(IR)Y-15

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROJECT REPORT
Yemen Arab Republic Investigations
(IR)Y-15

PETROGRAPHIC AND TRACE-ELEMENT DATA ON ROCKS FROM THE YEMEN ARAB REPUBLIC

Prepared by the U.S. Geological Survey in cooperation with the Central Planning Organization, the Ministries of Economy and Agriculture, and the Mineral and Petroleum Authority of the Yemen Arab Republic, under the auspices of the Agency for International Development, U.S. Department of State.

1979

PETROGRAPHIC AND TRACE-ELEMENT DATA ON ROCKS FROM THE YEMEN ARAB REPUBLIC

by

William C. Overstreet, Mary M. Donato,
Maurice J. Grolier, James A. Domenico,
George L. Crenshaw, and Gordon C. Tibbitts, Jr.,
U.S. Geological Survey

and

Mohammad Mukred Ibrahim,
Mineral and Petroleum Authority
Ministry of Economy, Yemen Arab Republic

The project report series presents information resulting from various kinds of scientific, technical, or administrative studies. Reports may be preliminary in scope, provide interim results in advance of publication, or may be final documents.

U. S. Geological Survey
[Reports- OPEN FILE REPORT] 80-132
This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.

CONTENTS

CONTENTS--Continued

CONTENTS--Continued

FIGURES

TABLES

PETROGRAPHIC AND TRACE-ELEMENT DATA ON ROCKS FROM THE YEMEN ARAB REPUBLIC

By

William C. Overstreet, Mary M. Donato,
Maurice J. Grolier, James A. Domenico,
George L. Crenshaw, and Gordon C. Tibbitts, Jr.,
U.S. Geological Survey

and

Mohammad Mukred Ibrahim,
Mineral and Petroleum Authority
Ministry of Economy, Yemen Arab Republic

ABSTRACT

Petrographic descriptions are given for rocks in the Yemen Arab Republic (YAR), including mainly Precambrian igneous and metamorphic rocks from the southeastern part of the country, which previously was geologically undescribed. Also included are descriptions of Cretaceous and/or Tertiary lavas of the Yemen Volcanics, Miocene(?) alkali granite, Pliocene caprock of the Guma salt dome, and late Pleistocene and Holocene basalts of the Aden Volcanic Series (?). The petrographic studies permitted the selection of 11 samples of rock for future use in obtaining isotopic analyses for age determinations.

Analyses of these rock specimens for trace amounts of gold, indium, mercury, selenium, and thallium completed the geochemical studies. Results of these analyses are interpreted to show that regional geochemical exploration should be undertaken for base and precious metals near Jibal Hufash, the Manakhah area, the region around Al Bayda, the Sa'dah-Majadh area, and the Wadi Jawf area. Additional studies of trace elements in commercial salt deposits of the YAR should be made to evaluate the amounts of mercury and selenium in this industrial raw material.

INTRODUCTION

Purpose of present work

A study of the regional geology, mineral deposits, petrography, and paleontology of the Yemen Arab Republic was begun in 1975 as part of the Water and Mineral Survey Project of North Yemen conducted by the U. S. Geological Survey (USGS) in cooperation with the Yemen Ministries of Agriculture and of Economy. The work was sponsored by the Government of the Yemen Arab Republic (YAR) and the Agency for International Development, U.S. Department of State (USAID). The regional geology was described in a set of preliminary geologic maps (Grolier and Overstreet, 1976a-1976i), and the first results of investigations of mineral deposits were given in 1976 (Overstreet, Domenico, and others, 1976).

The purpose of this report is to present petrographic descriptions of rocks collected in the Yemen Arab Republic (YAR) during 1975-6 and to present the results of analyses for five trace elements--gold, mercury, indium, selenium, and thallium--in these rocks, thereby completing petrographic and geochemical discussions begun in 1976-7 (Overstreet and others, 1976; Grolier and others, 1977). An interpretation of the possible economic significance of these new data is given.

Rock samples

Field work in the Yemen Arab Republic in 1975 yielded two collections of rock samples: those numbered in the MJG-75 series were collected by Maurice J. Grolier; those numbered in the 75-OT series were collected by William C. Overstreet. The sites where these samples were collected and field descriptions of the rocks are listed in table 1 and shown on figure 1 of the report by Overstreet and others (1976). Additional field work was done in the YAR during 1976 by Grolier. Rocks collected at that time bear numbers in the MJG-76 series. Full descriptions of these rocks and localities, as well as of the localities sampled independently by James W. Aubel (represented by the JA-75 series) and Roy O. Jackson (shown by the ROJ sample), are given in table 2 and figures 1A and 2 of the report by Grolier and others (1977). Because the purpose of the present work is to release additional petrographic and trace-elements data on rocks described in the previous reports of 1976 and 1977, the reader is referred to them for descriptions of the sources of the samples discussed here. However, to insure proper comparison between those descriptions of localities and the additional data introduced here, named localities, latitudes, and longitudes are given below in the discussions of the samples.

A petrographic study of the rocks collected in the YAR during 1975 and 1976 was begun in 1976 by Mary M. Donato, U.S. Geological Survey, and completed in 1977. A total of 103 specimens are described below.

Acknowledgments

It is a pleasure to acknowledge the interest and help of the following officials, whose assistance made possible the work described below: His Excellency, Dr. A. A. El-Eryani, formerly Chairman of the Central Planning Organization, now Minister of Education, YAR; Hamoud Ahmid Daif Allah, President, Mineral and Petroleum Authority, Ministry of Economy, YAR; and Aldelmo Ruiz, Director, USAID Mission to the YAR.

James W. Aubel, then a U.S. Peace Corps Volunteer and geologist working with the USAID water supply project in the YAR, helped in collecting the rock samples described in this report. Analyses of three specimens of Miocene(?) alkalic granite were contributed by Roy O. Jackson and Dwight L. Schmidt, U.S. Geological Survey. This help is gratefully acknowledged.

PETROGRAPHIC DESCRIPTIONS

Geologic background

A review of the results of previous investigations of the geology of the Yemen Arab Republic showed that the petrology of the country has been sporadically discussed (Roman, 1926; Comucci, 1929; Shukri and Basta, 1955a; 1955b; Karrenberg, 1956; 1959), but the emphasis has been on the Tertiary and/or Cretaceous Yemen Volcanics, the Miocene(?) alkali granite, and the late Pleistocene to Holocene Aden Volcanic Series. The Precambrian basement rocks of the YAR, comprising a vast array of metamorphosed sedimentary rocks and plutonic felsic, intermediate, and mafic intrusive rocks, have received scant attention. One of the purposes of the present report is to give petrographic descriptions of the basement rocks, particularly the Precambrian rocks exposed in the southeastern part of the YAR, which had not been described until the field work of 1976 (Grolier and others, 1977, pp. 28-31, fig. 2).

The geologic framework of the YAR was interpreted through use of Landsat-1 imagery to yield a series of preliminary geologic maps at 1:500,000 scale (Grolier and Overstreet, 1976a-1976i) which were later consolidated for publication as a single sheet (Grolier and Overstreet, 1978, in press). The units (table 1) shown on that geologic map are modified from those reported by Geukens (1966), and include five major successions of rocks separated by unconformities:

Silt, clay, and sand in mud flats along the Red Sea coast; river terrace deposits, alluvial fans, gravel, loess, eolian sand, and basalt flows and dikes of the Aden Volcanic Series(?)	Upper Pleistocene and Holocene	QUATERNARY
Unconformity		
Tuffaceous sediment and evaporites of the Baid Formation	Pliocene(?) or	
Hypabyssal andesite and diabase dikes	Miocene(?)	
Alkali granite, syenite, and diorite in subvolcanic plugs, stocks, and plutons	Miocene(?)	TERTIARY AND/OR
Alkali basalt flows	Lower Miocene(?) and Upper Oligocene(?)	CRETACEOUS
Saprolite and laterite	Eocene(?)	
Yemen Volcanics Tawilah Group and Medj-zir Series	Tertiary and/or Cretaceous	
Unconformity		
Amran Series	Upper	JURASSIC
Kohlan Series	Lower	
Unconformity		
Wajid Sandstone		ORDOVICIAN
Unconformity		
Granite, granodiorite, injection gneiss, gabbro, mafic dikes, metavolcanic and metasedimentary rocks		PRECAMBRIAN

Table 1. Synopsis of geologic units in the Yemen Arab Republic.

DESCRIPTION OF MAP UNITS

Geologic names and symbols given below apply to the whole area of the Yemen Arab Republic; some names and symbols may not appear on the geologic map of an area covered by an individual LANDSAT-1 image. Names and descriptions of geologic units, unless otherwise noted, are adopted from U.S. Geological Survey and Arabian American Oil Company, 1963, Geologic map of the Arabian Peninsula; U.S. Geol. Survey Misc. Geol. Inv. Map 270-A, and Brown, G. F., and Jackson, R. O., 1959, Geology of the Asir quadrangle, Kingdom of Saudi Arabia: U.S. Geol. Survey Misc. Geol. Inv. Map 217-A.

Unit	Description
Qsb	Silt, clay, and muddy sand; commonly saturated with brine and salt encrusted; in mud flats (sabkhas) along the Red Sea coast
Qu	River-terrace deposits, alluvial fans, gravel, sand, and silt including unmapped alluvium which overlies rock salt at Jabal Kūshah, near Guma; numerous loess deposits particularly in the central plains. Wherever possible, alluvial deposits have been divided regionally on a basis of reflectance, natural vegetation and crops, altitude, and location into six subunits, as follows: Qal_6, alluvial gravel, sand, and silt restricted to channels and flood plains of present-day ephemeral streams Qal_5, alluvial gravel, sand, and silt on river terraces and fans, adjacent to and higher than the flood plains of present-day streams; generally darker than Qal_6; may include colluvium at base of foothills Qal_4, same as above, but darker and possibly older Qal_3, same as Qal_4, but higher and older Qal_2, same as Qal_3, but higher and farther inland from the Red Sea Coast Qal_1, alluvial gravel heavily coated with desert varnish, restricted to dissected river terraces on the south valley slope of Wādī Jawf, north of Jabal Bahrah and west of Wādī Raghwān
Qk	Yellow and green marly limestone, white limestone, and reef limestone, undifferentiated, exposed on Kamarān Island. Fossiliferous, and of probable Pleistocene age (MacFadyen, 1930; Cox, 1931). Probably correlative with unmapped marine terrace deposits which disconformably overlie Plio-Miocene tuffaceous sandstone at the Al Luhayyah diapirs
Ql	Loess deposits, with calcareous concretions and caliche layers; fossil mollusks abundant locally; may include alluvial silt alternating with alluvial or colluvial gravel
Qe	Eolian sand, commonly mobile
Qa	Basalt flows and dikes; numerous scattered cones and craters; at places covered with tuff and volcanic bombs. May be rock and time equivalent of the Aden Volcanic Series in the People's Democratic Republic of Yemen; in the Ṣan'ā' region, lava flows have been divided regionally on a basis of reflectance into four subunits, as follows: Qa_4, very dark basaltic lobate flows, extruded in historical times, possibly in 3rd century A. D. (Rathjens, G., and Wissman, H. V., 1934, v. 2, p. 13; v. 3., p. 105, fig. 51; p. 162–163; Rathjens, C., and Wissman, 1942, v. 33, p. 276) Qa_3, dark basaltic flows Qa_2, thin basalt flows, discontinuous over older rocks; appears lighter gray than units Qa_3 and Qa_4 on LANDSAT–1 images Qa_1, basalt flows forming a continuous mantle over older rocks; Qa_1 and Qa_2 possibly are part of only one eruption phase

Table 1. continued

Tba	BAID FORMATION—Gray, red, and green siliceous and tuffaceous shale and sandstone; also limestone and evaporite layers. Includes rock salt of salt domes at Aş Şalif and Jabal Qimmah, and at Jabal Kūshah near Guma. Generally unfossiliferous, but middle to late Miocene microflora reported by Klaus (*in* Heybroek, 1965, p. 34-35) from rock salt at Jabal Kūshah, and at Aş Şalif, and late Pliocene microfauna reported from marine sediments overlying salt (Goerlich, 1956, p. 213-214). Correlated with rocks of the Baid Formation exposed in Wādī, Baid, Saudi Arabia, because of similar lithology (Gillmann, Letullier, and Renouard, 1966, p. 1479-1480, pl. 1, fig. 4).
Ta	Hypabyssal andesite and diabase intrusives, commonly glomeroporphyritic, and in dike swarms
Tgr	Alkali granite and diorite in subvolcanic plugs, stocks, and plutons (Karrenberg, 1959, v. 17, no. 1, p. 33–36); leucocratic granite locally has primary flow banding. Crests of unbreached plugs may be overlain by hydrothermally altered rocks of the Yemen Volcanics, locally in northwestern part of the Yemen Arab Republic mapped as Tertiary laccoliths (U.S. Geol. Survey and Arabian American Oil Co., 1963). Some granitic plutons as at Jibal Sabir, south of Ta'izz 22.7±0.9 m.y. is reported for a granite sample from Jabal Sabir collected by R.O. Jackson (Field No. ROJ–1), and analysed by R. F. Marvin, H. H. Mehnert, and Violet Merritt (Marvin, 1974, written commun. to G. F. Brown). A similar K-Ar age (22.0±0.7 m.y.) is reported by Marvin (1974, written commun. to Brown) for a syenite sample which had been collected from a plug cutting a laterite deposit in the Sirat Plateau, Saudi Arabia, by Brown (Field No. 519B).
Tb	Alkali basalt flows. Erosional remnants on laterite (Tl) developed over Precambrian crystalline rocks; basalts probably equivalent to As Sirat volcanic rocks of Saudi Arabia (Coleman, and others, 1975) for which isotopic ages of 25 to 29 m.y. are reported (Brown, 1970, p. 75–87); may be equivalent to Yemen Volcanics sub-unit TKy_6
Tl	Laterite and saprolite, mainly white, may be yellow or red, developed on upper surface of Precambrian crystalline rocks by prolonged weathering during Eocene (?) time, to 50 meters in thickness; probably equivalent to laterite in As Sirat Mountains, Saudi Arabia (Brown and others, 1959)
TKy	YEMEN VOLCANICS, undivided—Bedded alkalic flows and pyroclastic rocks including but not restricted to rhyolite, comendite, pantellerite, trachyte, andesite, basalt, and ankaramite (Shukri and Basta, 1955, v. 36, p. 129–163), with interbedded lenticles of fluviatile and lacustrine sand, clay, and shale; locally contains fresh-water Oligocene-Miocene fossils; upper surfaces of many volcanic beds weather to reddish paleosols a few centimeters to a few meters thick, particularly in middle and upper parts of the sequence; whole sequence of Yemen Volcanics at least 2,000 meters thick. Term Yemen Volcanics introduced here to replace former name Trap Series (Geukens, 1966), to emphasize presence of thick sequence of highly fractionated felsic volcanic rocks. Wherever possible, the Yemen Volcanics have been divided regionally on basis of reflectivity and stratigraphic succession into six subunits, as follows: TKy_6, dark basaltic flows; TKy_5, generally leucocratic felsic tuffs with some dark basaltic flows, associated with the formation and collapse of a circular volcanic structure, 8.5 km in diameter, in the north-central part of the area covered by LANDSAT–1 image 1189–06561; TKy_4, predominantly felsic and tuffaceous, with some basaltic flows, underlies TKy_6 and TKy_5; TKy_3, predominantly felsic and tuffaceous; older than TKy_4; TKy_2, predominantly felsic and tuffaceous; older than TKy_3; TKy_1, predominantly basaltic, but includes green felsic conglomerate, porphyritic trachyte, and pink tuffs; overlies the Tawilah Group. In certain areas the rock types are shown on the maps by symbols without definite boundaries, owing to the uncertainty of establishing the contact between subunits or between a subunit and the undivided Yemen Volcanics on the basis of reflectance.

Table 1. continued

Map unit	Description
TKt	TAWILAH GROUP AND MEDJ-ZIR SERIES undivided—Continental type coarse crossbedded sandstone with lenses of conglomerate and gravel; interbedded shale and sandstone in lower part; overlies rocks of Jurassic age or the basement complex; includes the Medj-zir Series, consisting of crossbedded sandstone with locally fossiliferous calcareous sandstone and shale; upper part of sandstone locally rich in hematite; the Medj-zir Series cannot be separated with certainty from the Tawilah Group on basis of stratigraphic relations or reflectance
Jam	AMRAN SERIES—Limestone, marl, and shale; lower part locally includes detrital beds. The series is overlain by a less widespread Upper Jurassic transition zone of gypsum, clay, marl, shale, sandstone, and some limestone. Of Callovian to Kimmeridgian age. In the extreme northwestern part of the Yemen Arab Republic formerly desiganted the Hanifa Formation (Brown and Jackson, 1959)
Jko	KOHLAN SERIES—Green shale with sandstone and conglomeratic bands in lower part; sandstone and some conglomerates in upper part. Contact with overlying Amran Series is gradational. May be in part Triassic in age; in the extreme northwestern part of the Yemen Arab Republic, formerly designated as the Khums Formation (Brown and Jackson, 1959)
Ow	WAJID SANDSTONE—Partly crossbedded, locally conglomeratic sandstone; includes common quartz granule and pebble zones; of Ordovician age (Brown, 1970); formerly designated as Permian or older (U.S. Geol. Survey, and Arabian American Oil Co., 1963)
gp, sy	Peralkaline granite, gp, and syenite, sy, generally in circular plugs, stocks, and ring dikes
gr	Calc-alkaline granite, gray and pink, generally massive; includes some quartz monzonite; may have been intruded during second and third episodes of the Hijaz tectonic cycle recognized in southwestern Saudi Arabia (Greenwood and others, 1975, p. 23)
gg	Gneissic granite, gneissic granodiorite, and injection gneiss; commonly intruded by swarms of mafic dikes, contains numerous septa and inclusions of schist and gneiss; may have been intruded during second episode of Hijaz tectonic cycle
d, gb	Diorite, d, and gabbro, gb; may have been intruded during second episode of the Hijaz tectonic cycle
sl, sc	Slate, pelitic schist, and quartzite, sl; chlorite-schist, graphitic schist, sc; low-grade metamorphosed sedimentary rocks possibly of second and first episodes of Hijaz tectonic cycle
mq, bq	Marble, quartzite, and biotite gneiss, mq; biotite schist, biotite gneiss, and quartzite, bq, intruded by dikes of gneissic pink granite, diorite, and gabbro; medium- and high-grade metamorphosed sedimentary rocks possibly of second and first episodes of Hijaz tectonic cycle
sb, am	Mafic volcanic and metavolcanic rocks, with some interlayered metagraywacke and metaconglomerate, consisting of andesite, meta-andesite, metabasalt, greenstone, and chlorite schist, sb; hornblende gneiss, and amphibolite, am; possibly of second and first episodes of Hijaz tectonic cycle
ur	Predominantly granite, gneiss, and mica schist with subordinate quartzite, hornblende schist, and marble
wh	Chlorite-sericite schist, amphibole schist, graphite schist, marble, quartzite, slate, conglomerate, and greenstone
th	Thaniya Group, contorted and cleaved metasediments consisting of graphitic calcschist, quartzite, phlogopite marble, chert, and associated volcanics

The petrographic descriptions given below are for samples from the Aden Volcanic Series(?), Baid Formation, alkali granite, Yemen Volcanics, and units of the Precambrian basement.

Holocene and late Pleistocene rocks--

Aden Volcanic Series(?)

Five samples of vesicular olivine basalt of the Aden Volcanic Series(?) are included in the collection. Two of these are of known Holocene age and represent, respectively, the top (75-OT-7) and the bottom (75-OT-8) of the historic lava flow near Bayt al Hagr (15°33'25" N.; 44°09'30" E.), which was extruded about 1,700 years ago (Rathjens and Wissman, 1934, p. 105). Of the other three specimens, which are probably late Pleistocene to Holocene in age, sample 75-OT-9 is from the upper part of the Aden Volcanic Series(?) underlying the historic flow at Bayt al Hagr, and samples 75-OT-1 and 75-OT-2 are from the base of the Aden Volcanic Series(?) immediately overlying the Amran Series at a locality (15°36'45" N.; 44°00'35" E.) 8.7 km southeast of Umran.

Historic flow

Specimen 75-OT-7 from the top of the historic flow is vesicular olivine basalt consisting of about 75 percent[1] plagioclase, 15 percent olivine, and 10 percent opaque minerals, probably magnetite. The plagioclase occurs in the groundmass and as zoned phenocrysts; both forms show incipient resorption. Olivine forms phenocrysts which also show incipient resorption. The opaque material appears as anhedral grains in the groundmass. Plagioclase laths in the groundmass are pilotaxitic, and the phenocrysts of plagioclase show flow orientation. The vesicles constitute about 10 percent of the volume of the rock. They are amoeboid in shape, are stretched in the flow direction, and contain traces of calcite possibly produced by minor alteration of the rock.

The vesicular olivine basalt (75-OT-8) from the bottom of the historic flow consists of (in percent): plagioclase, 75; olivine, 10; opaque mineral, 5; clinopyroxene, 10; orthopyroxene, <1; and apatite, <1. The plagioclase, olivine, and opaque mineral occur in the same manner as in sample 75-OT-7. Grains of clinopyroxene are in the groundmass, but the orthopyroxene forms a single anhedral phenocryst with rims of granular clinopyroxene. Apatite is present in needles as

---

[1] All percentages are visual estimates based on observation of thin sections under the petrographic microscope.

an accessory mineral. Unusual vermicular resorption (?) textures were observed in some large phenocrysts of plagioclase and olivine, and some of the plagioclase grains show further growth following the episode of resorption. The orthopyroxene may be a xenocryst. About 15 percent of the rock is vesicles, but it is not altered.

Older lava

The lava below the historic flow at Bayt al Hagr (75-OT-9) consists of (in percent): plagioclase, 70; olivine, 15; clinopyroxene, 10; opaque mineral, 5; and glass, <1. Plagioclase is in the groundmass and also forms phenocrysts. The olivine forms phenocrysts, some of which are glomeroporphyritic. The clinopyroxene is generally in the groundmass, but a few phenocrysts are present. The opaque mineral and the glass are in the groundmass. Resorption features are common in the olivine phenocrysts. One subhedral phenocryst of clinopyroxene is ophitic: it encloses tiny plagioclase laths and olivine. Vesicles, which make up 10 percent of the rock, are round to ovoid. The rock is not altered.

Sample 75-OT-1, collected 1.2 m above the base of the Aden Volcanic Series(?) in the Umran area, is composed of (in percent): plagioclase, 75; olivine, 10; clinopyroxene, 10; and opaque mineral, 5. The plagioclase is in the groundmass as pilotaxitic grains and it also forms zoned, euhedral phenocrysts. The olivine is present as subhedral to anhedral phenocrysts and the clinopyroxene and opaque mineral are confined to the groundmass. A slight iron stain, or "iddingsite" alteration is on the rims of the olivine, and <1 percent of secondary calcite is in the vesicles.

The vesicular olivine basalt represented by sample 75-OT-2 came from a point 0.7 m above the base of the Aden Volcanic Series(?) in the Umran area. The rock consists of (in percent): plagioclase, 75; olivine, 10; clinopyroxene, 10; and opaque mineral, 5. The plagioclase forms pilotaxitic grains in the groundmass and zoned phenocrysts. Olivine forms subhedral to euhedral phenocrysts, and the clinopyroxene and opaque mineral are in the groundmass. Rare grains of clinopyroxene are glomeroporphyritic. Alteration of the olivine phenocrysts to "iddingsite" is more advanced than in sample 75-OT-1. Round vesicles make up 10 percent of the rock.

Pliocene(?) or Miocene(?) rocks--caprock of Guma salt dome in Baid Formation

The Guma salt dome (15°41'19" N.; 42°48'42" E.) is exposed 16 km east of the Red Sea coastal town of Al Luhayyah. The salt is Miocene(?) in age and forms a diapir capped by Pliocene(?) carbonate, gypsum, and anhydrite. Four specimens from the Guma salt dome (Grolier and others, 1977, table 2) were examined microscopically. Sample MJG-76-71 is an iron-stained rock that in thin section appears to be composed of fine-grained carbonate minerals and brown, structureless material. X-ray diffraction studies indicated calcite and dolomite. Thus, the specimen is a fine-grained, ferruginous dolomitic limestone.

Samples MJG-76-68, MJG-76-69A, and MJG-76-69B are composed of felted aggregates of gypsum and anhydrite; the identification of these two minerals was also confirmed by X-ray diffraction. The relative abundance of the two minerals is somewhat different in the three specimens. In sample MJG-76-68 medium-grained, bladed anhydrite forms a felted aggregate that makes up >98 percent of the rock. Veinlets of gypsum account for the remainder. Sample MJG-76-69A is composed of 2-5 mm laminae of fibrous gypsum interlayered with similar laminae of felted anhydrite. Limonite(?) gives brown and red stains to the rock. Specimen MJG-76-69B is a felted aggregate of anhydrite and gypsum containing 1 percent of calcite.

Miocene(?) rocks--alkali granite

Alkali granite of Miocene(?) age forms subvolcanic plugs, stocks, and plutons (Karrenberg, 1959, pp. 33-36) at many localities in the YAR. Two major localities are represented by the rocks studied: Jibal Sabir and Jibal Hufash. Jibal Sabir is a prominent mountain south of Ta'izz. Two samples (75-OT-27 and 75-OT-28) were taken from a locality (13°33'45" N.; 44°02'30" E.) on the north side of Jibal Sabir; sample 75-OT-27 represents a marginal phase and sample 75-OT-28 is core material. Jibal Hufash is a large mountain, the southern edge of which is crossed by the San'a'-Hudaydah road, where the rock was sampled (15°11'03" N.; 43°30'42" E.). Two samples were collected from the southern edge of this pluton: sample MJG-76-72A was taken 30 m into the pluton from its eastern contact, and sample MJG-76-72B was taken a few hundred meters farther into the pluton.

The alkali granite represented by specimen 75-OT-27 from Jibal Sabir consists of (in percent): subhedral microcline perthite, 70; anhedral quartz, 20; subhedral to anhedral amphibole, possibly riebeckite(?), having a pale brown core with pale blue-green rim, 5; subhedral clinopyroxene, 2; calcite interstitial with amphibole, <1; and accessory sphene, brown mica (phlogopite?), and opaque minerals, <1. The rock is coarse-grained, hypidiomorphic-granular with graphic interstitial intergrowths of potassium feldspar and quartz. Both cuneiform and vermicular intergrowths of potassium feldspar and quartz are present in the interstices between feldspar crystals. The ferromagnesian minerals form clusters, and the amphibole is not deeply colored. Moderate alteration makes the feldspars cloudy and the amphibole is partly altered to biotite and opaque minerals.

Sample 75-OT-28 of the alkali granite consists of (in percent): subhedral, perthitic potassium feldspar, 65; anhedral quartz, 25; strongly colored riebeckite, 10; and accessory epidote and opaque minerals, <1. The rock is coarse grained, hypidiomorphic-granular, and is nearly unaltered, the feldspars having only slight clouding.

The alkali granite from Jibal Hufash, represented by specimen MJG-76-72A from near the contact, is composed of (in percent): distinctly perthitic potassium feldspar, 70; quartz, 25-30; much-altered, dark bluish-green, anhedral riebeckite, 2-5; discrete grains (aside from perthitic lamellae) of plagioclase, <1; and opaque minerals, <1. The percentages of the minerals are difficult to estimate under the microscope owing to the coarse grain size of the rock; estimates of mineral composition were made from the hand specimen. The fabric is coarse grained, hypidiomorphic-granular. Amphibole forms irregular clusters of grains interstitial to the quartz and feldspar. Alteration causes the potassium feldspar to be cloudy and the amphibole to be riddled with opaque grains.

Specimen MJG-76-72B of the alkali granite consists of (in percent): distinctly perthitic potassium feldspar, 60; quartz, 40; biotite, clay, and opaque minerals that have replaced former amphibole, 2-3. The rock is coarse-grained, hypidiomorphic-granular. Moderate alteration has caused the potassium feldspar to be very cloudy and the amphibole to change to a mixture of secondary minerals so that no amphibole remains. Field observations of this specimen suggested a resemblance to granite (sample MJG-76-56A) in a small pluton in the southeastern part of the YAR (Grolier and others, 1977, p. 23), but the petrographic examination shows that they are dissimilar.

Through the courtesy of Glen F. Brown (written commun., December 29, 1976) and Roy O. Jackson (written commun., January 31, 1977), U.S. Geological Survey, the results of analysis of a specimen of granite (field number ROJ-1; laboratory number D165544) collected by Jackson at Jibal Sabir, has been made available (table 2).

Table 2.--Chemical composition of alkali granite from Jibal Sabir, near Ta'izz, Yemen Arab Republic, in percent.

[Analyzed by Wayne Mountjoy, J. S. Wahlberg, and T. L. Yagen, U.S. Geological Survey, 1973.]

SiO_2	73.50
TiO_2	0.25[1]
Al_2O_3	12.30
Total Fe as Fe_2O_3	2.35
MnO	0.11
MgO	0.10
CaO	0.35
Na_2O	4.74
K_2O	4.69
CO_2	<0.01
Loss on ignition	0.33
	98.72

[1] TiO_2 determined from spectrographic analysis in Grolier and others (1977, p. 34).

The K-Ar age of this specimen is 22.7±0.9 m.y. (Grolier and others, 1977, fig. 2).

Tertiary and/or Cretaceous rocks--Yemen Volcanics

Specimens from various stratigraphic units of the Yemen Volcanics exposed at different geographic localities in the YAR (Overstreet and others, 1976, table 1; Grolier and others, 1977, table 2) are described below in the petrographic categories of aphanitic crystal tuff, crystal-lithic tuff, crystal-lithic welded tuff, spherulitic welded tuff, vesicular welded tuff, welded tuff, basalt, and felsite.

Aphanitic crystal tuff

Specimen 75-OT-30 of aphanitic crystal tuff of unit TKy_1 (table 1) of the Yemen Volcanics is from a locality (15° 29'40" N.; 44°28'15" E.) near As Salahi in Wadi as Sirr, YAR. The rock is composed of (in percent): ash-sized particles of isotropic glass (clouded by opaque dust) that forms the matrix, 95; subhedral to anhedral crystals of clinopyroxene up to 1 mm in size which are somewhat embayed, <1; subhedral to euhedral crystals of anorthoclase(?) 1-2 mm across with some embayment, in the groundmass, 1; microlites (possible devitrification products) <0.5 mm across, in groundmass, ~3; opaque dust and clasts about 1 mm across in groundmass, <1; clays, trace. No directional fabric nor evidence of welding is present. Slight alteration is indicated by the clays and opaque material. The opaque materials impart a pinkish color to the hand specimen. The rock is an air-fall tuff.

Crystal-lithic tuff

Crystal-lithic tuff is represented by specimen MJG-76-4 from the TKy_2 unit (table 1) of the Yemen Volcanics exposed at a locality (14°13'25" N.; 44°35'15" E.) 2.6 km southeast of Adh Dharrah on the trail to Damt (Grolier and others, 1977, p. 8). The rock consists (in percent) of: a matrix of ash- to lapilli-sized fragments, ~93; vesicular lithic fragments and some sanidine phenocrysts, ~2; crystal fragments of quartz, <1; crystal fragments of sanidine, ~3; pumice and shards, 1. Lamination is crudely developed, and the rock is moderately altered with a pervasive brown stain and a trace of clay. Some vesicles are filled with quartz.

Crystal-lithic welded tuff

The single specimen (75-OT-26) of crystal-lithic welded tuff is from the TKy_4 unit (table 1) of the Yemen Volcanics at a locality (13°54'40" N.; 44°19'40" E.) 0.9 km southeast of Najd al Juma'i (Overstreet and others, 1976, p. 96). The rock is composed of (in percent): brown glass showing welded shard structures, 55; euhedral crystals and crystal fragments of anorthoclase(?) partly replaced by calcite, 20; lithic fragments, 20; and opaque material, 5. The lithic fragments range in size from 0.5 to 10 mm and consist predominantly of feldspar porphyry and opaque matter. Lamination in the tuff results from welding, but the distribution of the clasts is chaotic. Alteration is moderate. About 30 percent of the anorthoclase(?) is replaced by calcite, zeolite, and clay; this percentage is included in the estimate of 20 percent anorthoclase(?). This crystal-lithic welded tuff is distinctive from the other tuffs described, because of its glass-poor composition.

Spherulitic welded tuff

One sample of spherulitic welded tuff (75-OT-17) is available from unit TKy_4 (table 1) of the Yemen Volcanics. It is from a locality (13°24'00" N.; 44°19'35" E.) in Wadi Amlah 5.9 km northeast of Ar Rahidah (Overstreet and others, 1976, p. 96). The rock contains (in percent): glass with visible shard structures, 90; subhedral to euhedral crystals and fragments of anorthoclase(?) with tartan twins, 5; quartz in lenses and stringers resulting from devitrification of glass, percentage not estimated; secondary calcite, <1. Lamination of the tuff is caused by welding. The hand specimen is characterized by round spherulites(?) 1-2 cm in diameter. Some spherulites(?) have irregular cavities, but most have some concentric structure. Under the microscope the spherulites(?) are seen to have a nucleus of glass, like the rest of the groundmass, surrounded by concentric rings of quartz formed by devitrification. Moderate alteration is shown by the presence of irregular quartz formed by devitrification of glass, and by the secondary calcite.

Vesicular welded tuff

Vesicular welded tuff is represented by sample MJG-76-6 from unit TKy_3, or younger unit (table 1), of the Yemen Volcanics from a locality (14°26'44" N.; 44°34'37" E.) 23.3 km east of the eastern outskirts of Dhamar (Grolier and others, 1977, p. 9). This rock consists of (in percent): reddish-brown glass and welded shards that form a laminated matrix, ~93; crystals and fragments of sanidine, 2; crystals and fragments, some embayed, of quartz, ~1; sparse fragments of volcanic rock, <1. Slight alteration is indicated by some devitrification of the glass and the presence of a little opaque material.

Welded tuff

Five samples of welded tuff were examined: 75-OT-15 from the TKy_4 unit (table 1) of the Yemen Volcanics; MJG-76-2 from the TKy_2 unit; 75-OT-31 from the TKy unit; MJG-76-1A from the undivided TKy unit; and MJG-76-1B from the undivided TKy unit.

Sample 75-OT-15 is welded tuff exposed at a locality (14°41'35" N.; 44°20'25" E.) 15 km south of Ma'bar (Overstreet and others, 1976, p. 96). The composition of the rock is (in percent): glass matrix with well-preserved shard structures and some pumiceous fragments, 95; 0.1-0.5 mm crystal fragments of sanidine in the glass, 2; lithic fragments consisting mostly of feldspar- and opaque-mineral- bearing rock, highly oxidized, ~1; secondary calcite, <1; and opaque minerals in part hematite, ~1. Some lamination was caused by welding. The rock is altered by oxidation which imparts a pinkish color. Products of alteration include the calcite and hematite.

Specimen MJG-76-2 is from a locality (14°43'05" N.; 44°21'50" E.) about 9.7 km south-southeast of Ma'bar and 0.8 km north-northeast of Risabah (Grolier and others, 1977, p. 8). The rock consists of (in percent): a matrix of glass containing particularly well preserved shards, 85; rare crystal fragments of sanidine, $\sim$1; fragments of felsic volcanic rock composed of plagioclase, opaque minerals, and pumice, $\sim$10; and hematite dust throughout matrix, $\sim$5. Welding of the glass shards produced lamination. Moderate alteration gave a hematite stain.

Sample 75-OT-31 is from a locality (15°29'40" N.; 44°28'15" E.) near As Salahi in Wadi as Sirr (Overstreet and others, 1976, p. 96). This welded tuff is composed of (in percent): glass with well-preserved shard structures, 94; crystal fragments of sanidine, 1; plagioclase, 2; clinopyroxene, 1; fine disseminated grains of opaque minerals, $\sim$1; and green clay as an alteration from the glass, not estimated. Lamination is caused by welding of the tuff. Moderate alteration is shown by the conversion of glass to clay.

Sample MJG-76-1A of welded tuff is from a locality (15°07'50" N.; 43°55'42" E.) 2.7 km southwest of Al Khamis on the highway between San'a' and Hudaydah (Grolier and others, 1977, p. 8). The rock is composed of (in percent): glass with flattened, stretched, and compacted brown shards, 99; fragments of sanidine, clinopyroxene, orange mica (phlogopite?), and opaque minerals, together with rare lithic fragments consisting of clinopyroxene and magnetite, $\sim$1. The rock is strongly laminated due to welding, but is quite unaltered. The glass shows wispy, faint "curlicues" that appear to be perlitic texture.

Sample MJG-76-1B is from the same locality as MJG-76-1A, and it consists of (in percent): glass shards, 95; quartz formed as a devitrification product, 3; phenocrysts of sanidine, <1; and opaque minerals, <1. This rock is strongly laminated and has elongate, flattened gas pockets.

Basalt

Basalt, specimen 75-OT-16, is from a site (14°41'35" N.; 44°20'25" E.) 15 km south of Ma'bar (Overstreet and others, 1976, p. 96). The rock is composed of (in percent): plagioclase both in the groundmass and as phenocrysts up to 1 mm, 85; clinopyroxene in the groundmass and as larger grains, 5; opaque material in the groundmass consisting of granular opaque minerals and transparent, orange "iddingsite" that completely replaces olivine, 10; and minor flakes of possible secondary orange biotite, <1. The groundmass has a felted fabric. The clinopyroxene is pink titanaugite(?).

Felsite

Two samples of felsite from the map unit TKy, representing undivided Yemen Volcanics (table 1), were examined petrographically. Both samples are from a locality (15°11'03" N.; 43°30'42" E.) at the southern edge of Jibal Hufash on the San'a'-Hudaydah road (Grolier and others, 1977, p. 26).

Sample MJG-76-72C of felsite is composed of (in percent): potassium feldspar, ~60; quartz, ~30; and plagioclase, ~10. The texture is extremely inhomogeneous. It varies from fine-grained aplitic intergrowths of quartz and feldspar to lensoid pods of mosaic quartz and quartz veinlets 1 mm by 5-10 mm. A few of the potassium feldspars are phenocrysts, ~1 mm across and making up ~1 percent of the rock. Alteration was intense. The potassium feldspars are totally saussuritized, and some brownish iron stain is present.

Specimen MJG-76-72D consists of (in percent): distinctly perthitic potassium feldspar, ~70; quartz, ~30; and poikilitic riebeckite, <2. The fabric of the felsite is aplitic and/or granoblastic, and is texturally similar to sample MJG-76-72C. Brownish lobate shapes mentioned in the field notes are iron stains. The mafic minerals occur throughout. The presence of riebeckite in this sample probably shows that the felsite is an intrusive rock in the Yemen Volcanics and is genetically related to the alkali granite of Jibal Hufash instead of to the volcanic rocks.

Precambrian rocks

Most of the petrographic descriptions deal with rocks of Precambrian age, and most of those are specimens collected in 1976 (Grolier and others, 1977, pp. 8-27). Granitic rocks in these descriptions have been informally classified according to the following scheme based on estimated modal percentages:

Rock name	Modal percentages
Granite	Potassium feldspar is greater than plagioclase, quartz is more than 10 percent of the rock.
Leucogranite	Similar to granite, but ferromagnesian minerals are less than 5 percent of the rock.
Granodiorite	Potassium feldspar is less than plagioclase, quartz is less than 10 percent of the rock.

Names may be modified by the presence of a varietal mineral, for example, biotite granite.

The anorthite component of the plagioclase feldspar was estimated optically by extinction angles to the (010) cleavage in sections normal to the X crystal direction (Deer, Howie, and Zussman, 1966, p. 333).

Felsite and feldspathic segregations

A sample (MJG-76-28C) of a felsite dike that intrudes biotite gneiss at a locality (14°15'36" N.; 45°20'03" E.) in the southeastern YAR (Grolier and others, 1977, p. 14, fig. 2) consists of (in percent): quartz, 40; microcline perthite as porphyroclasts, 35; plagioclase, 25; and accessory allanite (metamict), sphene, and biotite. Gridiron twinning in the microcline is spotty, with possibly some conversion of the microcline to orthoclase. The rock is a protoclastic felsite showing slight alteration by incipient breakdown of minerals to sericite, clay(?), and mixtures of epidote and clinozoisite.

Specimen MJG-76-37C of a feldspathic segregation in metadiorite at a locality (14°00'32" N.; 45°40'43" E.) about 14 km northeast of Al Bayda' (Grolier and others, 1977, p. 16). The rock is composed of (in percent): microcline porphyroclasts, 40-50; granular quartz that "flows" around the porphyroclasts of microcline, 30; deformed plagioclase, 25; and chlorite, sphene, calcite, and epidote, 3-5. The rock is protoclastic, medium to fine grained, and is moderately altered. Some grains of plagioclase are partly clouded, and secondary epidote and chlorite are sparsely present near the altered feldspar.

Granite and granite gneiss of probable late Precambrian age

The rocks described in this section resemble the late Precambrian peralkaline granite mapped in the Kindgom of Saudi Arabia (U.S. Geological Survey and Arabian American Oil Company, 1963, map).

Riebeckite granite.--Sample MJG-76-50 of riebeckite granite is from a locality (13°58'50" N.; 45°34'43" E.) from an exposure at the northern entrance to the town of Al Bayda' (Grolier and others, 1977, p. 21). The town itself is built on this granite. The rock consists of (in percent): distinctly perthitic potassium feldspar, 60; strained, incipiently recrystallized quartz, 35-40; intensely pleochroic riebeckite in anhedral grains or acicular prisms, <5; and brown biotite commonly associated with the riebeckite, <1. The fabric of the rock is allotriomorphic granular. Alteration is absent, but the rock has undergone some deformation and recrystallization. Except for this deformation and recrystallization, the riebeckite granite at Al Bayda' has a strong microscopic resemblance to the Miocene(?) alkali granites at Jibal Sabir (75-OT-27 and 75-OT-28) and at Jibal Hufash (MJG-76-72A and MJG-76-72B). This problem of resemblance will require detailed geologic mapping and isotopic age determinations to resolve, but other evidence shows substantial differences in the content of selected minor elements (Grolier and others, 1977, pp. 34-35):

	Late Precambrian riebeckite granite (ppm)	Miocene(?) alkali granites (ppm)
Ti	700	2,000
Mn	70	3,000
Be	2	7
La	20	100
Nb	<50	100
Zr	100	300

Alkali feldspar granite.--Four examples of alkali feldspar granite were collected: MJG-76-29A, MJG-76-33A, MJG-76-39A, and MJG-76-39B.

Specimen MJG-76-29A is from a sill exposed (14°15'16" N.; 45°21'45" E.) in biotite diorite gneiss. The alkali feldspar granite is composed of (in percent): orthoclase perthite with strikingly coarse perthite lamellae, 60; plagioclase, ~5; quartz, 30; dark green hornblende, ~4; and accessory sphene and opaque minerals, ~1. The fabric is allotriomorphic granular. Slight alteration is shown by minor iron stain and development of a trace of sericite. The rock might be called a one-feldspar granite that apparently originally crystallized as a nearly one-feldspar phase, which, upon cooling, exsolved sodium-rich and potassium-rich phases of feldspar. The estimate of the abundance of plagioclase refers only to discrete grains of plagioclase; it does not include sodium-rich feldspar lamellae in the perthite.

Sample MJG-76-33A is gneissic alkali feldspar granite from a locality (14°09'08" N.; 45°25'30" E.) in the southeastern part of the YAR (Grolier and others, 1977, p. 15). The rock is composed of (in percent): strained microcline perthite, 65; severely strained and sutured quartz, 30; biotite, 3; opaque minerals, 2. The fabric of the rock is strongly gneissic; the component minerals are so severely strained that they approach cataclasis, and locally a mortar texture is present. Flakes of biotite are parallel to the general planar trend of shearing and thus define the foliation. Biotite is also present in fractures in the rock. Despite the shearing, the minerals in the rock are unaltered.

Sample MJG-76-39A, located at 14°02'43" N.; 45°42'48" E. (Grolier and others, 1977, p. 17) an alkali feldspar granite, consists of (in percent): microcline perthite, 50; quartz having some undulatory extinction, 40; plagioclase (as discrete grains, not counting stringers in perthite), 10; minor clots of chlorite, biotite, sphene, and opaque minerals after hornblende (?) or biotite (?) <1. The fabric of the rock is coarse grained, hypidiomorphic granular. The microcline is coarsely perthitic. Some vermicular inclusions of quartz are in the plagioclase. Slight alteration is shown by the conversion of the ferromagnesian minerals to chlorite and sphene.

Sample MJG-76-39B is a graphic alkali feldspar granite from the same area as MJG-76-39A (Grolier and others, 1977, p. 17). This alkali feldspar granite is made up of (in percent): potassium feldspar, 55-60; quartz, 40; plagioclase, 2; magnetite(?), <1. The rock is fine- to medium-grained with graphic texture. Alteration of feldspars to sericite is minor.

Biotite granite.--Two specimens of biotite granite are represented: MJG-76-26B and MJG-76-36A. The first of these is from a locality (14°16'30" N.; 45°15'17" E.) 3.9 km south-southeast along the road from As Sawadiyah, and the second is from a point (13°59'31" N.; 45°39'43" E.) 9.6 km east-northeast of Al Bayda' (Grolier and others, 1977, pp. 13 and 16).

Specimen MJG-76-26B is from a dike of biotite granite intrusive into biotite gneiss. The biotite granite consists of (in percent): microcline perthite, 70; plagioclase, 15; quartz with strained extinction, 10; biotite, 3; and accessory muscovite, epidote, chlorite, and apatite, 2. The fabric of the rock is medium grained allotriomorphic granular. Vague directional fabric seen in the hand specimen is not evident in the thin section. Myrmekite is present at the boundaries between the microcline and plagioclase. Slight to moderate alteration of the granite is shown by the presence of the epidote and chlorite.

Sample MJG-76-36A of biotite granite is from a dike in metadiorite. The granite is composed of (in percent): microcline perthite, 35; quartz, 35; plagioclase, and some antiperthite (blebs of microcline in plagioclase), 20; biotite, some of which is altered to chlorite and opaque minerals, 5-8; and opaque minerals, 2. The fabric of the rock is hypidiomorphic granular with superimposed gneissic structure. Slight alteration is shown by sericite derived from feldspars, and chlorite derived from biotite.

Granite and granite gneiss.--One sample each of granite (MJG-76-14) and granite gneiss (MJG-76-15) is represented in this group of specimens. The granite is from a locality (14°22'46" N.; 44°57'32" E.) about 2 km southeast of Abbas, and the granite gneiss is from a point (14°21'36" N.; 44°59'43" E.) about 6.8 km southeast of Abbas (Grolier and others, 1977, p. 10).

Specimen MJG-76-14 of granite consists of (in percent): anhedral microcline perthite, 35; slightly sericitized plagioclase (An_{30}), 25;

quartz, 35; magnetite (?), ~1; oxidized biotite, 2; and muscovite and chlorite, 2. The fabric is fine-grained allotriomorphic granular. Alteration of feldspar to sericite and of biotite to chlorite and opaque minerals was slight.

Sample MJG-76-15 of granite gneiss is composed of (in percent): microcline perthite, 50; plagioclase, 20; somewhat elongate but anhedral quartz, 25; sparse, small flakes of muscovite, 2; and a trace of opaque minerals, biotite, and chlorite. The fabric is allotriomorphic granular and superimposed gneissosity is indicated by some elongation of the grains of quartz and feldspar. Some myrmekite is developed at the boundaries of the grains of microcline and plagioclase. Slight alteration of the rock is evident from sparse sericitization of the feldspars, replacement of the biotite by opaque minerals (only a trace of biotite remains), and some iron stain.

Granodiorite porphyry.--A single specimen of granodiorite porphyry (MJG-76-13) was collected at a point (14°22'46" N.; 44°57'32" E.) 2 km by road southeast of Abbas (Grolier and others, 1977, p. 10). The groundmass consists of (in percent): a fine-grained mixture of laths of plagioclase(?), potassium feldspar, and opaque minerals, 48, with blebs of quartz, 2. Prominent phenocrysts of plagioclase, 40 percent, and calcite and opaque minerals after hornblende(?), 10 percent. The plagioclase phenocrysts are 3-15 mm across; some are glomeroporphyritic, and they have oscillatory-normal zoning. A feeble flow orientation is present in the groundmass. Alteration was moderate to intense: all former ferromagnesian phenocrysts are replaced and the plagioclase phenocrysts are slightly sericitized.

Granodiorite.--Two specimens of granodiorite are represented: sample MJG-76-32A from a position at 14°10'31" N.; 45°23'46'E., and sample MJG-76-56A from a site at 14°04'01" N.; 45°29'46" E. (Grolier and others, 1977, pp. 15 and 23).

Sample MJG-76-32A consists of (in percent): plagioclase with mottled extinction, caused by strain or by intergrowths of microcline, 55; microcline, <5; quartz, 30; anhedral actinolite (?) after hornblende, 5; sphene, allanite, and opaque minerals, 3; secondary epidote, clinozoisite, and chlorite, 2. The amphibole is pale bluish green, and is locally converted to epidote and clinozoisite. The fabric of this granodiorite is allotriomorphic granular.

Sample MJG-76-56A is composed of (in percent): antiperthite, 45; microcline, 20; quartz, 5; hornblende, 10; biotite, 15; opaque minerals, biotite, and sphene, 5. The antiperthite is patchy near the core of the grain, but grades outward to more and more abundant patches of microcline. Rims of the antiperthite are entirely microcline and vermicular intergrowths of microcline and quartz. Clustering of the hornblende and biotite is common. This coarse-grained rock has an allotriomorphic-granular fabric, and is not altered.

Older granite and granite gneiss

The granite, granite gneiss, and granodiorite described below resemble the older felsic intrusive rocks of the Precambrian Shield in Saudi Arabia (U.S. Geological Survey and the Arabian American Oil Company, 1963, map), and they may have been intruded mainly during the second episode of the Hijaz tectonic cycle recognized in Saudi Arabia (Greenwood and others, 1976, p. 519). This is in contradistinction to the granite and granite gneiss of probable late Precambrian age, which seems mainly to have been intruded during the third episode of the Hijaz tectonic cycle.

The order of discussion of these intrusive rocks is by general mineralogical composition (which is not by geologic age), the leucogranites first and the granodiorites last. The possibility exists, however, that the leucogranites may be as young as the third episode of the Hijaz tectonic cycle. Detailed geologic mapping and the determination of the isotopic ages of appropriately situated plutons will be needed to establish the ages of this diverse array of granitic rocks.

Leucogranite gneiss.--Three specimens of leucogranite gneiss are described below. Sample MJG-76-9 is from a locality (14°26'11" N.; 44°53'50" E.) 8.8 km by road southeast of Rida' (Grolier and others, 1977, p. 9). Samples MJG-76-19A and MJG-76-19B were taken from the same site (14°21'05" N.; 45°05'04" E.) about 21.4 km east-southeast of Abbas (Grolier and others, 1977, p. 11).

Sample MJG-76-9 is an unaltered leucogranite gneiss lacking mafic minerals. It contains (in percent): strained blebs of xenoblastic quartz, 35; xenoblastic microcline, 30; plagioclase, 25; and muscovite in the plane of foliation, 10. The rock has an allotriomorphic-granular fabric with superimposed gneissosity.

Sample MJG-76-19A of the leucogranite gneiss consists of (in percent): microcline perthite, 45; quartz, 40; plagioclase, 10; biotite, 3; and accessory sphene, apatite, and opaque minerals, ~1. The fabric is medium-grained allotriomorphic granular with superimposed gneissosity. Some cataclasis is evident from granulation, mortar texture, and incipient recrystallization of the quartz. The rock is unaltered.

Leucogranite gneiss with specimen number MJG-76-19B is composed of (in percent): orthoclase perthite and sparse microcline, 35; plagioclase with sparse patch antiperthite, 35; quartz, 25; xenoblastic hornblende, 3; and accessory muscovite, sphene, and rounded opaque minerals, 2. The rock is gneissic with elongated grains of feldspar and quartz, and incipient cataclasis. Minor to moderate alteration is shown by the presence of sericite.

Biotite granite.--Biotite granite is represented among the specimens by sample MJG-76-24 from a locality at 14°19'30" N.; 45°10'53" E. (Grolier and others, 1977, p. 12). The rock consists of (in percent): quartz, 45; subhedral microcline perthite, 40; sericitized, subhedral plagioclase, 10; reddish biotite with many haloes around inclusions of zircon, 5; and accessory opaque minerals and zircon, ~1. The rock is hypidiomorphic granular with a suggestion of preferred orientation of feldspars in the thin section, but not obviously gneissic in the hand specimen.

Hornblende-biotite granite.--Sample MJG-76-41B of hornblende-biotite granite is from a locality at 14°03'11" N.; 45°43'32" E. (Grolier and others, 1977, p. 18). The rock is composed of (in percent): microcline perthite, 35; plagioclase, 20; quartz, 15; green hornblende with some grains having blue-green rims, 15; biotite, 10; and sphene, apatite, zircon, and opaque minerals, ~5. Some myrmekite has developed along the boundaries between the microcline and the plagioclase grains. The fabric of the rock is hypidiomorphic granular. Slight alteration of the rock is shown by some sericite on the plagioclase and by the blue-green rims (possibly actinolite) on the hornblende.

Granite gneiss.--The ten specimens of granite gneiss described below are from localities as follows (Grolier and others, 1977, table 2):

Sample Number	Locality: North latitude	Locality: East longitude
MJG-76-16	14°21'25"	45°01'30"
-21	14°20'06"	45°06'45"
-25	14°18'08"	45°13'07"
-27A	14°16'33"	45°17'56"
-27B	do.	do.
-28A	14°15'36"	45°20'03"
-30	14°13'46"	45°22'09"
-33B	14°10'31"	45°23'46"
-44	14°02'00"	42°42'40"
-53C	14°02'55"	45°32'17"

Specimen MJG-76-16 is granite gneiss consisting of (in percent): anhedral microcline perthite, 35; anhedral quartz, 30; subhedral plagioclase, 25; subhedral biotite, 10; and accessory hornblende, epidote, apatite, and opaque minerals, <1. Myrmekite is present locally. The rock is medium grained, hypidiomorphic granular with no directional fabric evident in the thin section, but gneissic texture is apparent in the hand specimen owing to a strong preferred orientation of the biotite. Only minor alteration is present.

The granite gneiss in sample MJG-76-21 is composed of (in percent): xenoblastic microcline perthite, 40; quartz, 35; plagioclase (about An_{30}), 15; deep-green hornblende with strong absorption, 5; opaque minerals, 1-2; and a trace of muscovite. The gneissic texture is evidenced by the orientation of elongate clusters of hornblende. Alteration is slight.

Sample MJG-76-25 of granite gneiss consists of (in percent): subhedral microcline perthite with inclusions of quartz and plagioclase, 50; subhedral plagioclase with rare patchy antiperthite, 10; anhedral quartz, 35; biotite, 5; and accessory zircon, garnet, apatite, and chlorite, <1. Myrmekite is common at the boundaries between grains of microcline and plagioclase. The sparse garnets form round grains. The rock is coarse grained, allotriomorphic granular, and its gneissic texture is more evident in the hand specimen than in the thin section. It is similar to MJG-76-16, but has less plagioclase.

Sample MJG-76-27A is granite gneiss consisting of (in percent): microcline perthite, 50; quartz, 25; plagioclase, some with patchy antiperthite, 5-10; biotite, 10; deep olive-green hornblende, 5; and accessory sphene, apatite, zircon, and opaque minerals, ~1. The rock is medium grained, allotriomorphic granular with a superimposed gneissic texture that is more obvious in the hand specimen than in the thin section. The gneiss is unaltered.

Specimen MJG-76-27B is mineralogically identical to MJG-76-27A, but the grain size is finer and the gneissic texture is more strongly developed than in MJG-76-27A. The granite gneiss of specimen MJG-76-27B is composed of (in percent): microcline perthite, 50; quartz, 25; plagioclase, 5-10; biotite, 10; hornblende, 5; sphene, apatite, zircon, and opaque minerals, ~1. The gneissic texture is defined by biotite flakes and by the distinct segregation of felsic and mafic minerals.

Granite gneiss, sample MJG-76-28A, is composed of (in percent): microcline-orthoclase perthite, 45; quartz, 35; plagioclase, many untwinned, some antiperthitic, 15; biotite, 3; and accessory apatite and opaque minerals, ~1. The potassium feldspar seems to be partly orthoclase and partly microcline; the large grains have untwinned cores that may be orthoclase. The rock is coarse grained and has crude gneissic layering defined by the flakes of biotite. Alteration is absent.

Sample MJG-76-30 is granite gneiss that contains (in percent): quartz, 45; microcline perthite, 35; plagioclase, 10; irregular flakes and fine-grained, matted, lenticular aggregates of biotite, sphene, and epidote, 8; sphene and epidote, ~2. The rock is nearly protoclastic gneiss, with some granulation and shearing, and the gneissic fabric is emphasized by the mafic constituents being confined to thin segregations. Development of epidote with the biotite in the sheared zones is considered as alteration.

Specimen MJG-76-33B of granite gneiss consists of (in percent): microcline perthite, 45; severely strained quartz, 30; plagioclase, 20-25; greenish-brown biotite and epidote, 2; and accessory zircon, sphene, allanite(?), and opaque minerals, <1. The gneissic texture is defined by strong dimensional preferred orientation of grains of quartz and feldspar. Slight alteration is inferred from the presence of the epidote.

The gneissic granite represented by sample MJG-76-44 consists of (in percent): microcline and orthoclase(?) perthite, 35; strained and sutured quartz, 35; sericitized plagioclase, 25; and accessory biotite, sericite, zircon, and sphene, ~3. The rock is medium grained, allotriomorphic granular with mortar texture in which large crushed grains are set in an incipiently recrystallized matrix. Local, lenticular parts of the rock have aplitic (nearly graphic) texture. Slight to moderate alteration is indicated by the replacement of plagioclase by sericite.

Sample MJG-76-53C is granite gneiss composed of (in percent): strained and elongate quartz, 35; microcline perthite, 25; plagioclase, 30-35; biotite flakes aligned along fractures, 5; sericite, chlorite, and opaque minerals, <1. The plagioclase tends to form large subround grains which may be former phenocrysts. The fabric is allotriomorphic granular with superimposed gneissic texture. Alteration of feldspar to sericite is minor.

Protomylonitic granite gneiss.--Four specimens are described as protomylonitic granite gneiss (Grolier and others, 1977, table 2):

Sample Number	Locality North latitude	East longitude
MJG-76-35C	13°59'00"	45°37'13"
-38A	14°01'25"	45°41'56"
-42B	14°03'42"	45°45'50"
-52C	14°01'13"	45°34'02"

Sample MJG-76-35C is composed of (in percent): strained, lenticular grains of quartz, 25; plagioclase, completely riddled with sericite and epidote, 25; two varieties of hornblende, 25; broken porphyroclasts of potassium feldspar, 15-20; contorted grains of chlorite, 5; epidote, 3; and secondary sphene, <1. The hornblende shows a crude zonation in color or patchy overgrowths of pale green after dark green hornblende. The rock is a coarse-grained protomylonitic gneiss; cataclasis is evident in the quartz, potassium feldspar, and plagioclase. Moderate to strong alteration is shown by the presence of such secondary minerals as sphene, chlorite, epidote, and sericite.

Specimen MJG-76-38A of protomylonitic granite gneiss is made up of (in percent): microcline porphyroclasts, 45; tiny recrystallized granules of quartz, 40; altered porphyroclasts of plagioclase, 10-15; and sericite, 3. The potassium feldspar and plagioclase are fractured and rounded porphyroclasts in a fine granular incipiently recrystallized matrix of quartz. The fabric of the rock is protomylonitic: granular quartz "flows" around the porphyroclasts of potassium feldspar and plagioclase. Slight to moderate alteration to sericite affects the plagioclase.

Sample MJG-76-42B of protomylonitic granite gneiss consists of (in percent): microcline perthite with mortar texture, 40; lensoidal, sutured, polycrystalline grains of quartz, 35; twinned plagioclase in matrix, 20; and chlorite, hornblende (?), muscovite, zircon, and opaque minerals, ~5. Large (up to 5 mm) porphyroclasts of potassium feldspar and quartz are in a matrix of recrystallized quartzo-feldspathic material. The muscovite, chlorite, and opaque minerals appear to be secondary alteration products, because they are present along the boundaries of grains and in fractures.

The protomylonitic granite gneiss, sample MJG-76-52C, contains (in percent): porphyroclasts of perthitic feldspar up to ~1 cm across, 40; strongly deformed, granular, mosaic-textured, and incipiently recrystallized quartz, 30; plagioclase in broken grains and porphyroclasts up to 1 cm across, 25; muscovite flakes between the porphyroclasts of feldspar, 3; biotite, 1; chlorite and epidote, ~1. The potassium feldspar and plagioclase form large porphyroclasts in a matrix of quartz and plagioclase. Some mortar texture noted, but protomylonitic texture is dominant, and gneissosity is difficult to define on the scale of the thin section owing to the coarse grain size. However, the effects of deformation are obvious in the strained minerals and quartzose matrix. Minor alteration has resulted in the formation of sericite, epidote, and chlorite.

Granodiorite gneiss.--Two specimens of granodiorite gneiss are represented: sample MJG-76-37B from a locality (14°00'32" N.; 45°40'43" E.) 14.4 km by road northeast of Al Bayda', and sample MJG-76-54A from a point at 14°03'07" N.; 45°31'23" E. (Grolier and others, 1977, table 2).

Sample MJG-76-37B contains (in percent): plagioclase, some grains antiperthitic, 50; strained and sutured quartz, 40; potassium feldspar, 5; and secondary chlorite (two generations), sericite, and epidote, ~5.

The plagioclase forms large, subhedral grains that do not appear to be true porphyroblasts. These grains originally may have been phenocrysts in an igneous rock of porphyritic texture. In its present state, the rock is hypidiomorphic granular with a superimposed gneissic texture. Moderate alteration is indicated by the presence of chlorite, epidote, and sericite.

Specimen MJG-76-54A of granodiorite gneiss consists of (in percent): plagioclase, some with patchy antiperthite, 40; orthoclase perthite, 20; quartz, 15; brownish-green biotite, some of which partially replaces hornblende, 10; dark-green hornblende, ~8; sphene, ~2; epidote, possibly secondary, ~2; and accessory allanite and apatite, <1. The gneissic banding of the rock is evident in thin section from the preferred orientation of the hornblende, biotite, and plagioclase. Some cataclasis resulted in the granulation of quartz and plagioclase followed by incipient recrystallization of both minerals. Minor to moderate alteration probably caused the formation of the epidote.

Diabase and gabbro

The diabase and gabbro represented in these specimens may be mainly from the second episode (table 1) of the Hijaz tectonic cycle recognized in Saudi Arabia (Greenwood and others, 1976, table 1), but the stratigraphic position is uncertain, and isotopic age data are needed to confirm this premise. The four specimens of diabase and gabbro described below were taken from the following localities (Grolier and others, 1977, table 2):

Specimen Number	Rock Type	Locality	
		North latitude	East longitude
MJG-76-36C	Diabase	13°59'31"	45°39'43"
-41A	Diabase	14°03'11"	45°43'32"
-41C	Gabbro	do.	do.
-42C	Diabase	14°03'42"	45°45'50"

Diabase of specimen MJG-76-36C is composed of (in percent): normally zoned plagioclase with some perthiric margins, 50; clinopyroxene, 20; deep green hornblende, 15; green and brown biotite, 5; opaque minerals, 3; quartz, 3; slender needles of accessory apatite, 1. The fabric is intergranular, and the rock is moderately altered. The hornblende may be secondary; some clusters of the ferromagnesian minerals are quite altered, and fringes of uralite are present on the clinopyroxene.

Sample MJG-76-41A of diabase consists of (in percent): plagioclase ($>An_{55}$) with normal zoning, 40; subophitic clinopyroxene, 35; opaque minerals, 10; serpentine or talc after olivine(?), 10; and actinolite(?) after clinopyroxene, ~5. The rock has a massive medium-grained diabasic texture. Slight alteration is shown by replacement of olivine(?) grains by opaque minerals and serpentine, and by the presence of blue-green rims on some hornblende.

Sample MJG-76-42C is an altered diabase consisting of (in percent): zoned plagioclase, 50; subophitic, slightly uralitized clinopyroxene, 25; two varieties of amphibole, 20; and opaque minerals, 5. One variety of amphibole is brown; the other is pale green and may be tremolite or actinolite. The pale green amphibole occurs as felted, irregular but crudely round patches that might represent former amygdules or interstitial glass, but is more likely to have been ferromagnesian phenocrysts. The rock is fine grained and has a diabasic texture. Alteration of the original minerals was moderate and formed chlorite, amphibole, and epidote.

The gabbro specimen MJG-76-41C is an olivine-two pyroxene gabbro composed of (in percent): subhedral laths of plagioclase having an anorthite content greater than An_{50}, 55; subophitic orthopyroxene that may be inverted pigeonite, 10; subophitic clinopyroxene with exsolution lamellae of orthopyroxene, 25; subhedral olivine, 5; opaque minerals, 2; brown hornblende, ~1; and reddish-brown flakes of biotite, ~1. Both the clinopyroxene and the orthopyroxene show exsolution lamellae of the other pyroxene. Magnetite commonly occurs with the hornblende and/or the biotite. Some odd vermicular intergrowths of pyroxene and plagioclase, as well as of magnetite and pyroxene, are present. The rock is massive and quite unaltered, but the hornblende and biotite may be secondary.

Metamorphosed igneous rocks of intermediate and mafic composition

Most of the igneous rocks of intermediate and mafic composition represented in this suite of specimens are metamorphosed to various degrees, perhaps reflecting their stratigraphic position among the older rocks in the YAR (table 2). Actually, the degrees of metamorphism, although representing several grades of regional metamorphism, are similar to those described above for the older granite and granite gneiss. Both volcanic and plutonic rocks are included among the specimens described below.

Meta-andesite.--Sample MJG-76-36B of meta-andesite(?) is from a locality (13°59'31" N.; 45°39'43" E.) 9.6 km east-northeast of Al Bayda' (Grolier and others, 1977, p. 16). This rock is composed of (in percent): plagioclase, ~An_{40}, some grains zoned, 55; quartz, 10-15; olive-green hornblende, 15; pale olive-green biotite, 10; sphene and opaque minerals, 3; and secondary epidote, clinozoisite, and chlorite, 2. The fabric is hypidiomorphic granular, and moderate alteration produced sericite, epidote, and chlorite.

Sample MJG-76-52A of meta-andesite is from a point (14°01'13" N.; 45°34'02" E.) 7.1 km north-northwest of Al Bayda' (Grolier and others, 1977, p. 21). This meta-andesite consists of (in percent): calcic plagioclase partly corroded and altered to sodic plagioclase, 65; epidote after clinopyroxene(?), 12; pervasive olive-green biotite, 15; pervasive, intergranular white mica, ~5; sphene, 3; and calcite, <1. Massive hypidiomorphic-granular texture is still evident. Alteration is moderate to intense, as shown by epidote replacing former phenocrysts of clinopyroxene, and by the presence of secondary biotite, calcite, and white mica.

Metabasalt (greenstone).--Two specimens of metabasalt (greenstone) were collected: MJG-76-35A from a locality (13°59'00" N.; 45°37'13" E.) 4.8 km by road east-northeast of Al Bayda', and MJG-76-49C from an exposure at the east end of the airfield runway (13°57'42" N.; 45°32'22" E.) at Al Bayda' (Grolier and others, 1977, table 2). In both, the original igneous textures are only faintly preserved.

Sample MJG-76-35A is composed of (in percent): tiny grains of brownish-green, fibrous amphibole, possibly actinolite, 30; granular epidote, 35; pale green chlorite, 20; albite, 10; sphene, <5; opaque minerals, ~2; and clay(?) and quartz, ~1. Relict albite laths confirm the igneous protolith (= parent rock) of this greenstone, as does the fine-grained, nearly felted fabric of the rock. Veinlets of epidote and clay(?) are pervasive, and intense alteration is also shown by the presence of the chlorite and quartz.

The greenstone represented by specimen MJG-76-49C consists of (in percent): fine-grained granular epidote, 80; strained quartz in irregular blebs and veins, 10; chlorite, especially present in amygdules, 5; calcite, ~2; and fibrous blue-green actinolite intergrown with epidote, ~3. Relict texture in plane-polarized light indicates igneous origin, because clear outlines of former laths of plagioclase are visible; and equally visible are kidney- or oval-shaped blebs that were probably amygdules. All are now replaced by epidote. The alteration was intense; epidote, chlorite, calcite, and actinolite were all formed from pre-existing minerals. What was thought in the field description to have been garnet is probably iron-stained grains of epidote, because in thin section, garnet is absent. Morever, the grade of metamorphism represented by the rock is too low for garnet to be present.

Metagranodiorite.--Specimens MJG-76-35B, from a point (13°59'00" N.; 45°37'13" E.) 4.8 km by road east-northeast of Al Bayda', and MJG-76-48B, from a locality (13°57'50" N.; 45°29'45" E.) 5 km by road east of Al Zahair (Grolier and others, 1977, table 2), are metagranodiorite.

The rock represented by sample MJG-76-35B is composed of (in percent): completely sericitized plagioclase, 35; potassium feldspar with strain shadows, 15; hornblende much altered to chlorite, 20;

strongly deformed quartz, 10; chlorite, 5-8; epidote after plagioclase, and in veins, ~5; sericite after plagioclase, ~5; and sphene, 2. A poorly developed gneissic texture is overprinted on an hypidiomorphic-granular fabric. Evidence of cataclasis includes granulation of quartz and feldspars, strain shadows in those minerals, fractures, and a high degree of shearing. However, the rock is incompletely recrystallized, and the development of such new minerals as chlorite, sericite, and sphene is more attributable to alteration after cataclastic deformation than to metamorphic crystallization (crystalloblastesis).

Sample MJG-76-48B of metagranodiorite consists of (in percent): strained and sutured quartz, 40; subhedral, twinned plagioclase, 30; xenoblastic grains of epidote in plagioclase and also in veinlets, 15; chlorite, 8; white mica, 2-5; and sphene, 2. The original hypidiomorphic-granular fabric has a superimposed incipient crystalloblastesis that produced greenschist facies minerals: epidote, chlorite, and sphene. A vague gneissic texture is definable. A trace of original igneous zoning remains in some grains of plagioclase, and all have strong albite twinning. The thin section is criss-crossed by veinlets of epidote.

Metadiorite.--Five specimens of metadiorite are represented among these rocks (Grolier and others, 1977, table 2):

Sample Number	Locality	
	North latitude	East longitude
MJG-76-32B	14°10'31"	45°23'46"
-37A	14°00'32"	45°40'43"
-42A	14°03'42"	45°45'50"
-43	14°04'49"	45°48'15"
-52B	14°01'13"	45°34'02"

The metadiorite represented by sample MJG-76-32B is a hornblende gneiss consisting of (in percent): green to bluish-green hornblende, 75; plagioclase about An_{40}, 20; quartz, 3; sphene, 2; and minor epidote after plagioclase, 1. The hornblende in this specimen is more blue than the hornblende in sample MJG-76-29B, described under hornblende-pyroxene gneiss, and the metamorphic grade of this metadiorite is lower than the grade of the hornblende-pyroxene gneiss. Gneissic texture is defined by the hornblende. Slight alteration is shown by the minor epidote formed from plagioclase.

The highly altered condition of the epidotized metadiorite of sample MJG-76-37A makes difficult the determination of the original texture and mineralogy of the rock. It is composed of (in percent): highly altered plagioclase with some relict twins, 40; green hornblende partly altered to blue-green hornblende, 25; epidote in veins and as partial replacement of hornblende, 15-20; chlorite, 5-10; sericite, ~5; calcite, with epidote, after plagioclase and hornblende, ~2; quartz, ~2; sphene, ~1; and opaque minerals, ~1. The original rock appears to have had an hypidiomorphic-granular texture overprinted by slight gneissic texture. The rock is extremely altered, as shown by epidote in veins and replacing plagioclase and hornblende, and by the replacement of the plagioclase and hornblende by lesser amounts of chlorite, sericite, and sphene.

Sample MJG-76-42A is also an epidotized metadiorite composed of (in percent): unaltered plagioclase, ~10; green hornblende partly altered to blue-green hornblende, 25; sericite after plagioclase, ~25; epidote after plagioclase and hornblende, ~15; chlorite after hornblende, 10; calcite after hornblende, ~5; opaque minerals, possibly primary, 3-5; sphene, 2; and apatite(?), 2. The original mineralogy of the rock may have been about 70 percent plagioclase and 30 percent hornblende. The original fabric is indeterminable, because alteration was extreme. Epidote, chlorite, sphene, calcite, sericite, and apatite(?) are all secondary minerals.

Specimen MJG-76-43 is gneissic metadiorite composed of (in percent): plagioclase preserving some compositional zoning, 45; sieve-textured hornblende with inclusions of quartz, 20; quartz, 20; biotite, 10; accessory apatite, sphene, and opaque minerals, ~5; epidote, <1; calcite, <1. The rock has a medium-grained, hypidiomorphic-granular fabric on which a gneissic texture is superimposed. The texture of the grains of hornblende is interpreted to indicate that the hornblende is late. Slight alteration is shown by biotite partly changed to chlorite, and by the presence of epidote and calcite.

The metadiorite in sample MJG-76-52B is composed of (in percent): unaltered plagioclase ~An_{70}, 50; brownish-green, anhedral hornblende, 40; patches and rims of clinopyroxene with the hornblende, 10; epidote, 1; and opaque minerals, ~1. The fabric is allotriomorphic granular.

Hornblende gneiss.--A sample of hornblende gneiss (MJG-76-38C) was described in the field (14°01'25" N.; 45°41'56" E.) as a pyroxenite dike that intrudes augen gneiss (Grolier and others, 1977, p. 17) proved by microscopic examination to be intensely metamorphosed. The rock consists of (in percent): hornblende with strained extinction, 70; sericitized plagioclase, 15; quartz, 10; epidote replacing hornblende and plagioclase, 3; accessory sericite, chlorite, apatite, and opaque minerals, ~2. The rock has a medium-grained gneissic texture with some cataclasis shown by the granulation of feldspar and quartz. Moderate alteration has caused sericite and epidote to form from the plagioclase, and chlorite and epidote to crystallize along fractures and veins.

Hornblende-plagioclase gneiss.--Specimen MJG-76-53B of hornblende-plagioclase gneiss is from a locality (14°02'55" N.; 45°32'17" E.) 11.9 km northwest of Al Bayda' (Grolier and others, 1977, p. 22), where the field relations showed that the rock was a metamorphosed diorite interlayered with feldspathic biotite gneiss. Its composition is (in percent): plagioclase, ~An_{40}, some grains zoned, 40; hornblende, 50; subrounded, wedge-shaped grains of sphere in clusters along the boundaries of grains of hornblende, 5; quartz, <1; opaque minerals, <1; and epidote and sericite, <1. Slight alteration is shown by the secondary epidote and sericite.

Hornblende-biotite schist.--Sample MJG-76-22, located 14°19'50"N.; 45°08'33"E., was thought in the field to resemble biotite schist produced by the retrograde metamorphism of gabbro or pyroxenite, but mafic igneous rocks were not observed at the site (Grolier and others, 1977, p. 12). In thin section the rock was seen to consist of (in percent): strongly pleochroic red-brown to tan biotite, 15; brown hornblende, 70; plagioclase, ~An_{45}, 10; embayed remnants of former porphyroblasts of garnet, ~3; and quartz and opaque minerals, 2. A later metamorphic event is interpreted to have affected this rock, causing the deterioriation of the garnet and the retrograde growth of biotite. No clear textural evidence exists for the relative ages of the hornblende and the biotite. The garnet porphyroblasts are partially or totally replaced by plagioclase, biotite, and opaque minerals resulting in leucocratic augen. The rock is strongly schistose.

Hornblende-pyroxene gneiss.--Sample MJG-76-29B of hornblende-pyroxene gneiss from a locality (14°15'16" N.; 45°21'45" E.) where field relations were interpreted to indicate that the gneiss was metamorphosed diorite (Grolier and others, 1977, p. 14). The gneissic rock consists of (in percent): dark-green hornblende, 45; plagioclase, An_{30-40}, 40; pale-green clinopyroxene, some altering to amphibole, 10; sphene and opaque minerals, ~5; and epidote and sericite, <1. The hornblende and pyroxene co-exist as two discrete phases with no significant amount of reaction between the two minerals. The rock is medium grained and the gneissic texture is defined by oriented hornblende and plagioclase. Slight alteration is shown by the local presence of sericite, epidote, blue-green amphibole, and minor conversion of clinopyroxene to amphibole.

Metamorphosed sedimentary and pyroclastic rocks

The metamorphosed sedimentary and pyroclastic rocks described below are probably from units equivalent to those in the first and second episodes of the Hijaz tectonic cycle of Saudi Arabia (table 2).

Marble.--Two specimens of marble are represented: sample MJG-76-51B from a locality (13°59'12" N.; 45°34'32" E.) 2.4 km northwest of Al Bayda', and sample MJG-76-59A from a point (14°14'02" N.; 45°23'25" E.) 3.6 km by road north-northwest of Al Qa (Grolier and others, 1977, table 2).

Sample MJG-76-51B is very fine grained, siliceous, dolomitic marble that consists of (in percent): very fine grained calcite with dolomite(?), 95; mosaic quartz in fine layers and veinlets, 5; and sparsely distributed flakes of white mica, <1. The rock has fine-scale layering and is only slightly recrystallized, but whether the layering is sedimentary or metamorphic cannot be determined with certainty.

Sample MJG-76-59A of medium-grained marble consists of (in percent): calcite, 98; sparse, irregularly distributed white mica, 2; and apatite(?), <1. The patchiness and irregularity of the boundaries of the grains of calcite is interpreted to result from incomplete recrystallization.

Calc-silicate rock.--A sample of calc-silicate rock (MJG-76-38B) from an interbedded sequence of gneiss and greenstone exposed at 14°01'25" N.; 45°41'56" E. (Grolier and others, 1977, p. 17) consists of (in percent): calcite, 95; prisms of tremolite, 3; rounded clots of chlorite, 2; and veinlets of chrysotile, <1. The calcite is deformed and granulated but not much recrystallized. Probably the rock should be referred to as cataclastic or protomylonitic marble or tremolite-bearing marble.

Calcareous quartzite.--Specimen MJG-76-54B of calcareous quartzite, from a locality at 14°03'01" N.; 45°31'50" E. (Grolier and others, 1977, p. 22), consists of (in percent): sutured, lenticular, strained quartz, 55-60; xenoblastic calcite, 40; sphene, ~2; clinozoisite, <1; and white mica, tourmaline and opaque minerals, ~1. A gneissic texture is produced by compositional banding of quartz-rich and calcite-rich layers 2-5 mm thick.

Slaty argillite.--Sample MJG-76-55A of slaty argillite, exposed at 14°03'35" N.; 45°31'03" E. (Grolier and others, 1977, p. 22) is composed of (in percent): quartz, ~20; biotite, ~50; albite, 25; epidote-clinozoisite along fractures, 2-3; amphibole, <1; and opaque minerals, <1. The rock is a very fine grained slate with a matrix consisting of biotite, quartz, and feldspar(?). Sparse clasts of plagioclase ~1 mm across are present, and the slaty cleavage wraps around the clasts. Quartz-rich lenses may reflect original sedimentary compositional variation.

Sericite schist.--Specimen MJG-76-49B of sericite schist from an exposure (13°57'42" N.; 45°32'22" E.) at the east end of the Al Bayda' airfield (Grolier and others, 1977, p. 20) consists of (in percent): plagioclase, 45; quartz, 30; sericite in bands and flakes, 15; irregularly shaped grains of calcite, 5; idiomorphic opaque minerals about 1 mm across, ~2. Schistosity is defined by sericite-rich layers that alternate on a scale of 1-2 mm with layers rich in quartz and feldspar, but some coarse-grained flakes of muscovite are distributed throughout the rock. About 2-5 percent of the total plagioclase is in porphyroclasts of twinned plagioclase that form augen in a matrix of quartz and feldspar. The sericitic layers wrap around these augen. Possibly the protolith of this sericite schist was felsic tuff.

Chlorite schist.--Two specimens of chlorite schist are represented: MJG-76-51A from an exposure (13°59'12" N., 45°34'32" E.) 2.4 km from Al Bayda', and sample MJG-76-55B from a collecting site at 14°03'35" N.; 45°31'03" E. (Grolier and others, 1977, p. 22).

Sample MJG-76-51A is a calcareous chlorite schist that consists of (in percent): elongate grains of calcite, 60; chlorite, 10; opaque minerals forming a disseminated dust, 15; quartz, 8-10; albite (?), 5; and sphene, 2. Schistosity is defined by the elongation of the calcite grains and the preferred orientation of the chlorite. Some crenulation of the schistosity is evident. Dark clots about 5 mm across contain randomly oriented, tiny laths of plagioclase. These aggregates may represent microlites in volcanic clasts in the protolithic carbonate-rich sediment.

Specimen MJG-76-55B of actinolite-chlorite schist contains (in percent): actinolite locally altered to brown mica, 75; chlorite, 15; pale brown mica (biotite or phlogopite), ~5; tiny stringers of granules of sphene, <1; and opaque minerals, <1. The matrix of the schist is flaky actinolite and interleaved chlorite in which are set porphyroblasts of fibrous actinolite (identified by X-ray diffraction) up to ~5 mm in length. The felted texture of the porphyroblasts is interpreted to indicate that this actinolite replaces an earlier mineral. Some porphyroblasts are rolled in the matrix.

Quartz-chloritoid schist.--Sample MJG-76-57A of quartz-chloritoid schist was identified at its field locality (14°05'33" N.; 45°27'34" E.) as quartz-sericite-actinolite schist (Grolier and others, 1977, p. 23). The rock consists of (in percent): quartz, 25; calcite, 20; epidote, 20; chloritoid in tabular grains or flakes that have characteristic pleochroism and twinning, 20; biotite, 5-10; and opaque prismatic grains of ilmenite (?), 5. The schistosity of the rock is defined by the orientation of the chloritoid, biotite, and opaque minerals.

Biotite schist.--Three samples of biotite schist are represented (Grolier and others, 1977, table 2):

Sample Number	Locality: North latitude	Locality: East longitude
MJG-76-8B	14°26'11"	44°53'50"
-17	14°21'03"	45°03'07"
-23	14°19'30"	45°10'53"

Sample MJG-76-8B contains (in percent): xenoblastic plagioclase, 40-45; xenoblastic, round, or lenticular quartz, 30; biotite with slight preferred orientation, 15; calcite and potassium feldspar(?), ~5; clusters and stringers of subidioblastic opaque minerals, 3; muscovite, 2; and chlorite and apatite, ~1. Schistosity is defined by the preferred orientation of the biotite. Slight alteration of biotite to chlorite and plagioclase to sericite has occurred.

Specimen MJG-76-17 of biotite schist is composed of (in percent): albite-twinned plagioclase, 35; quartz, 30; strongly pleochroic pale brown to red-brown biotite, 20; microcline, 15; and accessory apatite, zircon(?), and opaque minerals, <1. Some myrmekite is present in the plagioclase where the grains of plagioclase are adjacent to grains of microcline. Strong schistosity is defined by biotite flakes and by lenticular grains of quartz and feldspar. Alteration of feldspar to sericite is slight.

Sample MJG-76-23 is biotite schist that consists of (in percent): plagioclase with some patchy antiperthite, 40; microcline and orthoclase(?), 25; quartz, 20; reddish-brown biotite, 10; small, xenoblastic garnets that are extremely irregular in shape, 2; and accessory apatite, zircon, and opaque minerals, ~1. The schistosity of the rock is defined by the alignment of the flakes of biotite.

Biotite-hornblende schist.--A specimen of biotite-hornblende schist, MJG-76-28B, from an exposure at 14°15'36" N.; 45°20'03" E. (Grolier and others, 1977, p. 13) contains (in percent): plagioclase, ~An_{30}, 40; quartz, 30; reddish-brown biotite, 15; olive-green, anhedral hornblende, ~13; and accessory microcline, zircon, sphene, and opaque minerals, ~2. Some deformation without recrystallization is indicated by strained quartz and by kinked twin lamellae in the plagioclase. Slight alteration has resulted in local changes in color of the hornblende from olive-green to bluish green. Biotite locally is slightly altered.

Feldspathic gneiss.--The protoliths of the two specimens of feldspathic gneiss described here may have been felsic to intermediate volcanic rocks. Specimen MJG-76-10 is from an exposure (14°24'36" N.; 44°54'53" E.) in a small pass about 16.6 km southeast by road from Rida', and specimen MJG-76-49D is from the east end of the runway of the airfield at Al Bayda' (13°57'42" N.; 45°32'22" E.) (Grolier and others, 1977, table 2).

Sample MJG-76-10 of feldspathic gneiss consists of (in percent): xenoblastic quartz, some elongate grains having preferred orientation, 35; xenoblastic plagioclase, 35; microcline, 25; muscovite aligned parallel to the gneissic banding, 4; and opaque minerals, <1. The feldspar is slightly sericitized.

Sample MJG-76-49D is composed of (in percent): plagioclase in porphyroclasts and fine-grained matrix, 65; granoblastic lenses and layers of quartz, 15; whispy fine layers (~1 mm) of sericite, 10;

euhedral as well as flaky granular particles of opaque minerals throughout the rock, 8; accessory zircon(?) and sphene(?), ~1. The gneiss has a strong directional fabric, and the plagioclase augen show the effects of crushing. This feldspathic gneiss bears a resemblance to specimen MJG-76-49B, although the augen of plagioclase and opaque minerals are more abundant and mica is less abundant in MJG-76-49B than in MJG-76-49D. The rock is unaltered.

Biotite-bearing feldspathic gneiss.--Four specimens of biotite-bearing feldspathic gneiss, described below, were collected at the following localities (Grolier and others, 1977, table 2):

Sample Number	Locality: North latitude	Locality: East longitude
MJG-76-8A	14°26'11"	44°53'50"
-26A	14°16'30"	45°15'17"
-31	14°12'38"	45°22'29"
-34	14°06'26"	45°26'50"

Sample MJG-76-8A is a fine-grained, biotite-feldspar gneiss made up of (in percent): microcline perthite, ~75; quartz, 15; biotite, 5; and muscovite, tourmaline, apatite, chlorite, plagioclase(?), and opaque minerals, ~5. The gneissic texture of the rock is defined by biotite flakes and by segregations of quartz and feldspar. Some of the muscovite appears to be poikiloblastic and crosscuts the biotite. Only minor alteration was noted.

The biotitic feldspathic gneiss represented by specimen MJG-76-26A consists of (in percent): plagioclase, 35; quartz in round blebs, strained lensoid grains, and as inclusions in feldspars, 20; potassium feldspar, 25; biotite, 15; xenoblastic hornblende with overgrowths of biotite, 2; and accessory garnet, zircon, apatite, and chlorite, ~1. The gneissic fabric is defined by biotite and hornblende; some layers rich in biotite and hornblende alternate with layers rich in quartz and feldspar. Minor alteration is shown by chlorite partly developed from biotite.

Sample MJG-76-31 of biotite-bearing feldspathic gneiss is composed of (in percent): quartz, 45; subrounded porphyroclasts of plagioclase, 25; microcline, 20; biotite with epidote and white mica, 3-5; and accessory idioblastic, sphene, epidote, white mica, and apatite, 1-2. The gneissic texture is produced by weak cataclasis and recrystallization of elongate grains of quartz and feldspar.

The biotite-bearing feldspathic gneiss represented by sample MJG-76-34 consists of (in percent): subhedral plagioclase, ~An_{40}, 60; quartz, 25; orthoclase perthite, 5-10; biotite, 5; epidote in anhedral, irregular grains, 3; and accessory zircon and metamict allanite, <1. The gneissic texture is accentuated by the elongation of feldspars and quartz, and by the orientation of the biotite. The rock is not altered.

Hornblende-plagioclase gneiss.--Three specimens of hornblende-plagioclase gneiss are described below. Their sources are (Grolier and others, 1977, table 2):

Sample Number	Locality North latitude	East longitude
MJG-76-11	14°24'36"	44°54'53"
-48A	13°57'50"	45°29'45"
-58	14°12'00"	45°22'45"

Sample MJG-76-11 of hornblende-plagioclase gneiss is made up of (in percent): plagioclase, 45; olive-green hornblende, 15; quartz, 15; brown biotite intergrown with hornblende, 5; xenoblastic epidote, in part with hornblende, 8; elongate clusters of xenoblastic opaque minerals, 2-3; and accessory sphene and apatite, 1. Some preferred orientation of hornblende was observed in the gneissic fabric of the rock. This gneiss is unaltered.

Hornblende-plagioclase-quartz gneiss is represented by sample MJG-76-48A which contains (in percent): plagioclase, 40; quartz, 30; hornblende, 20; epidote and clinozoisite mostly in veins but partly associated with the hornblende, 5; chlorite, white mica, and actinolite(?), ~2; and accessory sphene, ~1. The gneissic texture is indicated by some segregation of the minerals into hornblende-rich layers and layers rich in quartz and feldspar. Quartz-rich layers are also the most coarsely crystallized. Moderate alteration is shown by the presence of epidote, chlorite, sphene, sericite, and actinolite locally along fractures and in certain layers.

Sample MJG-76-58 of hornblende-plagioclase gneiss yielded a somewhat unrepresentative thin section composed in part of a single huge (8 cm) porphyroblast of potassium feldspar and adjacent veinlet of potassium feldspar, quartz, and plagioclase. With these reservations the composition is (in percent): hornblende, much altered to actinolite, 40; plagioclase, slightly sericitized and altered to epidote, 40-50; epidote locally makes up as much as 80 percent of the gneiss, but is generally about 10 percent; small (0.5 mm) idioblastic wedges of sphene, 2. The gneissic texture is defined by oriented grains of hornblende. Retrograde metamorphism has partly changed green hornblende to actinolite, and plagioclase to epidote.

Hornblende-biotite gneiss.--Sample MJG-76-53A of hornblende-biotite gneiss is from an exposure at 14°02'55" N.; 45°32'17" E. (Grolier and others, 1977, p. 21). The rock is composed of (in percent): twinned plagioclase, 35; quartz, 20; microcline, 5; biotite, 20; dark green hornblende intergrown with biotite and sphene, 15; sphene, 3; and xenoblastic grains of epidote sparsely distributed with biotite and hornblende, ~2. Strong layering is defined by biotite and hornblende. The rock is not altered.

Suitability of described rocks for isotopic analyses for age determinations

Part of the purpose for the petrographic examination of the rocks listed above was to determine which of the specimens of igneous rocks were suitable for potassium-argon and strontium-rubidium isotopic analyses for age determination so that the essentially unresearched dating of rocks in the YAR might begin. Results from isotopic determinations on rocks from the YAR would fill a gap between the geochronology published for the Precambrian Shield in the Kingdom of Saudi Arabia (Fleck and others, 1976; Schmidt and others, 1973; Roberts and others, 1975; and Greenwood and others, 1976) and that published for areas south of the YAR (Greenwood and Bleackley, 1967; Greenwood, Bleackley, and Beydoun, 1967).

Priorities for age determinations were assigned by Grolier and Overstreet to the various groups of rocks available in this suite of samples so that the rock units of greatest stratigraphic interest could be highest in priority for geochronologic investigations. These priorities are: (1) Tertiary and/or Cretaceous lavas of the Yemen Volcanics--unweathered material has proven difficult to collect; (2) Miocene(?) alkali granite; (3) Precambrian granite; and (4) Quaternary basalt of the Aden Volcanic Series.

Upon the advice of R. J. Fleck, U.S. Geological Survey, the most suitable samples are:

(1) Tertiary and/or Cretaceous lavas of the Yemen Volcanics.--
Sample MJG-76-1A of welded tuff.
A sanidine separate would be datable, but the mineral is sparse in the specimen, and there is probably not enough to permit recovery of 2-3 g needed for analysis.

(2) Miocene(?) alkali granite.--
Sample 75-OT-28 of riebeckite granite.
An amphibole separate will be suitable.

(3) Precambrian granites.--
Sample MJG-76-9 of granite gneiss.
A white mica separate is datable, but it will yield a minimum metamorphic age.

Sample MJG-76-15 of granite gneiss. A separate of the mica is datable, but it will yield a minimum metamorphic age.

Sample MJG-76-26B of granite. Biotite is datable, but it will yield a minimum age.

Sample MJG-76-28A of granite gneiss. Biotite is datable, but it will yield a minimum age.

Sample MJG-76-41B of granite. A hornblende separate is datable.

Sample MJG-76-50 of riebeckite granite. A separate of the amphibole is datable, but it will yield a minimum metamorphic age.

Sample MJG-76-56A of granite. Hornblende or a hornblende-biotite pair is datable.

(4) Quaternary basalt of the Aden Volcanic Series.--

Sample 75-OT-1 of basalt. A whole-rock determination is possible after an HCl leach to remove carbonate minerals that line vesicles.

Sample 75-OT-2 of basalt. A whole-rock determination is possible after an HCl leach to remove carbonate minerals that line vesicles.

The most suitable geochronological procedure to use with the Precambrian rocks would be strontium-rubidium analyses of suites of rocks of varying composition from the same pluton to establish an isochron for each suite. This would require re-collecting, an option not available for this set of samples. Therefore, preparation was begun in January 1978 of the mineral separates for the determinations indicated above.

TRACE-ELEMENT DATA

The present trace-element data complete the presentation of geochemical data begun for these rocks in earlier reports (Overstreet and others, 1976; Grolier and others, 1977). The reason for the additional trace-element data is that the limits of determination imposed by the original spectrographic method of analysis either caused too high a lower limit of determination, as for gold, or the method is unsuitable for the volatile elements such as mercury, selenium, indium, and thallium. All of these elements are useful in the detection of possible geochemical haloes around mineralized areas.

Methods of analysis

Three methods of analyses were used: (1) atomic absorption analysis for gold, indium, and thallium; (2) flameless atomic absorption for mercury; and (3) fluorimetric analysis for selenium.

Atomic absorption

The analyses for gold were made by James A. Domenico using the atomic absorption method described by Ward and others (1969), which permits a lower limit of determination of 0.05 part per million (ppm) Au. Indium and thallium were sought by the atomic absorption procedure discussed by Hubert and Lakin (1973). Domenico was the analyst, and the method allows a lower limit of determination of 0.2 ppm In and 0.2 ppm Tl.

Flameless atomic absorption

Mercury was determined by Elizabeth A. Plasse using the procedure of flameless atomic absorption described by Vaughn and McCarthy (1964). A sensitivity of 0.02 ppm Hg is achieved, and the reported values are within ± 50 percent of the actual concentration.

Fluorimetric analysis

Selenium was determined by George L. Crenshaw using a fluorimetric procedure he developed (Crenshaw and Lakin, 1974). The lower limit of determination achieved by this method is 0.04 ppm Se.

Results

The results of these analyses are given in table 3.

Table 3.--Results of analyses for gold, indium, mercury, selenium, and thallium in selected samples of rocks from the Yemen Arab Republic, in parts per million.

[Gold, mercury, and selenium determined in 1977 by, respectively, J. A. Domenico, E. A. Plasse, and G. L. Crenshaw, U.S. Geological Survey, and indium and thallium were determined in 1978 by J. A Domenico; N = not determined at limit of detection; L = detected, but below limit of determination.]

Field number	Laboratory number	Element and lower limit of determination				
		Au (0.05)	In (0.2)	Hg (0.02)	Se (0.04)	Tl (0.2)
MJG-76-1A	MAM-824	N	0.2	0.02	0.3	1.8
-1B	-825	N	.2	.04	1.3	0.4
-2	-826	N	.2	.04	1.5	.6
-3	-827	N	N	.02	1.5	.2
-4	-828	N	L	.04	.8	.4
-5	-829	N	L	.04	1.7	.2
-6	-830	N	L	.02	1.5	.2
-7	-831	N	L	.04	.5	L
-8A	-832	N	L	.02	.4	.6
-8B	-833	N	L	.02	.9	.4
-9	-834	N	L	.02	1.7	.6
-10	-835	N	.2	N	1.3	.4
-11	-836	N	L	.04	.7	.2
-12	-837	N	L	N	.9	.2
-13	-838	N	L	.02	1.0	1.6
-14	-839	N	L	.02	.6	.2
-15	-840	N	L	.02	2.0	.6
-16	-841	N	L	.02	1.5	.6
-17	-842	N	.8	N	1.3	.4
-18A	-843	N	L	N	2.6	.2
-18B	-844	N	L	.02	.4	.8
-19A	-845	N	N	.02	1.5	.6
-19B	-846	N	L	.02	.4	.2
-20A	-810	N	N	.02	.5	N
-20B	-811	N	L	.02	.5	.2
-21	-847	N	L	.02	1.5	.6
-22	-848	N	L	N	1.7	.2

Table 3.--Results of analyses for gold, indium, mercury, selenium, and thallium in selected samples of rocks from the Yemen Arab Republic, in parts per million--continued.

Field number	Laboratory number	Element and lower limit of determination				
		Au (0.05)	In (0.2)	Hg (0.02)	Se (0.04)	Tl (0.2)
MJG-76-23	-849	N	N	N	.7	.4
-24	-850	N	L	N	.7	.8
-25	-851	N	L	N	.6	.6
-26A	-852	N	L	N	1.5	.2
-26B	-853	N	N	N	.8	.6
-27A	-854	N	L	N	.8	.8
-27B	-855	N	L	.02	.6	.6
-28A	-856	N	L	N	4.2	.8
-28B	-857	N	L	.02	.6	.8
-28C	-858	N	L	N	.6	.2
-28D	-812	N	L	.02	.4	L
-29A	-859	N	.2	N	.4	.8
-29B	-860	N	L	N	.8	L
-30	-861	N	L	N	1.3	.6
-31	-862	N	L	N	.8	.6
-32A	-863	N	L	N	.6	L
-32B	-864	N	.2	.02	.8	L
-32C	-865	N	.2	.04	.7	L
-33A	-866	N	L	.02	.6	.4
-33B	-867	N	L	.02	.8	.4
-34	-868	N	L	.02	.4	.2
-35A	-869	N	L	N	.7	.2
-35B	-870	N	L	N	1.7	.4
-35C	-871	N	N	N	.4	.4
-36A	-872	N	L	N	.6	.4
-36B	-873	N	.2	.02	.8	.4
-36C	-874	N	L	.04	.5	.8
-37A	-875	N	N	.02	2.0	.4
-37B	-876	N	L	.04	.5	.2
-37C	-877	N	L	.02	.5	.4
-38A	-878	N	L	.02	.4	.4
-38B	-879	N	L	.04	.6	N
-38C	-880	N	.2	.04	.6	.2

Table 3.--Results of analyses for gold, indium, mercury, selenium, and thallium in selected samples of rocks from the Yemen Arab Republic, parts per million--continued.

Field number	Laboratory number	Element and lower limit of determination				
		Au (0.05)	In (0.2)	Hg (0.02)	Se (0.04)	Tl (0.2)
MJG-76-39A	-881	N	L	.02	.5	.2
-39B	-882	N	L	.02	.9	.4
-40	-883	N	L	N	.8	L
-41A	-884	N	L	.02	.6	.2
-41B	-885	N	L	N	.5	L
-41C	-886	N	L	N	.9	.4
-42A	-887	N	L	N	.9	.2
-42B	-888	L	.2	N	.6	.2
-42C	-889	N	.2	N	2.0	.2
-43	-890	L	L	N	.6	.2
-44	-891	N	L	N	.4	.6
-45A	-892	N	L	N	.4	1.8
-45B	-813	N	L	.04	.2	N
-45C	-893	N	.2	N	.4	.6
-45D	-894	N	.2	.04	.5	1.0
-45E	-895	N	.6	.02	1.0	2.0
-45F	-896	N	.6	.02	.7	1.8
-45G	-897	N	.2	.02	.6	1.6
-45H	-898	N	.8	.02	.9	2.6
-45I	-899	L	L	.02	1.2	.4
-46	-814	N	.2	.02	.5	L
-47	-900	N	.2	N	.6	.4
-48A	-901	N	L	N	1.7	L
-48B	-902	N	L	N	.7	L
-49A	-903	N	.2	N	.5	L
-49B	-904	N	L	.02	.8	.2
-49C	-905	N	L	.04	1.2	L
-49D	-906	N	N	.02	.8	.6
-50	-907	N	L	.04	.8	.6
-51A	-908	N	L	.02	.6	L
-51B	-909	N	N	.02	1.2	L
-52A	-910	N	L	.02	1.0	L

Table 3.--Results of analyses for gold, indium, mercury, selenium, and thallium in selected samples of rocks from the Yemen Arab Republic, in parts per million.--continued.

Field number	Laboratory number	Element and lower limit of determination				
		Au (0.05)	In (0.2)	Hg (0.02)	Se (0.04)	Tl (0.2)
MJG-76-52B	-911	N	L	N	1.0	N
-52C	-912	N	N	N	1.2	.2
-53A	-913	N	L	N	5.3	L
-53B	-914	N	L	N	5.5	L
-53C	-915	N	L	.02	.7	L
-54A	-916	N	L	N	.7	.2
-54B	-917	N	N	.04	1.2	N
-55A	-918	N	N	N	.7	.4
-55B	-919	N	L	N	1.2	.2
-56A	-920	N	L	N	2.2	L
-56B	-815	N	L	.04	.3	L
-57A	-921	N	L	N	1.2	L
-57A1	-922	N	N	N	3.0	L
-57B	-816	N	L	.04	.7	L
-58	-923	N	N	N	2.5	L
-59A	-924	N	L	.06	1.2	L
-59B	-817	N	L	.04	.8	L
-60	-925	N	.2	.06	1.5	.6
-67C	-926	N	L	N	1.7	L
-68	-927	N	N	.02	1.7	N
-69A	-928	N	L	.04	3.4	N
-69B	-929	N	N	.02	2.2	N
-70A	-930	N	L	.02	3.2	L
-71	-931	N	L	N	1.0	.2
-72A	-932	N	L	N	2.7	.6
-72B	-933	N	.2	N	2.5	.6
-72C	-934	N	L	N	4.3	1.0
-72D	-818	N	.2	.04	.3	.8
-73A	-819	N	L	.08	.4	.6
-73B	-820	N	.2	.02	.6	.6
-73C	-821	N	L	.02	.2	.8
-74A	-822	N	L	.06	.4	.4
MJG-76-74B	MAM-823	N	L	.16	.4	.8

Interpretation of results

For three elements--Au, In, and Tl-the lower limit of determination as shown in table 3 is higher than recent estimates of crustal abundances. Thus, entries in table 3 of N (= not determined at lower limit of detection) and L (= detected, but below the limit of determination) fail to show the concentrations, compared to crustal abundances, for Au, In, and Tl in these rocks:

Element	Lower limit of determination (ppm, table 3)	Crustal abundance (ppm)	Reference
Au	0.05	0.003-0.004	Simons and Prinz, 1973, p. 266
In	.2	.14	Weeks, 1973, table 1
Hg	.02	<0.08	Bailey and others, 1973, p. 407
Se	.04	(estim.) .05	Lakin and Davidson, 1973, p.575
Tl	.2	1.0	Robinson, 1973, p. 634

With respect to the actual abundances of these elements in the rocks from the YAR, compared to crustal abundances, the data for Au are uniformative, as are much of the data for In. The data for Hg are more meaningful than the presence of the many N's would suggest, because the lower limit of determination is slightly less than the crustal abundance of Hg. The data for Se show no N's nor L's; thus, all values reported for these specimens exceed the crustal abundance for Se. Most of the values for Tl shown in table 3 are less than the estimated normal crustal abundance, which suggests that the average crustal abundance is actually estimated at too high a value, or that the rocks of the YAR are deficient in Tl.

Gold

Values for gold in table 3 include three samples shown to have Au, but the quantity is below the lower limit of determination. For each sample, an estimate was made of the probable amount:

Sample	Probable amount of Au (ppm)
MJG-76-42B	L = 0.02
-43	L = .04
-45I	L = .02

All three samples are from the extreme southeastern corner of the YAR (Grolier and others, 1977, fig. 2), and may, despite their low tenors in Au, indicate an as yet unrecognized area of mineralization (El Shatoury and Al Eryani, 1977, fig. 5). However, the source rocks are granite and metadiorite, none of which displays enrichment in elements that might be interpreted as further evidence of mineralization (Grolier and others, 1977, table 3; this report, table 3).

Indium

A summary of the distribution of In, Hg, Se, and Tl is given in table 4 by geologic age and petrographic character of the analyzed samples. Indium in these rocks tends to be near the crustal abundance, as indicated by the data in table 4. Slight rises in the abundance of In are also associated with increased Sn content of the rock, particularly in the Precambrian pegmatite represented by the MJG-76-45 series of samples:

Sample number	Content in ppm: In	Content in ppm: Sn (Grolier and others, 1977, table 2)
MJG-76-45C	0.2	150
-45D	.2	20
-45E	.6	100
-45F	.6	100
-45G	.2	50
-45H	.8	200
-56A	L	30
-72A	L	15
-72B	.2	15
-72C	L	15

Table 4.--Relation of average abundances of indium, mercury, selenium, and thallium to age and petrographic character of selected rocks from the Yemen Arab Republic.

[Data from tables 1 and 3; Grolier and others, 1977, tables 2 and 3; values in parts per million; N = not determined at limit of detection; L = detected, but below limit of determination.]

Age and kind of rock; number of rocks in average shown in parentheses	Average (Lower limit of determination in parentheses)			
	In (0.2)	Hg (0.02)	Se (0.04)	Tl (0.2)
Holocene: iron oxide weathering crust on Tertiary felsite (1)	0.2	0.02	0.6	0.6
Pliocene Baid Formation: (5)	L	N	2.0	L
divided into:				
Ferruginous sandstone (1)	L	N	1.7	L
Gypsum-anhydrite (3)	N	.02	3.4	N
Ferruginous dolomitic limestone(1)	L	N	1.0	.2
Miocene: Rock salt (1)	L	.02	3.2	L
Miocene (?): Alkali granite (2)	L	N	2.6	.6
Tertiary and/or Cretaceous:				
Volcanic rocks of Yemen Volcanics(11)	L	.05	1.0	.7
Carbonaceous siltstone in Yemen Volcanics (2)	L	.03	1.6	.2
Cretaceous Tawilah Group:				
Ferruginous sandstone (1)	.2	.06	1.5	.6
Precambrian igneous rocks:				
Felsite, pegmatite, quartz veins, and feldspathic segregations (19)	L	.02	.7	.7
Granite and granite gneiss of Late Precambrian age (13), divided as follows--	L	.02	.9	.4

Table 4.--Relation of average abundance of indium, mercury, selenium, and thallium to age and petrographic character of selected rocks from the Yemen Arab Republic--continued.

Age and kind of rock; number of rocks in average shown in parentheses	Average (Lower limit of determination in parentheses)			
	In (0.2)	Hg (0.02)	Se (0.04)	Tl (0.2)
Riebeckite granite (1)	L	.04	.8	.6
Alkali feldspar granite (4)	L	.02	.6	.4
Biotite granite (3)	L	L	.7	.3
Granite and granite gneiss (2)	L	.02	2.0	.6
Granodiorite porphyry (1)	L	.02	1.0	1.6
Granodiorite (2)	L	N	1.4	L
Older granite and granite gneiss (22), divided as follows--	L	L	1.0	.4
Leucogranite gneiss (3)	L	.02	1.2	.5
Biotite granite (1)	L	N	.7	.8
Hornblende-biotite granite (1)	L	N	.5	L
Granite gneiss (11)	L	L	1.2	.5
Protomylonitic granite gneiss (4)	L	N	.6	.3
Granodiorite gneiss (2)	L	L	.6	.2
Diabase (3)	L	.02	1.0	.4
Gabbro (1)	L	N	.9	.4
Metamorphosed igneous rocks of intermediate and mafic composition (15), divided as follows--	L	L	.8	L
Meta-andesite (2)	L	.02	.9	.2
Metabasalt (2)	L	L	.9	L
Metagranodiorite (2)	L	N	1.2	.2
Metadiorite (5)	L	L	1.0	.2
Hornblende gneiss (1)	.2	.04	.6	.2
Hornblende-plagioclase gneiss (1)	L	N	5.5	L

Table 4.--Relation of average abundances of indium, mercury, selenium, and thallium to age and petrographic character of selected rocks from the Yemen Arab Republic--continued.

Age and kind of rock; number of rocks in average shown in parentheses	Average (Lower limit of determination in parentheses)			
	In (0.2)	Hg (0.02)	Se (0.04)	Tl (0.2)
Hornblende-biotite schist (1)	L	N	1.7	.2
Hornblende-pyroxene gneiss (1)	L	N	.8	L
Metamorphosed sedimentary and pyroclastic rocks (26), divided as follows--	L	L	1.1	.2
Marble (2)	L	.04	1.2	L
Calc-silicate rock (2)	L	.02	.7	L
Calcareous quartzite (1)	N	.04	1.2	N
Slaty argillite (2)	L	N	.6	.4
Sericite schist (2)	L	L	.6	L
Chlorite schist (2)	L	N	.9	L
Quartz-chloritoid schist (1)	L	N	1.2	L
Biotite schist (3)	.3	L	1.0	.4
Biotite-hornblende schist (1)	L	.02	.6	.8
Feldspathic gneiss (2)	L	L	1.0	.5
Biotite-bearing feldspathic gneiss (4)	L	L	.8	.4
Hornblende-plagioclase gneiss (3)	L	L	1.6	L
Horblende-biotite gneiss (1)	L	N	5.3	L

A geochemical association of In and Sn has long been recognized (Hartley and Ramage, 1897). Evidently the data on In from the analyses by atomic absorption confirm the results for Sn by emission spectrography (Grolier and others, 1977, table 2), but none of these samples can be regarded as an ore for Sn. The possible presence of Sn in the late Precambrian granites still requires thorough geochemical exploration.

A weak concentration of In in materials enriched in iron oxides is also noticeable in the data given by table 4. The weathering crust of Holocene age on felsite of the Yemen Volcanics, derived probably from pyrite in the volcanic rocks (Grolier and others, 1977, pp. 39-40), contains only 0.2 ppm In, but this is a little greater amount of the element than was reported (table 3) for most rocks. The same quantity of In was found in ferruginous sandstone of the Cretaceous Tawilah Group.

Mercury

Mercury is slightly more abundant in the Cretaceous and younger rocks of the YAR than it is in the Precambrian rocks (table 4). Mostly the abundances of Hg are below the average crustal abundance of 0.08 ppm (Bailey and others, 1973, p. 407) in the sampled rocks from the YAR. Even in the Yemen Volcanics the average abundance of Hg is slightly less than the crustal abundance. The values for Hg reported in table 3 confirm the amounts described earlier (Grolier and others, 1977, p. 40) for the element in hydrothermally altered lavas of the Yemen Volcanics, in which as much as 0.16 ppm Hg was found where these rocks are intruded by the pluton of alkali granite at Jibal Hufash. Thus, even a small rise in the amount of Hg in the rocks of the YAR is locally associated with hydrothermal alteration.

Selenium

A marked tendency was found for the amount of Se to be above the average crustal abundance of 0.05 ppm (Lakin and Davidson, 1973, p. 575) in rocks from the YAR represented by the samples listed in table 3, and for Se in the Cretaceous and younger rocks to exceed the abundance of Se in the Precambrian rocks (table 4). Despite this generalization, the highest values reported here for Se are in unaltered Precambrian hornblende gneisses (samples MJG-76-53A and MJG-76-53B). The values of 5.3 ppm and 5.5 ppm Se found for these two rocks are unassociated with high values for Au, In, Hg, or Tl. Indeed, these four elements are below the lower limits of determination in these samples (table 3), and spectrographic analyses of the rocks disclosed no apparent anomalous trace elements (Grolier and others, 1977, table 3). The source of these samples is near one of the large, northeast-trending fault zones in the extreme southeastern part of the YAR (Grolier and others, 1977, fig. 2), but mineral deposits have not been noted in the immediate area (El Shatoury and Al Eryani, 1977, fig. 5).

The salt dome at Guma about 16 km east of the coastal town of Al Luhayyah (Grolier and others, 1977, p. 25) was the source of several samples having high values for Se. The rock salt itself (sample MJG-76-70A), at the site of mining, contains 3.2 ppm Se as well as 0.02 ppm Hg (table 3). Caprock composed of mixtures of gypsum and anhydrite (samples MJG-76-68, MJG-76-69A, and MJG-76-69B) contains from 1.7 ppm to 3.4 ppm Se (table 3), ferruginous dolomitic limestone (sample MJG-76-71) contains 1 ppm Se, and ferruginous sandstone (sample MJG-76-67C) has 1.7 ppm Se. If the rock salt from this deposit is enriched generally in Se as indicated by the single analyzed sample, then some care would be in order on the uses to which it is put (Lakin, 1972; Dorn and others, 1973). Further analyses for Se and Hg in the rock salt are needed to determine if these elements are present on average at levels sufficiently high to constitute potential hazards to health.

The group of samples representing hydrothermally altered tuffs and felsites of the Yemen Volcanics, exposed on the San'a'-Hudaydah road at the southern edge of Jibal Hufash (Grolier and others, 1977, pp. 48-51), in general proved to have lower amounts of Se than was expected from their contents of other trace elements:

Sample number (MJG-76-series)	Rock type	Selected elements (in ppm)								
		As	Cu	Hg	In	Mo	Pb	Se	Tl	Zn
72A	Alkali granite	N	N	N	L	10	20	2.7	0.6	300
72B	Do.	N	L	N	0.2	N	20	2.5	.6	500
72C	Felsite	N	L	N	L	10	70	4.3	1.0	N
72D	Altered felsite	N	L	0.2	.2	N	L	.3	.8	300
73A	Do.	200	5	.08	L	10	70	.4	.6	N
73B	Iron oxide crust	1,500	5	.02	.2	30	100	.6	.6	N
73C	Altered tuff	N	7	.02	L	N	15	.2	.8	500
74A	Altered felsite	N	5	.06	L	20	20	.4	.4	N
74B	Do.	L	7	.16	L	30	50	.4	.8	N

Despite the absence of high values for Se, which would have strongly supported the possible presence of metallization in this area of hydrothermal alteration, the amount of geochemical sampling thus far done is too small to permit dismissal of the area from further geochemical exploration for deposits of base metals.

Thallium

The content of Tl in Miocene and younger sedimentary rocks (table 4) is less than in the Miocene(?) and older igneous and metamorphic rocks of the YAR. Exceptions to this generalization are the ferruginous Tawilah Sandstone of Cretaceous age and the Holocene iron-rich weathering crusts, both of which contain 0.6 ppm Tl, and are thus among the Tl-enriched specimens. Among the plutonic rocks, an exception must also be made for the Precambrian metamorphosed sedimentary and pyroclastic rocks, which tend to contain sparse Tl.

Interest in the abundances of Tl in these rocks arises from the observations of Ewers and Keays (1977, p. 1346) that in a hydrothermal system with base and precious metals, the Tl tends to be dispersed farther than those elements. The Tl enrichment halos were predicted to be more pervasive and uniform than those for other metals, because the Tl would be deposited away from hydrothermal sources through response to decreasing temperature. Ewers and Keays (1977, p. 1352) also postulated that Tl, which can substitute for K in silicates, might survive the metamorphism of the hydrothermally altered rock, and be a guide to pre-metamorphic ores. Abundances of 0.3 to 3.34 ppm Tl were reported for rocks in the zone of hydrothermal alteration (Ewers and Keays, 1977, table 3). These data suggested to the present writers that a halo of Tl around a deposit of base or precious metals would provide a larger target for exploration than the deposit itself. Furthermore, the presence of Tl might disclose covered or blind ore deposits. Therefore, the set of samples was analyzed for this element.

None of the high values for Tl in table 3 is associated with a known ore deposit, except the remarkable group of values reaching from 1 ppm to 2.6 ppm associated with samples MJG-76-45A variously to MJG-76-45H, which are from a sheet-mica pegmatite (Grolier and others, 1977, table 2). Evidently, this anomalous occurrence represents an example of Tl substituting for K in potassium feldspars of the pegmatite. On average, the samples from Precambrian pegmatites and feldspathic segregations contain more Tl than the other rocks represented (table 4).

In the area of hydrothermally altered Yemen Volcanics of Cretaceous and/or Tertiary age at the southeastern contact of the pluton of alkali granite that makes up Jibal Hufash, the volcanic rocks contain from 0.4 ppm to 1.0 ppm Tl. These values are within the range of abundances reported for Tl in hydrothermally altered rocks studied by Ewers and Keays (1977, table 3). Thus, the values for Tl, although not high, support other trace-element data that have been interpreted to indicate the need for further geochemical exploration in this region.

Sample MJG-76-1A from the Yemen Volcanics exposed on the San'a'-Hudaydah road was collected east of the Manakhah area where, in the vicinity of Jabal Haraz, chalcopyrite and native copper have been reported in the Yemen Volcanics (Ansaldi, 1933, p. 193).

Altered granodiorite porphyry of Precambrian age, sample MJG-76-13, contains 1.6 ppm Tl, and is from the general vicinity of known copper deposits (El Shatoury and Al Eryani, 1977, fig. 5), but copper minerals were not observed at the sampling site.

RECOMMENDATIONS

Some of the data presented here are interpreted to indicate the need for further field and laboratory investigations. The following recommendations (fig. 1) are offered as a guide for new geologic studies in the YAR, and to emphasize those formerly proposed (Overstreet and others, 1976, pp. 55-61; Grolier and others, 1977, pp. 81-82):

1. The isotopic ages of the rocks identified here as suitable for that purpose should be determined.

2. Systematic geologic mapping and sampling of rocks in the YAR should be begun to provide the material for isochron ages of intrusive rocks.

3. Detailed geochemical surveys should be started to test the possibilities for deposits of base and/or precious metals at (1) the Yemen Volcanics adjacent to the contacts of the pluton at Jibal Hufash (Grolier and others, 1977, pp. 49-51; Overstreet and others, 1976, p. 60); (2) the Manakhah area in the vicinity of Jabal Haraz (Grolier and others, 1977, pp. 48-49, 81); (3) the region around Al Bayda' (data in this report); (4) the Sa'dah-Majadh area (Overstreet and others, 1976, pp. 33-55, 58-59); and (5) Wadi Jawf area (Grolier and others, 1977, p. 81).

4. The trace-element composition of rock salt in the salt domes along the Red Sea coastal plain and in the northeastern and eastern parts of the YAR in the Safir region should be investigated, particularly for Hg and Se, as well as a broad spectrum of other elements. The relative abundances of trace elements in the deposits of the coastal plain should be compared with those associated with metal-rich brines of the Red Sea.

5. Exploration for uranium has previously been recommended in bituminous beds and alluvial deposits with carbonized wood in the Yemen Volcanics, and in the purple and green shales in the Tawilah Group and Medj-zir Series (Overstreet and others, 1976, p. 59). Recent advances in the use of hydrogeochemical exploration in the search for uranium and base metals (Cadigan and Felmlee, 1977; Miller, 1977) makes the regional application of hydrogeochemical methods, even in the arid environment of the YAR, particularly attractive. Hydrogeochemical surveys should be undertaken for uranium and base metals in areas underlain by the Cretaceous and younger sedimentary and volcanic rocks of the Tawilah Group, Yemen Volcanics, Baid Formation, and Aden Volcanic Series(?), and by the Jurassic sedimentary rocks of the Kohlan Series and Amran Series (fig. 1).

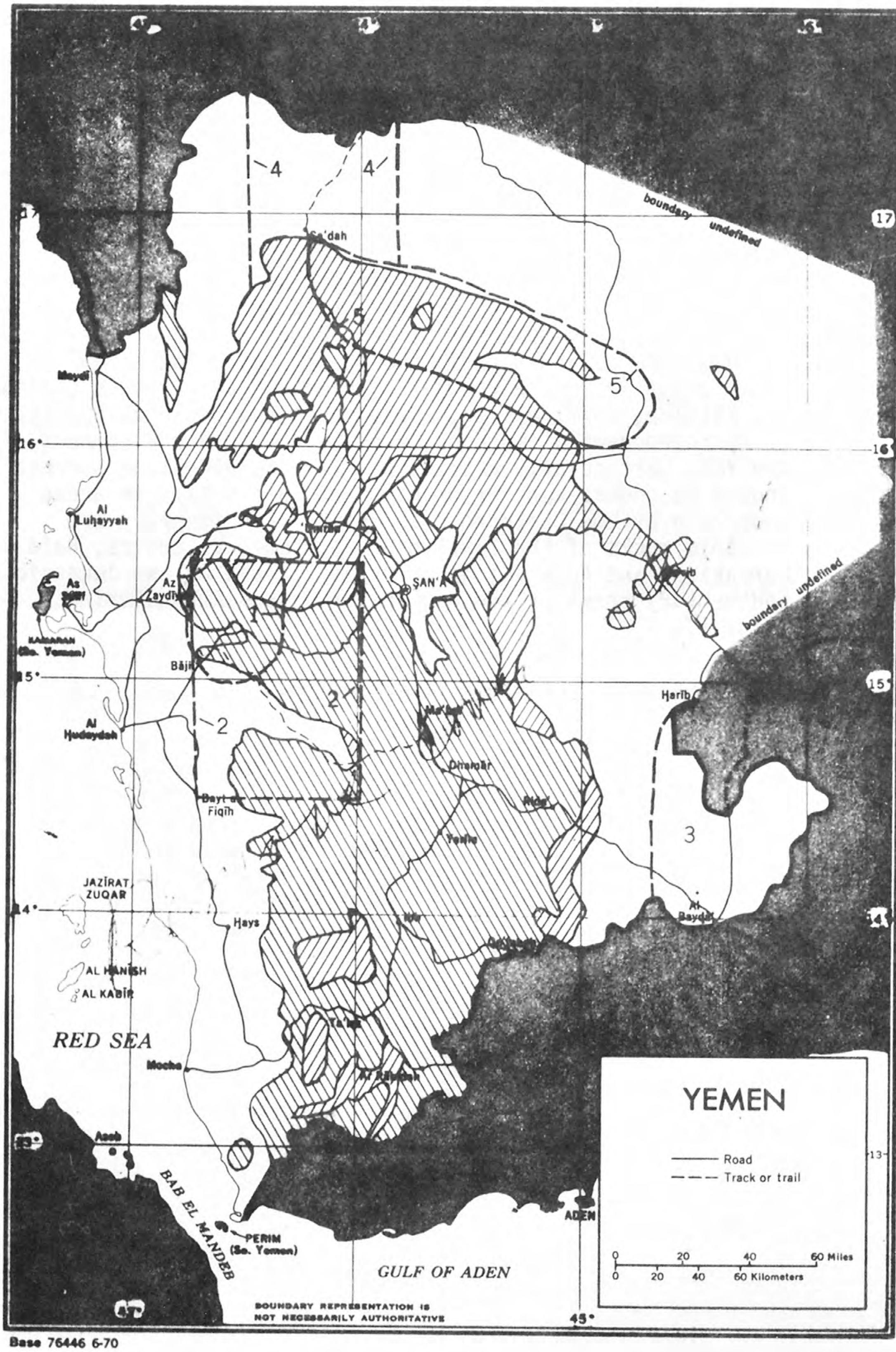


Figure 1. Index map of the Yemen Arab Republic showing the localities recommended for geochemical and hydrogeochemical surveys (geology adapted form El Shatoury and Al Eryani, 1977, fig. 1).

EXPLANATION

Generalized areas for detailed geochemical exploration for base and precious metals:

1. Yemen Volcanics at the contact of the pluton at Jibal Hufash.

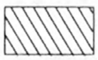
2. Manakhah area in the vicinity of Jabal Haraz.

3. Al Bayda' region.

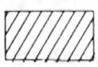
4. Sa'dah Majadh area.

5. Wadi Jawf.

Generalized areas for regional hydrogeochemical surveys for uranium and base metals:



Cretaceous and younger sedimentary and volcanic rocks of the Tawilah Group, Yemen Volcanics, Baid Formation, and Aden Volcanic Series(?).



Jurassic sedimentary rocks of the Kohlan Series and Amran Series.

REFERENCES

Ansaldi, Cesare, 1933, Il Yemen, nella storia e nella leggenda: Collezione di opere e di monografie a cura del ministero-delle colonie N. 17: Roma, sindicato italioano arti grafiche, 266 p.

Bailey, E. H., Clark, A. L., and Smith, R. M., 1973, Mercury, in Brobst, D. A., and Pratt, W. P., eds., United States mineral resources: U.S. Geol. Survey Prof. Paper 820, p. 401-414.

Brown, G. F., 1970, Eastern margin of the Red Sea and coastal structures in Saudi Arabia: Roy. Soc. London Phil. Trans., v. 267, p. 75-87.

Brown, G. F., and Jackson, R. O., 1959, Geology of the Asir quadrangle, Kingdom of Saudi Arabia, U.S. Geol. Survey Misc. Geol. Inv. Map I-217A, scale 1:500,000.

Cadigan, R. A., and Felmlee, J. K., 1977, Radioactive springs geochemical data related to uranium exploration: Jour. Geochem. Explor., v. 8, pp. 381-395.

Coleman, R. G., Fleck, R. J., Hedge, C. E., and Ghent, E. D., in press, The volcanic rocks of southwest Saudi Arabia and the opening of the Red Sea; Saudi Arabia Dir. Gen. Mineral Resources, Red. Sea Vol.

Comucci, Probo, 1929, Sopra alcune rocce vulcanice della regione di Sanaa (Arabia): Soc. Toscana Sci. Nat., Mem., no. 40, p. 70-78.

Cox, L. R., 1931, The geology of the Farsan Islands, Gizan, and Kamaran Island, Red Sea, pt. 2., Molluscan paleontology: Geol. Magazine, v. 68, p. 1-13.

Crenshaw, G. L., and Lakin, H. W., 1974, A sensitive and rapid method for the determination of trace amounts of selenium in geologic materials: U.S. Geolological Survey Journal Research, v. 2, no. 4, p. 483-487.

Deer, W. A., Howie, R. A., and Zussman, J., 1966, An introduction to the rock-forming minerals: New York, John Wiley and Sons, Inc., 528 p.

Dodge, F. C. W., and Rossman, D. L., 1975, Mineralization of the Wadi Qatan area, Kingdom of Saudi Arabia: U.S. Geological Survey Open-file report 75-309, 71 p.

Dorn, C. R., Pierce, J. O., 2nd, Chase, J. R., and Phillips, P. E., 1973, Cadmium, copper, lead, and zinc in blood, milk, muscle, and other tissues of cattle from an area of multiple source contamination, in Hemphill, D. D., ed., Trace elements in environmental health: Columbia, Mo., Univ. of Missouri, p. 191-202.

El Shatoury, H. M., and Al Eryani, M. L., 1977, Review on mineral occurrences in Yemen Arab Republic: Mining Geology, v. 27, p. 277-288.

Ewers, G. R., and Keays, R. R., 1977, Volatile and precious metals zoning in the Broadlands geothermal field, New Zealand: Econ. Geology, v. 72, no. 7, p. 1337-1354.

Fleck, R. J., Coleman, R. G., Cornwall, H. R., Greenwood, W. R., Hadley, D. G., Prinz, W. C., Ratté, J. S., and Schmidt, D. L., 1976, Geochronology of the Arabian Shield, western Arabia:K-Ar results: Geol. Soc. America Bulletin, v. 87, no. 1, p. 9-21.

Geukens, F., 1966, Geology of the Arabian Peninsula, Yemen: U.S. Geolological Survey Professional Paper 560-B, 23 p., 17 figs., 1 table.

Gillmann, M., Letullier, A., and Renouard, G., 1966, La Mer Rouge: Geologie et probleme pétrolier: Revue de l'Inst. Franc. Petrole, v. 21, no. 10, p. 1467-1487, illus.

Goerlich, F. Von, 1956, Mikropälontologische und stratigraphische Untersuchungen im Königreich Yemen: Paläont. Zeit., v. 30, p. 213-214.

Greenwood, J. E. G. W., and Bleackley, D., 1967, Geology of the Arabian Peninsula, Aden Protectorate: U.S. Geolological Survey Professional Paper 560-C, 96 p.

Greenwood, J. E. G. W., Bleackley, D., and Beydoun, Z. R., 1967, Photogeologic map of Western Aden Protectorate, sheets I and II: London, printed for D.O.S. by the Ordnance Survey, 1:250,000 scale.

Greenwood, W. R., Hadley, D. G., Anderson, R. E., Fleck, R. J., and Schmidt, D. L., 1976, Late Proterozoic cratonization in southwestern Saudi Arabia: Royal Soc. [London] Philos. Trans., v. 280, p. 517-527.

Grolier, M. J., Domenico, J. A., Donato, Mary, Tibbitts, G. C., Jr., Overstreet, W. C., and Ibrahim, M. M., 1977, Data from geologic investigations in the Yemen Arab Republic during 1976: U.S. Geological Survey Open-file Rept. 77-733, [(IR)Y-12], 103 p., 8 figs., 5 tables.

Grolier, M. J., and Overstreet, W. C., 1976a, Preliminary geologic map of the northwestern region, Yemen Arab Republic, Landsat-1 image no. 1136-07012: U.S. Geological Survey Open-file Rept. 76-737 [(IR)Y-1], map, scale 1:500,000.

________, 1976b, Preliminary geologic map of Tihama and Red Sea escarpment, north of Bajil, Yemen Arab Republic, Landsat-1 image no. 1136-07015: U.S. Geological Survey Open-file Rept. 76-738 [(IR)Y-2], map, scale 1:500,000.

________, 1976c, Preliminary geologic map of Tihama between Zabid and Hudaydah, Yemen Arab Republic, Landsat-1 image no. 1118-07021: U.S. Geological Survey Open-file Rept. 76-739 [(IR)Y-3], map, scale 1:500,000.

________, 1976d, Preliminary geologic map of the region east of Sa'dah, Yemen Arab Republic, Landsat-1 image no. 1117-06553: U.S. Geological Survey Open-file Rept. 76-740 [(IR)Y-4], map, scale 1:500,000.

________, 1976e, Preliminary geologic map of north Yemen, region north of San'a', Yemen Arab Republic, Landsat-1 image no. 1189-06555: U.S. Geological Survey Open-file Rept. 76-741 [(IR)Y-5], map, scale 1:500,000.

________, 1976f, Preliminary geologic map of San'a', Qa'tabah, Ibb, Zabib, and Bajil area, Yemen Arab Republic, Landsat-1 image no. 1189-06561: U.S. Geological Survey Open-file Rept. 76-742 [(IR)Y-6], map, scale 1:500,000.

________, 1976g, Preliminary geologic map of the Ta'iz region, Yemen Arab Republic, Landsat-1 image no. 1189-06564: U.S. Geological Survey Open-file Rept. 76-743 [(IR)Y-7], map, scale 1:500,000.

Grolier, M. J., and Overstreet, W. C., 1976h, Preliminary geologic map of the northeastern region, Yemen Arab Republic, Landsat-1 image no. 1152-06501: U.S. Geological Survey Open-file Rept. 76-744 [(IR)Y-9], map, scale 1:500,000.

________, 1976i, Preliminary geologic map of the southeastern region of the Yemen Arab Republic, Landsat-1 image no. 1206-06504: U.S. Geological Survey Open-file Rept. 76-745 [(IR)Y-10], map, scale 1:500,000.

________, 1978, Geologic map of the Yemen Arab Republic: U.S. Geological Survey map, scale 1:500,000, in press.

Hartley, W. N., and Ramage, Noel, 1897, The wide dissemination of some of the rarer elements, and the mode of their association in common ores and minerals: Jour. Chem. Soc., v. 71, p. 533.

Heybroek, F., 1965, The Red Sea Miocene evaporite basin, in Salt Basins around Africa: The Institute of Petroleum, London, p. 17-40.

Hotchkiss, Henry, 1963, Petroleum developments in Middle East and adjacent countries in 1962: American Association Petroleum Geology Bulletin, v. 47, no. 7, p. 1420-1421, fig. 11.

Hubert, A. E., and Lakin, H. W., 1973, Atomic absorption determination of thallium and indium in geologic materials, in Jones, M. J., ed., Geochemical Exploration 1972: London, The Institution of Mining and Metallurgy, p. 383-387.

Karrenberg, Herbert, 1956, Junger Magmatismus und Vulkanismus in Sudwestarabien (Jemen): Internat. Geol. Congress, 20th Sess., Mexico, Sec. I-Vulcanologia del Cenozoico, p. 171-185.

________, 1959, Junger Magmatismus in Sudwest Arabien (Jemen): Techn. Mitt. Krupp, v. 17, no. 1, p. 33-36.

Lakin, H. W., 1972, Selenium accumulation in soils and its absorption by plants and animals, in Cannon, H. L., and Hopps, H. C., eds., Geochemical environment in relation to health and disease: Geological Society America Spec. Paper 140, p. 45-53.

Lakin, H. W., and Davidson, D. F., 1973, Selenium, in Brobst, D. A., and Pratt, W. P., eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 573-576.

MacFayden, W. A., 1930, The geology of the Farsan Islands, Gizan, and Kamaran Island, Red Sea, part 1, General geology: Geology Magazine, v. 67, p. 310-315.

Miller, W. R., 1977, Application of hydrogeochemistry to the search for base metals: Ottawa, Canada, An Internatational Symposium on Geophysics and Geochemistry Applied to the Search for Metallic Ores, preprint, 20 p.

Overstreet, W. C., Domenico, J. A., Grolier, M. J., Tibbitts, G. C., Jr., and Ibrahim, M. M., 1976, Trace elements in some rocks and slag from the Yemen Arab Republic, and their bearing on the iron ore near Sa'dah: U.S. Geological Survey Open-file Rept. 76-264 [(IR)Y-8], 70 p., 10 figs., 13 tables.

Overstreet, W. C., and Rossman, D. G., 1970, Reconnaissance geology of the Wadi Wassat quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Open-file Report (IR) SA-117, 68 p.

Rathjens, Carl, and Wissman, Herrmann V., 1934, Sudarabien Reise, v. 3: Landeskundliche Ergebnisse: Hamburg, Friedrichsen, De Gruyter, & Co., M.B.H., 229 p.

Roberts, R. J., Greenwood, W. R., Worl, R. G., Dodge, F. C. W., and Kiilsgaard, T. H., 1975, Mineral deposits in western Saudi Arabia: U.S. Geological Survey Open-file Rept. SA(IR)-201, 60 p.

Robinson, Keith, 1973, Thallium, in Brobst, D. A., and Pratt, W. P., eds., United States mineral resources: U.S. Geol. Survey Prof. Paper 820, p. 631-636.

Roman, D. R., 1926, Petrographical studies in Yemen (Arabia): Inst. Geol. al Romaniee Anuarul, v. 21, pp. 301-348.

Schmidt, D. L., Hadley, D. G., Greenwood, R. G., Gonzalez, Louis, Coleman, R. G., and Brown, G. F., 1973, Stratigraphy and tectonism in the southern part of the Precambrian Shield of Saudi Arabia: Saudi Arabian Dir. Gen. Mineral Resources, Bulletin 8, 13 p.

Shukri, N. M., and Basta, E. Z., 1955a, Petrography of the alkaline rocks of Yaman: L'Inst. d'Egypte Bull., v. 36, p. 129-163.

________, 1955b, A classification of the pyroclastic rocks of Yaman: L'Inst. d'Egypte, v. 36, pp. 165-175.

Simons, F. S., and Prinz, W. C., 1973, Gold, in Brobst, D. A., and Pratt, W. P., eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 263-275.

U.S. Geological Survey and the Arabian American Oil Company, 1963, Geologic map of the Arabian Peninsula: U.S. Geol. Survey Misc. Geol. Inv. Map I-270-A, scale 1:2,000,000.

Vaughn, W. W., and McCarthy, J. H., 1964, An instrumental technique for the determination of submicrogram concentrations of mercury in soils, rocks, and gas, in Geological Survey Research 1964: U.S. Geological Survey Professional Paper 501-D, p. D123-D127.

Ward, F. N., Nakagawa, H. M., Harms, T. F., and Van Sickle, G. H., 1969, Atomic absorption methods of analysis useful in geochemical exploration: U.S. Geological Survey Bulletin 1289, p. 33-38.

Weeks, R. A., 1973, Gallium, germanium, and indium, in Brobst, D. A., and Pratt, W. P., eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 237-246.

APPENDIX

Three specimens of brachiopods received by M. J. Grolier in 1976 from members of the Department of Geology, Sana'a University, Yemen Arab Republic, and stated to have been collected at a locality in the highlands to the southeast of Ta'izz in the vicinity of Najd Thujahat, were described by Bruce R. Wardlaw, U.S. Geological Survey (Wardlaw, B. R., written communication, 1978). The source of these fossils is near the top of an escarpment at an altitude of 2,000 m east of a tributary to Wadi Warazan where the Tawilah Sandstone of Cretaceous age overlies Precambrian metamorphic rocks. The Amran Limestone of Late Jurassic age has not previously been reported from this area, but unless the source locality was mistaken, the report of the paleontologic examination of the three specimens shows that the material represents a Middle to Upper Jurassic fauna:

"Two specimemts belong to the Tetrarhynchiinae, the common Jurassic rhynchonellids (though they range from Triassic to Lower Cretaceous). These specimens appear to be Goniorhynchia sp. in that they are multiocostate with strong costae, lacking or with a reduced median septum, no septalium, and with strong dental plates. These are common to the Middle Jurassic. One specimen belongs to the Zeilleriacea and appears to be related to cf. Zeillerina which is an Upper Jurassic form.

It is difficult to give a good call on just three specimens, especially when interior characters are very important in Mesozoic identifications.

This appears to represent a Jurassic fauna (Middle to Upper). It would, therefore, suggest that the Amran Limestone is present in this area...."