source with an apparent mean age of 710 Ma (Stacey and others, 1984). However, a granite sill within the Abt formation along the northern Al Amar suture contains highly discordant zircons that indicate a much older, possibly early Proterozoic, source. The $^{207}Pb/^{206}Pb$ ages range from 1,409 to 1,898 Ma (Calvez and others, 1985b).

The origin of the Abt formation and the paleotectonic setting of the eastern Arabian Shield have been the subjects of several investigations. In each case, a subduction model was proposed (fig. 13); however the polarity of subduction and the presence and location of older continental crust have varied (Thekair, 1976; Al Shanti and Mitchell, 1976; Nawab, 1979; Schmidt and others, 1979; Al-Shanti and Gass, 1983; Camp and others, 1984; Stacey and others, 1984). There is general agreement among the various investigators that the Abt formation is an accretionary complex that formed in an arc basin, and that linear belts of ophiolitic rocks define the Urd and Al Amar-Idsas sutures. A more detailed account of the various models is presented in the discussion.

Urd Suture

The Urd suture (as defined herein) is a northwest-trending belt of serpentinized peridotite and gabbro. It forms the westernmost of the two ophiolitic belts of the eastern Arabian Shield and is best exposed near the village of Halaban at about lat 23°30' N. (fig. 1). The ultramafic and mafic rocks near Halaban were mapped as part of the ophiolitic complex of the Urd group by Delfour (1979b). Much of the suture consists of a 1-10-km-wide belt containing elongated losenges of metagabbro associated with lenses of serpentinized peridotite, talc-anthophyllite schist, and listwänite (fig. 12b). Spinel lineation was noted in peridotite replaced by anthophyllite southwest of Halaban; however, as

A

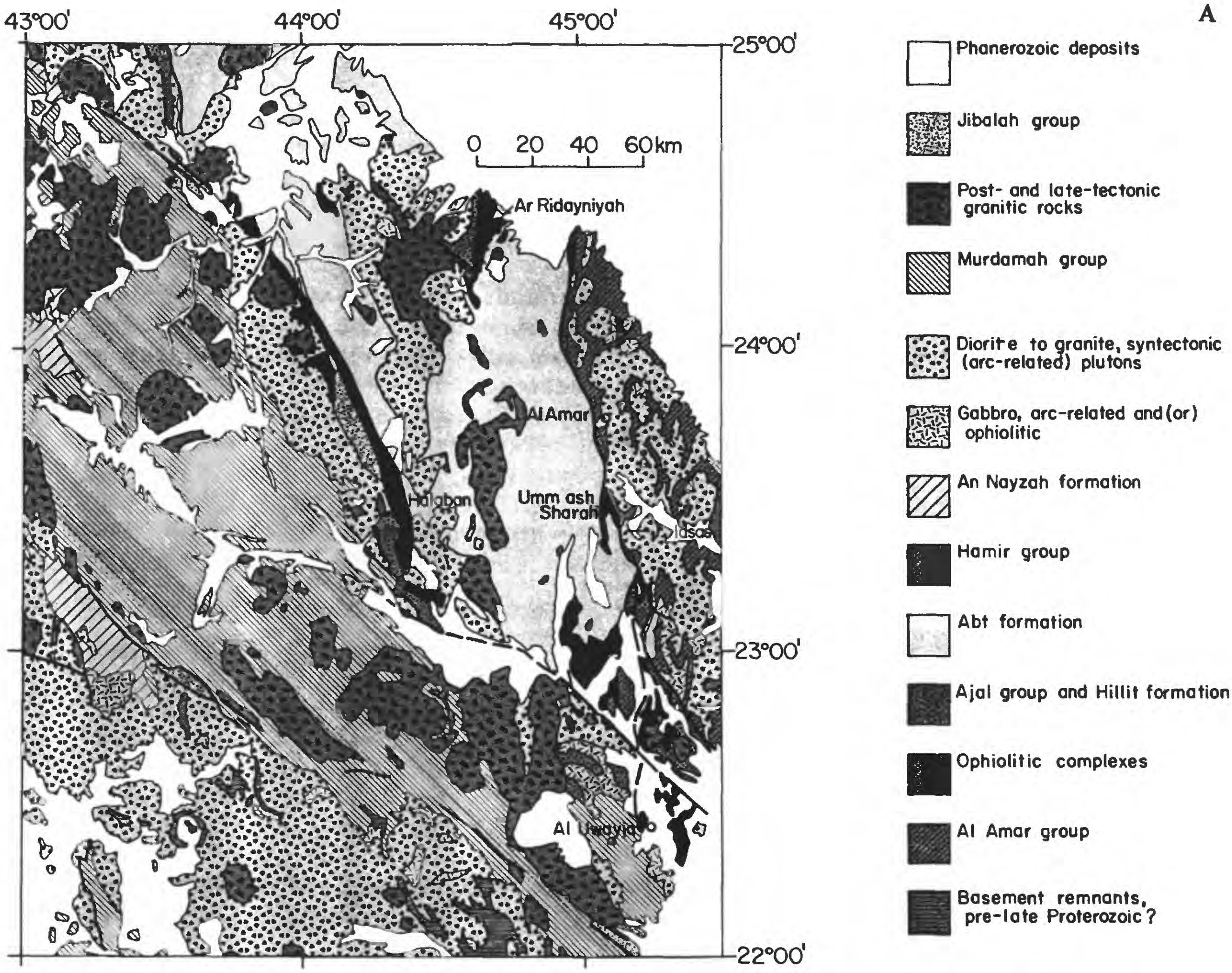
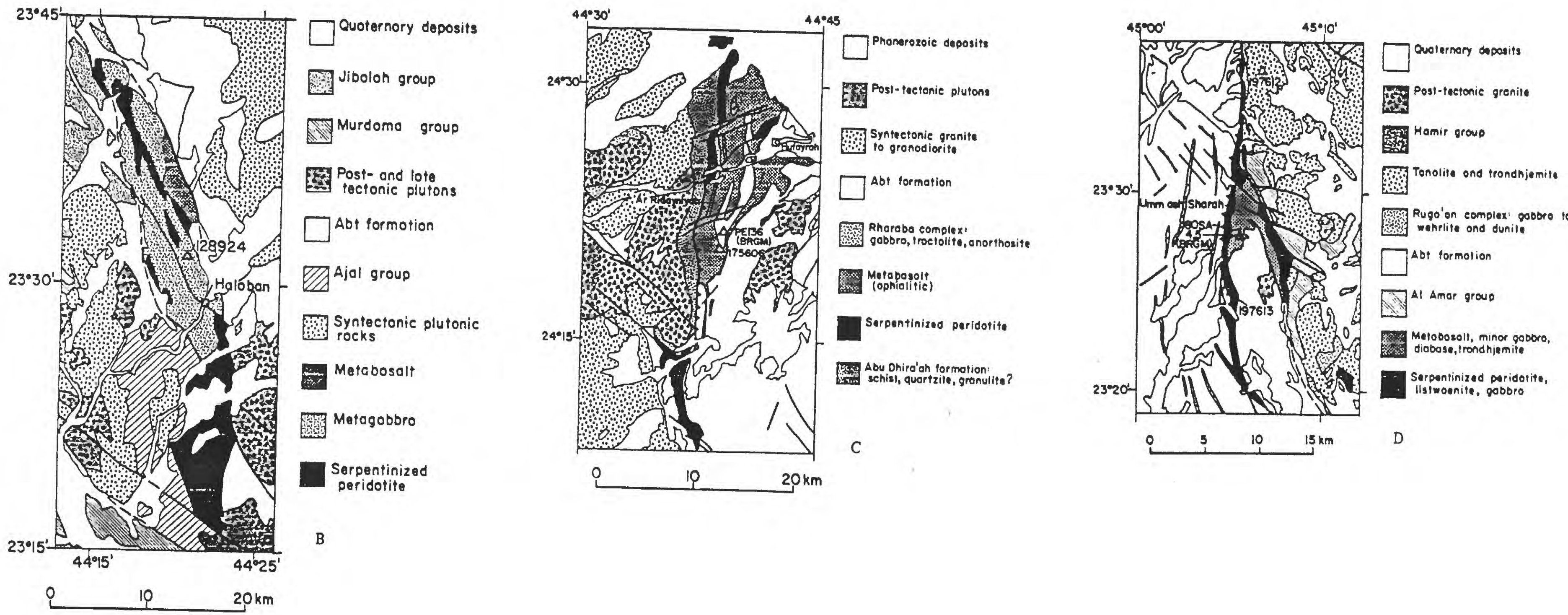


Figure 12.--Geologic map of the eastern Arabian Shield (a) adapted from Johnson and others (1986) showing the Halaban and Al Amar-Idsas ophiolite-lined sutures. Localities of U-Pb zircon samples (triangles) are shown in maps of the Halaban (b), Ar Ridayniyah (c), and Umm ash Sharah (d) areas. Maps derived from Delfour (1979b), Delfour and others (1982), and Vaslet and others (1983).


23°45'
23°30'
23°15'
44°15'
44°25'
128924
Haloban
0 10 20 km
Quaternary deposits
Jibalah group
Murdama group
Post- and late tectonic plutons
Abt formation
Ajal group
Syntectonic plutonic rocks
Metabasalt
Metagabbro
Serpentinized peridotite
B
44°30'
44°45
24°30'
24°15'
Ar Ridaynah
PE136 (BRGM)
175606
0 10 20 km
Phanerozoic deposits
Post-tectonic plutons
Syntectonic granite to granodiorite
Abt formation
Rharaba complex: gabbro, troctolite, anorthosite
Metabasalt (ophiolitic)
Serpentinized peridotite
Abu Dhira'ah formation: schist, quartzite, granulite?
C
45°00'
45°10'
23°30'
23°20'
197612
Umm ash Sharah
80SA-4-5 (BRGM)
197613
0 5 10 15 km
Quaternary deposits
Post-tectonic granite
Hamir group
Tonalite and trondhjemite
Ruga'an complex: gabbro to wehrlite and dunite
Abt formation
Al Amar group
Metabasalt, minor gabbro, diabase, trondhjemite
Serpentinized peridotite, listwaenite, gabbro
D

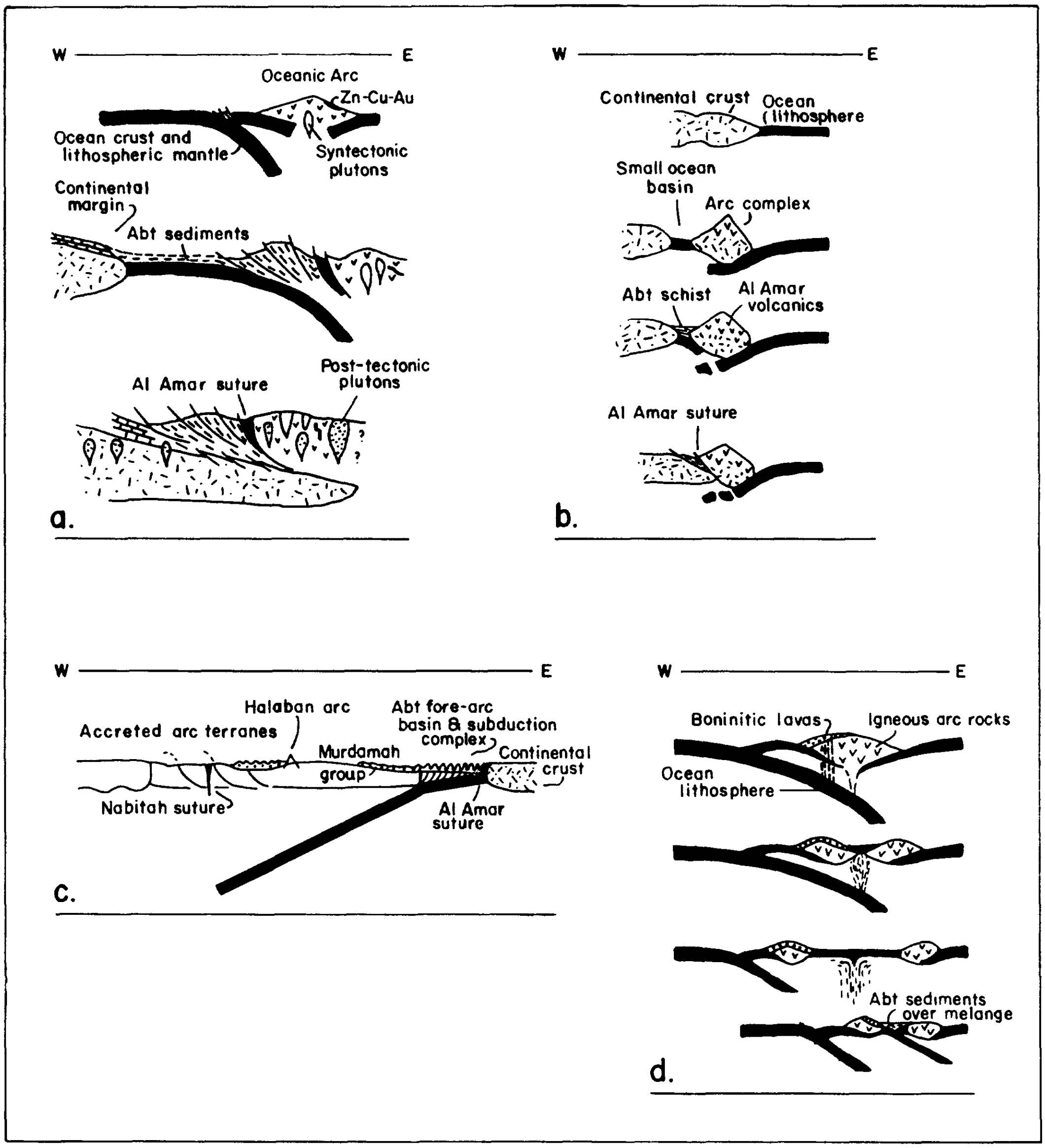


Figure 13.--Comparison of plate tectonic models for the eastern Arabian Shield: (a) Al-Shanti and Mitchell (1976), (b) Nawab (1979), (c) Schmidt and others (1979), (d) Al-Shanti and Gass (1983).

the spinel (magnetite) is anomalously abundant (1-2 percent) and large (1-2 mm), it was probably produced by relatively low-temperature metamorphic segregation of magnetite into large crystals around chromite cores. The lineation was probably produced by serpentine diapirism. Ultramafic rocks are more abundant in the southern part of the belt and tend to be segregated along the western margin of the suture. The eastern margin is composed of interlayered metagabbro, Abt schist, and small bands of metavolcanic rocks with lenses of serpentinite (Delfour, 1979b).

Zircon from a gabbro sample from near the village of Halaban was dated by Stacey and others (1984). Additional zircon samples were not collected during this study.

Al Amar-Idsas Suture

The Al Amar-Idsas suture, or Idsas suture of Schmidt and others (1979), is poorly exposed in a north-south trending valley between the Abt schist on the west and the Al Amar group to the east. The Al Amar group contains greenschist- to amphibolite-facies, andesitic- to sodic-rhyolitic volcanic, hypabyssal, and related volcaniclastic and sedimentary rocks (Vaslet and others, 1983; fig. 12a). Trondhjemite and tonalite plutons intrude the Al Amar group, and possibly older sills of similar composition intrude the Abt schist. South of the village of Al Amar and the ancient Al Amar zinc-gold mine, ophiolitic rocks occur as lenses of listwänite along the Al Amar-Idsas fault zone (Thekair, 1976).

In the Umm ash Sharah area (fig. 12c), the ophiolitic rocks are more widely exposed and form two belts separated by Abt schist in a structure interpreted to be an overturned synform (Vaslet and others, 1983). Layered (but deformed) websterite intercalated with serpentinized dunite and harzburgite, basaltic pillow lavas containing lenses of chert and pyrite or gossan, and minor keratophyre and sodic rhyolite are also recognized in this area by Vaslet and others. Chromites from the serpentinized peridotites of the Al Amar suture show a wide range in Cr/Cr+Al (fig. 5); the values are similar to those of Tethyan ophiolites (Le Metour and others, 1982) and to those within the "Type II" field of Dick and Bullen (1984).

Uranium-lead zircon samples were collected from fault lenses of metagabbro within serpentine or serpentine-matrix melange in the Umm ash Sharah area and from the southernmost part of the ophiolite belt near Al Uwayja (fig. 12a). A sample of hornblende tonalite from the batholith northeast of Umm ash Sharah was collected to help define the age of the Ar Rayn microplate. In addition, samples were collected from an aplite dike that intruded the northern end of the Al Amar-Idsas suture, southeast of Jabal Ar Ridaniyah (fig. 12c).

ANALYTICAL METHODS

Chemistry and mass spectrometry analyses of lead and uranium from bulk zircon fractions follow the procedures of Krogh (1973) with minor modifications. Laboratory blank levels for lead in zircons were monitored within the range 0.3 to 1.0 nanograms. Corrections for common lead inherent in the zircons were made by using either the composition of lead from feldspar in the same samples, or by a modified form of the Stacey and Kramers (1975) model where μ = 9.22 since 3.7 Ga.

Single zircon and very small zircon fractions were analyzed using a multisample, HF-vapor dissolution chamber (Krogh, 1978). Individual zircon grains were hand-picked from very small populations (30-100 grains) of 60- to 200-mesh size. The grains were weighed and transferred to miniature PFA teflon dissolution vials, spiked with ^{205}Pb-^{233}U-^{230}Th, and dissolved with HF + HNO_3 at 210° C in a large (6 cm inner diameter) TFE teflon Parr-style bomb designed to accomodate 7 vials. The samples were then loaded directly to single rhenium filaments using the silica-gel method. Lead blanks were measured between 40 and 180 picograms and averaged 70 picograms. Uranium and thorium blanks were 5 and 15 picograms respectively.

Feldspar concentrates were washed with 7N HNO_3 and 6N HCl and then leached in warm 5 percent HF, a procedure adopted by Ludwig and Silver (1977) in order to minimize any *in situ* radiogenic lead component. This was followed by dissolution at 160°C using a solution of HF, HNO_3 and $HClO_4$. Lead was extracted using a bromide-form anion-exchange resin column.

Isotope ratios were measured with a 30 cm radius, 90° sector, automated mass spectrometer. Uranium analyses involved a triple filament assembly; lead was run with silica-gel on a single rhenium filament. Corrections for lead fractionation were determined from analysis of the standard NBS SRM-981 at about +0.12 percent per mass unit. For feldspar lead, precision of isotope ratios with respect to ^{204}Pb is $\pm$0.10 percent or better (95 percent confidence limits). Uncertainties in Pb/U ratios are approximately $\pm$1.2 percent.

All isotopic ratios for single and very small zircon fractions were measured during the same run using an NBS-type, two-stage mass spectrometer equipped with a pulse-count multiplier. Corrections for isobaric interferences were made when necessary. Blank corrections were made using (204):(206):(207):(208) = (1.00):(19.01):(15.65):(38.48). Values for the initial lead were chosen as described above for the best estimated age of the sample. Uncertainties on the Pb/U ratios range from 0.65 percent and 1.6 percent, resulting in a 0.2 percent to 0.5 percent uncertainty in $^{207}Pb/^{206}Pb$.

Uncertainties for the intercepts between regression lines and concordia are also 95 percent confidence limits. They are calculated by the method of Ludwig (1980) in which errors are propagated throughout the entire analytical procedure, and from which the $^{206}Pb/^{238}U$ - $^{207}Pb/^{235}U$ correlation coefficients are computed (table 2). These coefficients determine the size of the error envelopes for the data points in concordia diagrams and help to determine the intercept errors. Significant common lead corrections adversely affect the correlation coefficients when $^{206}Pb/^{204}Pb$ values are less than approximately 800. Uranium decay constants are those of Jaffey and others (1971).

RESULTS

GEOCHRONOLOGY

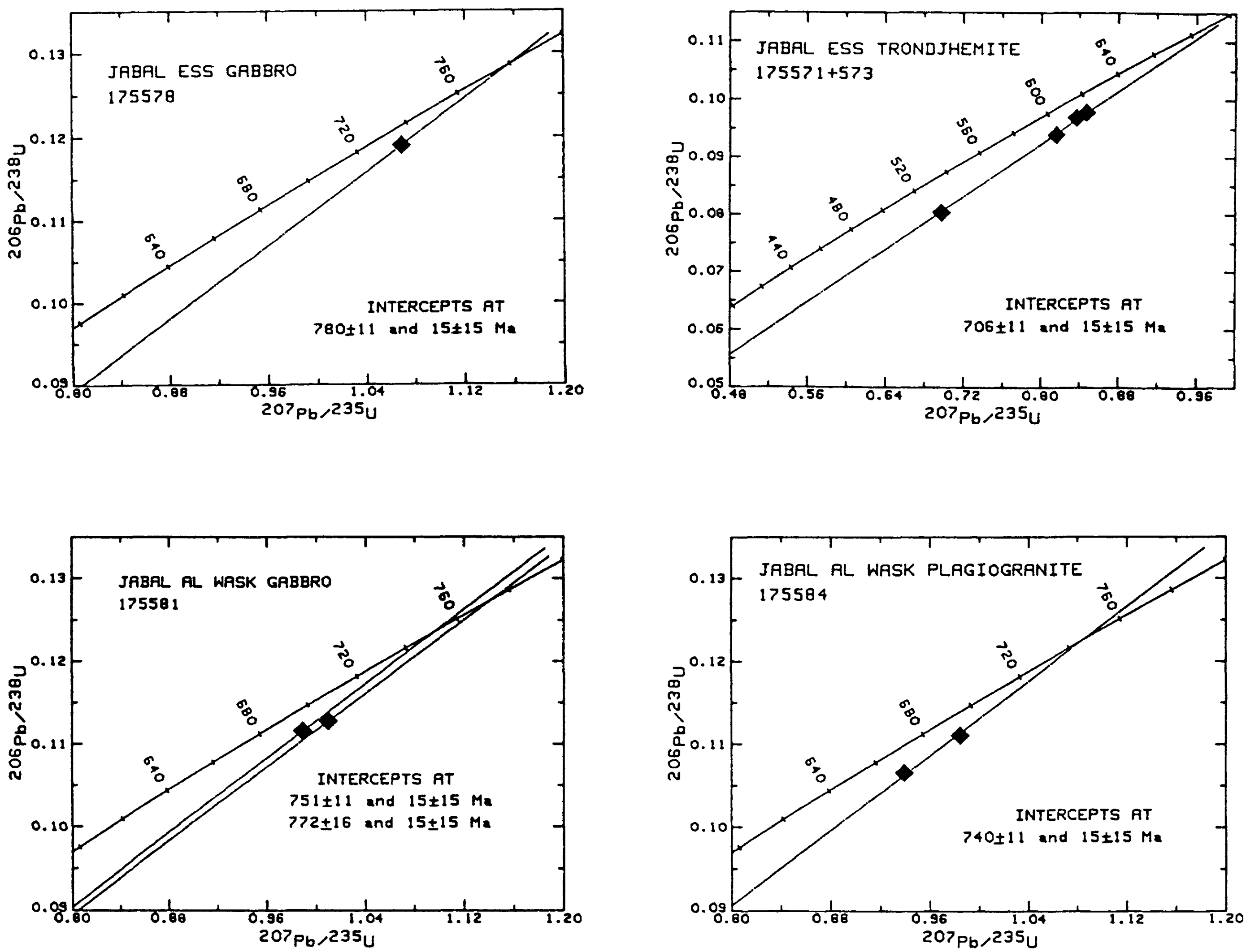
Uranium-lead data for zircons from ophiolitic rocks of the Arabian Shield are given in table 2, concordia diagrams are shown in figure 14 and model ages are summarized and compared to ages of arc rocks in figure 15. Zircon dating of ophiolitic rocks requires collecting large samples (50-100 kg). Nevertheless, the zircon yield in the gabbros was typically small, and ranged from just a few

Table 2.--U-Pb analytical data for zircons from ophiolitic and related rocks of the Arabian Shield.

[Zircon fractions are specified by mesh size and their M - magnetic, or NM - non-magnetic characteristics or by physical features as described in the footnote. Rho is the $^{207}Pb/^{235}U$-$^{206}Pb/^{238}U$ correlation coefficient (Ludwig, 1980).]

Locality & Sample No. (Mesh size) or Fraction No.	Sample weight mgm	U ppm	Pb ppm total	Atomic Ratios			Apparent Ages Ma.			Rho	Measured
				$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$		$\frac{^{206}Pb}{^{204}Pb}$
NORTHWESTERN ARABIAN SHIELD											
Jabal Ess 175578 gabbro											
(-150+250)NM	5.24	272.0	37.34	0.11900	1.06910	0.06516	725	738	770	0.950	1250
175571+573 trondjhemite											
(+200)NM	13.44	249.4	25.64	0.09776	0.84672	0.06282	601	623	702	0.966	1193
(-200+250)NM	8.96	270.0	27.51	0.09686	0.83663	0.06265	596	617	696	0.950	990
(-250+325)NM	17.20	294.5	28.75	0.09388	0.81559	0.06301	578	606	708	0.950	1326
(-400)MAG	14.64	370.2	31.79	0.08031	0.69726	0.06297	498	537	707	0.936	814
Jabal al Wask 175581 gabbro											
(-100+250)	7.23	705.3	84.69	0.11159	0.98862	0.06426	682	698	750	0.950	1367
(-250)	1.07	662.6	80.01	0.11276	1.00930	0.06492	689	708	772	0.950	1179
175584 plagiogranite											
(+150)	4.87	869.7	98.69	0.10660	0.93910	0.06389	653	672	738	0.950	5756
(-325)	2.19	569.6	65.96	0.11110	0.98436	0.06426	679	696	750	0.967	3573
Salajah 197845 tonalite											
(-100+150)NM	8.65	185.4	18.96	0.10300	0.88869	0.06258	632	646	694	0.975	2100
(-100+150)NMA	6.14	140.6	15.28	0.10950	0.94588	0.06265	670	676	696	0.976	3065
Jar 197870 tonalite											
(+100)NM	7.96	294.7	30.93	0.10430	0.90044	0.60262	640	652	695	0.977	3302
(-150+200)NM	15.65	276.5	28.52	0.10316	0.89021	0.06258	633	646	694	0.982	5080
(-325)NM	5.64	288.3	31.15	0.10408	0.89873	0.06263	638	651	695	0.980	2603
WEST-CENTRAL ARABIAN SHIELD											
Thurwah 175925+937 gabbro											
(+100)	4.06	137.0	20.37	0.13556	1.2717	0.06804	820	833	870	0.942	1096
(-100+200)	6.63	173.7	25.49	0.13772	1.5437	0.08129	832	948	1228	0.797	1969
(-200)	5.07	225.4	32.19	0.13592	1.5473	0.08256	822	949	1259	0.969	2501
Umq 175471 diorite (Measured Pb blank: 0.04 ng)											
3(P4)*	0.015	207.9	36.10	0.13984	1.2842	0.06660	844	839	825	0.945	389.7
4(P4)*	0.011	622.6	111.5	0.12784	1.1805	0.06697	776	792	837	0.978	479.4
5(P4)*	0.28	531.3	72.1	0.10523	0.97129	0.06695	645	689	836	0.974	1166.9
Umq 175592 keratophyre (Measured Pb blank: 0.04 ng and 0.02 ng)											
3(P8)	0.025	163.7	21.4	0.12472	1.1217	0.06523	758	764	782	0.927	374.4
4(P8)	0.031	159.3	21.0	0.11564	1.10306	0.06464	705	719	763	0.982	401.9
NABITAH SUTURE ZONE											
Tuluhah 175585+588 plagiogranite											
(+200)	4.68	200.4	28.88	0.11836	1.08500	0.06648	721	746	821	0.875	595
(-200)	3.36	188.0	25.16	0.11374	1.05350	0.06718	694	731	843	0.956	526
Ad Dafinah 175595 quartz diorite											
(+100)MAG	12.09	98.3	10.78	0.11159	0.96970	0.06302	682	688	709	0.950	1743
(-325)NM	5.55	127.1	15.44	0.11300	0.99380	0.06379	690	701	735	0.950	457
(-325)MAG	11.10	116.1	13.54	0.11546	1.02310	0.06427	704	715	750	0.950	971
Tathlith 197642 gabbro (Measured Pb blank 0.082 ng)											
6(P4)*	0.012	829.6	86.8	0.09475	0.79176	0.06061	584	592	625	0.938	734.2
EASTERN ARABIAN SHIELD											
Ar Ridaniyah 175606 metadacite dike											
(+200)NM	5.04	310.0	31.70	0.09942	0.88960	0.06489	611	646	771	0.950	924
(-200+250)	3.75	352.0	36.80	0.09763	0.86880	0.06454	601	635	759	0.950	559
(-250+325)	5.83	381.0	36.90	0.09612	0.85500	0.06452	592	627	758	0.950	1432
(-325)NM	4.68	398.0	37.70	0.09354	0.81240	0.06300	576	604	709	0.950	1110
Urd 128924 gabbro											
(+150)	7.29	63.2	7.83	0.11192	0.96410	0.06248	684	685	690	0.950	1337
(-150)	10.38	59.6	7.24	0.10847	0.93700	0.06265	664	671	696	0.950	1085

* Hand-picked zircon fraction features: 3(P4)- one crystal fragment, prism, purple tint, translucent, highly fractured; 4(P4)- single large crystal, translucent, subhedral to euhedral, fractured, contains dark inclusion(s); 5(P4)- 7 crystals, all euhedral and slightly purple in color; 6(P4)- 5 crystals, euhedral, purple-brown, fractured.



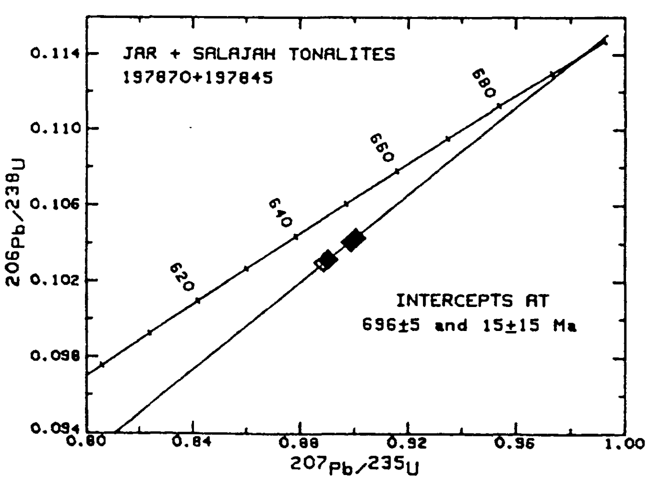


Figure 14.--Concordia diagrams for zircons from ophiolitic and related rocks from the Arabian Shield.

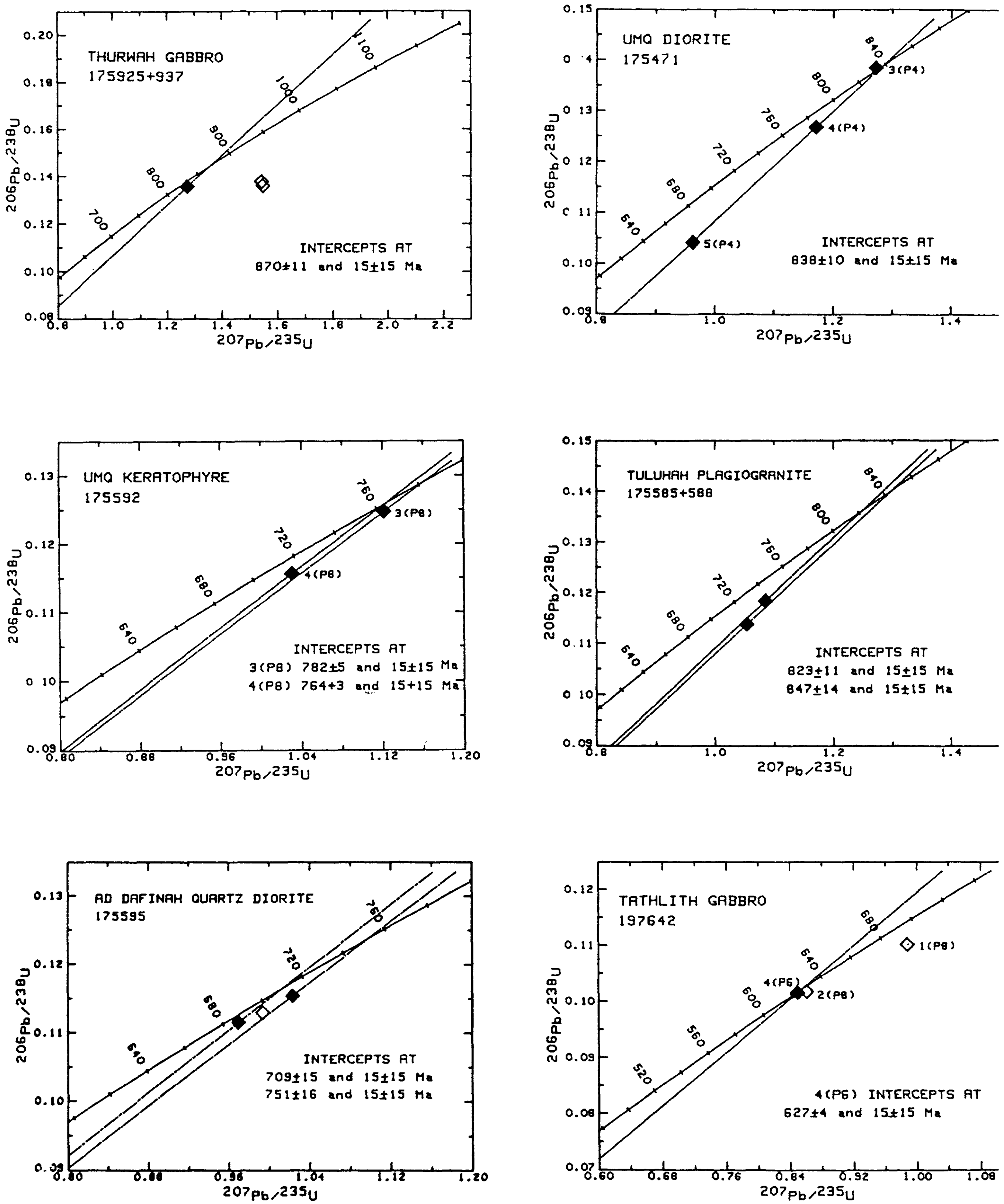


Figure 14.--Concordia diagrams for zircons--Continued

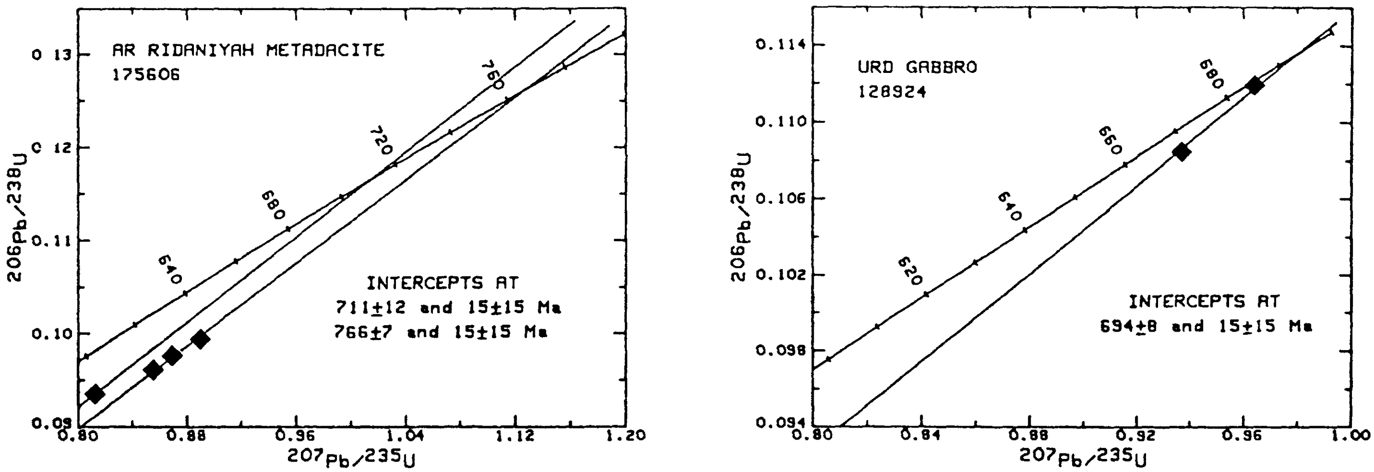


Figure 14.--Concordia diagrams for zircons--Continued

crystals (or none at all) to a maximum of 50 mg. Consequently, in most cases sufficient zircon was separated for only two or three size fractions. The uranium and radiogenic-lead concentrations in ophiolitic zircons are low; this favors near-concordant data because the crystals have not become strongly metamict.

Unfortunately, the data are not completely concordant, nor in most cases are there highly discordant fractions to tightly bracket lead-loss chords. Consequently we have applied a lead-loss model to the data, and we report zircon model ages in table 3. The model applied herein is based on the assumption that episodic lead-loss occurred during a Tertiary event related to uplift during Red-Sea rifting. Zircon data from a large area of the southern Arabian Shield define a lower intercept of 15±15 Ma and form the basis for this model (Cooper and others, 1979; Stoeser and others, 1984). Such a model is also consistent with geologic evidence that the Arabian Shield was a stable platform between the close of the Precambrian and the Tertiary rifting.

In some samples, however, the ophiolite data do not fit a model chord closely, and we believe that the different $^{207}Pb/^{206}Pb$ ages are due to an earlier loss of lead during sea-floor alteration and obduction metamorphism. The effect of such a process would be to spread the data out along short chords near concordia, so that subsequent Tertiary lead-loss would result in the observed scatter. Early lead loss of the type we envision for the Arabian Shield ophiolites has been documented in studies of the early Paleozoic ophiolites of Newfoundland (Mattinson, 1975; 1976). The Arabian Shield ophiolites are typically more altered than adjacent arc rocks and some show a metamorphic zonation from greenschist facies in volcanic rocks, to amphibolite facies in hypabyssal and plutonic rocks. This is very similar to the zonation produced by sea-floor alteration in Phanerozoic ophiolites. The fact that most of the ophiolites appear to have composite origins within magmatic arc terranes also suggests that lead-loss might have occurred during emplacement.

We present two model ages for those samples with near-concordant data that do not closely fit a single lead-loss chord (e.g., samples 175581, 175471, 175585+588, 175595, 175606; table 3). These ages are derived from chords tied at a lower intercept of 15±15 Ma, and fit through the zircon fraction data points farthest from and closest to concordia. Following our model, these ages are

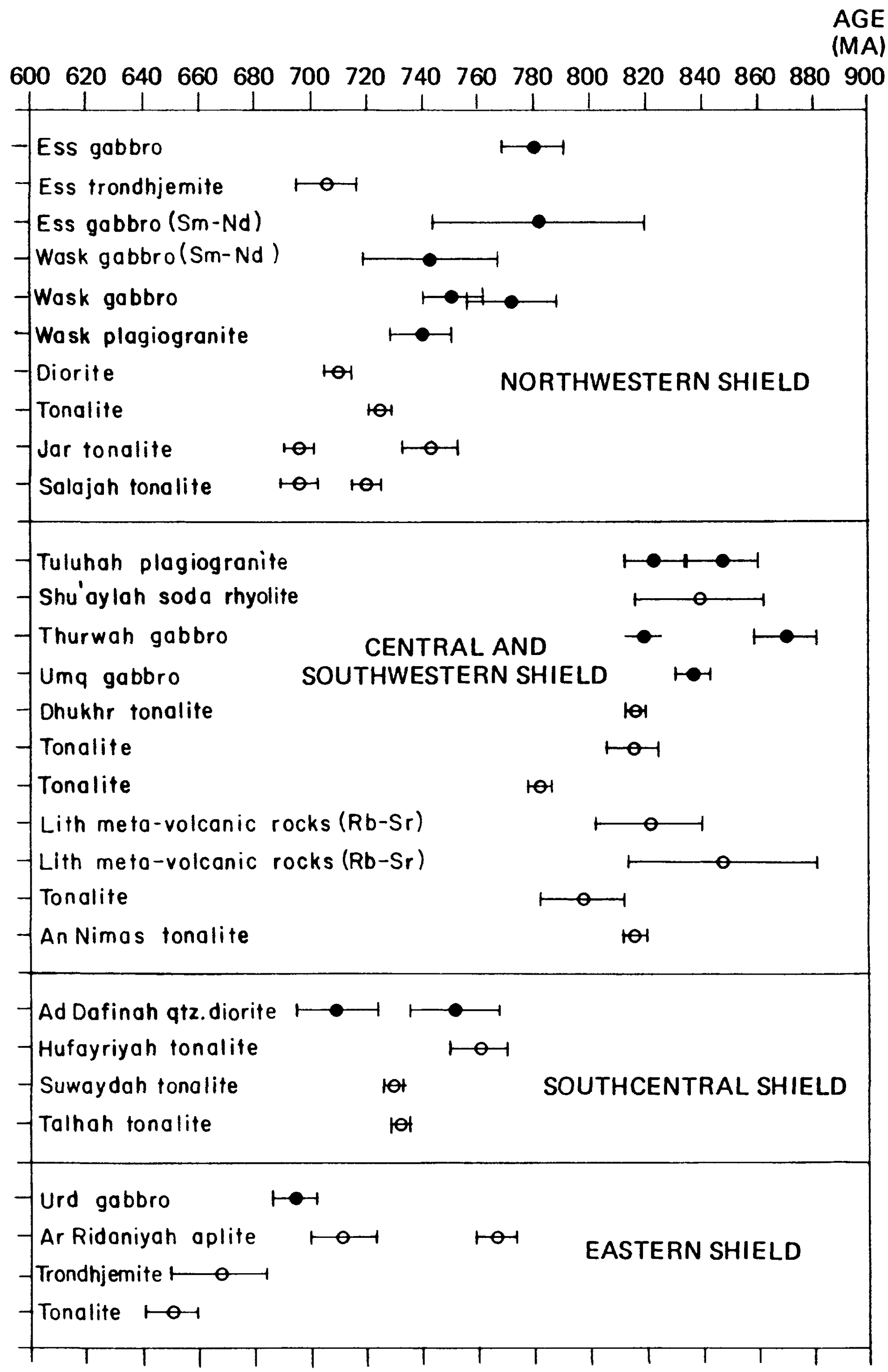


Figure 15.--Summary of radiometric ages for ophiolitic and arc basement rocks for various regions of the Arabian Shield. Solid circles used for ophiolitic rocks, open circles for arc-plutonic and volcanic rocks.

Table 3.--Summary of $^{207}Pb/^{206}Pb$ data for zircons from ophiolitic and related rocks of the Arabian shield, together with U-Pb model ages that assume Pb loss at 15±15 Ma.

[Uncertainties quoted are model dependent and are computed for 95% confidence levels using the method of Ludwig (1980).]

Locality & Rock Type	Sample No.	Zircon Fractions (mesh size)	$^{207}Pb/^{206}Pb$ Age Ma	Upper Intercept Age for Pb loss at 15±15 Ma
NORTHWESTERN ARABIAN SHIELD				
Jabal Ess gabbro	175578	(-150+250)	780	780±11
trondjhemite	175571+573	4 fractions	696-708	706±11
Jabal al Wask gabbro	175581	(-100+250)	750	751±11
		(-250)	772	772±16
plagiogranite	175584	2 fractions	738,750	740±11
Salajah tonalite	197845	2 fractions	694,696	696±6
Jar tonalite	197870	3 fractions	694-695	696±5
WEST-CENTRAL ARABIAN SHIELD				
Thurwah gabbro	195925+937	(+100)	870	870±11
		(-100+200)	1228	
		(-200)	1259	
Umq diorite	175471	3(P4)*	825	825±11
		4(P4)*	837	839±4
		5(P4)*	836	
Umq keratophyre	175592	3(P8)	782	769±3
		4(P8)	763	(both)
NABITAH SUTURE ZONE				
Tuluhah plagiogranite	175585+588	(+200)	821	823±11
		(-200)	843	847±13
Ad Dafinah qtz diorite	175595	(+100)M	709	709±15
		(-325)NM	735	
		(-325)M	750	751±16
		3 fractions	709-750	732±27
Tathlith gabbro	197642	6(P4)*	625	626±4
EASTERN ARABIAN SHIELD				
Ar Ridaniyah aplite dike	175606	(-325)M	709	711±12
		3 largest fractions	758-771	766±7
Urd gabbro	128924	2 fractions	690,696	694±8

* Hand-picked zircon fractions, see descriptions in Table 2

interpreted to be approximately the ages of magmatism, and metamorphism, respectively. Strictly interpreted, these represent the minimum age of magmatism and the maximum age of metamorphism because we are not necessarily sampling endpoints of the initial short chords near concordia mentioned above. Support for our model-interpretation of the zircon data is provided by good agreement between the magmatic model ages and Sm-Nd isochron ages for ophiolites of the northwestern Arabian Shield (Claesson and others, 1984).

Northwestern Arabian Shield

A single zircon fraction from a gabbro at Jabal Ess (sample 175578) yielded a model age of 780±11 Ma (fig. 14). This compares well with a Sm-Nd mineral isochron age of 782±36 Ma obtained for the same sample by Claesson and others (1984). In contrast, the model age yielded by 4 zircon fractions from the trondhjemite pluton near Jabal Ess (175571+573) is 706±11 Ma (fig. 14). This younger age is in accord with field evidence that the trondhjemite intruded ophiolitic gabbro. We regard the pluton as part of the magmatic arc complex that postdates the ophiolite, and not as comagmatic plagiogranite as initially proposed by Shanti and Roobol (1982).

Two data points from the Jabal Wask gabbro (175581) have Tertiary lead-loss model ages of 772±16 Ma and 751±11 Ma (fig. 14). Data from two fractions of zircon from the Jabal Wask plagiogranite (sample 175584) yield a model age of 740±11 Ma when regressed together with a lower intercept of 15±15 Ma (fig. 14). Our zircon model ages agree well with a Sm-Nd mineral isochron of 743±24 Ma for a gabbro from Jabal Wask obtained by Claesson and others (1984). Also from Jabal Wask, Ledru and Auge (1984) report a revised age of 776±9 Ma for plagiogranite that is in considerably better agreement with our data than the 882±12 Ma originally indicated by De La Boisse and others (1980), and Kemp and others (1980).

We have also analyzed four zircon fractions from two tonalite bodies (Jar and Salajah) that are exposed south of the Jabal al Wask complex. The data from the two units are identical and indicate a common model age of approximately 696 Ma (table 3). Spread between the data was increased with a more concordant point, produced by analysis of an abraded fraction of the Salajah sample. The precision improved when all five analyses were regressed together, but the common model age remained unchanged at 696±5 Ma (fig. 14).

Our sample of Jar tonalite comes from about 50 km southeast of a sample dated at 743±10 Ma by Kemp and others (1980) and is from a zone of tonalite dikes that intrude ophiolitic diorite and gabbro. This tonalite was mapped as an older phase of the Jar batholith by Kemp (1981) (fig. 6). Our sample of the Salajah tonalite was collected approximately 10 km northwest of a sample dated at 725±12 Ma by Kemp and others (1980) and revised to 720±5 Ma by Ledru and Auge (1984) (fig. 6). It is from a phase of the pluton that intruded meta-sedimentary rocks of both the Al Ays and Farri groups as mapped by Pellaton (1979).

The discrepency between our zircon dates and those reported by Kemp and others (1980) and Ledru and Auge (1984) suggests that other similar tonalitic and trondhjemitic rocks with ages ranging from about 740 to 700 Ma exist within the mapped areas of Jar and Salajah tonalites. We suggest that these are composite-arc batholiths, the earliest phases of which were intruded shortly after ophiolitic magmatism, and the later phases intruded the ophiolitic rocks as well as the volcanic and sedimentary products of the early phases of arc magmatism. Our sample of gabbro from the Nabt complex (fig. 6) yielded very little zircon. Single-zircon and Sm-Nd work is currently underway to to date this mafic-ultramafic complex directly. Intrusive relations indicate that the Nabt complex is older than the granodiorite dated by Kemp and others (1980) at 611±14 Ma, older than the Kamal pluton, and older than parts of the the Salajah tonalite (725±12 Ma to 696±5 Ma), but younger than the anomalous, high-grade Al Hinu formation.

West-central Arabian Shield

Three fractions of zircons from the Thurwah ophiolite were analyzed (fig. 14). The coarse-grained fraction yielded nearly concordant data with a Tertiary lead-loss model age of 870±11 Ma that we take to be a maximum estimate of the magmatic age of the ophiolite. The other two fractions are highly discordant and yielded model ages of about 1,250 Ma. Assuming that both fractions represent mixtures of crystals of different ages, the upper-intercept model age of the more discordant data point (~1,250 Ma) would indicate a minimum age for the older component. Similarly, the upper intercept model age (~870 Ma) would be a maximum estimate of the age of the younger magmatic component.

The older (>1,250 Ma) component is best explained by assimilation of older material during emplacement of the gabbro. The zircons were separated from a combined sample of two coarse-grained hornblende gabbros from the western part of the Thurwah ophiolite. It is not known if both, or only one of the two samples contained the two distinct zircon types. Gabbro from the Thurwah complex has been recollected to attempt to verify these unusual results.

Three zircon fractions of a hornblende diorite from the Bir Umq complex yielded an upper intercept age of 829± 87 Ma (fig. 14) with a lower intercept of -40 Ma. A second regression through the more precise analyses, 4(P4) and 5(P4), yields an age of 837±6 Ma. The lower intercept of 5±31 Ma suggests that the second regression may be the better estimate of the true age. The most concordant analysis, 3(P4), unfortunately yielded the youngest $^{207}Pb/^{206}Pb$ age of all three analyses, causing the negative lower intercept in the first regression. The analysis 3(P4) is from a zircon fragment containing the least amount of lead, the lowest $^{206}Pb/^{204}Pb$ value, and consequently the largest errors. It is noted that a forced regression from 3(P4) through a lower intercept of 15±15 Ma yields an age of 825±11 Ma, and a forced regression through the two more precise analyses yields an age of 839±4 Ma; both clearly overlap the second regression age of 837±6 Ma. Despite the concordant nature of 3(P4), it is our belief that the second regression is the best estimate of the true age of the diorite.

Two small zircon fractions from the Bir Umq keratophyre yielded an upper-intercept age of 793±12 Ma, with an unusually high lower intercept of 285±79 Ma (fig. 14). Application of the Tertiary lead-loss model results in a best-fit upper intercept age of 769±3 Ma. Although the magmatic age of the keratophyre is not tightly bracketed, the model ages are considerably younger than the preferred date of the Bir Umq diorite (837±6 Ma). The keratophyre is accordingly interpreted to be a postobduction pluton, and the initial motion on the basal Bir Umq thrust apparently occurred between about 770 and 837 Ma.

Nabitah Suture Zone

Tertiary lead-loss model ages of 847±14 Ma and 823±11 Ma are shown in figure 14 for two zircon fractions from a plagiogranite of the Bir Tuluhah ophiolitic complex. We regard the difference in these ages to be an indication of early alteration and obduction metamorphism as explained earlier. Three zircon fractions from quartz diorite from near Ad Dafinah in the central Nabitah suture zone yielded model ages between 751±16 Ma and 709±15 Ma (fig. 14) and a composite model age of 732±27 Ma (table 3). A single fraction of zircon separated from a gabbro that crops out east of the village of Tathlith, along the southern part of the Nabitah suture, yielded a model age of 626±4 Ma (fig. 14). We believe that the Tathlith gabbro is part of an intrusion that postdates the ophiolite; therefore the model age can only be regarded as a minimum age for the ophiolitic rocks of the southern suture. Another gabbro , intruded into the Hamdah serpentinite, gave an age of 664±12 Ma (Cooper and others, 1979). Samples of gabbro from the Hamdah ophiolitic complex, at the southern end of the Nabitah suture yielded zircon quantities too small for routine analysis. These rocks are currently being investigated using single zircon and Sm-Nd methods.

Eastern Arabian Shield

U-Pb data for zircons separated from an aplite dike intruded into the northern part of the Al Amar suture near Ar Ridaniyah are shown in figure 14. Intercept ages of 766±7 Ma and 711±12 Ma result from the Tertiary lead-loss model. The older age is defined by three zircon fractions, whereas the younger age is based on the finest grained (-325) nonmagnetic fraction. The younger age (711±12 Ma) may result from lead loss during subduction metamorphism prior to final suturing of the Afif and Ar Rayn plates at 660 Ma to 640 Ma (Stacey and others, 1984). The zircons with the older model age (766±6 Ma) may have been inherited from some of the crustal rocks that probably existed in the region prior to that activity, or their age may represent the magmatic age of the aplite. Calvez and others (1985b) sampled a similar aplite dike from the same area and obtained three zircon fractions with $^{207}Pb/^{206}Pb$ ages of 1,409, 1,572, and 1,898 Ma.

Samples were also collected from the central and southern parts of the Al Amar suture in the Umm ash Sharah and Al Uwayja areas (figs. 12d, 12a). These yielded only small amounts of zircon and are currently being analyzed by the single zircon method.

Zircon data from a hypersthene gabbro of the Urd ophiolite near the village of Halaban (fig. 12b) were originally published by Stacey and others (1984). They are included here for completeness, and the two near-concordant data points together give a model age of 694±8 Ma (fig. 14) that is probably the magmatic age of this ophiolite.

FELDSPAR LEAD DATA

Lead isotopic ratios were measured from feldspars in the samples of this study. The ratios have not been corrected for decay of *in situ* uranium and thorium, but were HF leached prior to dissolution in order to minimize any radiogenic lead component. Unless the U-Pb systems have been obviously reset by later metamorphic events, we assume these ratios are close to initial values at the time of emplacement. They are shown in table 4, and are plotted in figure 16 together

Table 4.--Lead isotope data from feldspars in the samples of this study.

[Lead model ages are computed from Stacey and Kramers (1975).]

Locality & Sample No.		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb Model Age Ma	Zircon Model Age Ma
NORTHWESTERN ARABIAN SHIELD						
Jabal Ess	175571+573	17.594	15.432	37.013	441	707
	175578	17.654	15.485	37.220	504	781
Salajah	197845	17.534	15.460	36.992	547	696
Jar	197870	17.427	15.428	36.868	566	696
WEST-CENTRAL ARABIAN SHIELD						
Thurwah	175925+937	18.391	15.589	38.105	152	870
	197601	18.435	15.606	37.965		
Bir Umq (Keratophyre)	175592	18.233	15.525	37.317		
NABITAH SUTURE ZONE						
Tuluhah	175585+588	18.833	15.570	38.105	-235	823
Ad Dafinah	175595	17.521	15.432	36.936	499	709
Tathlith	197642	18.038	15.541	37.492	322	626
EASTERN ARABIAN SHIELD						
Ar Ridaniyah	175606	17.401	15.492	37.168	713	711
Urd	128924	17.093	15.410	36.934	795	694

with the evolution curves from the plumbotectonics model of Zartman and Doe (1981) and the fields for present day mid-ocean ridge basalt (MORB) (Tatsumoto, 1978).

The samples whose data lie closest to the mantle curves are those from Jabal Ess, Salajah, Jar and Ad Dafinah, and in each graph of figure 16, these late Precambrian data lie on an extension of the field for present day MORB. The $^{206}Pb/^{204}Pb$ ratios range between 17.4 to 17.65. These ratios are equivalent to present day (decay-corrected) values of 18.4 to 18.65 (assuming $\mu_{mantle} = 8.5$).

Feldspar data from Tuluhah, Bir Umq and Tathlith are quite radiogenic, and may indicate recent equilibration with their whole-rock lead. As previously described, the Bir Umq and the Tathlith feldspars are from rocks that could be younger than spatially associated ophiolitic serpentinite and basaltic rocks. Both the Bir Umq and Tathlith rocks could have been produced by late Proterozoic arc magmatism. A comparison to the mantle-evolution curve in figure 16 may therefore not be appropriate for these samples. However, some minor crustal contamination from an older source seems necessary to account for the presence of

Table 5.--Source data not determined in this study, but used for radiometric dates shown in figures 15 and 17.

Date	Method	Rock Type	Reference
710±05	U-Pb	Diorite	Hedge (1984)
725±04	U-Pb	Tonalite	"
782±38	Sm-Nd	Gabbro	Claesson and others (1984)
743±24	Sm-Nd	Gabbro	"
743±10	U-Pb	Tonalite	Ledru and Auge (1984)
720±05	U-Pb	Tonalite	"
821±40	Rb-Sr	Granodiorite	Calvez and others (1984)
839±23	U-Pb	Na-rhyolite	"
760±10	U-Pb	Tonalite	"
816±03	U-Pb	Tonalite	"
821±19	Rb-Sr	Metavolcanics	Kröner and others (1984)
847±34	Rb-Sr	Metavolcanics	"
797±15	U-Pb	Tonalite	Cooper and others (1979)
816±04	U-Pb	Tonalite	"
815±09	U-Pb	Granodiorite	J. S. Stacey, unpub. data
728±10	U-Pb	Tonalite gneiss	"
782±04	U-Pb	Diorite gneiss	Stacey and Agar (1985)
729±03	U-Pb	Tonalite	Stoeser and others (1984)
732±03	U-Pb	Tonalite	Stoeser and others (1984)
1829±45 & 471±94	U-Pb	Paragneiss	Stacey and Agar (1985)
658±107 & 1628±201	U-Pb	Granodiorite	Stacey and Hedge (1984)
645±16 & 2067±74	U-Pb	Gabbro & Trondhjemite	Calvez and others (1985a)
667±17	U-Pb	Trondhjemite	Calvez and others (in prep., as cited by Vaslet and others (1983))
650±09	U-Pb	Tonalite	Stacey and others (1984)

certain other samples that have slightly elevated $^{207}Pb/^{204}Pb$ values that plot above the mantle-growth curve in figure 16. Note that mantle lead is exceedingly sensitive to continental contamination because of its low concentration (<1 ppm), compared with that in continental rocks (>10 ppm). All of the data from the west and central parts of the Arabian Shield plot below the mantle curve in the $^{208}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$ diagram of figure 16, indicating a low Th/U value that is typical for the source environment of MORB (Tatsumoto, 1978).

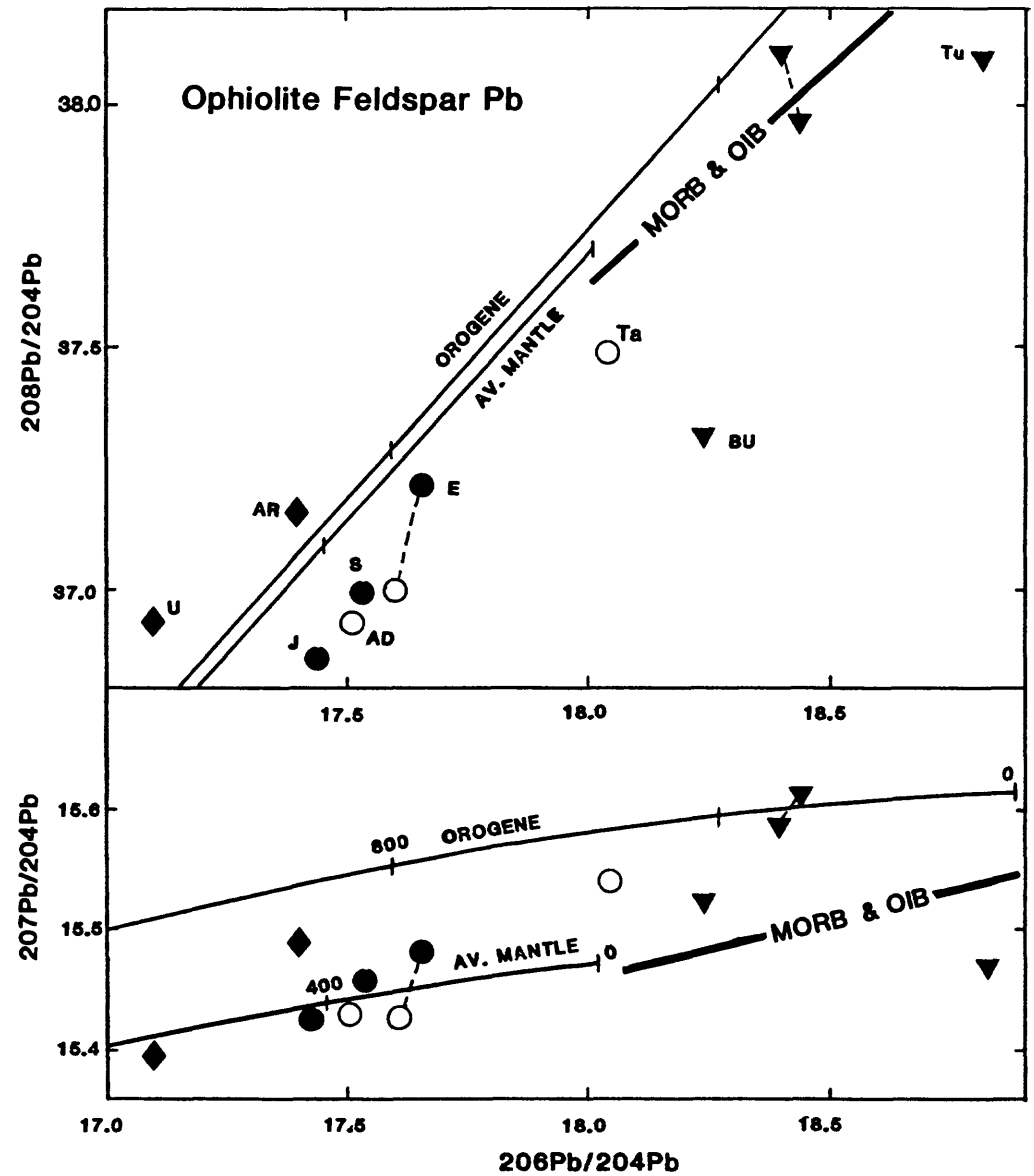


Figure 16.--Feldspar lead-isotope-ratio data from ophiolitic and related rocks of the Arabian Shield. Abbreviations: U = Urd gabbro, AR = Ar Ridayniyah metadacite, J = Jar tonalite, S = Salajah tonalite, AD= Ad Dafinah quartz diorite, E = Jabal Ess gabbro and trondhjemite, Ta = Tathlith gabbro, BU = Bir Umq Keratophyre, Th = Thurwah gabbro, Tu = Tuluhah plagiogranite. Symbols indicate regions of the Arabian Shield as follows: diamonds = eastern, filled circles = northwestern, squares = Nabitah suture, triangles = west-central. Filled symbols are from ophiolitic rocks; open symbols represent probable magmatic arc rocks.

The most obvious example of crustal contamination is shown by the data from Thurwah, where lead values from two different gabbro samples straddle the orogene curve in figure 16. Zircon data from a Thurwah gabbro yielded $^{207}Pb/^{206}Pb$ ages of both approximately 870 Ma and 1250 Ma, as discussed previously. The higher age is best explained by assimilation of older metasedimentary rocks during intrusion of the gabbro.

Data from the Urd ophiolite sample from near Halaban in the eastern Arabian Shield, are considerably less radiogenic than those of the first group, even though the sample is the youngest in this study. Such retarded uranogenic lead growth must be due to residence in a low U/Pb environment; specifically an environment in which uranium was depleted relative to both lead and thorium (i.e., normal Th/Pb and high Th/U). This type of depletion and retarded uranogenic lead growth causes the data point to plot to the left of the $^{208}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$ mantle-growth curve in figure 16.

The lead from the metadacite dike from Ar Ridaniyah may have been derived ultimately from Urd-type mantle, but because of its higher $^{207}Pb/^{204}Pb$ value, it clearly exhibits a significant component of older crustal lead.

DISCUSSION AND CONCLUSIONS

ARC ACCRETION OR CONTINENTAL RIFTING?

Before discussing the implications of our geochronologic and isotopic data for microplate accretion, it is first appropriate to address general objections to an arc-accretion model for the Arabian Shield. Alternative models suggest that the Arabian-Nubian Shield formed in an intracratonic setting, either by repeated rifting and compression (Garson and Shalaby, 1976; Stern, 1979; 1981; Delfour, 1981; Kemp and others, 1982a) or as a greenstone belt (Engel and others, 1980). These models note the presence of bimodal (but subalkaline) volcanism in some rock suites and the scarcity of high-pressure, low-temperature metamorphic assemblages. However, these models have generally been flawed by the lack of evidence favoring preexisting continental crust within the central Arabian-Nubian Shield, by the lack of bimodal alkaline volcanics, and by the abundance of calc-alkaline, intermediate volcanic and plutonic rocks (Bokhari and Kramers, 1981; Schmidt and Brown, 1982; Roobol and others, 1983; Reischmann and others, 1985).

The anomalous subalkaline bimodal volcanics (tholeiite-low potassium dacite and rhyolite) of the Arabian Shield may have analogues in the products of Quaternary and Tertiary immature arc magmatism at Tonga-Kermadec and in the Lesser Antilles (Bryan, 1979; Tomblin, 1979). Low-potassium bimodal volcanism is generally restricted to the oldest rock suites of the Arabian Shield (the 'sequence' C of Jackson and Ramsay, 1980), such as the Baish group of southwestern Saudi Arabia (Reischmann, 1981; Reischmann and others, 1985; Pallister, 1986). These rocks apparently represent early stages of arc development and of production of "first cycle" melts (Bryan, 1979) uncontaminated by subducted sediments or continental material.

The absence of high-pressure, low-temperature metamorphic belts in the Arabian Shield is difficult to explain in the context of an accretionary model, and is generally attributed to retrogression accompanying post-accretion regional greenschist metamorphism. A single blueschist (crossite-schist) locality has been discovered associated with serpentinite in the Midyan region of the Arabian Shield (Al Tayyar and Smith, 1981).

Gass (1979) offers an attractive alternative explanation for the scarcity of blueschist and eclogite in the Shield. He points out that these rocks must have been rapidly uplifted from great depths (about 30 km) and suggests that blueschists may be exposed only where extensive amounts of subduction have taken place (corresponding to about 1,000 km of convergence). The reasoning is as follows: large amounts of subduction are required to cause subduction-zone stepping; this stepping in turn would be required to trigger uplift of down-dragged metamorphic rocks from earlier subduction cycles. Accordingly, if Proterozoic subduction was of limited scale during the accretion of the Arabian Shield, blueschist assemblages might not have been uplifted. On the other hand, if subduction rates were slow, the geotherm might not have been depressed sufficiently for blueschist to form in the first place.

Reymer and Schubert (1984) point out that the Arabian-Nubian Shield apparently grew too rapidly to be explained by Phanerozoic rates of island-arc growth. According to their calculations it would require at least 10 island arcs, each 2,500 km long, and all operating simultaneously to produce the Shield in 300 Ma. Reymer and Schubert consider the Shield to be continuous from east of the Nile River to the Zagros Mountains and calculate an area of 6×10^6 km^2. However, the character of the basement below the Phanerozoic rocks that cover the eastern part of this Shield is almost entirely unknown, as alluded to by Reymer and Schubert in a subsequent publication (Reymer and Schubert, 1986). This basement may include large regions of older continental rocks, such as the early Proterozoic fragment recently discovered in the eastern Arabian Shield (Stacey and Hedge, 1984; Stacey and Agar, 1985). Recalculation of a minimum growth rate for the Arabian-Nubian Shield, using only the area within the Shield boundary in figure 1 ($\sim 1 \times 10^6$ km^2), a crustal thickness of 40 km, subtracting the volume of known early Proterozoic rocks, and using an arc volcanism period of 360 Ma (640 to 1,000 Ma; Stoeser and Camp, 1985) results in a crustal growth rate of approximately 0.1 km^3/a. This rate is about 0.1 of the Phanerozoic world-wide arc addition rate and about an eighth of the rate calculated for the Shield by Reymer and Schubert (1984). Although we acknowledge that Proterozoic and Phanerozoic crustal growth processes (and rates) need not be identical, we believe that an arc- and exotic-terrane-accretion model best explains the Arabian Shield.

IMPLICATIONS OF OPHIOLITE AGES AND ISOTOPIC CHARACTERISTICS FOR CONTINENTAL ACCRETION

Northwestern Arabian Shield

Any tectonic model developed to explain the evolution and emplacement of the Jabal Ess and Jabal al Wask ophiolitic complexes must account for the following relationships:

1) The complexes occur within a large region of the western Arabian Shield that is characterized by rocks with oceanic chemical and isotopic affinities.
2) The ophiolitic rocks were emplaced tectonically into a sequence of arc volcanic and sedimentary rocks (the lower and middle formations of the Farri group) and are unconformably overlain by similar volcanic and sedimentary rocks of the Al Ays group.

3) Bakor (1973) reported very low niobium abundances from the Jabal al Wask spilites, and Shanti and Roobol (1982) indicate that the Jabal Ess pillow basalts are chemically similar to abyssal tholeiite.
4) Both ophiolitic complexes are internally disrupted by faulting, especially the Jabal al Wask complex.
5) Chrome-spinel in harzburgite and dunite from both complexes shows the wide compositional range characteristic of "Type II" alpine-type peridotites (fig. 5).
6) Serpentine-matrix melange crops out locally; it contains blocks of gabbro, diabase, and basalt, but only rarely graywacke.
7) Some Al Ays group sediments overlie the ophiolitic rocks unconformably and have local basal conglomerates that contain ophiolitic debris.
8) The rock types of both the Farri and Al Ays groups are similar. Both contain abundant silicic volcanic rocks and related sedimentary materials. The western facies of the Al Ays group in the Jabal al Wask area is dominated by sedimentary rocks; the eastern by volcanic rocks (Kemp, 1981).
9) Radiometric ages of gabbros from the Jabal Ess ophiolite (~780 Ma) are older than those of the oldest dated arc pluton in the region (~740 Ma); however the ages of gabbros and plagiogranite from the Jabal al Wask complex (~740-770 Ma) overlap with the ages of that pluton (fig. 15).
10) U-Pb zircon dates on tonalite to diorite plutons range from about 740 to about 700 Ma and indicate a long period of arc magmatism in the region (fig. 15).
11) The upper formation of the Farri group (ophiolitic pillow basalt) was intruded by a phase of the "syntectonic" Jar tonalite pluton, dated at 743±10 Ma.
12) Felsic volcanic rocks and related sedimentary rocks of both the Farri and Al Ays groups were intruded by the Salajah tonalite, dated at 696±5 Ma.

These features are consistent with the interpretation that the ophiolitic rocks are allochthonous bodies emplaced into a sequence of arc volcanic and sedimentary rocks during closure of basins floored by ocean crust and located ajacent to a magmatic arc. It is important to note that the ophiolitic gabbros from Jabal Ess and Jabal Wask are among the oldest dated rocks in the north-western Arabian Shield (fig. 15). Early reports of older arc pluton ages, such as the zircon date (796±23 Ma) on the Jar tonalite (Calvez and others, 1984), were in error and have been revised to dates of less than 750 Ma (Ledru and Auge, 1984). Only the 821±40 Ma Rb-Sr isochron reported by Calvez and others (1982; 1984) for a trondhjemite pluton northwest of the Yanbu suture suggests the presence of older rocks in the region, and this isochron may not be accurate (Jean-Yves Calvez, oral commun., 1986).

It has been argued on geologic, geochemical, and chronologic grounds that the ophiolites of the northwestern Arabian Shield are fragments of oceanic lithosphere formed in back-arc basins (Bakor and others, 1976; Shanti and Roobol, 1982; Claesson and others, 1984). Such a model is consistent with the younger ages for gabbro from the Jabal al Wask complex that overlap with the early phase of the Jar tonalite, but is difficult to reconcile with the older ages from Jabal Ess. Unless there are undated magmatic arc rocks in the Jabal Ess region that are older than about 780 Ma, the Jabal Ess gabbros predate arc magmatism in the region, and probably represent fragments of pre-existing oceanic crust on which the Hijaz magmatic arcs were built. The wide compositional range in chrome-spinels from most of the Arabian Shield ophiolites (fig. 5) suggests that the peridotite tectonites originated as oceanic mantle that underwent melt extraction in both mid-ocean ridge and arc settings (Dick and Bullen, 1984). Pending more definitive evidence, we regard the Jabal Ess gabbros to be disrupted fragments of pre-arc oceanic crust. Our zircon dates on the Jar and Salajah tonalites and on the Jabal Ess trondhjemite indicate that a major phase of arc plutonism was still underway at about 700 Ma, 40 to 80 million years after the ophiolites of northwestern Arabia formed.

The intense disruption of the Jabal al Wask ophiolitic complex resembles fracture-zone tectonics as described by Saleeby (1979) for the Kings-Kaweah ophiolite belt of California. At Jabal al Wask, and indeed at most of the ophiolitic suites of the Arabian Shield, gabbro, basalt, and diabase crop out in serpentine-matrix melange characterized by steeply dipping fabrics. Much of this deformation could have occurred in an oceanic (fracture zone) setting prior to accretion; however, some of the deformation also involves younger rocks and can be shown to postdate emplacement of the ophiolitic rocks.

West-central Arabian Shield

Zircon U-Pb data with relatively old magmatic model ages were obtained from gabbro of the Thurwah (820-870 Ma) and Bir Umq (837 ± 6 Ma) ophiolitic rocks (fig. 15). The Bir Umq age is only about 20 million years older than a zircon age given by Calvez and others (1984) for the Dhukhr tonalite (816 ± 3 Ma), south of Bir Umq (fig. 17). We therefore conclude that the ophiolitic rocks of Bir Umq (and possibly also at Thurwah) represent ocean crust that formed less than approximately 20 million years prior to early arc magmatism in the region; this suggests a near- or intra-arc setting for ophiolitic magmatism.

The Thurwah and Bir Umq dates suggest that the northern boundary of >900-800-Ma rocks within the Asir microplate of Stoeser and Camp (1985) should extend north to the Bir Umq-Port Sudan suture (fig. 17). In addition, the older pre-late-Proterozoic zircon ages and the radiogenic lead-isotope ratios in feldspars from the Thurwah gabbro suggest incorporation of older continental crust. This raises the possibility that fragments of middle Proterozoic to early-Proterozoic age are entrained within the Hijaz microplate of the western Arabian Shield, and are perhaps analagous to parts of the Afif continental block described by Stacey and Agar (1985) and Agar (1985) from the eastern Shield (fig. 17). Rocks such as the gneissic Al Hinu formation (intruded by the Nabt complex gabbro, fig. 6) may represent small exotic fragments of older continental crust.

Calvez and others (1985b) have re-evaluated U-Pb zircon data from the central and western Arabian Shield in terms of a pre-late Proterozoic contamination model. They find limited discordance among zircon fractions separated from felsic volcanic rocks from near the Jabal al Wask suite, from east of the northern Nabitah suture, and from southwest of Bir Umq. Although there is no direct evidence for the presence of older zircons (rounded grains or cores) in the separated fractions, Calvez and others suggest that the discordance indicates inheritance from older continental rocks that possibly only exist at depth in the central and western Shield.

We believe that the discordant zircon data from the central and western Arabian Shield is more adequately explained by the incorporation of continental crustal fragments during island-arc accretion. There is limited geophysical evidence of an east-west structural grain at a depth of ≥ 20 km (Gettings, oral

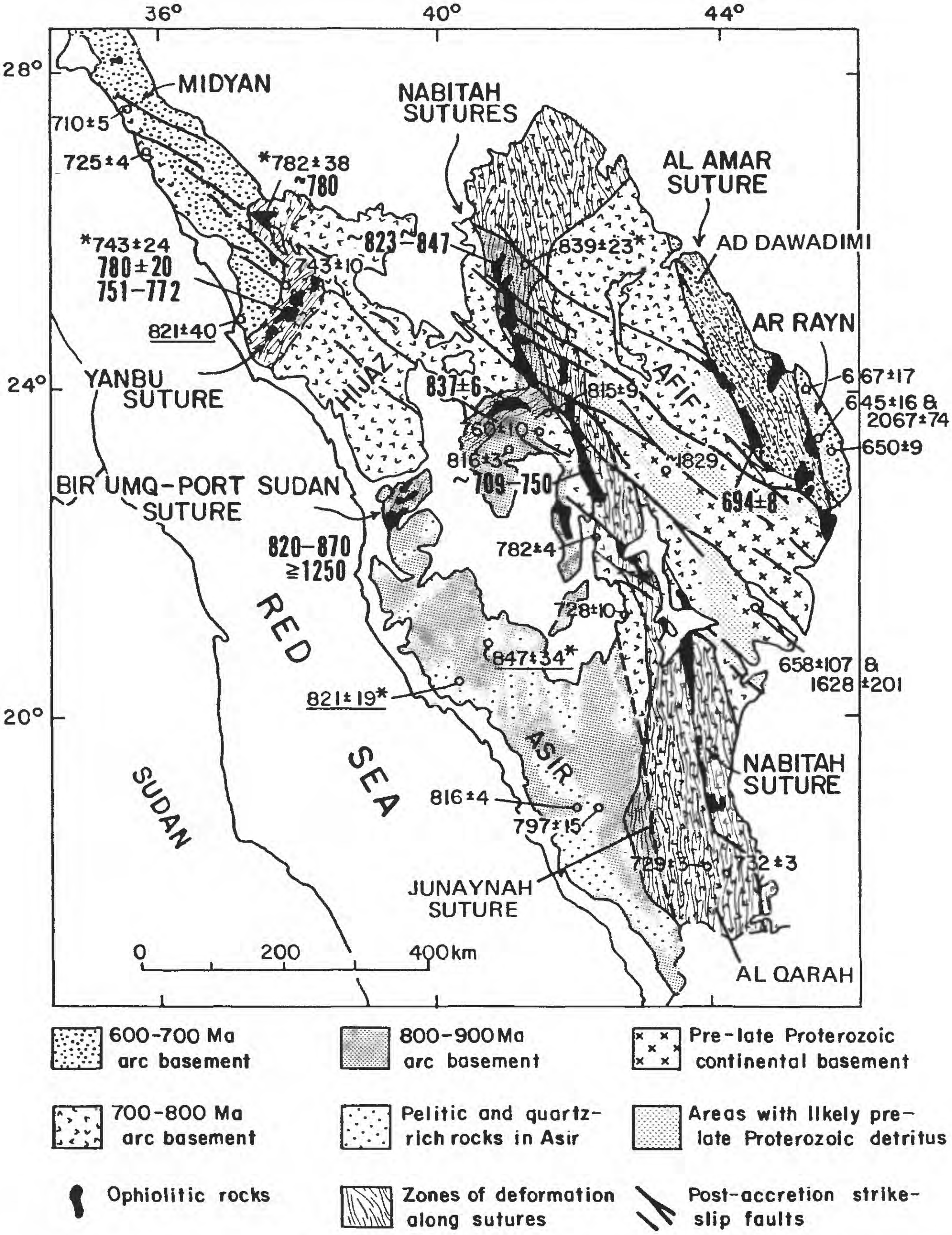


Figure 17.--Terrane map of the Arabian Shield showing U-Pb zircon model ages determined in this study (shown in bold print) compared to the oldest reliable dates on arc plutons and volcanic rocks. Dates preceded by asterisks are from volcanic rocks. Underlined dates are Rb-Sr isochron determinations. Source data for dates not determined in this study given in table 5.

commun., 1984). Camp and Stoeser (written commun., 1986) suggested that this grain may represent transform-fault structure within a pre-accretion oceanic substrate of the arc rocks of the Arabian Shield. However, it is also possible that the deep geophysical anomalies could represent structures within, or relicts of, an early- to middle Proterozoic mafic lower crust.

Nabitah Suture Zone

The age of the Tuluhah ophiolite of the northern Nabitah suture zone is about 823-847 Ma. Unfortunately, it has not been possible to date rocks of any well-defined ophiolite suite from the central and southern Nabitah zone directly; the ages of these ophiolitic rocks have only been established to be coeval with, or older than, the Ad Dafinah quartz diorite (~709-750 Ma), and older than gabbros that intrude the Hamdah complex (626 ± 4 and 664 ± 12 Ma). The oldest arc plutonic and volcanic rocks near the suture range from about 840 Ma in the north to about 730 Ma in the southern parts of the belt (fig. 17). These results indicate that the oldest magmatic arc rocks, and probably the ophiolitic (ocean crustal) rocks as well, along the belt vary more than 100 million years in age; this relationship is difficult to explain in terms of a single subduction-derived suture.

Two possibilities are apparent; either the northern Nabitah zone is correlative with the older of two parallel sutures in the southern Arabian Shield (fig. 17), or it is a continuation of the Bir Umq-Port Sudan suture, and is unrelated to the true Nabitah suture zone of the central and southern Shield. The concept of two parallel sutures in the southern Shield is implicit in those plate tectonic models that call for accretion of the 800-900 Ma Asir microplate to a younger 700 to 800 Ma Hulayfah arc assemblage <u>prior</u> to suturing with a similar-aged Hulayfah arc complex east of the Nabitah zone (Schmidt and others, 1979; Stoeser and Camp, 1985). The older, western suture (the Junaynah suture of Schmidt and others, 1979) in the south is shown as a dashed line in figure 17 and does not contain abundant ophiolitic rocks, possibly as a consequence of the deeper level of exposure and greater degree of deformation in this region of the Shield.

Because of the old (about 830 Ma) dates obtained from the Bir Tuluhah ophiolitic complex and from the volcanic rocks east of the Tuluhah belt reported by Calvez and others (1984, 1985b), we know that rocks equivalent in age to those of the Asir microplate extend as far north as Bir Tuluhah (fig. 1). Because magmatic ages of the ophiolitic rocks at Thurwah, Bir Umq, and Tuluhah overlap in the range 820 to 870 Ma, and because known radiometric ages greater than 800 Ma are restricted to the Asir microplate and to a narrow belt <u>east</u> of the Tuluhah belt, we consider it more likely that the Tuluhah belt is actually an extension of the Bir Umq-Port Sudan suture rather than a continuation the Junaynah zone. We therefore propose that it be termed the Tulahah segment of the Bir Umq-Port Sudan suture.

We also propose that the primary elongation of early (pre-680 Ma) subduction zones and related arc complexes in the western Arabian Shield was parallel to the northeasterly trend represented by the Bir Umq-Port Sudan and Yanbu sutures, and that these trends were transposed during later collision with the Afif microplate. This collision apparently took place along the Nabitah suture zone <u>sensu stricto</u> in the central and southern Arabian Shield between 680 and 640 Ma (Stoeser and others, 1984). The location of the equivalent collisional boundary in the northern Shield is more problematic, but it may correspond to a belt of ophiolitic rocks east of the main Tuluhah segment (fig. 17) and may also extend into a series of listwänite-bearing thrust faults such as those mapped by Quick and Doebrich (1986) and Cole (1986) in the northeastern Shield.

Offset between ophiolitic rocks of the Nabitah suture has been used to calculate a composite strike-slip displacement of about 300 km on various strands of the Najd fault system (Schmidt and others, 1979). In neither of the two interpretations presented above is the Tuluhah segment (fig. 9) of the Bir Umq-Port sudan Suture correlated with the main ultramafic belt of the southern (Hamdah) (fig. 11c) and central (Ad Dafinah) (fig. 10) segments of the Nabitah zone. Accordingly, we question the estimation of 125 km of strike-slip displacement on the central strand of the Najd system (at about lat 24^{o} N.).

Eastern Arabian Shield

Thekair (1976; p. 207-208) proposed a tectonic model for the eastern Arabian Shield in which Abt formation sediments (fig. 12a) were deposited on oceanic crust marginal to a "paleo-Arabian craton", and in which eastward subduction developed below this Arabian plate, with ensuing formation of a Halaban (Hulayfah) island-arc complex (within the Ar Rayn microplate of fig. 1). He suggested that syntectonic granite intruded the complex at a late stage and may have been derived by melting of the craton, of Abt sediments, and of the lower parts of the Hulayfah arc. He concluded that large slabs of the underlying oceanic crust (and mantle) were detached and brought up along the Al Amar-Idsas fault zone where final stages of serpentinization and carbonatization of ultramafic rocks took place.

Al-Shanti and Mitchell (1976) elaborated on this model and interpreted the Abt schist as an accretionary complex scraped off the downgoing oceanic plate adjacent to the Hulayfah arc complex (fig. 13). They suggested that subduction ended because of collision of a continental mass from the west, a mass composed of calcareous and quartzofelspathic "continental margin" metasediments and underlain by continental basement (the "older basement complex" of Delfour, 1979b).

On the basis of the regional geology and chemistry of volcanic rocks east of the Abt schist and a few lava flows intercalated in the Abt, Nawab (1979) argued that the Abt schists were derived from a volcanic arc to the east and from "calc-alkaline sediments" from a continental source to the west. He suggested that the region might better be explained in terms of westward dipping subduction and formation of a marginal (back-arc) basin ajacent to a continental mass to the west (fig. 13). In this manner, sediments from continental rocks to the west and an evolving arc to the east would be accommodated. In contrast, Schmidt and others (1979) consider the rocks to the east of the Abt schist to be an allochthonous block with continental basement that collided with an intraoceanic arc complex to the west. They propose a model that calls for westward-directed subduction in which the Abt schist represents an accretionary complex formed from fore-arc basin sediments which were derived from an arc to the west and the continental block to the east (fig. 13).

Al-Shanti and Gass (1983) were impressed by the very low concentration of high field-strength elements of mafic rocks from both the Al Amar-Idsas and Urd sutures. They noted that the concentrations of zirconium, titanium and niobium are too low even for the back-arc, marginal-sea settings commonly proposed for Phanerozoic ophiolites. The abundances of these trace elements are similar to those of boninitic rocks of the Troodos ophiolite. Al-Shanti and Gass (1983) proposed that the ophiolitic rocks were either formed in a transform fault (to allow melt derivation from extremely depleted mantle peridotite) and partly subducted in a trench, or they represent the products of fore-arc magmatism. Initial magmas formed in fore-arc regions during arc rifting are thought to result in boninitic magmas (Crawford and others, 1981). Al-Shanti and Gass (1983) favored a fore-arc magmatic setting and suggested that the Abt schist might have been deposited in a basin that developed from rifting of an arc complex. This would be similar to the evolution of the Philippine-Mariana region of the western Pacific.

Camp and others (1984) disagreed with the Al-Shanti and Gass model. They pointed out that the ophiolitic rocks cannot be proven to be boninitic because of the possible role of metasomatism in these greenschist and amphibolitic facies rocks. Also, even given this uncertainty, only a few of the analyzed rocks could be classified as boninitic. They also pointed out that, as the rocks on either side of the Abt schist basin are different in terms of metallogenic signature, magnetic characteristics, and lead-isotope characteristics, they cannot be rifted fragments of the same arc complex.

Gass (1984) replied that the trace-element characteristics are very similar to those of boninites, and that even in the Arakapas Lavas of the Troodos ophiolite, only about 10 percent of the volcanic rocks are boninitic. He agreed that the dissimilarity of the terranes on either side of the Abt schist makes it appear unlikely that they are rifted parts of a single arc. However, the extreme depletion in high field-strength elements strongly suggests that the ophiolitic rock originated above a subduction zone.

Results of recent U-Pb zircon dating in the region by Stacey and others (1984) indicate that the ophiolitic rocks of the Urd suture are much younger than assumed by Al-Shanti and Gass (1983). Stacey and others do not rule out any of the above tectonic models, however. The Urd suture was mapped by Delfour (1979b) as separating an "older basement complex" of granite, orthogneiss, diorite, and migmatite on the west from Abt schist. However, zircon dating of a tonalite from this complex yielded an age of 677±9 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7030 and does not indicate derivation from older evolved basement. Zircon from a hypersthene gabbro northwest of the village of Halaban (fig. 12b) yielded a near-concordant result of 694±8 Ma; this was interpreted as the magmatic age of the ophiolite and a maximum deposition age for the Abt schist. These data show that the "older basement complex" of Delfour is, at least in part, younger than the Urd ophiolite, and is somewhat younger than arc rocks of the Hijaz microplate in the northwestern Arabian Shield (fig. 1).

On the basis of a mean model age of 710 Ma for detrital zircons from the Abt schist, Stacey and others (1984) argue that the Abt formation is an accretionary wedge developed during subduction of oceanic crust to the east below the Ar Rayn plate. They also state that convergence ceased due to collision of the Afif plate from the west with the Ar Rayn plate (fig. 1). In these respects, their tectonic reconstruction is similar to the original model proposed by Al-Shanti and Mitchell (1976; fig. 12). They point out that "pre-orogenic" Al Amar-group volcanic arc rocks are present in the Ar Rayn province but absent in the Afif plate, a relationship that indicates eastward directed subduction.

The age of the Abt schist cannot be used to establish relative age relations between source rocks for the Abt and the ophiolitic rocks because it probably represents a mixture of zircons of different ages, and because only a single fraction was dated. The 710-Ma model age is based on the assumption that the observed discordance was produced by a relatively young (Tertiary uplift) event, as has been established for most discordant data from other parts of the Arabian Shield (Cooper and others, 1979; Stoeser and others, 1984). A more complex scenario, involving mixing of a small number of much older zircons with younger zircons (e.g., 650 Ma) followed by Tertiary lead loss from the mixture could also explain the discordancy and cannot be discounted. Similar zircon mixing was proposed by Calvez and others (1985b) for granites that cut the Abt schist.

Although the Urd-suture gabbro yielded a U-Pb zircon age of 694$\pm$8 Ma, the northern part of the Al Amar-Idsas suture is intruded by an aplite dike with zircon model ages of 766$\pm$7 Ma and 711$\pm$12 Ma. As previously noted, Calvez and others (1985b) obtained pre-late Proterozoic zircons with $^{207}Pb/^{206}Pb$ ages between 1,409 and 1,898 Ma from another aplite dike in the same region. At present, it is not possible to determine if our older model age represents contamination of the aplite with inherited zircons, or an older magmatic age and a younger metamorphic event.

If the 766$\pm$7-Ma model age does approximate a magmatic age for the aplite, it would indicate that the northern part of the Al Amar-Idsas suture is considerably older than the Urd suture. This relationship would be difficult to reconcile with the interpretation proposed by Al-Shanti and Gass (1983) that the regional paleostructure of the Abt schist basin was a synclinorium floored by oceanic crust. Calvez and others (1985b) obtained U-Pb zircon data from the Bir Assaliyah gabbro-trondhjemite complex, within the Al Amar suture near Umm ash Sharah (fig. 12d). They report $^{207}Pb/^{206}Pb$ zircon ages of 1196, 1589, and 1413 Ma for trondhjemite and 798, 735, and 857 Ma for gabbro. The highly discordant character of the trondhjemite data clearly indicates inclusion of pre-late Proterozoic zircons. In addition, Calvez and others (1985b) noted inherited cores in zircons from the trondhjemite. They state that the complex intrudes rocks of the adjacent Al Amar group dated at 651$\pm$43 Ma and cite a lower intercept of 645$\pm$16 Ma for the combined gabbro and trondhjemite data.

The Bir Assaliyah <u>gabbro</u> zircon data are similar to those from several of the ophiolites reported in this study. They show limited scatter close to concordia and could be interpreted according to the obduction-metamorphism and Tertiary lead-loss model that we have applied to the other ophiolites. This would result in model ages close to the reported $^{207}Pb/^{206}Pb$ ages of 798, 735 and 857 Ma.

The Bir Assaliyah area lies <u>within</u> the Al Amar suture, a melange belt characterized by serpentine and listwänite-lined faults. Until it is clearly established that the <u>gabbro</u> of the Bir Assaliyah complex intrudes rocks of about 650 Ma, we continue to entertain the possibility that ophiolitic rocks of the Al Amar suture may be considerably older than those of the Urd suture.

Phanerozoic Analogues: Indonesia and Alaska

Model ages for magmatism reported herein suggest that several of the Arabian Proterozoic ophiolitic suites are roughly coeval with the oldest nearby arc rocks (fig. 17). The Thurwah ophiolite gabbro shows evidence of inherited pre-late Proterozoic zircons; however, even in this case, the most concordant zircon fractions yield Tertiary lead-loss model ages that are similar to ages of the oldest nearby arc rocks. The incorporation of older zircons (presumably from a middle to early Proterozoic source) by ophiolitic gabbro suggests one of several distinct tectonic settings.

Several workers have suggested that older continental detritus may have been introduced into the intra-oceanic arc sequences of the western Arabian Shield by transport along trenches from distant continental landmasses (Jackson and Ramsay, 1980; Pallister, 1986). Longitudnal transport of sediments over great distances within the Manila Trench is documented by Lewis and Hayes (1984). Transport of Indian Craton sediments through the Brahmaputra-Ganges river and delta system and along the Java trench to the Indonesian arc system is noted by Hamilton (1979). Relatively high $^{207}Pb/^{206}Pb$ in lavas from Java are attributed to subduction and melting of sediments derived from the Australian and Indian Precambrian shields (Whitford and Jezek, 1982). Assimilation of zircons from subducted sediments into basaltic melt, however, would probably result in complete dissolution. The apparent presence of older zircons in the Thurwah samples suggests that the zircons were derived from wall rocks that were intruded shortly before cooling of the gabbro, and presumably at a high crustal level. A back-arc setting for the ophiolites of the northwestern Arabian Shield (Shanti and Roobol, 1982) would place ophiolitic magmatism on the wrong side of the inferred arc for trench-sediment contamination. Therefore, either a more complex model involving intrusion of earlier-accreted trench sediments is called for, or a different mechanism for transport of pre-late Proterozoic zircons is indicated.

The evidence for pre-late Proterozoic rocks in the western Arabian Shield tends to support continental accretion models that call for the multiple rifting of a pre-existing continental crust as proposed for the Arabian-Nubian Shield by Garson and Shalaby (1976), Stern (1979; 1981), Engel and others (1980), and Kemp and others (1982). An alternative model that more closely fits the geology of the Arabian Shield suggests accretion of a complex region of island arcs, back-arc basins, and rifted island arcs, and small fragments of older continental crust, such as described in the Indonesian region by Hamilton (1978). In the Indonesia region, possible Precambrian rocks are mapped on western Buru in the northern Banda Sea, a continental fragment within a terrane of chiefly Quaternary and Tertiary island-arc rocks (Hamilton, 1978, plate 1). Such a model would help to reduce the anomalously high rates of arc accretion calculated by Reymer and Schubert (1984; 1986). It is also in accord with the concept of exotic-terrane accretion put forward for the Arabian-Nubian Shield by Kröner (1985). This concept involves accretion of rocks not generated in intraoceanic arcs, such as continental microplates and oceanic plateaus.

Alaska and the western North American Cordillera represent a Phanerozoic accreted terrane (Silver and Smith, 1983) that is probably similar in many respects to an early stage in the development of the Arabian Shield. Mainland Alaska is composed of a complex mosaic of island arcs and exotic terranes, many of which apparently originated in southerly latitudes and were transported with adjacent oceanic plates to be accreted in subduction complexes that vary widely in age (Jones and others, 1982, 1984; Churkin and others, 1982). Relatively old rocks, or rocks that show U-Pb isotopic evidence of inheritance from Proterozoic sources (such as the Yukon crystalline terrane of Churkin and others, 1982, and the Kilbuck terrane of Turner and others, 1983) are entrained within young oceanic and arc-volcanic and plutonic terranes.

The Microplate Model

Stoeser and Camp (1985) divided the Arabian Shield into five terranes ("microplates", as used herein) bounded by ophiolite-lined sutures. Johnson and Vranas (1984) proposed ten separate terranes, each having characteristic types of mineralization and each bounded by ophiolite-bearing as well as ophiolite-free faults and zones of deformation. We believe that the microplates of Stoeser and Camp are actually composed of numerous rock-belts that should be defined as separate terranes according to current usage of the terrane concept in Phanerozoic accretionary regions such as Alaska. However, lacking definitive indicators of paleo-positions (such as paleomagnetic data and faunal associations), we prefer to define a minimum number of microplates and base them on the presence of ophiolitic sutures. We therefore retain the major divisions of Stoeser and Camp, subdividing only the Al Qarah microplate from the Asir and adding the Ad Dawadimi microplate (Johnson and Vranas, 1984) that contains the Abt schist belt in the eastern Shield (figs. 1 and 17).

We use the ages of the ophiolitic rocks to date the oceanic crust that must have been in the now-collapsed basins that existed within or between arc complexes and we compare the ages of the oldest arc rocks in each microplate to get an indication of the "arc basement" age. As all of the microplates have undergone post-accretion magmatism, the younger limit of arc activity is often difficult to establish and is not a useful microplate discriminator.

The boundary between the 800-900 Ma intraoceanic Asir microplate and the 700-800 Ma Hijaz microplate appears to extend north to the Bir Umq-Port Sudan suture and probably continues north along the western part of the Nabitah mobile belt as shown in figure 17. We consider the ophiolitic rocks that formerly defined the northernmost part of the Nabitah suture (extending through the Tuluhah complex) to be a continuation of the Bir Umq-Port Sudan Suture.

With the revision of the pre-750 Ma radiometric dates in the Hijaz microplate to younger ages, there is no longer a clear age distinction between the Hijaz and Midyan microplates. Both microplates contain older suites of arc plutonic and volcanic rocks ranging in age from 700 to 750 Ma. The Midyan microplate apparently contains many young (about 625 Ma) calc-alkaline rocks (Clark, 1985), but these rocks were deposited on a 700-725-Ma arc basement.

The western part of the Hijaz microplate and the northernmost parts of the Asir microplate apparently contain either fragments or detritus from pre-late Proterozoic continental crust and in this respect are similar to the Afif microplate and its early Proterozoic fragment.

The age of final suturing between the various microplates is exceedingly difficult to establish; it can only be rigorously bracketed by the ages of the ophiolitic rocks and the ages of rocks that either intrude, or are deposited over, the sutures. The age of final accretion along the Yanbu suture is indicated by the dates from the Jabal al Wask gabbros (~740 Ma) and from the Kamal layered intrusion (618±27 Ma, Sm-Nd mineral isochron, written commun., Holly Stein, 1986). The Kamal intrusion is undeformed and transects the northeast extension of the suture (fig. 6). Final suturing along the Yanbu zone probably also postdates the Salajah tonalite (740-695 Ma) and is therefore restricted to 620-700 Ma.

At present, it is not possible to bracket closely the ages of other sutures in the Arabian Shield. It is only possible to give a lower limit by using the common "post-orogenic" (610-510 Ma) plutons that perforate the Arabian Shield and are generally regarded to be the products of melting induced by crustal thickening following accretion (Stoeser, 1986). Ideally, the age of final suturing is bracketed between the ages of the latest magmatic arc rocks and earliest post-collisional magmas in ajacent microplates. Here, however, there are a number of problems in making this distinction. There is abundant evidence in the Arabian Shield of overlapping ages of arc magmatism within single microplates. Modern analogues show that there is a time lag between the end of plate convergence and the cessation of "subduction-related" magmatism. Distinctions between "synorogenic" and "postorogenic" plutons are not necessarily diagnostic because both compressional and tensional regimes are known to occur within active arcs.

LEAD-ISOTOPE CHARACTERISTICS

The lead-isotope results from the two eastern Arabian Shield samples (Ar Ridaniyah and Urd) are of particular interest. Table 4 shows that in both cases the Stacey and Kramers (1975) feldspar-lead model ages are greater than their zircon ages, i.e., the uranium-derived lead growth is retarded compared to single-stage development since 3.7 Ga. For all the other samples in the study, the Stacey-Kramers model ages are less than their zircon ages by a considerable margin; this indicates more rapid growth than predicted by single-stage evolution.

Such a contrast in lead characteristics has been noted in other crustal rocks of the Arabian Shield (Stacey and Stoeser, 1983). Arc rocks in the west have feldspar model ages <u>less</u> than their zircon ages, but many plutonic rocks in the eastern Arabian Shield have Stacey-Kramers model ages that are <u>greater</u> than their zircon ages. Stacey and Stoeser (1983) decided that the lead data from the east-central Shield rocks indicate the presence of older continental lower crust, perhaps as old as 2,000 Ma. Subsequently, zircon from the Kabid gneiss of the south-central Afif microplate yielded an upper intercept age of 1,829$\pm$45 Ma (Stacey and Agar, 1985). Calvez and others (1985a, 1985b) reported U-Pb data from early Proterozoic zircons at two locations in the east-central Shield.

We note that the Urd ophiolite lead data may be a late Precambrian equivalent of the data from the Cretaceous Samail ophiolite in Oman. Samples from both areas exhibit uranium depletion relative to thorium and lead, so that their data lie just above the mantle curve in the $^{208}Pb/^{204}Pb$ graph of figure 16. In addition, for both samples the Stacey-Kramers model age is 50-100 Ma less than the zircon age. The presence of Archean continental crust nearby in Oman is indicated by the very high ratios obtained from a Cretaceous(?) galena from Wadi Nuju (Stacey and others, 1980). Chen and Pallister (1981) noted that most of the igneous rocks of the Samail ophiolite have $^{207}Pb/^{204}Pb$ values that plot within the MORB field, but that the serpentinized peridotites have anomalously high $^{207}Pb/^{204}Pb$ as well as $^{208}Pb/^{204}Pb$ values. They suggested that these results as indicate that the ophiolitic magmas formed from an oceanic mantle source with slightly high Th/U and that the peridotites were serpentinized in a continental (post-obduction) setting. Hamelin and others (1984) confirmed the relatively high $^{208}Pb/^{204}Pb$ values of the Samail ophiolite and suggested that the ophiolite originated in an interarc or premature arc setting (presumably where melting of an already highly depleted mantle source would be expected).

The evidence of the presence of Archean continental crust, as inferred from lead-isotope data from galena and serpentinite in Oman and the retarded lead-isotope characteristics of Samail igneous rocks, is either coincidental and related to an unusual oceanic mantle source for the igneous rocks, or results from involvement with subcontinental mantle or ancient lower continental crust in an unknown manner. A similar arguments can be used to explain the unusual lead character of the Urd ophiolite where the existence of older crust has been established to the south (fig. 17).

Retarded uranogenic lead-isotope growth has been found almost exclusively in rocks from continental mantle or lower crustal sources. The xenoliths and basalts from the Snake River Plain-Yellowstone region are good examples (Leeman 1979; Doe and others, 1982). However, retarded lead-isotope characteristics have been observed also in the Koolau volcanic series in Hawaii (Stille and others, 1983); these rocks are distinct from typical Hawaiian lavas in having epsilon Nd of approximately 1 and $^{87}Sr/^{86}Sr$ values as high as 0.70412.

The retarded lead-isotope characteristics of the Urd gabbro therefore do not define a unique tectonic setting. However, the ophiolitic rocks of the Urd and Al Amar sutures also have unusually low abundances of high field-strength elements, and this feature led Al-Shanti and Gass (1983) to propose a fore-arc setting and boninitic affinity for these rocks. This model provides an appealing method for high field-strength and large-ion lithophile-element depletion. The lead-isotope data, however, would require uranium depletion well before ophiolitic (fore-arc) magmatism.

We believe that the geologic setting and ophiolitic character of the Urd and Al Amar-Idsas mafic and ultramafic rocks, the association with arc volcanic rocks and basinal sediments, and the strong depletion of high field-strength elements favors an oceanic setting, probably within a volcanic arc. The Urd gabbro was probably derived from a mantle source that was depleted in uranium relative to thorium and lead well before ophiolitic magmatism. However, we cannot rule out assimilation of lower continental crust or subcontinental mantle, perhaps in the early stages of development of a marginal back-arc basin within the edge of an early Proterozoic continent or continental fragment. This is suggested by the presence of 2,000-Ma zircons in the Al Amar region (Calvez and others, 1985a, 1985b) and the 1,830-Ma gneiss to the south in the Afif microplate.

Lead-isotope data from the Precambrian ophiolites are spatially associated with the Groups I and II types of lead designated for the crustal rocks of the Arabian Shield by Stacey and others (1980) and Stacey and Stoeser (1983). The ophiolite data are of two main types. The first type, lead with equivalent composition to that from present day MORB is found in the ophiolites of the northwestern Arabian Shield, as well as in the rocks from the Nabitah suture zone (apparently along its entire length). The arc rocks of the western Arabian Shield have evolved from this type of mantle as has their Group I type lead. There is significant contamination from older crustal material at Thurwah, but the source of this contamination has not yet been established.

The second type, lead with retarded $^{206}Pb/^{204}Pb$ growth yielding apparently elevated $^{208}Pb/^{204}Pb$ values relative to MORB, exists in the Urd ophiolitic complex in the Halaban region of the eastern Shield. This indicates derivation from a mantle source with low U/Pb and consequently high Th/U relative to MORB. It also suggests that either the geographic association of lead with retarded $^{206}Pb/^{204}Pb$ growth with Group II (continental) lead in the eastern Arabian Shield (Stacey and Stoeser, 1983) is coincidental, or that the crustal rocks of the eastern Shield have evolved from mantle with high Th/U. Alternatively, the retarded $^{206}Pb/^{204}Pb$ in the Urd gabbro may indicate assimilation of continental lower-crustal rocks, perhaps during initial stages of the development of a marginal back-arc basin. Clearly, more detailed geologic, geochemical, and isotopic studies of these unusual rocks are needed.

The Nabitah suture represents an important boundary within the Arabian Shield that separates rocks of oceanic affinity on the west from those on the east that have interacted with older continental crust. Lead-isotope data are currently available from only one ophiolitic sample from the eastern Arabian Shield; however, these data are clearly distinct from ophiolitic data obtained from rocks west of the Nabitah belt. Work is in progress to determine if the dichotomy in lead-isotope compositions between the western and eastern provinces extends to other ophiolitic rocks of the eastern Shield.

METALLOGENESIS, TERRANE MODELS, AND OPHIOLITES

The definition of exotic-terrane boundaries has obvious importance for mineral exploration. Significant lead-zinc-silver, tin-tungsten-beryllium, flourine, and rare-metal (REE, U, Nb, Ta, Zr) mineralization is more likely to exist in terranes that either have continental roots or have undergone extensive remelting. On the other hand, oceanic-arc terranes tend have concentrations of copper-zinc-gold-silver and contain Kuroko-type deposits.

In addition to the importance of terrane mapping to mineral exploration, the ophiolitic rocks themselves are targets for certain types of mineralization. Cyprus-type copper mineralization hosted by pillow lava is rare in the Arabian Shield, but does occur in association with the Bir Umq complex and at Ash Shizm, north of the Jabal Ess complex (see reviews by Johnson and Vranas, 1984; Johnson and others, 1986). In addition, ophiolitic peridotite and serpentinite have been widely prospected for chromite and related nickel and platinium-group metal deposits. World-wide, ophiolitic chromite deposits are dwarfed by those of continental layered intrusions such as the Bushveld, but podiform chromite is currently being mined in the Zambales ophiolite (Philippines) and in the Samail ophiolite (Oman). To date, chromite segregations within the Proterozoic Arabian Shield ophiolites have not been of sufficient size or abundance to justify mining.

Based on this study's field reconnaissance of the ophiolitic rocks of the Arabian Shield, we consider the most intriguing mineral exploration targets to be cobalt and gold mineralization related to the serpentinites. A number of workers have related gold mineralization to ultramafic source rocks (see review in Pyke, 1976). Viljoen and others (1969) proposed that the ultramafic komatiites of the Archean Barberton greenstone belt are the source rocks for gold deposits within the Steynsdorp goldfields. Pyke (1976) noted a close spatial association of gold deposits with Archean ultramafic rocks in northeastern Ontario and suggested that the ultramafic rocks were the principal source rocks that, through talc-carbonate alteration of serpentinite, released significant amounts of gold. According to Buisson and Leblanc (1985), the gold mineralization in listwänites of the Arabian Shield ophiolites resulted from late-stage hydrothermal alteration of the ultramafic rocks in fault zones. They suggest that gold and cobalt are leached from the opaque minerals in serpentinite, transported upward in fault zones, and progressively concentrated into listwänite and late quartz veins (bibirites).

Gold mineralization has been found along the length of the Nabitah mobile belt in the Arabian Shield and tends to be concentrated in quartz veins related to plutons that intrude serpentinized peridotites and carbonated serpentinite (Worl, 1979). This setting is similar to that in the southern part of the Mother Load system of the Sierra Nevada foothills of California (Knopf, 1929). Gold mineralization has been discovered along the metagabbro and serpentinite-listwänite-lined Raha fault zone in the northeastern Shield (Smith, 1985). Ancient gold mines are also located along the contact of a quartz diorite pluton that intruded serpentinite of the Jabal al Wask complex (Chevremont and Vaillant, 1983).

The mineralized Bou Azzer ophiolite of Morocco, as described by Leblanc (1981) and Leblanc and Billaud (1982), provides a useful model for mineral exploration in the ophiolitic suites of the Arabian Shield. Cobalt (Ni-Fe) arsenide orebodies related to the Bou Azzer ophiolite in Morocco have produced 50,000 tons of cobalt metal (4 to 8 percent of world production since 1930). This Moroccan ophiolite has similar internal characteristics and is exposed in a tectonic setting similar to some of the ophiolites of the Arabian Shield. The Bou Azzer ophiolite is within a Pan-African mobile belt at the contact with the 2.0-Ga west African Eburnean Craton in the central Anti-Atlas mountains, and is indirectly dated at about 790 Ma. The ophiolitic rocks are disrupted by faulting and are intruded by mafic plutons; listwänite and bibirite are extensively developed from serpentinite; laterites have formed over the ophiolitic rocks; podiform chromite is present in the serpentinite and copper sulfides occur in associated mafic lavas. Based on a geochemical study, Boudinier and others (1984) suggested that the Bou Azzer ophiolite formed in marginal basin behind an active island arc.

Leblanc and Billaud (1982) concluded that the secondary magnetite (derived through serpentinization of peridotite) is the source for cobalt, nickel, and native gold at Bou Azzer. The cobalt orebodies are always in contact with serpentinite, either along steep fault contacts, along contacts with gabbro or diorite, or along the contact of the serpentinite with the overlying sedimentary and volcanic rocks. The orebodies occur within quartz-carbonate gangue (listwänite and bibirite) that contains residual chromite grains. Leblanc and Billaud (1982) proposed a metallogenic model that calls for the concentration of cobalt and nickel in three main stages: 1) serpentinization of peridotite, resulting in concentration of the metals into magnetite, 2) weathering and breakdown of serpentinite producing concentrations of cobalt and nickel in Mn-Fe hydroxides, serpentines, and bibirite, and 3) remobilization and concentration of cobalt in arsenides within latest Pan-African structures. Bouisson and LeBlanc (1985) noted that native gold is present within the Bou Azzer listwänites and arsenides, and they proposed that gold and cobalt are both derived from magnetite in serpentinite, and are transported together as sulfur and arsenic complexes during hydrothermal alteration of serpentinites.

A speculative model for gold mineralization within the Arabian Shield can be developed by combining elements of the Bou Azzer mineralization model of Bouisson and LeBlanc (1985) with the metallogenic model for the Sierra Nevada foothills belt developed by Böhlke and Kistler (1985). Gold (and cobalt) may be derived from ultramafic rocks deep within sutures. Other source rocks are possible, but ultramafic rocks are favored because; first, they contain high gold (as well as cobalt and nickel) abundances compared to other crustal rocks, second, they tend to be concentrated along major crustal flaws (sutures) that may act as channelways for deeply derived hydrothermal fluids, and third, serpentinization and reaction of magnetite produced during serpentinization provide mechanisms for concentration and liberation of gold, cobalt, nickel, and other metals.

In accreted-arc terranes, such as the Arabian Shield or the Cordillera of western North America, subduction and consequent devolatilization of subducted oceanic crust must have occurred repeatly, and must have taken place under crust that already contained sutures from earlier subduction and arc accretion events. These pre-existing sutures could be hydrothermally reactivated by fluids derived from deep-seated arc magmas and their metamorposed host rocks. Serpentinization concentrates cobalt, nickel, and gold into magnetite, and magnetite may liberate these metals either during steatization or directly through reactions with hydrothermal fluids. The result could be the upward transport of gold and related metals (derived initially from peridotite) along old suture zones, followed by deposition of the gold in quartz veins near, or within, the suture. One may further speculate that native gold is deposited with Co-Ni arsenides in listwänites, and in bibirites or quartz veins, due to reduction of hydrothermal fluids upon mixing with water present at shallow crustal levels within serpentinites.

Most of the known metallic-ore districts of Arabia were "rediscovered" in the 20th century with relative ease because of the presence of ancient workings. In contrast, ancient man would not have developed cobalt and nickel deposits, and one would not expect to find ancient cobalt and nickel workings. Mineral exploration has progressed in the Arabian Shield to the point that significant new discoveries will probably be mostly cryptic, either as buried deposits or of a type not formerly sought by the ancients (such as bauxite, tin, tungsten, and cobalt). Therefore, exploration based on mineralization models will become increasingly important. An obvious exploration target, based on the Bou Azzer and Sierra Nevada foothills models is for gold, cobalt, and nickel associated with the very common listwänite and bibirite zones that bound many of the late Proterozoic ophiolites of Arabia.

DATA STORAGE

Data work and materials used in preparation of this report are archived as Data File USGS-DF-07-04 stored in the office of the U.S. Geological Survey Mission in Jeddah, Saudi Arabia.

No updated information was added to the Mineral Occurrence Documentation System (MODS) data bank and no new localities were established in connection with this work.

REFERENCES CITED

Abo Rashid, A., 1973, Geology and mineralization of Rabigh quadrangle--Hijaz area: Saudi Arabian Directorate General of Mineral Resources Report.

Agar, R. A., 1985, Stratigraphy and palaeogeography of the Siham group: direct evidence for a late Proterozoic continental microplate and active continental margin in the Saudi Arabian Shield: Journal of the Geological Society of London, v. 142, p. 1205-1220.

Aguttes, J., 1971, Geology and mineral exploration of the Jabal Ash Sheba quadrangle, photomosaic 104 West: Bureau de Recherches Geologiques et Minieres Technical Record 71 JED 6, 35 p.

Aguttes, J., and Duhamel, M., 1971, Geology and mineral exploration of the Jabal Sayid quadrangle, photomosaic 111 East: Bureau de Recherches Geologiques et Minieres Technical Record 71 JED 4, 49 p.

Al-Rehaili, M. H., 1980, Geology of the mafic-ultramafic complex of Bi'r 'Umq area: M.Sc. thesis, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia.

Al-Rehaili, M. H., Bokhari, M. M., Delfour, J., El-Mahdy, O. R., Kemp, J., Letalenet, J., Roobol, M. J., Sahl, M., and Turkistani, A. R., 1978, Evolution and mineralization of the Arabian-Nubian shield, in Guide-book for an excursion in the Jabal Sayid region: King Abdulaziz University, Institute of Applied Geology, Research Series No. 6, 67 p.

Al-Rehaili, M. H., and Warden, A. J., 1980, Comparison of the Bir Umq and Hamdah ultrabasic complexes, Saudi Arabia, in Tahoun, S. A., ed., Evolution and mineralization of the Arabian-Nubian Shield, v. 4: King Abdulaziz University Institute of Applied Geology Bulletin 3, Oxford-New York, Pergammon Press, p. 143-156.

Al-Shanti, A. M., and Gass, I. G., 1983, The upper Proterozoic ophiolite melange zones of the easternmost Arabian shield: Journal of the Geological Society of London, v. 140, p. 867-876.

Al-Shanti, A. M. S., and Mitchell, A. H. G., 1976, Late Precambrian subduction and collision in the Al Amar--Idsas region, Arabian Shield, Kingdom of Saudi Arabia: Tectonophysics, v. 30, p. T41-T47.

Al Tayyar, J. A., and Smith, J. W., 1981, A preliminary note on Precambrian blueschist rocks in the Midyan area: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report DGMR-OF-01-13, 7 p.

Anonymous, 1972, Penrose field conference on ophiolites: Geotimes, v. 17, p. 24-25.

Aslac, C., Lacomme, A., Delfour, J., Sabir, H., Le Metour, J., Turkistani, A. R., Kemp, J., Al-Shanti, A., Fauvelet, E., 1982, Guide-book for excursion "B" in the Jabal Sayid region: First Symposium, International Geological Correlation Project 164, Pan-African Crustal Evolution in the Arabian-Nubian Shield, King Abdulaziz Faculty of Earth Sciences Research Series No. 15, 58 p., 7 pl.

Bakor, A. R., 1973, Jabal al Wasq: a Precambrian basic and ultrabasic igneous complex in the northern Hijaz of Saudi Arabia: Unpublished thesis, University of Leeds (England), 170 p.

Bakor, A. R., Gass, I. G., and Neary, C. R., 1976, Jabal al Wask, northwest Saudi Arabia: An Eocambrian back-arc ophiolite: Earth and Planetary Science Letters, v. 30, p. 1-9.

Barker, F., 1979, Trondhjemite: Definition, environment and hypothesis of origin, in Barker, F., ed., Trondhjemites, dacites, and related rocks: Elsevier, Amsterdam, p. 1-12.

Baubron, J. C., Delfour, J., and Vialette, Y., 1976, Geochronological measurements (Rb/Sr; K/Ar) on rocks of the Arabian Shield of Saudi Arabia: Bureau de Recherches Geologiques et Minieres (Saudi Arabian Mission) Open-File Report 76-JED-22, 152 p.

Bokhari, F. Y., and Kramers, J. D., 1981, Island arc character and late Precambrian age of volcanics at Wadi Shwas, Hijaz, Saudi Arabia: Geochemical and Sr and Nd isotopic evidence: Earth and Planetary Science Letters, v. 54, p. 409-422.

Boudier, F., and Coleman, R. G., 1981, Cross section through the peridotite in the Samail ophiolite, southeastern Oman Mountains: Journal of Geophysical Research, v. 86, No. B4, p. 2573-2592.

Boudinier, J. L., Dupuy, C., and Dostal, J., 1984, Geochemistry of Precambrian ophiolites from Bou Azzer, Morocco: Contributions to Mineralogy and Petrology, v. 87, p. 43-50.

Bowden, R. A., Smith, G. H., and Hopwood, T., 1981, Reconnaissance geological map of the Jabal Sayid District: Saudi Arabian Deputy Ministry of Mineral Resources Open-File Report RF-0F-01-8.

Brown, G. F., and Coleman, R. G., 1972, The tectonic framework of the Arabian Peninsula: International Geological Congress, 24th, Canada, Section 3, p. 300-305.

Brown, G. F., and Jackson, R. O., 1960, The Arabian Shield: International Geological Congress, 21st, Copenhagen, Proceedings, Section 9, p. 69-77.

Bryan, W. B., 1979, Low-K2O dacite from the Tonga-Kermadec island arc: Petrography, chemistry, and petrogenesis, in Barker, F., ed., Trondhjemites, dacites, and related rocks: Elsevier, Amsterdam, p. 581-600.

Buisson, G., and Leblanc, M., 1985, Gold in carbonatized ultramafic rocks (listwänites) from ophiolite complexes: Economic Geology, v. 80, p. 2028-2029.

Böhlke, J. K., and Kistler, R. W., 1986, Rb-Sr, K-Ar, and stable isotope evidence for the ages and sources of fluid compounds of gold-bearing quartz veins in the northern Sierra Nevada foothills metamorphic belt, California: Economic Geology, v. 81, p. 296-322.

Calvez, J. Y., Alsac, C., Delfour, J., Kemp, J., and Pellaton, C., 1984, Geologic evolution of western, central and eastern parts of the northern Precambrian Shield, Kingdom of Saudi Arabia, in Proceedings Volume No. 6., Pan-African Crustal Evolution in the Arabian-Nubian Shield, International Geological Correlation Project No. 164: King Abdulaziz University Faculty of Earth Sciences, Jeddah, Saudi Arabia, p. 24-48.

Calvez, J. Y., Delfour, J., and Feybesse, J. L., 1985a, 2,000-million-years old inherited zircons in plutonic rocks from the Al 'Amar region: New evidence for an early Proterozoic basement in the eastern Arabian Shield: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-05-11, 28 p.

Calvez, J. Y., Delfour, J., Kemp, J., and Elsass, P., 1985b, Pre Pan-African inherited zircons from the northern Arabian Shield: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-05-13, 22 p.

Calvez, J. Y., Pellaton, C., Alsac C., Tegyey, M., 1982, Geochronology and geochemistry of plutonic rocks in the Umm Lajj and Jabal al Buwanah areas: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-02-36, 36 p.

Camp, V. E., 1984, Island arcs and their role in the evolution of the western Arabian Shield: Geological Society of America Bulletin, v. 95, p. 913-921.

Camp, V. E., Jackson, N. J., Ramsay, C. R., Roobol, M. J., Stoeser, D. B., and White, D. L., 1984, *Discussion* on the Upper Proterozoic ophiolite mèlange zones of the easternmost Arabian Shield: Journal of the Geological Society of London, v. 141, p. 1083-1087.

Chen, J. H., and Pallister, J. S., 1981, Lead isotopic studies of the Samail ophiolite, Oman: Journal of Geophysical Research, v. 86, p. 2699-2708.

Chevremont, P., 1984, Petrology of the Ha'il and Lakathah ultramafic-mafic complexes: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-04-2, 34 p.

Chevremont, P., and Johan, Z., 1981, Wadi Kamal-Wadi Murratijah ultramafic-mafic layered complex: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-01-36, 143 p.

_______________, 1982a, Wadi Al Hwanet-Jabal Iss ophiolitic complex: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-02-14, 30 p.

_______________, 1982b, The Al 'Ays ophiolitic complex: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-02-5, 65 p.

Chevremont, P., and Vaillant, F. X., 1983, Mineral investigation for chromite and gold related to the Al 'Ays ultramafic complex: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-03-7, 66 p.

Churkin, M. Jr., Foster, H. L., and Chapman, R. M., 1982, Terranes and suture zones in East Central Alaska: Journal of Geophysical Research, v. 87, No. B5,
p. 3718-3730.

Claesson, S., Pallister, J. S., and Tatsumoto, M., 1984, Samarium-Neodymium data on two late Proterozoic ophiolites of Saudi Arabia and implications for crustal and mantle evolution: Contributions to Mineralogy and Petrology, v. 85, p. 244-252.

Clark, M. D., 1985, Late Proterozoic crustal evolution of the Midyan region, northwestern Saudi Arabia: Geology, v. 13, p. 611-615.

Cole, J. C., 1986, Geology of the Aban al Ahmar quadrangle, Sheet 25F, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for mineral Resources Open-File Report USGS-OF-04-9, 86 p. DMMR Geoscience Map GM-105A.

Coleman, R. G., 1977, Ophiolites: Ancient oceanic lithosphere?: Springer-Verlag, Berlin, 229 p.

Coleman, R. G., and Peterman, Z. E., 1975, Oceanic plagiogranite: Journal of Geophysical Research, v. 80, p. 1099-1108.

Condie, K. C., 1982, Plate tectonics and crustal evolution: Pergamon Press, New York, Second Edition, 310 p.

Cooper, J. A., Stacey, J. S., Stoeser, D. B., and Fleck, R. J., 1979, An evaluation of the zircon method of isotopic dating in the southern Arabian Craton: Contributions to Mineralogy and Petrology, v. 68, p. 429-439.

Crawford, A. J., Beccaluva, L., and Serri, G., 1981, Tectono-magmatic evolution of the west-Philippine-Mariana region and the origin of Boninites: Earth and Planetary Science Letters, v. 54, p. 346-356.

Davies, F. B., 1984, Strain analysis of wrench faults and collision tectonics of the Arabian-Nubian Shield: Journal of Geology, v. 92, p. 37-53.

De La Boisse, H., Kemp, J., Calvez, J. Y., Lancelot, J. R., 1980, U-Pb dating of Precambrian rocks of the Arabian Shield. Comparison with the crustal evolution of Western Africa, International Geological Congress, 26th, Paris, Abstract Volume II, p. 580.

Delfour, J., 1967, Report on the mineral resources and geology of the Hulayfah-Musayna'ah region (sheet 78, zone 1 north): Bureau Recherches Geologiques et Minieries Open-File Report SG-JED-66-A-8, 138 p.

_______________, 1977, Geology of the Nuqrah quadrangle, 25E, Kingdom of Saudi Arabia: Saudia Arabian Directorate General of Mineral Resources Geologic Map GM-28, 31 p.

_______________, 1979a, Upper Proterozoic volcanic activity in the northern Arabian Shield, Kingdom of Saudi Arabia in Cooray, P. G., and Tahoun, S. A., eds., Evolution and mineralization of the Arabian-Nubian Shield, King Abdulaziz University Institute of Applied Geology Bulletin, v. 2, p. 59-75.

Delfour, J., 1979b, Geologic map of the Halaban quadrangle, sheet 23G, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-46-C, 31 p., 1 pl.

_______________, 1980, Geologic map of the Wadi ar Rika quadrangle, sheet 22G, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-51-C, 34 p., 1 pl.

_______________, 1981, Geologic, tectonic and metallogenic evolution of the northern part of the Precambrian Arabian Shield (Kingdom of Saudi Arabia): Bureau de Recherches Geologiques et Minieres Bulletin (ser. 2) sec. II, No. 1-2, p 1-19.

Delfour, J., Dhellemmes, R., Elsass, P., Vaslet, D., Brosse, J., LeNindre, Y., and Dottin, O., 1982, Geologic map of the Ad Dawadimi Quadrangle, Sheet 24G, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM-60-A, 36 p.

Dick, H. J. B., 1977, Partial melting in the Josephine Peridotite I, The effect on mineral composition and its consequence for geobarometry and geothermometry: American Journal of Science, v. 277, p. 801-832.

Dick, H. J. B., and Bullen, T., 1984, Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas: Contributions to Mineralogy and Petrology, v. 86, p. 54-76.

Dixon, T. H., 1981, Age and chemical characteristics of some pre-Pan-African rocks of the Egyptian Shield: Precambrian Research, v. 14, p. 119-133.

Doe, B. R., Leeman, W. P., Christiansen, R. L., and Hedge, C. E., 1982, Lead and strontium isotopes and related trace elements as genetic tracers in the upper Cenozoic rhyolite-basalt association of the Yellowstone Plateau volcanic field: Journal of Geophysical Research, v. 87, p. 4785-4806.

Duparc, L., Molly, E., and Borloz, A., 1927, Sur la bibirite, une roche nouvelle: Society Physics, Geneva, Comptes Rendus, v. 44, p. 3.

Duyverman, H. J., Harris, N. B. W., and Hawkesworth, C. J., 1982, Crustal accretion in the Pan African: Nd and Sr isotope evidence from the Arabian Shield: Earth and Planetary Science Letters, v. 59, p. 315-326.

Egyptian Geological Survey and Mining Authority, 1981, Geologic map of Egypt: Egyptian Ministry of Industry and Mineral Resources, scale 1:2,000,000.

El Bayoumi, R. M. A., 1980, Ophiolites and associated rocks of Wadi Ghadir, East of Gebel Zabara, Eastern Desert, Egypt: Unpublished thesis., Cairo University, Cairo, Egypt, 227 p.

Engel, A. E. J., Dixon, T. H., and Stern, R. J., 1980, Late Precambrian evolution of Afro-Arabian crust from ocean arc to craton: Geological Society of America Bulletin, Part I., v. 91, p. 699-706.

Fitches, W. R., Graham, R. H., Hussein, I. M., Ries, A. C., Shackleton, R. M., and Price, R. C., 1983, The Late Proterozoic ophiolite of Sol Hamed, NE Sudan: Precambrian Research, v. 19, p. 385-411.

Fleck, R. J., 1981, Age of diorite-granodiorite gneisses of the Jiddah-Makkah region, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-01-1, 18 p. DMMR Professional Paper PP-2, P. 21-27.

Fleck, R. J., Coleman, R. G., Cornwall, H. R., Greenwood, W. R., Hadley, D. G., Schmidt, D. L., Prinz, W. C, and Ratte, J. C., 1976, Geochronology of the Arabian Shield, western Saudi Arabia: K-Ar results: Geological Society of America Bulletin, v. 87, p. 9-21.

Fleck, R. J., Greenwood, W. R., Hadley, D. G., Anderson, R. E., and Schmidt, D. L., 1980. Rubidium-strontium geochronology and plate-tectonic evolution of the southern part of the Arabian Shield: U.S. Geological Survey Professional Paper 1131, 38 p.

Fleet, M. E., and Barnett, R. L., 1978, Al^{IV}/Al^{VI} partitioning in calciferous amphiboles from the Frood Mine, Sudbury, Ontario; Canadian Mineralogist, v. 16, p. 527-532.

Frisch, W., and Al-Shanti, A., 1977, Ophiolite belts and the collision of island arcs in the Arabian Shield: Tectonophysics, v. 43, p. 293-306.

Garrison, J. R., Jr., 1980, The Coal Creek serpentinite, Llano uplift, Texas: A fragmant of an incomplete Precambrian ophiolite: Geological Society of America Abstracts with Programs, v. 12, No. 7, p. 431.

Garson, M. S., and Shalaby, I. M., 1976, Precambrian-Lower Paleozoic plate tectonics and metallogenesis in the Red Sea region, in Strong, D. F., ed., Metallogeny and plate tectonics: Geological Association of Canada, Special Paper 14, p. 573-595.

Gass, I. G., 1979, Evolutionary model for the Pan-African crystalline basement, in Tahoun, S. A., ed., Evolution and mineralization of the Arabian-Nubian Shield, v. 1: King Abdulaziz University, Institute of Applied Geology, Bulletin 3, Oxford-New York, Pergammon Press, p. 11-20.

_______________, 1981, Pan-African (Upper Proterozoic) plate tectonics of the Arabian-Nubian Shield: Upper Proterozoic to Lower Palaeozoic tectonics (Pan-African event), in Kröner, A., ed., Precambrian plate tectonics: Elsevier, Amsterdam, p. 387-405.

_______________, 1984, *Discussion* on the Upper Proterozoic ophiolite mélange zones of the easternmost Arabian Shield: Journal of the Geological Society of London, v. 141, p. 1083-1087.

George, R. P., Jr., 1978, Structural petrology of the Olympus ultramafic complex in the Troodos ophiolite, Cyprus: Geological Society of America Bulletin, v. 89, p. 845-865.

Ghent, E. D., and Stout, M. Z., 1981, Metamorphism at the base of the Samail ophiolite, southeastern Oman Mountains: Journal of Geophysical Research, v. 86, No. B4, p. 2557-2571.

Gilboy, C. F., and Skiba, W., 1978, Geology of the Rabigh quadrangle, sheet 22/39A, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources DGMR Open-File Report 739.

Gonzalez, Louis, 1974, Geology of the Jabal Ishmas quadrangle: U. S. Geological Survey Saudi Arabian Project Report 186, 34 p. (U.S. Geological Survey Open-File Report 75-181).

Greenwood, W. R., 1981, Geology of the Jibal al Qahr quadrangle, sheet 19G, Kingdom of Saudi Arabia, with a Geographic map compiled by F. J. Fuller: U.S. Geological Survey Saudi Arabian Mission Miscellaneous Document 49 (Interagency Report 389), 33 p.

Greenwood W. R., and Anderson, R. E., 1977, Palinspastic map of the Red Sea area prior to Miocene sea-floor spreading, in Red Sea research 1970-1975: Saudi Arabian Directorate General of Mineral Resources Bulletin 22, p. Q1-Q5.

Greenwood, W. R., Anderson, R. E., Fleck, R. J., and Roberts, R. J., 1980, Precambrian geologic history and plate tectonic evolution of the Arabian Shield: Saudi Arabian Directorate General of Mineral Resources Bulletin 24, 35 p.

Greenwood, W. R., Hadley, D. G., Anderson, R. E., Fleck, R. J., and Schmidt, D. L., 1976, Late Proterozoic cratonization in southwestern Saudi Arabia: Philosophical Transactions of the Royal Society of London, ser. A, v. 280, p. 517-527.

Greenwood, W. R., Stoeser, D. B., Fleck, R. J., and Stacey, J. S., 1982, Late Proterozoic island-arc complexes and tectonic belts in the southern part of the Arabian Shield, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-02-8, 46 p. USGS Open-File Report 83-296.

Hamelin, D., Duprè, B., and Allègre, C. J., 1984, The lead isotope systematics of ophiolite complexes: Earth and Planetary Science Letters, v. 67, p. 351-366.

Hamilton, W., 1979, Tectonics of the Indonesian region: U.S. Geological Survey Professional Paper 1078, 345 p.

______________, 1981, Crustal evolution by arc magmatism: Philosophical Transactions of the Royal Society of London, series A, v. 301, p. 279-291.

Hargraves, R. B., 1981, Precambrian tectonic style: A liberal uniformitarian interpretation, in Kröner, A., ed., Precambrian plate tectonics: Elsevier, Amsterdam, p. 21-56.

Hedge, C. E., 1984, Precambrian geochronology of part of northwestern Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-04-31, 12 p.

Helaby, A. M., and Worl, R. G., 1980, Exploration and evaluation of the Hajrah-Hamdah group of ancient gold mines, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Mission, Technical Record 3 (Interagency Report 297), 52 p.

Hopson, C. A., Coleman, R. G., Gregory, R. T., Pallister, J. S., and Bailey, E. H., 1981, Geologic section through the Samail ophiolite and associated rocks along a Muscat-Ibra Transect, southeastern Oman Mountains: Journal of Geophysical Research, v. 86, No. B4, p. 2527-2544.

Hopson, C. A., Pallister, J. S., and Coleman, R. G., 1979, Petrologic processes at oceanic crust-mantle boundary, southeastern Samail ophiolite, Oman: Transactions of the American Geophysical Union (EOS), v. 60, p. 962

Irvine, T. N., 1967, Chromian spinel as a petrogenetic indicator; Part 2, Petrologic applications: Canadian Journal of Earth Science, v. 4, p. 71-103.

Jackson, E. D., and Thayer, T. P., 1972, Some criteria for distinguishing between stratiform, concentric, and Alpine peridotite-gabbro complexes: International Geological Congress, 24 th, Section 2, p. 289-296.

Jackson, N. J., and Ramsay, C. R., 1980, Time-space relationships of Upper Precambrian volcanic and sedimentary units in the Central Arabian shield: Journal of Geological Society of London, v. 137, p. 617-628.

Jaffey, A. H., Flynn, K. F., Glendenin, L. E., Bentley, W. C., and Essling, A. M., 1971, Precision measurments of half-lives and specific activities of ^{235}U and ^{238}U: Physics Reviews, v. 4, p. 1889.

Johnson, P. R., 1983, A preliminary lithofacies map of the Saudi Arabian Shield--Explanatory notes: Saudi Arabian Deputy Ministry for Mineral Resources Technial Record RF-TR-03-2, 72 p.

Johnson, P. R., Scheibner, E., and Smith, E. A., 1986, Mineral occurrence base map of the Arabian Shield, Riofinix Geological Mission, in Smith, E. A., Barnes, D. P., Johnson, P. R., Bognar, B., Garfield, L., and Scheibner, E., eds., A review of the geology, mineralization, and mineral resource potential of the Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-05-1, 322 p.

Johnson, P. R., and Vranas, G. J., 1984, The origin and development of late Proterozoic rocks of the Arabian Shield: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report RF-OF-04-32, 96 p.

Jones, D. L., Silberling, N. J., Coney, P. J., and Plafker, G., 1984, Lithotectonic terrane map of Alaska (west of 141st Meridian), in Siberling, N. J., and Jones, D. L., eds., Lithotectonic terrane maps of the North American Cordillera: U.S. Geological Survey Open-File Report 84-523, p. A1-A12.

Jones, D. L., Silberling, N. J., Gilbert, W., and Coney, P., 1982, Character, distribution, and tectonic significance of accretionary terranes in the Central Alaska Range: Journal of Geophysical Research, v. 87, No. B5, p. 3709-3717.

Kahr, V., P., 1961, General geologic report on field trips to the area north of Yanbu al Bahr: Saudi Arabian Directorate General of Mineral Resources Open-File Report 126, 213 p.

Kazmin, V., Shifferaw, A., and Balcha, T., 1978, The Ethiopian basement: Stiatigraphy and possible manner of evolution: Geologische Rundschau, v. 67, No. 2., p. 531-546.

Kemp, J., 1981, Geologic map of the Wadi al 'Ays quadrangle, sheet 25C, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM-53C, 39 p.

Kemp, J., 1982, Reconnaissance geology of the Al 'Ays quadrangle 25/38 C, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-02-43, 101 p.

Kemp, J., Pellaton, C., and Calvez, J. Y., 1980, Geochronological investigations and geological history in the Precambrian of Northwestern Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-01-1, 120 p.

______________, 1982a, Cycles in the Chelogenic evolution of the Precambrian shield in part of northwestern Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Professional Paper 1, p. 27-41.

Kemp, J., Gros, Y., and Prian, J., 1982b, Geologic map of the Mahd adh Dhahab quadrangle, sheet 23E, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM-64-A, 39 p. 1.

Kennedy, W. Q., 1964, The structural differentiation of Africa in the Pan-African (±500 m.y.) tectonic episode: Research Institute of African Geology, University of Leeds, 8th Annual Report, p. 48-49.

Knopf, A., 1929, The Mother Load system of California: U.S. Geological Survey Professional Paper 157, 88 p.

Krogh, T. E., 1973, A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations: Geochimica et Cosmochimica Acta, v. 37, p. 485-494.

______________, 1978, Vapour transfer for the dissolution of zircons in a multi-sample capsule at high pressure, in Zartman, R. E., ed., Short papers of the fourth international conference on geochronology, cosmochronology and isotope geology: U.S. Geological Survey Open-File Report No. 78-701, p. 233-234.

Kröner, A., 1980, Pan African crustal evolution: EPISODES, v. 1980, No. 2, p. 3-8.

______________, 1981, Precambrian plate tectonics: in Kröner, A., ed., Precambrian plate tectonics: Elsevier, Amsterdam, p. 57-90.

Kroőer, A., 1984, Late Precambrian plate tectonics and orogeny: A need to redefine the term Pan-African, in Klerkx, J., and Michot, J., eds., Gèologie africaine-African Geology: Tervuren, p. 23-28.

______________, 1985, Ophiolites and the evolution of tectonic boundaries in the Late Proterozoic Arabian-Nubian Shield of northeast Africa and Arabia: Precambrian Research, v. 27, p. 277-300.

Kröner, A., Halpern, M., Tegtmeyer, A., and Basahel, A., 1984, Age and significance of metavolcanic sequences and granitoid gneisses from the Al-Lith area, southwestern Arabian Shield: Proceedings Volume, International Geological Correlation Project 164, Pan-African Crustal Evolution in the Arabian Nubian Shield, King Abdulaziz Faculty of Earth Sciences Research Series No. 6, p. 380-388.

Kushiro, I., 1960, Si-Al relations in clinopyroxenes from igneous rocks: American Journal of Science, v. 258, p. 548-554.

Leblanc, M., 1981, The Late Proterozoic ophiolites of Bou Azzer (Morocco): Evidence for Pan-African plate tectonics, in Kröner, A., ed., Precambrian plate tectonics: Elsevier, Amsterdam, p. 435-451.

Leblanc, M., and Billaud, P., 1982, Cobalt arsenide orebodies related to an Upper Proterozoic ophiolite: Bou Azzer (Morocco): Economic Geology, v. 77, p. 162-175.

Ledru, P., and Auge, T., 1984, The Al 'Ays ophiolitic complex petrology and structural evolution: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-04-15, 57 p.

Leeman, W. P., 1979, Primitive lead in deep crustal xenoliths from the Snake River plain, Idaho: Nature, v. 281, p. 365-366.

Le Metour, J., Johan, V., and Tegyey, M., 1982, Relationships between ultramafic-mafic complexes and volcanosedimentary rocks in the Precambrian Arabian Shield: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-02-15, 109 p.

______________, 1983, Geology of the ultramafic-mafic complexes in the Bi'r Tuluhah and Jabal Malhijah areas: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-03-40, 47 p.

Letalenet, J., 1979, Geologic map of the 'Afif quadrangle, sheet 23F, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-47-A, 20 p.

Lewis, S. D., and Hayes, D. E., 1984, A Geophysical study of the Manilla Trench, Luzon, Philippines, 2, Fore arc basin structùral and stratigraphic evolution: Journal of Geophysical Research, v. 89, No. B11, p. 9196-9214.

Ludwig, K. R., 1980, Calculation of uncertainties of U-Pb isotope data: Earth and Planetary Science Letters, v. 46, p. 212-220.

Ludwig, K. R., and Silver, L. T., 1977, Lead-isotope inhomogeneity in Precambrian igneous K-feldspars: Geochimica et Cosmochimica Acta, v. 41, p. 1457-1471.

Mattinson, J. M., 1975, Early Paleozoic ophiolite complexes of Newfoundland: Isotopic ages of zircons: Geology, v. 3, p. 181-183.

______________, 1976, Ages of zircons from the Bay of Islands ophiolite complex, western Newfoundland: Geology, v. 4, p. 393-394.

Mooney, W. D., Gettings, M. E., Blank, H. R., and Healy, J. H., 1985, Saudi Arabian seismic-refraction profile: A travel time interpretation of crustal and upper mantle structure: Tectonophysics, v. 111, p. 173-246.

Moorbath, S., and Taylor, P. N., 1981, Isotopic evidence for continental growth in the Precambrian, in Kröner, Alfred, ed., Precambrian plate tectonics: Elsevier, Amsterdam, p. 491-525.

Moore, J. M., 1979, Tectonics of the Najd transcurrent fault system, Saudi Arabia: Journal of the Geological Society of London, v. 136, p. 446-454.

Moore J. M., and Al-Shanti, A. M., 1979, Structure and mineralization in the Najd fault system, Saudi Arabia, in Tahoun, S. A., ed., Evolution and mineralization of the Arabian-Nubian Shield, v. 2: Oxford-New York, Pergammon Press, p. 17-28.

Nassief, M. O., 1981, Geology and petrology of the Jabal Thurwah area, Western Province, Saudi Arabia: Unpublished Ph.D. thesis, University of Lancaster, 180 p.

Nassief, M. O., Macdonald, R., and Gass, I. G., 1984, The Jebel Thurwah Upper Proterozoic Ophiolite Complex, western Saudi Arabia: Journal of the Geological Society of London, v. 141, p. 537-546.

Nawab, Z. A., 1979, Geology of the Al-Amar-Idsas region of the Arabian Shield, in Tahoun, S. A., ed., Evolution and mineralization of the Arabian Nubian Shield, v. 2: King Abdulaziz University, Institute of Applied Geology, Bulletin 3, Oxford-New York, Pergammon Press, p. 29-39.

Nicolas, A. F., Boudier, F., and Bouchez, J. L., 1980, Interpretation of peridotite structures from ophiolitic and oceanic environments: American Journal of Science, v. 280-A(1), 192-210.

Overstreet, W. C., 1978, A geological and geochemical reconnaissance of the Tathlith one-degree quadrangle, sheet 19/43, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Mission Project Report (IR)230, 132 p.
USGS Open-File 78-1027.

Pallister, J. S., 1986, Geologic map of the Al Lith quadrangle, sheet 20 D, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM-95-A, (in press).

Pallister, J. S., and Hopson, C. A., 1981, Samail ophiolite plutonic suite: field relations, phase variation, cryptic variation and layering, and a model for a spreading ridge magma chamber: Journal of Geophysical Research, v. 86, No. B4, p. 2593-2644.

Pearce, J. A., and Gale, G. H., 1977, Identification of ore-deposition environment from trace-element geochemistry of associated igneous host rocks, in Volcanic processes in ore genesis: London, Geological Society of London and the Institution of Mining and Metallurgy, p. 14-24.

Pellaton, C., 1976, Geology and mineral exploration of the Wadi Daghalah quadrangle, 26/37D: Bureau de Recherches Geologiques et Minieres Technical Record 76-JED-10, 24 p.

Pellaton, C., 1979, Geologic map of the Yanbu' al Bahr quadrangle, sheet 24C, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM-48-A, 16 p.

Powers, R. W., Ramirez, L. F., Redmond, C. D., and Elberg, E. L., Jr., 1966, Geology of the Arabian Peninsula -- Sedimentary Geology of Saudi Arabia: U.S. Geological Survey Professional Paper 560-D, 147 p.

Pyke, D. R., 1976, On the relationship between gold mineralization and ultramafic volcanic rocks in the Timmins area, northeastern Ontario: Canada Institute of Mining and Metallurgical Bulletin, v. 69, No. 773, p. 79-87.

Quick, J. E., and Doebrich, J. L., 1986, Geology of the Wadi ash Shu'bah quadrangle, Sheet 26E, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-04-11, 41 p. USGS Open-File Report 87-501.

Raase, R., 1974, Al and Ti contents of hornblende, indicators of pressure and temperature of regional metamorphism: Contributions to Mineralogy and Petrology, v. 45, p. 231-236.

Ramsay, C. R., 1983, Geology of the Rabigh quadrangle, sheet 22D, Kingdom of Saudi Arabia (from original synthesis by W. J. Skiba, C. F. Gilboy, and J. W. Smith): Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map, DGMR-OF-03-15, 90 p.

Reischmann, T., 1981, Petrographie und Geochemie spät- Proterozoischer vulkanite der Wadi Lith region, Saudi Arabien: Unpublished Ph.D. dissertation, University of Mainz, Mainz, West Germany, 180 p.

Reischmann, T., Kröner, A., and Basahel, A., 1985, Petrography, geochemistry and tectonic setting of metavolcanic sequences from the Al-Lith area, southwestern Arabian Shield: Proceedings Volume, International Geological Correlation Project 164, Pan-African Crustal Evolution in the Arabian Nubian Shield, King Abdulaziz Faculty of Earth Sciences Research Series No. 6, p. 365-379.

Reymer, A., and Schubert, G., 1984, Phanerozoic addition rates to the continental crust and crustal growth: Tectonics, v. 3, p. 63-77.

_______________, 1986, Rapid growth of some major segments of continental crust: Geology, v. 14, p. 299-302.

Ries, A. C., Shackleton, R. M., Graham, R. H., and Fitches, W. R., 1983, Pan-African structures, ophiolites and melange in the Eastern Desert of Egypt: A traverse at 26° N.: Journal of the Geological Society of London, v. 140, p. 75-95.

Roobol, M. J., Ramsay, C. R., Jackson, N. J., and Darbyshire, D. P. F., 1983, Late Proterozoic lavas of the Central Arabian Shield--evolution of an ancient volcanic arc system: Journal of the Geological Society of London, v. 140, p. 185-202.

Rooney, L. F., and Al-Koulak, Z., 1978, Asbestos occurrences in serpentinites of the Hamdah area, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Project Report (IR)239, 22 p. USGS Open-File 78-360.

Saleeby, J., 1979, Fracture zone tectonics, continental margin fragmentation, and emplacement of the Kings-Kaweah ophiolite belt, Southwest Sierra Nevada, California, in Coleman, R. G., and Irwin, W. P., eds., North American ophiolites: State of Oregon, Department of Geology and Mineral Industries Bulletin 95, p. 141-159.

Schmidt, D. L., 1981, Geology of the Jabal Yafikh quadrangle, sheet 20/43B, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Mission Miscellaneous Document 39 (Interagency Report 397), 99 p. in press, DMMR Geologic Map series.

Schmidt, D. L., and Brown, G. F., 1982, Major-element chemical evolution of the Late Proterozoic shield of Saudi Arabia: Saudi Arabia Deputy Ministry for Mineral Resources Open-File Report USGS-OF-02-88, 34 p. 1984, Proc. 1st Symp. of Pan-African Crustal Evolution in the Arabian-Nubian Shield IGCP no. 164 King Abdulaziz University, Jiddah, no. 6, p. 1-21.

Schmidt, D. L., and Hadley, D. G., and Brown, G. F., 1982, Middle Tertiary continental rift and evolution of the Red Sea in southwestern Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-03-6 (Interagency Report 503), 56 p. USGS Open-File 83-641.

Schmidt, D. L., Hadley, D. G., and Stoeser, D. B., 1979, Late Proterozoic crustal history of the Arabian Shield, southern Najd Province, Kingdom of Saudi Arabia, in Tahoun, S. A., ed., Evolution and mineralization of the Arabian-Nubian Shield, v. 2, King Abdulaziz University, Institute of Applied Geology Bulletin 3, Oxford-New York, Pergammon Press, p. 41-57.

Shanti, M., and Roobol, M. J., 1979, A late Proterozoic ophiolite complex at Jabal Ess in northern Saudi Arabia: Nature, v. 279, p. 488-491.

_______________, 1982, Pan African crustal evolution in the Arabian Nubian Shield, in, Guide-book for an excursion to the Jaba Ess-Ash Shizm area of northern Saudi Arabia: King Abdulaziz University, Faculty of Earth Sciences, Research Series, No. 14, 35 p.

Shaw, D. M., 1976, Development of the early continental crust, Part 2: Prearchean, protoarchean, and later eras, in Windley, B. F., ed., The early history of the earth: John Wiley and Sons, London-New York, p. 33-53.

Shimron, A. E., 1984, Evolution of the Kid Group, southeast Sinai Peninsula: thrusts, melanges, and implications for accretionary tectonics during the late Proterozoic of the Arabian-Nubian Shield: Geology, v. 12, p. 242-247.

Silver, E. A., and Smith, R. B., 1983, Comparison of terrane accretion in modern Southeast Asia and the Mesozoic North American Cordillera: Geology, v. 11, p. 198-202.

Smith, C. W., 1985, Preliminary studies of the Raha fault zone and enclosing rocks in the Buqaya area, Jabal as Silsilah quadrangle, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-05-29, 21 p. USGS Open-File 86-29.

Stacey, J. S., and Agar R. A., 1985, U-Pb isotopic evidence for the accretion of a continental microplate in the Zalm region of the Saudi Arabian Shield: Journal of the Geological Society of London, v. 142, p. 1189-1203.

Stacey, J. S., Doe, B. R., Roberts, R. J., Delevaux, M. H., and Gramlich, J. W., 1980, A lead isotope study of mineralization in the Saudi Arabian Shield: Contributions to Mineralogy and Petrology: v. 76, p. 175-188.

Stacey, J. S., and Hedge, C. E., 1984, Geochronologic and isotopic evidence for early Proterozoic crust in the eastern Arabian Shield: Geology, v. 12, p. 310-313.

Stacey, J. S., and Kramers, J. D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth and Planetary Science Letters, v. 26, p. 207-221.

Stacey, J. S., and Stoeser, D. B., 1983, Distribution of oceanic and continental leads in the Arabian-Nubian Shield: Contributions to Mineralogy and Petrology, v. 84, p. 91-105.

Stacey, J. S., Stoeser, D. B., Greenwood, W. R., and Fischer, L. B., 1984, U-Pb zircon geochronology and geologic evolution of the Halaban-Al Amar region of the eastern Arabian Shield, Kingdom of Saudi Arabia: Journal of the Geological Society of London, v. 141, p. 1043-1055.

Stern, R. J., 1979, Late Precambrian ensimatic volcanism in the Central Eastern Desert of Egypt: unpublished Ph.D. dissertation, University of California, San Diego, California, 210 p.

_______________, 1981, Petrogenesis and tectonic setting of late Precambrian ensimatic volcanic rocks, central eastern desert of Egypt: Precambrian Research, v. 16, p. 195-230.

Stille, P., Unruh, D. M., and Tatsumoto, M., 1983, Pb, Sr, Nd and Hf isotopic evidence of multiple sources for Oahu, Hawaiian basalts: Nature, v. 304, p. 25-29.

Stoeser, D. B., 1986, Distribution and tectonic setting of plutonic rocks of the Arabian Shield: Journal of African Earth Sciences, v. 4, p. 21-46.

Stoeser, D. B., and Camp, V. E., 1985, Pan-African microplate accretion of the Arabian Shield: Geological Society of America Bulletin, v. 96, p. 817-826.

Stoeser, D. B., Fleck, R. J., and Stacey, J. S., 1982, Geochronology and origin of an early tonalite gneiss of the Wadi Tarib batholith and the formation of syntectonic gneiss complexes in the southeastern Arabian Shield, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-02-62, 27 p.

1984, Proc. 1st Symp. on Pan-African Crustal Evolution in the Arabian-Nubian Shield IGCP Proj. 164, King Abdulaziz University, Jiddah, no. 6, p. 351-364.

Stoeser, D. B., Stacey, J. S., Greenwood, W. R., and Fisher, L. B., 1984, U/Pb zircon geochronology of the southern part of the Nabitah mobile belt and Pan-African continental collision in the Saudi Arabian Shield: Saudi Arabian Deputy Ministry for Mineral Resources Technical Record USGS-TR-04-5, 88 p. USGS Open-File Report 85-239.

Strong, D. F., 1979, Proterozoic tectonics of northwestern Gondwanaland: new evidence from eastern Newfoundland: Tectonophysics, v. 54, p. 81-101.

Sustrac, G., 1980, The basic and ultrabasic rocks of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Open-File Report BRGM JED-OF(OR)-80-8, 239 p.

Tarling, D. H., 1978, The first 600 million years, in Tarling, D. H., ed., Evolution of the earth's crust: Academic Press, London-New York-San Francisco, p. 1-17.

Tatsumoto, M., 1978, Isotopic composition of lead in oceanic basalts and its implication to mantle evolution: Earth and Planetary Science Letters, v. 38, p. 63-87.

Thekair, M. E., 1976, Carbonate rocks in Al Amar-Asihailiya district of Saudi Arabia: King Abdulaziz University, Institute of Applied Geology Research Series No. 1, 223 p.

Thorpe, R. S. 1978, Tectonic emplacement of ophiolitic rocks in the Precambrian Mona complex of Anglesey: Nature, v. 276, p. 57-58.

Tilton, G. R., Hopson, C. A., and Wright, J. E., 1981, Uranium-lead isotopic ages of the Samail ophiolite, Oman, with applications to Tethyan ocean ridge tectonics: Journal of Geophysical Research, v. 86, No. B4, p. 2763-2775.

Tomblin, J. F., 1979, Dacite of the Lesser Antilles, in Barker, F., ed., Trondhjemites, dacites, and related rocks: Elsevier, Amsterdam, p. 601-628.

Turner, D. L., Forbes, R. B., Aleinikoff, J. N., Hedge, C. E., and McDougall, Ian, 1983, Geochronology of the Kilbuck terrane of southwestern Alaska: Geological Society of America Abstracts with Programs, v. 15, p.407.

U.S. Geological Survey and Arabian American Oil Company (ARAMCO), 1963, Geologic Map of the Arabian Peninsula: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-270A, scale 1:2,000,000.

Vaslet, D., Delfour, J., Manivit, J., Le Nindre, Y., Brosse, J., and Fourniguet, J., 1983, Geologic Map of the Wadi ar Rayn quadrangle, sheet 23H, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM-63-A, 46 p.

Viljoen, R. P., Saager, R., and Viljoen, M. J., 1969, Metallogenesis and ore control in the Steynsdorp Goldfield, Barberton Mountain Land, South Africa: Economic Geology, v. 64, p. 778-797.

Whitford, D. J., and Jezek, P. A., 1982, Isotopic constraints on the role of subducted sialic material in Indonesian island-arc magmatism: Geological Society of America Bulletin, v. 93, p. 504-513.

Windley, B. F., 1981, Precambrian rocks in light of the plate-tectonic concept, in Kröner, A., ed., Precambrian plate tectonics: Elsevier, Amsterdam, p. 1-20.

Worl, R. G., 1979, The Jabal Ishmas-Wadi Tathlith gold belt, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Mission Project Report IR264, 108 p. 1980, King Abdulaziz University, Institute of Applied Geology Bull. 3, v. 4, Pergamon Press, Oxford-New York, p. 61-69.

______________, 1981, Reconnaissance geology of the Jabal al Hajrah 7 1/2-minute quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabia Mission Technical Record 2, 21 p. USGS Open-File 81-1218.

Worl, R. G., and Elsass, F. E., 1980, Evaluation of mineralization in serpentinite and enclosing rocks in the Hamdah area, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Mission Project Report 276, 33 p. USGS Open-File 81-446.

Zartman, R. E., and Doe, B. R., 1981, Plumbotectonics-the model: Tectonophysics, v. 75, p. 135-162.