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CONTRIBUTIONS TO THE GEOCHEMISTRY, ECONOMIC GEOLOGY, AND GEOCHRONOLOGY OF THE YEMEN ARAB REPUBLIC

by

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ABSTRACT

Results of major-element analyses of a group of Precambrian granitoid rocks exposed around Rida' and Al Bayda, Yemen Arab Republic (YAR), are compared with data on Precambrian granitoid rocks in the Kingdom of Saudi Arabia. The comparison shows that the rocks at Rida' and Al Bayda comprise a posttectonic suite of latest Precambrian age, probably between 620 Ma and 560 Ma years, making them among the youngest Precambrian rocks in the YAR. Some are so shown on the geologic map of the YAR. However, the most strongly gneissic of these rocks were mapped with the oldest Precambrian gneissic granite. The chemical data indicate that the difference between the gneissic and the massive rocks reflects syntectonic and posttectonic emplacement with reference to the end of the Precambrian orogeny and final cratonization of the Shield. For strict classification of the Precambrian granitoid rocks of the YAR, definition of the stratigraphic succession of the Precambrian metavolcanic and metasedimentary rocks, major-element geochemistry, and geochronology are required.

The Sn-bearing granitic pluton to the east of Sa'dah in the northern YAR is a posttectonic alkali granite similar to late Precambrian stanniferous granite plutons in the eastern and southern Shield of Saudi Arabia.

The major-element composition of rhyolite tuff in the Yemen Volcanics in the YAR affords convincing evidence that the tuff is correlative with rhyolite in the Liyyah Formation in Saudi Arabia which is part of the Jizan Group of late Oligocene and early Miocene age. The age assigned to the Yemen Volcanics on the geologic map may be too great. The probable age is Oligocene and early Miocene.

Two new K-Ar ages of the olivine basalt of the Aden Volcanic Series (?) of 1.54 ± 0.12 million years and 2.21 ± 0.13 million years indicate that the base of this Series in the YAR is probably Pliocene instead of Pleistocene. The disastrous earthquake of 13 December 1982, reportedly was caused by movement of magma beneath the Dhamar-Rida' volcanic field showing that these youthful flood-basalt fields are still active. The need to study and evaluate earthquake risk is critical particularly in connection with the new dam of Ma'rib.

Similarities of Quaternary alluvial stratigraphy in the YAR with sections reported for gold placers in Saudi Arabia, including particularly a gradient

spike related to sand choke in wadis, suggest that traditional views of mean bed scour and fill during floods in ephemeral streams in semiarid climate are not fully applicable in the arid part of the YAR. Therefore, the possibility for proximate eluvial and alluvial gold placers must not be dismissed on theoretical grounds alone.

Exploration by inclined diamond-drill holes under the gossan at Jabal Al Maidan and Jabal Al Ma'aden in the Sa'dah area is urged to determine the metal contents of unweathered sulfide minerals. Concentrations as high as 550 ppm As, 1,000 ppm Ni, 60 ppm Cu, 300 ppm Co, and 6,000 ppm Zn reported by the German Geological Advisory Group in the YAR may reflect co-precipitation and concentration in secondary iron minerals during weathering, but across the border in Saudi Arabia surface gossan similar to that at Sa'dah was shown to be depleted by factors of 5-10 relative to the unoxidized sulfides below the gossan for the metals Cu, Pb, Zn, Ni, and Co.

INTRODUCTION

Purpose of report

The present report has as its purpose the release of previously unpublished results of chemical analyses made on specimens of rocks, ores, and slags collected in 1975, 1976, and 1979 by personnel of the U.S. Geological Survey (USGS) in connection with various cooperative activities with agencies of the Government of the Yemen Arab Republic (YAR). Also included are new K-Ar ages on Pleistocene basalt and a new radiocarbon age for charcoal from the bank of Wadi Adhanah at the south edge of Ma'rib (15°25'30" N.; 45°20'18" E.). The results supplement and extend geochemical, geochronological, and economic geological data for the YAR previously issued by the USGS (Overstreet and others, 1976; Grolier and others, 1977; Overstreet and Grolier, 1980; and Overstreet and others, 1980). The report provides the opportunity to compare the ancient open-pit iron-ore mine at Jabal Al Maidan near Sa'dah in the northern part of the YAR with essentially identical deposits that have been extensively investigated in the southwestern part of the Kingdom of Saudi Arabia. Geological similarities between the deposits in the YAR and in Saudi Arabia are so considerable that some emphasis is given to insure that an adequate evaluation of the mineralization from the vicinity of Sa'dah northward to the border with Saudi Arabia is undertaken as part of the national program of minerals assessment.

Source of samples

Samples in the 75-OT series and in the MJG-76 series of field numbers discussed below in the section of text on Major elements in igneous rocks were collected respectively in 1975 by W. C. Overstreet and in 1976 by M. J. Grolier. The geographic locations, stratigraphic positions, petrographic descriptions, and minor-elements composition of these samples have been described in preceding reports (Overstreet and others, 1976; Grolier and others, 1977; Overstreet and others, 1980) where index maps show the localities sampled. Figure 1 in the present text is also a geographic index to the sources of these samples.

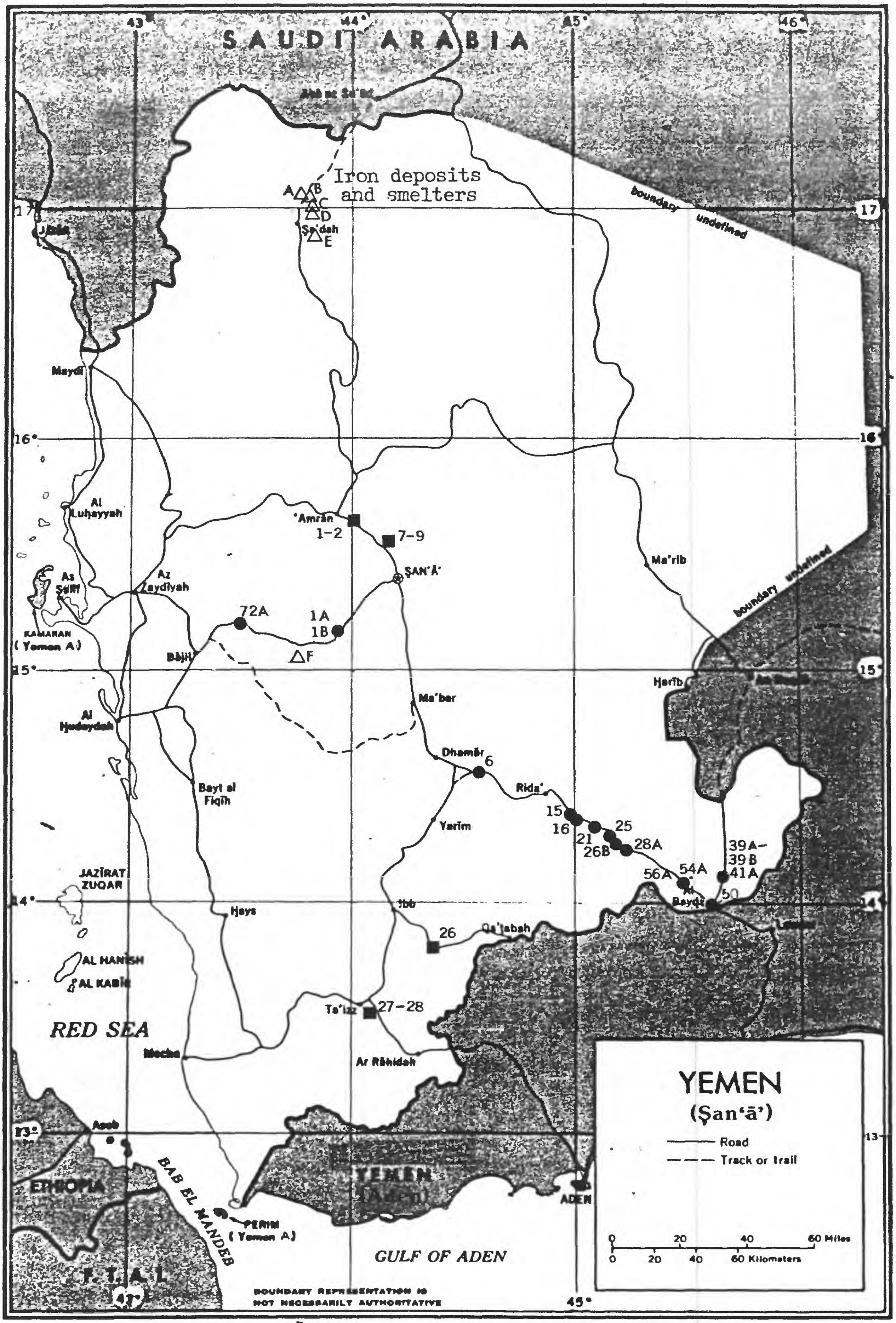


Figure 1. Index map of the Yemen Arab Republic showing sources of samples of geologic materials.

EXPLANATION

75-OT series: samples of igneous rocks numbered 75-OT-1, 75-OT-2, 75-OT-7, 75-OT-8, 75-OT-9, 75-OT-26, 75-OT-27, 75-OT-28.

MJG-76 series: samples of igneous rocks numbered MJG-76-1A, MJG-76-1B, MJG-76-6, MJG-76-15, MJG-76-16, MJG-76-21, MJG-76-25, MJG-76-26B, MJG-76-28A, MJG-76-39A, MJG-76-39B, MJG-76-41A, MJG-76-50, MJG-76-54A, MJG-76-56A, MJG-76-72A.

79-TK series and 79-OT series: samples of rocks, ores, and slags for spectrographic analysis.

<u>Sa'dah area</u>

A. Slag pile at Al Shatt, samples of slag numbered 79-OT-38 through 79-OT-44.

B. Jabal Al Maidan open-pit iron-ore mine, samples of rocks and ore numbered 79-OT-1 through 79-OT-13.

C. Jabal Ayub circular shaft mine, samples of rock numbered 79-TK-6 and 79-OT-14 through 79-OT-23.

D. Vicinity of Ath Therwa in Wadi Agnam, samples of rock numbered 79-TK-2 and 79-OT-24.

E. Jabal Al Ma'aden open-pit iron-ore mine, samples of rock and ore numbered 79-TK-7 and 79-OT-25 through 79-OT-35.

<u>Manakhah area</u>

F. Samples of rock numbered 79-TK-3 through 79-TK-5 and 79-OT-45 through 79-OT-51.

Samples in the 79-TK series and in the 79-OT series of field numbers, discussed below in the section of text on Minor elements in rocks, ores, and slags, were collected in 1979 respectively by T. H. Kiilsgaard and W. C. Overstreet. The general distribution of these samples is shown on figure 1. Specific localities sampled and descriptions of the 55 specimens used for semiquantitative spectrographic analyses for minor elements are listed in table 1.

Field sample Ma'rib 758 (laboratory number W-3457) was collected in 1975 by Dwight L. Schmidt from exposures in the bank of Wadi Adhanah at Ma'rib (fig. 1).

Acknowledgments

Field and laboratory work in 1975-76, and the K-Ar geochronology, were done in connection with Participating Agency Service Agreement ASIA (IC) 22-74, Water and Mineral Survey Project of North Yemen, between the Agency for International Development, U.S. Department of State (USAID) and the USGS in cooperation with the former Mineral and Petroleum Authority, Ministry of Economy, Yemen Arab Republic. Field work in the YAR by USGS during 1979 was funded by the Reimbursable Development Program of USAID in cooperation with the Ministry of Petroleum and Mineral Affairs, YAR. The radiocarbon analysis in 1976 and the spectrographic analyses of the samples acquired in 1979 were undertaken by the USGS at no expense to the cooperating organizations as part of ongoing research in USGS on problems in the application of geochemical exploration to desert regions in the context of institution-to-institution investigations with the Yemen Oil and Mineral Corporation (YOMINCO), Ministry of Petroleum and Mineral Affairs.

The writers are indebted to many persons in the YAR who provided the support and assistance needed to carry out the work leading to this report. Special mention should be made of the help in 1975-76 of Dr. Abdul Karim El-Eryani, then Chairman of the Central Planning Organization, YAR; Mr. Hamoud Ahmid Daif Allah, then President of the Mineral and Petroleum Authority (predecessor organization of the Yemen Oil and Mineral Corporation) in the Ministry of Economy; Mr. Aldelmo Ruiz, then Director, USAID Mission to the Yemen Arab Republic; and Mr. Gordon C. Tibbitts, Jr., USGS, then Chief, Water and Mineral Survey Project of North Yemen. Geological field work at that time was aided by Mohammad Mukred Ibrahim, Assistant Chief Minerals Geologist, Mineral and Petroleum Authority; Mohammad Lutf Al-Eryani, Kuwait University; and James W. Aubel, U.S. Peace Corps. In 1979, Kiilsgaard and Overstreet had the opportunity of visiting several sites of special geologic interest in the YAR through the assistance of H. E. Ahmad Qaid Barakat, Minister of State for Petroleum Affairs and Natural Resources, YAR; Mr. Ali Jaber Alawi, Director General, YOMINCO, and Mr. Robert G. Huesmann, Director, USAID Mission to the YAR. Engineer-geologists Hazam Baker and Abdullah Al Thary, YOMINCO, were helpful associates on a field trip to the abandoned iron mines in the Sa'dah area in the northern part of the YAR. Geologist Abdul Wasse of YOMINCO and Abdullah Al Thary gave operational assistance during a trip to the Manakhah area in the west-central part of the YAR. Miss Zohra Merabet, engineer, Department of Hydrology, YOMINCO, assisted in many supportive ways in San'a'. It is indeed a pleasure to acknowledge the help received from these many people.

Table 1. List showing field sample numbers, descriptions, latitudes, and longitudes of rocks, ores, and slags collected during January 1979 in the Yemen Arab Republic

[79-OT series collected by W. C. Overstreet; 79-TK series collected by T. H. Kiilsgaard.]

Field sample number	Description of material sampled	North Latitude	East Longitude
	Sa'dah area, Jabal Al Maidan open-pit iron mine		
79-OT-1	Weathered, gray, foliated metatuff	17°01'30"	43°46'40"
-2	Weathered, gray-green, massive metatuff	Do.	Do.
-3	Non-graphitic carbonaceous schist	Do.	Do.
-4	White chert	Do.	Do.
-5	Collapse breccia	Do.	Do.
-6	Ferruginous chert	Do.	Do.
-7	Maroon to brown gossan, tuff relicts, east side of pit	Do.	Do.
-8	Gossan, central part of pit	Do.	Do.
-9	Maroon to dark brown gossan, west side of pit	Do.	Do.
-10	Gray, foliated metatuff	Do.	Do.
-11	Massive meta-andesite	Do.	Do.
-12	Dark maroon gossan, boxwork structure after pyrite	Do.	Do.
79-OT-13	Brown, gray, and white marble	Do.	Do.
	Sa'dah area, Jabal Al Ma'aden open-pit iron mine		
79-OT-25	Septum of clay and carbonate, south end of gossan	16°53'00"	43°49'05"
-26	Greenish-brown, massive gossan, south end of pit	Do.	Do.
-27	White to yellowish brown clayey septum in gossan	Do.	Do.
-28	Goethitic gossan from central part of outcrop	Do.	Do.
-29	Yellowish-brown ferruginous chert, central part of gossan	Do.	Do.
-30	Hematite, north-central part of gossan	Do.	Do.
-31	Goethite, north end of gossan	Do.	Do.
-32	Goethite, north-central part of gassan	Do.	Do.
-33	Black goethite from north end of gossan	Do.	Do.
-34	Fresh magnesite and calcite from north end of gossan	Do.	Do.
79-OT-35	Weathered magnesite and calcite from north end of gossan	Do.	Do.
79-TK-7	Black goethite, north end of gossan	Do.	Do.
	Sa'dah area, Jabal Ayub circular shaft mine		
79-OT-14	White magnesite and calcite	17°01'00"	43°48'00"
-15	White and pink magnesite	Do.	Do.
-16	Olivine-rich mafic dike	Do.	Do.
-17	Olivine-rich mafic dike	Do.	Do.
-18	Phlogopite (?)-magnesite rock	Do.	Do.
-19	Dike of hornblende granite	Do.	Do.
-20	Marble	Do.	Do.
-21	Marble with magnesite	Do.	Do.
-22	Gabbro dike	Do.	Do.
79-OT-23	Pink biotite granite intrusive into gabbro dike	Do.	Do.
79-TK-6	Pink biotite granite intrusive into gabbro dike	Do.	Do.
	Sa'dah area, vicinity of Ath Therwa in Wadi Agnam		
79-OT-38	Andesine gabbro with pyrite-coated joints	16°59'00"	43°48'00"
79-TK-1	Andesine gabbro with pyrite-coated joints	Do.	Do.
79-TK-2	Quartz syenite dike in gabbro	Do.	Do.
	Sa'dah area, slag pile at Ath Shatt		
79-OT-38	Black, smooth, ropy slag with large gas bubbles	17°01'45"	43°46'15"
-39	Gray to brown agglomeratic, scoriaceous slag	Do.	Do.
-40	Dark-brown, scoriaceous slag, many gas bubbles	Do.	Do.
-41	Brown, scoriaceous slag	Do.	Do.
-43	Black, massive slag with metallic sheen; small gas bubbles	Do.	Do.
79-OT-44	Black, massive slag with rare small gas bubbles	Do.	Do.
	Manakhah area, Yemen Volcanics		
79-OT-45	Purplish-gray, flow-banded, crystal lithic tuff	15°03'50"	43°42'45"
-46	Ash-flow tuff, purple, with perlitic cracks	15°03'30"	43°41'40"
-47	Saprolite of andesite porphyry	15°03'37"	43°42'30"
-48	Saprolite of dacite porphyry	15°03'25"	43°43'25"
-49	Saprolite of andesite tuff	15°04'10"	43°44'10"
-50	Green bedded tuff	15°04'25"	43°44'25"
79-OT-51	Green lithic crystal tuff	15°07'00"	43°55'30"
79-TK-3	Purple volcanic tuff with perlitic cracks	15°03'15"	43°41'25"
-4	Reddish lithic tuff, grading to purple	15°03'50"	43°42'45"
-5	Green volcanic tuff	15°07'00"	43°55'30"

Our appreciation is also expressed to associates in the laboratories of the USGS who performed the chemical analyses and geochronological determinations presented here: S. R. Morgan, P. R. Klock, B. M. Myers, S. E. Sims, and Meyer Rubin. The major-element data were processed by George Van Trump, Jr., using standard USGS computer programs for the presentation of petrologic parameters.

GEOCHEMISTRY

The geochemical data presented here include the results of major-element analyses of 24 samples of igneous rocks and the results of minor-element spectrographic analyses of 55 samples of rocks, ores, and slags from the YAR. The results of the major-element analyses are interpreted in terms of possible ages and tectonic settings of the igneous rocks. These interpretations suggest a re-definition of the stratigraphic succession employed by Grolier and Overstreet (1978) for the Precambrian rocks of the YAR. The trace-element data on the rocks, ores, and slags from the old iron mines in the vicinity of Sa'dah extend geochemical data already released on the southern part of these deposits (Overstreet and others, 1976) and tend to confirm that they are gossan on massive sulfide deposits essentially barren of base and precious metals. The possibility that northern extensions of these deposits may not be entirely barren makes them attractive targets for future mineral exploration. Trace-element data from rocks in the Manakhah area add to the information on the composition of the Yemen Volcanics.

Geologic background

The geologic literature dealing with the petrology, chemical composition, and isotopic ages of igneous rocks in the YAR tends to focus more on the Tertiary extrusive rocks of the Yemen Volcanics, the Miocene(?) alkali granites, and the Quaternary Aden Volcanic Series than on the crystalline rocks of Precambrian age (Roman, 1926; Comucci, 1929; Lipparini, 1954; Shukri and Basta, 1955a; 1955b; Karrenberg, 1956; 1959; Miclea, 1973; Kabash and Ghoweba, 1976; Civetta and others, 1978). This emphasis is also evident in reports comparing the rocks of the YAR with those of Ethiopia (El Hinnawi 1964; Gass, 1970; Clifford and Gass, 1970; Mohr, 1971; Pilzer and Rosler, 1975). In the present report, 12 new analyses of the major elements in plutonic rocks of Precambrian age are given as well as further new determinations of major elements and K-Ar ages of the younger intrusive and extrusive rocks.

The descriptions of the analyzed rocks given below are related to the stratigraphic succession shown on the geologic map of the YAR (Grolier and Overstreet, 1978), where five major successions of rocks are separated by unconformities (table 2). Although the major-element data are presented according to these stratigraphic positions, interpretation of the chemical data for the plutonic rocks of Precambrian age suggests that they may not represent older and younger suites. Instead, they may all be Late Precambrian, possibly less than ~650 Ma in age, through comparison with compositionally similar rocks in Saudi Arabia. The differences in age were assigned during the compilation of the geologic map of the YAR on a basis of apparent differences between gneissic and massive rocks (Grolier and Overstreet, 1978). These differences may be the result of syntectonic and posttectonic emplacement with perhaps little more than ~50 Ma difference in age between the oldest and the youngest of these Precambrian intrusive rocks.

Table 2. Stratigraphic succession of major geologic units in the Yemen Arab Republic

[After Grolier and Overstreet, 1978] Descriptions and names of units	Stratigraphic position			[Revised after this report and Schmidt and others, 1979] Description and names of units
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 (?) Unconformity	Holocene and upper Peistocene	QUATERNARY	Holocene, Pliocene, and upper Pliocene	(Same as left column) Uncomformity
Tuffaceous sediment and evaporites of the Baid Formation and Hypabyssal andesite and diabase dikes	Pliocene(?) or Miocene(?)	TERTIARY	upper Miocene	Evaporites, coastal plain and Red Sea
			late lower Miocene	Hypabyssal diabasic and basaltic dikes
Alkali granite, syenite, and diorite in subvolcanic plugs, stocks, and plutons	Miocene(?)		lower Miocene and upper Oligocene	Alkali granite, syenite and diorite in subvolcanic plugs, stock, and plutons
Alkali basalt flows	lower Miocene(?) and upper Oligocene(?)			Yemen Volcanics including sediments of the Baid Formation and alkali flood basalt
Saprolite and laterite	Eocene (?)		Eocene	Saprolite and laterite
Yemen Volcanics Continental-type crossbedded sandstone, conglomerate, and shale of the Tawilah Group and the Medj-zir Series Unconformity	Tertiary and/or Cretaceous	TERTIARY AND CRETACEOUS	Tertiary and Cretaceous	Continental-type crossbedded sandstone, conglomerate, and shale of the Tawilah Group and the Medj-zir Series Unconformity
Limestone, marl, and shale of Amran Series	Upper	JURASSIC	Upper	(Same as left column)
Green shale, sandstone, and conglomerate of the Kohlan Series Unconformity	Lower		Lower	(Same as left column) Unconformity
Partly crossbedded, locally conglomeratic Wajid Sandstone Unconformity		ORDOVICIAN		(Same as left column) Unconformity
Granite, granite gneiss, granodiorite, injection gneiss, gabbro, mafic dikes, metavolcanic and metasedimentary rocks		PRECAMBRIAN	Late Proterozoic	(Same as left column)

This inference of age on the basis of chemical composition of the plutonic rocks requires further geochemical and geochronological data based on detailed field work before it can replace the previous concept of stratigraphic succession. Therefore, in the descriptive presentation of the geochemical observations, the previously established succession is used. The implications of the major-element geochemistry, however, in terms of possible ages and tectonic settings of the plutonic rocks are addressed in a section on interpretation following presentation of the results of the analyses.

The results of the major-element analyses of the Yemen Volcanics appear to identify the material chosen for analysis as of probable late Oligocene and early Miocene age on a basis of comparison with other analyses. Age determinations by Civetta and others (1978) agree with this age assignment. The age of the Yemen Volcanics was imprecisely known and was given on the geologic map (Grolier and Overstreet, 1978) as Tertiary and/or Cretaceous. Throughout this report, the Yemen Volcanics will be referred to in general as Tertiary in age.

Major elements in igneous rocks

Following a description of the method used for analysis, the results of the analyses for major elements are discussed below under older Precambrian rocks, younger Precambrian rocks, Tertiary extrusive rocks (the Yemen Volcanics), Miocene(?) intrusive alkali granite, and Pleistocene and Holocene extrusive rocks (the Aden Volcanic Series(?)).

Method of analysis

Major elements were determined by the rapid rock analysis procedure of USGS (Shapiro, 1975) whereby x-ray spectrography is used for 15 oxides, and chemical procedures are used for FeO, H_2O+, H_2O-, and CO_2. The 15 oxides are:

SiO_2	P_2O_5
Al_2O_3	MnO
$FeTO_3$ 1/	ZrO_2
MgO	Cr_2O_3
CaO	NiO
Na_2O	BaO
K_2O	SrO
TiO_2	

1/ Total iron oxide.

The difference between the percentage of total iron oxide given by x-ray spectroscopy and the percentage of FeO determined chemically represents the value reported as Fe_2O_3. However, the method of dissolution used for the chemical determination of iron does not bring pyrite or chromite into solution.

The x-ray spectrographic analyses were made by S. R. Morgan and the chemical analyses were done by P. R. Klock. These data were processed by George Van Trump, Jr., to give various petrologic indices, normalized oxide values, normative minerals, and petrologic diagrams derived by computer through standard programs used by USGS.

Composition of older Precambrian rocks

The term older Precambrian rocks is derived from the distinctions shown on the geologic map of the YAR (Grolier and Overstreet, 1978) and the discussions of the petrography of diabase, granodiorite gneiss, and granite gneiss exposed along the road between Rida'and Al Bayda, and on the road extending northeastward from Al Bayda in the extreme southeastern part of the YAR (Grolier and others, 1977, figs. 1 and 2; Overstreet and others, 1980, p. 21-27). On that map and in those sources the older Precambrian igneous rocks are reported to be mainly of ages associated with the second episode of the Hejaz tectonic cycle identified in Saudi Arabia by Greenwood and others (1976, table 1); that is, between about 800 and 600 Ma old. The six samples of older Precambrian rocks are described by Grolier and others (1977, table 2) and by Overstreet and others (1980, p. 21-27). The sample numbers and localities are given as:

Rock type	Field number	Location (see fig. 1) North latitude	East longitude
Diabase	MJG-76-41A	14° 03' 11"	45° 43' 32"
Granodiorite gneiss	MJG-76-54A	14° 03' 07"	45° 31' 23"
Granite gneiss	MJG-76-16	14° 21' 25"	45° 01' 30"
Do.	MJG-76-21	14° 20' 06"	45° 06' 45"
Do.	MJG-76-25	14° 18' 08"	45° 13' 07"
Do.	MJG-76-28A	14° 15' 36"	45° 20' 03"

Diabase.--Specimen MJG-76-41A (fig. 1) is massive, medium-grained diabase with typically diabasic texture. The rock is seen by microscopic examination to consist of (in percent): plagioclase (>An_{55}) 40; clinopyroxene, 35; opaque minerals, 10; serpentine or talc after olivine (?), 10; and actinolite (?); after clinopyroxene, $\sim$5 (Overstreet and others, 1980, p. 26). Slight alteration is shown by the replacement of olivine (?) with opaque minerals and serpentine.

The major-element composition of this diabase is given in table 3, and the normalized oxide values recalculated to 100 percent are listed in Appendix 1 together with other petrologic parameters based on the chemical composition of the rock.

The results of the analysis (table 3) confirm the alteration noted by microscopic examination. This diabase has somewhat less Na_2O and considerably less K_2O than the world averages for diabase (Johannsen, 1937, table 93), and the normative plagioclase (Appendix 1) has a somewhat higher anorthite content (An_{69}) than that determined in the thin section (>An_{55}). Carbon dioxide is more abundant in sample MJG-76-41A than in typical diabase (Johannsen, 1937, table 93), but H_2O+ and H_2O- are about average. The alteration possibly was produced by low-grade regional metamorphism during the cratonization of the Arabian Shield between 650 and 560 Ma as recognized in southwestern Saudi Arabia (Greenwood and others, 1976, table 1).

Granodiorite gneiss.--The granodiorite gneiss (MJG-76-54A, fig. 1) shows in thin section a preferred orientation of hornblende, biotite, and plagioclase (Overstreet and others, 1980, p. 26). The quartz and feldspar have been granulated followed by incipient recrystallization of both minerals. Modal mineral

Table 3. Major-element composition of older Precambrian igneous rocks of the Yemen Arab Republic (in percent)

[Analyses by S. R. Morgan and P. R. Klock, U.S. Geological Survey, laboratory numbers in parentheses under field numbers.]

Oxide	Diabase	Granodiorite gneiss	Granite gneiss			
	MJG-76-41A (M-140482)	MJG-76-54A (M-140484)	MJG-76-16 (M-140475)	MJG-76-21 (M-140476)	MJG-76-25 (M-140477)	MJG-76-28A (M-140479)
SiO_2	46.06	62.54	70.77	73.23	74.73	72.77
Al_2O_3	15.78	17.36	14.83	13.69	12.76	13.50
Fe_2O_3	4.20	1.55	1.05	1.55	0.40	1.03
FeO	6.94	3.51	1.47	0.75	.95	1.49
MnO	0.176	0.168	0.076	.046	.023	0.051
MgO	9.32	1.28	.92	.18	.39	.55
CaO	10.78	3.54	2.61	.95	.87	1.41
Na_2O	1.79	4.70	3.19	3.84	2.11	3.18
K_2O	.23	3.06	3.72	4.64	6.48	4.91
TiO_2	1.14	.58	.30	.21	.19	.38
H_2O+	1.91	.77	.40	.17	.26	.13
H_2O-	.25	.09	.13	.13	.12	.15
P_2O_5	.13	.24	.10	.04	.08	.11
CO_2	.81	.18	.006	.11	.08	.06
ZrO_2	.008	.038	.015	.038	.024	.028
Cr_2O_3	.071	<.002	<.002	<.002	<.002	<.002
NiO	.026	<.001	<.001	<.001	<.001	<.001
BaO	.006	.135	.086	.145	.090	.076
SrO	.028	.049	.023	.011	.017	.011
Total	99.66	99.79	99.70	99.73	99.57	99.84

composition of the granodiorite gneiss is (in percent): plagioclase, 40p orthoclase perthite, 20; quartz, 15; biotite, 10; hornblende, ~8; sphene, ~2; epidote, ~2; allanite and apatite, <1.

The composition of the granodiorite gneiss is shown in table 3, and the normalized oxide values recalculated to 100 percent are given in Appendix 1 where other petrologic parameters based on chemical composition are presented. This specimen of granodiorite gneiss has somewhat less SiO_2 and more Al_2O_3 and Na_2O than the average granodiorite cited by Johannsen (1932, table 176), but the values are well within the ranges of percentages given for these oxides.

The normative distribution of the feldspars (Appendix 1) shows more plagioclase than the single modal analysis, even when allowance is made for plagioclase in the orthoclase perthite, but the difference is expectable where only one modal analysis was made.

Granite gneiss.--The four samples of granite gneiss identified on figure 1 (MJG-76-16, MJG-76-21, MJG-76-25, MJF-76-28A) are rather similar in their contents of modal quartz, but the amounts of modal potassium feldspar and plagioclase are variable owing to common perthitic intergrowths (Overstreet and others, 1980, p. 22-23):

Minerals	Sample numbers in MJG-76 series			
	16	21	25	28A
Quartz	30	35	35	35
Microcline perthite	35	40	50	--
Microcline-orthoclase perthite	--	--	--	45
Plagioclase	25	15	10	15
Biotite	10	--	5	3
Hornblende	--	5	--	--
Accessory minerals 1/	<1	1-2	<1	~1

1/ Includes, variously, opaque minerals, apatite, epidote, zircon, garnet, muscovite, and chlorite: see Overstreet and others (1980, p. 22-23) for individual mineralogical components.

The chemical composition of these samples of granite gneiss is shown in table 3. Most components are remarkably similar in abundance except CaO, Na_2O, and K_2O which vary rather widely. This variation may in part be caused by secondary alteration. These rocks resemble the alkali-lime granites of Johannsen (1932, table 94), which similarity is more marked in the normalized oxide values given in Appendix 1.

The normative minerals calculated from the chemical analyses (Appendix 1) afford confirmation of the modal quartz and also show the role of perthite in lowering the estimates of the abundance of modal plagioclase,

Composition of the younger Precambrian rocks

The younger Precambrian igneous rocks shown on the geologic map of the YAR (Grolier and Overstreet, 1978), and for which the results of chemical analyses are reported here, were thought to be similar to Late Precambrian granites in the Kingdom of Saudi Arabia (U.S. Geological Survey and the Arabian American Oil Company, 1963). These rocks are possibly 560-650 Ma in age and are associated with the second and third episodes of the Hijaz tectonic cycle as described by Greenwood and others (1976, table 1). Six samples of these younger Precambrian rocks were analyzed:

Rock type	Field number	Location (see fig. 1) North latitude	East longitude
Granodiorite	MJG-76-56A	14° 04' 01"	45° 29' 46"
Granite gneiss	MJG-76-15	14° 21' 36"	44° 59' 43"
Biotite granite	MJG-76-26B	14° 16' 30"	45° 15' 17"
Alkali feldspar granite	MJG-76-39A	14° 02' 43"	45° 42' 48"
Do.	MJG-76-39B	Do.	Do.
Riebeckite granite	MJG-76-50	13° 58' 50"	45° 34' 43"

These samples are also from exposures along the road between Rida' and Al Bayda, and on the road extending northeastward from Al Bayda (Grolier and others, 1977, figs. 1 and 2). Their geographic association in the same part of the YAR as the older Precambrian igneous rocks lends some support to the interpretation given in another section of text (below) that both the younger and the older Precambrian igneous rocks are parts of one suite.

The compositions of these younger Precambrian igneous rocks are given in table 4, and the normalized oxide values recalculated to 100 percent are included in Appendix 2 along with several petrologic ratios and numbers calculated from the chemical compositions of the rocks.

Granodiorite.--Sample MJG-76-56A of granodiorite consists of (in percent): antiperthite, 45; microcline, 20; quartz, 5; hornblende, 10; biotite, 15; opaque minerals and sphene, 5 (Overstreet and others, 1980, p. 20). Its chemical composition (table 4) is well within the range of compositions reported for granodiorite (Johannsen, 1932, table 176). More importantly for interpretative considerations, the composition is quite similar to that of the older Precambrian granodiorite gneiss (table 3, sample MJG-76-54A). Further chemical similarity between the two rocks is seen in the normalized oxide values and the molar data given in Appendices 1 and 2. Normative orthoclase is considerably less abundant, and normative anorthite is more abundant, in the younger granodiorite than in the older granodiorite gneiss.

Granite gneiss.--The granite gneiss (MJG-76-15) consists of (in percent): microcline perthite, 50; plagioclase, 20; quartz, 25; muscovite, 2; opaque minerals, biotite, and chlorite, 3 (Overstreet and others, 1980, p. 20) The chemical composition of the younger granite gneiss is more siliceous (table 4) than the compositions determined for the samples of older granite gneiss (table 3), but it is otherwise similar to the older rocks. Its composition is also toward the siliceous end of the range in chemical compositions reported for granite (Johannsen, 1932, tables 94 and 95). This high value for silica is reflected in the percentage of normative quartz (Appendix 2), which exceeds that of the samples of older granite gneiss (Appendix 1), and is equalled only by that of the younger Precambrian riebeckite granite (table 4, Appendix 2).

Table 4. Major-element composition of younger Precambrian igneous rocks of the Yemen Arab Republic (in percent)

[Analyses by S. R. Morgan and P. R. Klock, U.S. Geological Survey, 1979; laboratory numbers in parentheses under field numbers.]

Oxide	Granodiorite	Granite gneiss	Biotite granite	Alkali feldspar granite		Riebeckite granite
	MJG-76-56A (M-140485)	MJG-76-15 (M-140474)	MJG-76-16 (M-140475)	MJG-76-39A (M-140480)	MJG-76-39B (M-140481)	MJG-76-50 (M-140483)
SiO_2	63.60	77.21	74.15	76.52	77.97	77.19
Al_2O_3	15.16	12.42	14.25	12.44	12.04	11.45
Fe_2O_3	1.64	0.64	0.32	1.15	0.33	0.79
FeO	3.34	.17	.85	.34	.15	.42
MnO	.107	.018	.030	.018	.007	.009
MgO	1.27	.13	.31	<.02	.03	.05
CaO	2.65	.53	1.04	.38	.32	.27
Na_2O	4.31	2.56	3.79	3.57	3.05	3.79
K_2O	4.67	5.61	4.94	4.87	5.54	4.09
TiO_2	1.03	.10	.20	.12	.04	.07
H_2O+	.32	.28	.31	.09	.03	.22
H_2O-	.18	.08	.09	.16	.09	.10
P_2O_5	.25	.02	.06	.02	.02	.01
CO_2	.10	.08	.05	.06	.05	.05
ZrO_2	.105	<.002	.013	.026	<.002	.032
Cr_2O_3	<.002	<.002	<.002	<.002	<.002	<.002
NiO	<.001	<.001	<.001	<.001	<.001	<.001
BaO	.056	.048	.084	.015	.001	.001
SrO	.023	.011	.019	<.002	<.002	<.002
Total	98.81	99.91	100.51	99.78	99.67	98.54

Biotite granite.--The analyzed sample of biotite granite (MJG-76-26B; fig. 1) is made up of (in percent): microcline perthite, 70; plagioclase, 15; quartz, 10; biotite, 3; and accessory muscovite, epidote, chlorite, and apatite, 2 (Overstreet and others, 1980, p. 19).

The major-element composition of this specimen of biotite granite is shown in table 4, and various derivative petrologic parameters are given in Appendix 2. The biotite granite is the least siliceous of the younger Precambrian granites, resembling in that respect the older Precambrian granite gneiss (table 3). The other major elements, as reflected in the normative minerals of the younger biotite granite (Appendix 2) and the older granite gneiss (Appendix 1), are also similar:

Normative minerals	Percentages of normative minerals by rock type				
	Younger biotite granite	Older granite gneiss MJG-76-series			
	MJG-76-26B	-16	-21	-25	-28A
Quartz	30.2	30.9	31.2	35.2	31.5
Corundum	.09	1.1	0.7	0.9	0.7
Orthoclase	29.2	22.2	27.7	38.7	29.2
Albite	32.1	27.3	32.8	18.0	27.1
Anorthite	4.8	12.4	4.5	3.8	6.3
Hypersthene	1.8	3.8	0.5	2.1	2.7
Magnetite	0.5	1.5	2.0	0.6	1.5
Hematite	--	--	0.2	--	--
Ilmenite	0.4	0.6	0.4	0.4	0.7
Apatite	0.1	0.2	0.1	0.1	0.3

The younger biotite granite is chemically less distinguishable from the older granite gneiss than is the younger granite gneiss (table 4).

Alkali-feldspar granite.--The two analyzed samples of alkali-feldspar granite (MJG-76-39A and MJG-76-39B, fig. 1) are from the same locality (Grolier and others, 1977, p. 17), but they differ in grain size: MJG-76-39A is coarse grained and MJG-76-39B is fine grained. The modal composition of the coarse-grained granite is (in percent): microcline perthite, 50; quartz, 40, plagioclase, 10; accessory chlorite, biotite, sphene, and opaque minerals, <1 (Overstreet and others, 1980, p. 18-19). The fine-grained granite consists of (in percent): potassium feldspar, 55-60; quartz, 40; plagioclase, 2; and magnetite (?), <1 (Overstreet and others, 1980, p. 19).

The chemical composition of these two samples of alkali-feldspar granite are given in table 4, and the petrologic parameters derived from the composition appear in Appendix 2. The compositions generally resemble that of several specimens of postorogenic biotite alkali granite and biotite monzogranite of Saudi Arabia (Stoeser and Elliott, 1979, table 2). Chemical similarities are more marked between granitic plutons in the central part of the Precambrian Shield in Saudi Arabia and in the southeastern part of the Shield in the YAR than they are for granitic plutons in southwestern Arabia near the border with the YAR except for biotite monzonite at Jabal ar Rahadah in Arabia near the YAR (Stoeser and Elliott, 1979, fig. 2 and table 2). These similarities may indicate that the alkali-feldspar granite in the YAR are part of the post-orogenic sequence recognized in Saudi Arabia (Fleck and others, 1980).

Riebeckite granite.--The modal composition of the sample of younger Precambrian riebeckite granite (MJG-76-50, fig. 1) is (in percent): perthitic potassium feldspar, 60; quartz, 35-40; riebeckite, <5; and biotite, <1 (Overstreet and others, 1980, p. 17). The rock is slightly recrystallized as a result of deformation. This characteristic distinguishes it texturally from the riebeckite-bearing alkali granite of Miocene (?) age exposed at Jibal Sabir and at Jibal Hufash, YAR, described in a following section, which otherwise has a strong mineralogical similarity to the younger Precambrian riebeckite granite. As was noted in an earlier report (Overstreet and others, 1980, p. 10-11, 18), the problem of resemblance will require detailed geologic study, including isotopic age determinations, to clarify. That earlier report also showed that the riebeckite granite of younger Precambrian age might be distinguished from the Miocene (?) riebeckite granite by differences in their contents of minor elements:

Element	Abundances of minor elements in riebeckite granite (ppm)	
	Younger Precambrian	Miocene (?)
Ti	700	2,000
Mn	70	3,000
Be	2	7
La	20	100
Nb	<50	100
Zr	100	300

The major-element composition of the younger Precambrian riebeckite granite is listed in table 4, and other chemical and normative mineralogical parameters derived from the chemical composition are shown in Appendix 2. Major elements in two samples of the Miocene (?) riebeckite granite are shown in table 5, and other petrologic parameters are presented in Appendix 3. From the data in tables 4 and 5, it is apparent that the younger Precambrian riebeckite granite is closer in major-element composition to the younger Precambrian alkali-feldspar granite of the YAR than to the Miocene (?) alkali granite at Jibal Sabir and Jibal Hufash. The riebeckite-bearing younger Precambrian granite of the YAR appears to be similar chemically to the alkali granites of Late Precambrian age in Saudi Arabia (Stoeser and Elliott, 1979, table 2).

Composition of Tertiary extrusive rocks of the Yemen Volcanics

Four samples of rhyolitic tuff from the Yemen Volcanics were analyzed for major elements. Two samples are from the west-central part of the YAR and two are from the southern part of the country:

Rock type	Field number	Location (see fig. 1)	
		North latitude	East longitude
Welded tuff	MJG-76-1A	15° 07' 50"	43° 55' 42"
Do.	MJG-76-1B	Do.	Do.
Vesicular welded tuff	MJG-76-6	14° 26' 44"	44° 34' 37"
Crystal lithic tuff	75-OT-26	13° 54' 40"	44° 19' 40"

Table 5. Major-element composition of Tertiary igneous rocks of the Yemen Arab Republic--Yemen Volcanics and alkali granite (in percent)

[Analyses by S. R. Moore and P. R. Klock, U.S. Geological Survey, 1979; laboratory numbers in parentheses under field numbers.]

Oxide	Welded tuff		Vesicular welded tuff	Crystal lithic tuff	Alkali granite		
	MJG-76-1A (M-140471)	MJG-76-1B (M-140472)	MJG-76-6 (M-140473)	75-OT-26 (M-140468)	75-OT-27 (M-140469)	75-OT-28 (M-140470)	MJG-76-72A (M-140486)
SiO_2	69.35	72.15	75.05	70.50	65.56	73.28	72.54
Al_2O_3	12.45	13.43	11.48	12.37	16.12	12.43	12.42
Fe_2O_3	1.90	2.81	3.00	2.55	2.05	1.44	2.63
FeO	1.03	0.20	0.04	1.13	1.42	1.26	0.50
MnO	0.144	.128	.068	0.108	0.180	0.134	.187
MgO	.37	.12	.13	.50	.73	.12	.10
CaO	.69	.23	.46	1.38	1.24	.48	.32
Na_2O	3.13	3.45	3.64	4.04	6.07	4.24	4.32
K_2O	4.43	4.05	5.01	3.57	4.44	4.68	4.83
TiO_2	.52	.56	.25	.80	.83	.23	.39
H_2O+	4.28	1.51	.31	.63	.20	.22	.25
H_2O-	1.36	.98	.82	.59	.12	.12	.24
P_2O_5	.06	.03	.03	.12	.21	.03	.03
CO_2	.05	.28	.27	.90	.16	.05	.06
ZrO_2	.086	.082	.069	.076	.044	.105	.140
Cr_2O_3	<.002	<.002	<.002	<.002	<.002	<.002	<.002
NiO	<.001	<.001	<.001	<.001	<.001	<.001	<.001
BaO	.105	.094	.004	.100	.265	.010	.006
SrO	.008	.005	<.002	.026	.026	.003	<.002
Total	99.96	100.11	100.63	99.39	99.67	98.83	98.96

The welded tuffs are from undivided units of the Yemen Volcanics (TKy) on the geologic map of the YAR (Grolier and Overstreet, 1978), but the vesicular welded tuff (TKy_3 or younger) and the crystal lithic tuff (TKy_4) are from upper parts of the sequence. The welded tuffs from the undivided part of the Yemen Volcanics may be a little older than the other samples; however, as shown below in the section on Interpretation, all four samples are probably of early Miocene age. Isotopic ages of these tuffs have not been made, owing to an insufficient recovery of sanidine, nor have samples of interbedded basaltic units been collected and analyzed for age.

Welded tuff.--The two samples of welded tuff (MJG-76-1A and MJG-76-1B, fig. 1) are from the same locality. The rock represented by sample MJG-76-1A is strongly laminated due to welding but is quite unaltered and shows no devitrification. It consists of 99 percent of brown, flattened, stretched, and compacted glass shards with $\sim$1 percent of fragments of sanidine, clinopyroxenes, phlogopite (?), and opaque minerals together with sparse lithic fragments of clinopyroxene and magnetite (Overstreet and others, 1980, p. 15). Sample MJG-76-1B consists of (in percent): glass shards, 95; quartz formed as a devitrification product, 3; phenocrysts of sanidine, <1; and opaque minerals, <1. This specimen is also strongly laminated, but it retains flattened gas pockets (Overstreet and others, 1980, p. 15).

The major-element composition of these samples of welded tuff are shown in table 5 and the derived petrologic parameters are given in Appendix 3. The chemical composition of these glassy rocks shows that they are rhyolite (Johannsen, 1932, table 137).

The least altered of these welded tuffs, sample MJG-76-1A which from microscopic examination has no mineralogical or textural evidence of devitrification or other alteration (Overstreet and others, 1980, p. 15), contains a large amount of combined water (4.28 percent of H_2O+, table 5). Where the welded tuff is partly devitrified, as in specimen MJG-76-1B , the amount of combined water (1.51 percent, table 5) is much less, suggesting that water is lost from the glass during devitrification. The other specimens of welded tuff listed in table 5 are also partly devitrified and contain only 0.31 and 0.63 percent of H_2O+, which suggests that the original glass in these samples of the Yemen Volcanics contained more H_2O+ than the present partly devitrified rocks.

Vesicular welded tuff.--The sample of vesicular welded tuff from unit TKy_3 or younger rocks of the Yemen Volcanics consists of 93 percent of reddish-brown glass, 2 percent of crystals and fragments of sanadine, 1 percent of crystals and fragments of quartz, and some sparse fragments of volcanic rock (Overstreet and others, 1980, p. 14). Slight alteration is indicated by some devitrification of the glass.

The major-element composition of the vesicular welded tuff is given in table 5 and various petrologic parameters derived therefrom are reported in Appendix 3. The results of the chemical analysis show that the vesicular welded tuff is of rhyolitic composition more silicic than the other analyzed samples of the Yemen Volcanics.

Crystal lithic tuff.--The sample of crystal lithic tuff (75-OT-26, fig. 1) from unit TKy_4 of the Yemen Volcanics (Grolier and Overstreet, 1978) is a welded tuff composed of (in percent): brown glass with welded shards, 55; euhedral crystals and crystal fragments of anorthoclase (?) partly replaced by calcite, zeolite, and clay, 20; lithic fragments, 20; and opaque material, 5 (Overstreet and others, 1980, p. 13). The rock is distinctive from the other welded tuffs described above because of its low percentage of glass and because it is the most altered of these rocks.

The major-element composition of this welded crystal lithic tuff is listed in table 5. Various petrologic ratios and the normative minerals are given in Appendix 3. These data show that the rock is a rhyolite. Despite the microscopic evidence for replacement of anorthoclase (?) by zeolite and clay, the amount of water shown by the analysis is low.

Composition of Miocene (?) alkali granite

Alkali granite of Miocene (?) age is represented in these analyses by two samples from Jibal Sabir near Ta'izz in the southern part of the YAR and by one sample from Jibal Hufash in the west-central part of the YAR. The assignment of geologic age is based on a single K-Ar age determination of 22.7$\pm$0.9 Ma reported for a sample of alkali granite collected by R. O. Jackson, USGS, at Jibal Sabir and analyzed by R. F. Marvin, H. H. Mehnert, and Violet Merritt, USGS (Grolier and Overstreet, 1978). The three samples of alkali granite for which the results of major-element analyses appear in table 5 are from localities at:

Source of sample	Field number	Location (see fig. 1) North latitude	Location (see fig. 1) East longitude
Jibal Sabir	75-OT-27	13° 33' 45"	44° 02' 30"
Do.	75-OT-28	13° 33' 50"	44° 02' 10"
Jibal Hufash	MJG-76-72A	15° 11' 03"	43° 30' 42"

<u>Pluton at Jibal Sabir</u>.--The pluton of alkali granite at Jibal Sabir forms a prominent mountain at the southern edge of the city of Ta'izz. Of the two samples taken from this pluton, number 75-OT-27 represents a marginal phase and number 75-OT-28 is from the core. The marginal phase consists of (in percent): microcline perthite, 70; quartz, 20; riebeckite (?), 5; clinopyroxene, 2; calcite, <1; and sphene, phlogopite (?), and opaque minerals, <1 (Overstreet and others, 1980, p. 10). Moderate alteration has clouded the feldspars and changed some riebeckite (?) to biotite and opaque minerals. Specimen 75-OT-28 from the core is composed of (in percent): perthitic potassium feldspar, 65; quartz, 25; riebeckite, 10; and epidote and opaque minerals, <1.

The chemical composition of these two samples of Miocene(?) alkali granite is given in table 5 from which were generated the petrologic parameters in Appendix 3. The results of the analysis of sample 75-OT-28 are in remarkably close agreement with a previous analysis of Miocene(?) alkali granite from Jibal Sabir--specimen ROJ-1 collected by Roy O. Jackson, USGS, and used for the age determination cited above (R. O. Jackson, written commun., January 31, 1977):

Sample ROJ-1 analyzed by
Wayne Mountjoy, J. S. Wahlberg,
and T. L. Yagen, USGS, 1973, in percent

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 result of spectrographic analysis reported in Grolier and others (1977, p. 34).

The marginal phase represented by sample 75-OT-27 is, on the basis of chemical composition, an alkali feldspar quartz syenite, and the core phase, represented by samples 75-OT-28 and ROJ-1, are alkali feldspar granite.

Pluton at Jibal Hufash.--The sample of Miocene(?) alkali granite from the pluton at Jibal Hufash (MJG-76-72A) is a marginal phase from near the contact. It consists of (in percent): perthitic potassium feldspar, 70; quartz; 25-30; altered riebeckite, 2-3; plagioclase, <1; and opaque minerals, <1 (Overstreet and others, 1980, p. 11). Alteration of the rock has clouded the potassium feldspar and caused the riebeckite to be riddled with opaque mineral grains.

The chemical composition (table 5 and Appendix 3) is similar to samples 75-OT-28 and ROJ-1 from Jibal Sabir, and the rock is an alkali feldspar granite.

Composition of Pleistocene and Holocene
extrusive rocks--olivine basalt
of the Aden Volcanic Series (?)

The numerous and widespread basaltic flows and associated volcanic cones, craters, and tuff of Pleistocene and Holocene age in the YAR (Geukens, 1966, p. B16; Kabesh and Ghoweba, 1976; Grolier and Overstreet, 1978) may be the rock and time equivalent of the upper part of the Aden Volcanic Series in the People's Democratic Republic of Yemen (PDYR), described as being Miocene or Pliocene to Recent in age (Greenwood and others, 1967; Greenwood and Bleackley, 1967, p. C53-C56). On the geologic map of the YAR (Grolier and Overstreet, 1978) these volcanic rocks are shown largely as an undivided unit (Qa), but locally, particularly between San'a and Raydah, lava flows were divided by reflectance on LANDSAT-1 images into four units. The oldest flows of basalt form a continuous mantle over earlier rocks and may be about 1.5-2 Ma in age (see section of text on Geochronology). The youngest unit consists of very dark, lobate flows of basalt extruded in historical time, possibly about 1,700 years ago (Rathjens and Wissman, 1934, p. 105, 162-163, fig. 51; 1942, p. 276).

Three samples of the older lava and two samples of the historic flow were analyzed for major elements:

Source of sample	Field number	Location (see fig. 1) North latitude	East longitude
'Amran area			
Older lava	75-OT-1	15° 36' 45"	44° 00' 35"
Do.	75-OT-2	Do.	Do.
Bayt al Haqr area			
Older lava	75-OT-9	15° 33' 25"	44° 09' 30"
Historic flow	75-OT-7	Do.	Do.
Do.	75-OT-8	Do.	Do.

In the YAR the Aden Volcanic Series(?) consists mostly of olivine basalt (Kabesh and Ghoweba, 1976; Grolier and Overstreet, 1978; Schulze and Thiele, 1978, p. 27), but to the south in the PDRY other rocks besides basalt have been described in the Series including andesite, trachyte, dacite, and rhyolite (Shukri and Basta, 1955a; Greenwood and Bleackley, 1967, p. C44-C48). Inasmuch as three major fields of these young volcanic rocks have been identified in the YAR and named by Geukens (1966, p. B16) the San'a'-'Amran volcanic field, the Sirwah-Ma'rib field, and the Dhamar-Rada' field, but only the San'a'-'Amran field is represented by the samples used for this report, the possibility exists for rocks other than olivine basalt.

Older lava.--Of the samples from the 'Amran area (fig. 1), 75-OT-1 is massive to slightly vesicular olivine basalt from the lower part of the Aden Volcanic Series (?) 1.2 m above the base of the flow, and sample 75-OT-2 is vesicular olivine basalt 0.7 m above the base. This flow overlies limestone of the Upper Jurassic 'Amran Series and was sampled at a locality 8.7 km to the southeast of of 'Amran. The massive to slightly vesicular olivine basalt (75-OT-1) consists of (in percent): plagioclase, 75; olivine, 10; clinopyroxene, 10; and an opaque mineral, 5 (Overstreet and others, 1980, p. 9). Petrographic examination of the vesicular olivine basalt (75-OT-2) showed identical mineral composition (Overstreet and others, 1980, p. 9). Sample 75-OT-9 from the locality 0.6 km to the north-northeast of Bayt al Haqr is vesicular olivine basalt from the upper part of the Aden Volcanic Series (?) where it disconformably underlies the base of the historic lava flow. This lava (75-OT-9) below the historic flow is composed of (in percent): plagioclase, 70; olivine, 15; clinopyroxene, 10; an opaque mineral, 5; and glass, <1 (Overstreet and others, 1980, p. 9).

Major-element oxides in these three samples of older lava are presented in table 6, and derivative petrologic parameters are given in Appendix 4. These chemical data indicate that the rocks are strongly alkalic basalt.

Historic flow.--As exposed to the north-northeast of Bayt al Haqr, the historic lava flow is as much as 10 m thick in valleys eroded in older lava of the Aden Volcanic Series (?) and 1-1.4 m thick on the crests of small hills in the older lava. The upper surface of the historic flow is aa-type lava, rough and scoriaceous, and surmounted by blocks as much as 2.6x3.3x4 m in size with massive to sparsely vesicular cores. Welded to the surfaces of these blocks are many small, angular fragments of scoriaceous lava. Two specimens of vesicular olivine basalt were taken from the front of the flow at a point where the flow is 2.8 m thick. Sample 75-OT-7 is from the top of the flow and sample 75-OT-8 is from the base immediately above older lava.

The mineralogical composition of the surface sample (75-OT-7), as determined by microscopic examination, is (in percent): plagioclase, 75; olivine, 15; and magnetite (?), 10; and of the basal sample (75-OT-8) is plagioclase, 75; olivine, 10; clinopyroxene, 10; an opaque mineral, 5; orthopyroxene, <1; and apatite, <1 (Overstreet and others, 1980, p. 8).

Major-element oxides in these samples are shown in table 6, and various petrologic parameters are in Appendix 4. These rocks also are strongly alkalic basalt.

Interpretation of the composition related to the probably ages and tectonic settings of the igneous rocks

Recent reports dealing with the Precambrian Shield in Saudi Arabia and discussing the major-element chemical evolution of the rocks (Schmidt and Brown, in press; Stacey and Hedge, in press), geochronology and origin of gneiss complexes (Stoeser, Fleck, and Stacey, in press), ages and strontium initial ratios of plutonic rocks (Fleck and others, 1980; Schmidt, Hadley, and Stoeser, 1979), oceanic and continental leads (Stacey and Stoeser, 1984), and mineral potential of felsic plutons (Stoeser and Elliott, 1979; du Bray and others, 1983; Stuckless and others, 1983; du Bray, 1983) give a broad framework against which to interpret the geologic significance of the major-element compositions reported here for Precambrian rocks of the YAR. Similarly informative new data on middle Tertiary continental rift in southwestern Saudi Arabia (Schmidt, Hadley, and Brown, 1982) affords background against which to interpret the results of the present analyses of the Tertiary and Quaternary hypabyssal and volcanic rocks of the YAR.

From the following comparisons it is clear that the division of the Precambrian plutonic intrusive rocks exposed in the southeastern part of the YAR in the vicinity of Rida' and Al Bayda (Grolier and others, 1977, figs. 1 and 2; Overstreet and others, 1980, p. 16-26, table 1; this report, tables 1-4) into older and younger units on presence or absence of gneissic texture is in error. Owing to the scarcity of analyzed specimens of the Precambrian plutonic rocks in the other parts of the YAR, the reality of the classification of the plutonic rocks in the other parts of the YAR (Grolier and Overstreet, 1978) cannot be determined.

The modal mineral compositions of the igneous rocks whose chemical compositions are presented above were given in an earlier report (Overstreet and others, 1980, p. 3-27), but they are summarized here for the phaneritic rocks in table 7. Normalized oxide values and normative mineral compositions are listed in Appendices 1-3 based on the results of the chemical analyses of all the rocks using USGS computer programs (Stuckless and Van Trump, 1979). The normalized oxide values were calculated water-free. They were not corrected for the effects of oxidation and the introduction of CO_2 (Irvine and Baragar, 1971).

Table 6. Major-element composition of Pleistocene and Holocene extrusive rocks of the Yemen Arab Republic--olivine basalt of the Aden Volcanic Series (?) (in percent)

[Analyses by S. R. Morgan and P. R. Klock, U.S. Geological Survey, 1979; laboratory numbers in parentheses under the field numbers.]

Oxide	Older lava			Historic flow	
	75-OT-2 (M-140464)	75-OT-1 (M-140463)	75-OT-9 (M-140467)	75-OT-8 (M-140466)	75-OT-7 (M-140465)
SiO_2	46.78	47.16	45.31	48.13	47.52
Al_2O_3	16.50	15.98	16.10	17.01	17.02
Fe_2O_3	4.81	3.08	2.95	3.89	3.32
FeO	6.31	7.54	7.86	7.25	7.68
MnO	0.183	0.181	0.188	0.181	0.180
MgO	7.59	8.27	7.35	6.75	6.79
CaO	9.05	9.80	10.01	8.11	8.20
Na_2O	2.72	3.32	3.04	3.91	3.96
K_2O	.80	.84	1.10	1.11	1.09
TiO_2	2.24	2.15	2.37	2.24	2.23
H_2O+	1.09	.12	1.18	.29	.18
H_2O-	1.43	.24	.85	.15	.11
P_2O_5	.47	.46	.75	.57	.56
CO_2	.19	.73	.88	.24	.35
ZrO_2	.031	.028	.032	.031	.031
Cr_2O_3	.043	.042	.019	.017	.018
NiO	.018	.017	.012	.011	.012
BaO	.034	.023	.057	.033	.031
SrO	.071	.072	.110	.084	.084
Total	100.36	100.05	100.17	100.01	99.37

Table 7. Modal mineral composition of phaneritic igneous rocks from the Yemen Arab Republic (in percent)

[After Overstreet and others, 1980, p. 10-27; dash=not reported.]

Modal minerals	Rock names and sample numbers from tables 3-5 of this report; numbers used on figure 2														
	Older Precambrian igneous rocks (table 3)						Younger Precambrian igneous rocks (table 4)						Tertiary igneous rocks (table 5)		
	Diabase	Grano-diorite gneiss	Granite gneiss				Grano-diorite	Granite gneiss	Biotite granite	Alkali feldspar granite		Riebeckite granite	Alkali granite		
	MJG-76-41A	MJG-76-54A	MJG-76-16	MJG-76-21	MJG-76-25	MJG-76-28A	MJG-76-56A	MJG-76-15	MJG-76-26B	MJG-76-39A	MJG-76-39B	MJG-76-50	75-OT-27	75-OT-28	MJG-76-72A
	1	2	3	4	5	6	7	8	9	10	11	12	17	18	19
Quartz	--	15	30	35	35	35	5	25	10	40	40	35-40	20	25	25-30
Potassium feldspar	--	--	--	--	--	--	--	--	--	--	55-60	--	--	--	--
Perthitic potassium feldspar	--	20	--	--	--	--	--	--	--	--	--	60	--	--	--
Microcline	--	--	--	--	--	--	20	--	--	--	--	--	--	--	--
Microcline perthite	--	--	35	40	50	45	--	50	70	50	--	--	70	65	70
Antiperthite	--	--	--	--	--	--	45	--	--	--	--	--	--	--	--
Plagioclase	40	40	25	15	10	15	--	20	15	10	2	--	--	--	<1
Riebeckite	--	--	--	--	--	--	--	--	--	--	--	<5	5	10	2-3
Hornblende	--	8	--	5	--	--	10	--	--	--	--	--	--	--	--
Biotite	--	10	10	--	5	3	15	--	3	<1	--	<1	--	--	--
Clinopyroxene	35	--	--	--	--	--	--	--	--	--	--	--	2	--	--
Actinolite (after clinopyroxene)	5	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Talc after olivine (?)	10	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Magnetite	--	--	--	--	--	--	--	--	--	--	--	--	<1	--	--
Opagues, titanite	10	4	--	1-2	<1	1	5	--	--	--	--	--	<1	<1	<1
Apatite, zircon, epidote	--	<1	<1	--	--	--	--	--	2	--	--	--	--	--	--
Calcite	--	--	--	--	--	--	--	--	--	--	--	--	<1	--	--
Muscovite	--	--	--	--	--	--	--	2	--	--	--	--	--	--	--
TOTAL	100	98	~100	97	~100	99	100	97	100	~100	~100	~100	~99	~100	~100

Precambrian rocks.--Interpretation of the composition of the Precambrian igneous rocks from the southeastern part of the YAR is made on the basis of the results of modal analyses, major-element analyses, and minor-element analyses.

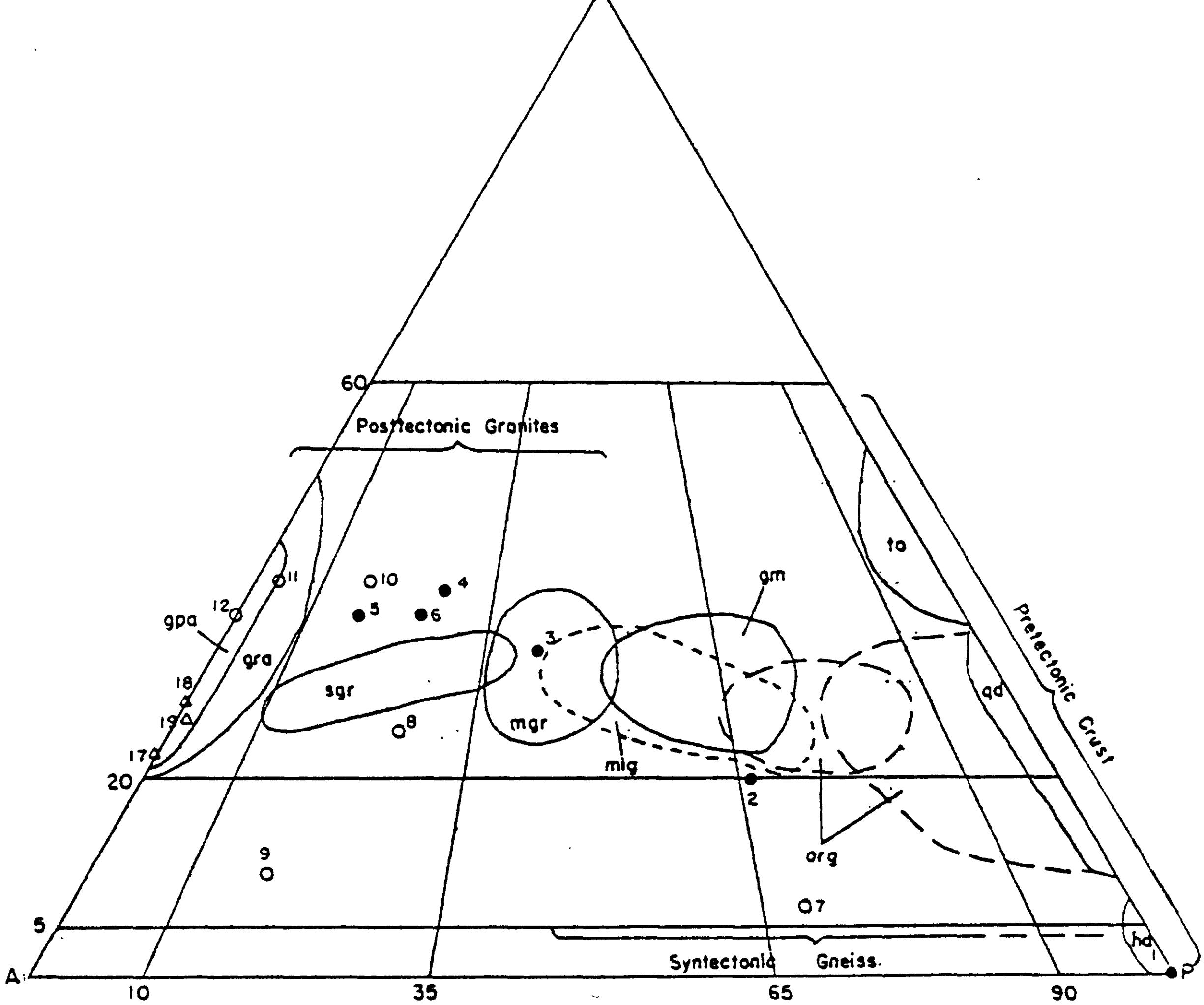
Modal data.--The modal mineral compositions of the Precambrian igneous rocks (table 7) are arranged below in percentages of the minerals and mineral groups recommended under the classification of plutonic rocks by the International Union of Geological Sciences (Streckeisen, 1976, p. 5) using letter symbols for the groups:

Sample numbers		Q 1/	A	P	F	M
Fig. 2	Field					
1	MJG-76-41A	-2/	--	40	--	60
2	MJG-76-54A	15	20	40	--	25
3	MJG-76-16	30	35	25	--	10
4	MJG-76-21	35	40	15	--	10
5	MJG-76-25	35	50	10	--	5
6	MJG-76-28A	35	45	15	--	5
7	MJG-76-56A	5	20	45	--	30
8	MJG-76-15	25	55	20	--	--
9	MJG-76-26B	10	70	15	--	5
10	MJG-76-39A	40	50	10	--	--
11	MJG-76-39B	40	58	2	--	--
12	MJG-76-50	35	61	--	--	4

1/ Minerals and mineral groups represented by the letters are Q=quartz; A=alkali feldspars (orthoclase, microcline, perthite, albite An00-05); P=plagioclase An05-100 (antiperthite was included here in this table, see below); F=feldspathoids; M=mafic and related minerals (micas, amphiboles, pyroxenes, olivines, opaque minerals, accessories (zircon, apatite, titanite, etc.), epidote, allanite, primary carbonates, etc.

2/ Dash=less than 1 percent or absent.

For the modal classification, the percentages of Q, A, and P were recalculated to 100 percent, and the values plotted on the QAP diagram in figure 2. Inasmuch as the dark-colored constituents of the rocks are used as a color index in the IUGS classification (M of table 7 minus the percentages of muscovite, apatite, and primary carbonate), the rock names from figure 2 are modified accordingly (Streckeisen, 1976, p. 22-24, fig. 5) to yield a nomenclature slightly different from that employed previously:



EXPLANATION
(Composition plotted at center of symbol)

Symbol	Sample numbers On figure	Sample numbers Field	Rock names from tables 3, 4, and 5
		Precambrian igneous rocks (tables 3 and 4)	
●	1	MJG-76-41A	Diabase
●	2	MJG-76-54A	Granodiorite gneiss
●	3	MJG-76-16	Granite gneiss
●	4	MJG-76-21	Granite gneiss
●	5	MJG-76-25	Granite gneiss
●	6	MJG-76-28A	Granite gneiss
O	7	MJG-76-56A	Granodiorite
O	8	MJG-76-15	Granite gneiss
O	9	MJG-76-26B	Biotite granite
O	10	MJG-76-39A	Alkali-feldspar granite
O	11	MJG-76-39B	Alkali-feldspar granite
O	12	MJG-76-50	Riebeckite granite
		Miocene (?) alkali granite (table 5)	
△	17	75-OT-27	From Jibal Sabir
△	18	75-OT-28	From Jibal Sabir
△	19	MJG-76-72A	From Jibal Hufash

Symbols used for fields occupied by Precambrian plutonic rocks in the Arabian Shield (modified from Schmidt, Hadley, and Stoeser, 1979, fig. 4)

hd = hornblende diorite
gd = quartz diorite
to = tonalite
org = orthogneiss
gm = granodiorite - monzogranite
mig = migmatite
mgr = monzogranite
sgr = syenogranite
gra = alkalic granite
gpa = peralkalic granite

Figure 2.-- QAP diagram of the phaneritic igneous rocks from the Yemen Arab Republic based on the modal mineral composition shown in table 7 plotted according to the modal mineral classification of the IUGS (Streckeisen, 1976, fig. 1a) and showing comparison with the modal compsitions of plutonic rocks in the Arabian Shield between about 800 Ma and 600 Ma ago, southern Najd, Kingdom of Saudi Arabia (Schmidt, Hadley, and Stoeser, 1979, fig. 4).

Sample numbers		Rock names	
Fig. 2	Field	Previously employed (Overstreet and others, 1980, p. 17-27)	IUGS terminology (Strickeisen, 1976, p. 12-15, fig. 5
1	MJG-76-41A	Diabase	Gabbro
2	MJG-76-54A	Granodiorite gneiss	Granodiorite
3	MJG-76-16	Granite gneiss	Monzogranite
4	MJG-76-21	Do.	Syenogranite
5	MJG-76-25	Do.	Do.
6	MJG-76-28A	Do.	Do.
7	MJG-76-56A	Granodiorite	Quartz monzodiorite
8	MJG-76-15	Granite gneiss	Leuco-syenogranite
9	MJG-76-26B	Biotite granite	Leuco-quartz syenite
10	MJG-76-39A	Alkali-feldspar granite	Leuco-syenogranite
11	MJG-76-39B	Do.	Alkali-feldspar granite
12	MJG-76-50	Riebeckite granite	Riebeckite-alkali-feldspar granite

Some interference in the use of modal analyses for naming the rocks is caused by absence of percentages of the anorthite molecule in descriptions of the plagioclase (Overstreet and others, 1980, p. 17-27), by the roles of epidote and muscovite (samples MJG-76-54A, - 16, 15, and 26B), and assignment of antiperthite to the field of A or P in figure 2 (samples MJG-76-54A, -25, -28A, and -56A). Because the descriptions tie the antiperthite to the plagioclass, it was placed with P. Nevertheless, the modal analyses show that the granitoid rocks in figure 2 tend to be rich in alkali feldspar, with the gneissic, so-called older Precambrian rocks dominantly grading from granodiorite to syenogranite, and the massive, so-called younger Precambrian rocks grading from syenogranite to riebeckite-alkali-feldspar granite in what appears to be a differentiation sequence that may lack major time breaks.

A comparison (fig. 2) of the modal analyses of the plutonic Precambrian rocks from the southeastern part of the YAR with the average modal compositions of plutonic rocks from the Precambrian Shield in the southern Najd Province, Kingdom of Saudi Arabia (Schmidt, Hadley, and Stoeser, 1979, fig. 4), shows that the Precambrian granitoid rocks from the YAR (exclusive of the granodiorite--2 and 7, fig. 2) are in the fields associated with the post-tectonic granites of the Arabian Shield. Both samples of granodiorite are in fields occupied by Precambrian syntectonic gneiss, and the granite gneiss of monzogranite composition (3, fig. 2) occupies a field where the syntectonic and posttectonic granitoid rocks of the Arabian Shield overlap in modal composition (Schmidt, Hadley, and Stoeser, 1979, fig. 4).

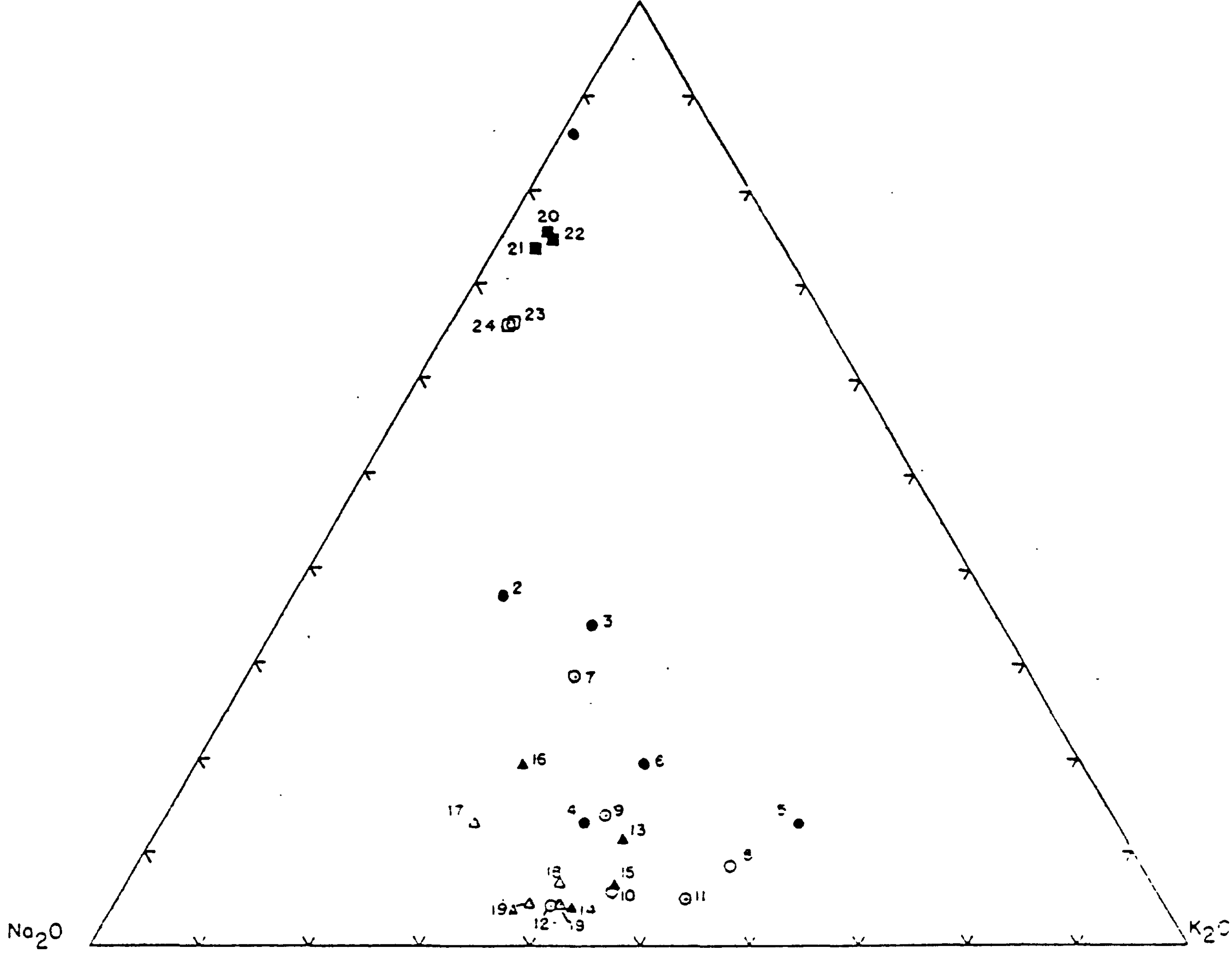
By comparison with the Precambrian rocks in the Arabian Shield, the Precambrian granitoid rocks in the southeastern part of the YAR, with the possible exception of the granodiorite, comprise a posttectonic suite of latest Precambrian age, certainly less than 660 Ma, and probably between 620 Ma and 560 Ma in age (Schmidt and Brown, in press). Thus, they are among the youngest of the Precambrian granitoid rocks in the YAR. They were so shown on the geologic map of the YAR (Grolier and Overstreet, 1978), where they are represented along the road leading southeastward from Rida' as peralkaline granite (gp, the youngest Precambrian granite: samples MJG-76-15,-39A,-39B,-50, and -56A) and calc-alkaline granite (gr, the next to youngest

Precambrian granite: sample MJG-76-21). However, the most strongly gneissic rocks (MJG-76-16, -25, -28A, and 54A) were placed with the oldest Precambrian granitoid rocks--the unit called gneissic granite (gg). Of these, even the granodiorite (samples MJG-76-54A and MJG-76-56A), as well as the diabase (MJG-76-41A), of figure 2 may be part of the sequence of younger Precambrian granitoid rocks. Chemical data afford a reliable means of comparing the plutonic igneous rocks of the YAR with those in the Kingdom of Saudi Arabia.

Major-element data.-The results of the chemical analyses for the major elements in the Precambrian plutonic rocks from the southeastern part of the YAR (tables 3 and 4; Appendices 1-2) show a trend toward alkalic and peralkalic compositions (figs. 3, 4, and 5). In the NCK ternary diagram (fig. 3), the overlap in composition between the so-called "older" Precambrian granitoid rocks (solid circles, samples 2-6) and the "younger" Precambrian granitoid rocks (open circles, samples 7-12) is evident, with the "older" syenogranite (fig. 2, sample 5) containing the most K_2O. As the content of silica increases from about 71 percent to 75 percent the amount of alkalis rises (fig. 4), but with a further rise in the content of silica, the amount of the alkalis declines slightly. This relation was also shown by the results of the modal analyses (fig. 2). Decrease in total iron as FeO is accompanied by very strong increases in alkalis (fig. 5) so that the so-called "older" Precambrian granitoid rocks (fig. 5 filled circles, sample numbers 2-6) are nearly separated from, but grade into, the so-called "younger" Precambrian granitoid rocks (fig. 5, open circles, sample numbers 7-12). Thus, the dominantly gneissic Precambrian rocks are richer in total iron than the massive granitoid rocks. This characteristic was also brought out by the modal color index developed from table 7 and figure 2 as well as the normative color indices:

Sample numbers: Figs. 3-5	Sample numbers: Field	Normative color index	Sample numbers: Figs. 3-5	Sample numbers: Field	Normative color index
1	MJG-76-41A	47	7	MJG-76-56A	12
2	MJG-76-54A	11	8	MJG-76-15	1
3	MJG-76-16	6	9	MJG-76-26B	3
4	MJG-76-21	3	10	MJG-76-39A	2
5	MJG-76-25	3	11	MJG-76-39B	0.6
6	MJG-76-28A	5	12	MJG-76-50	1

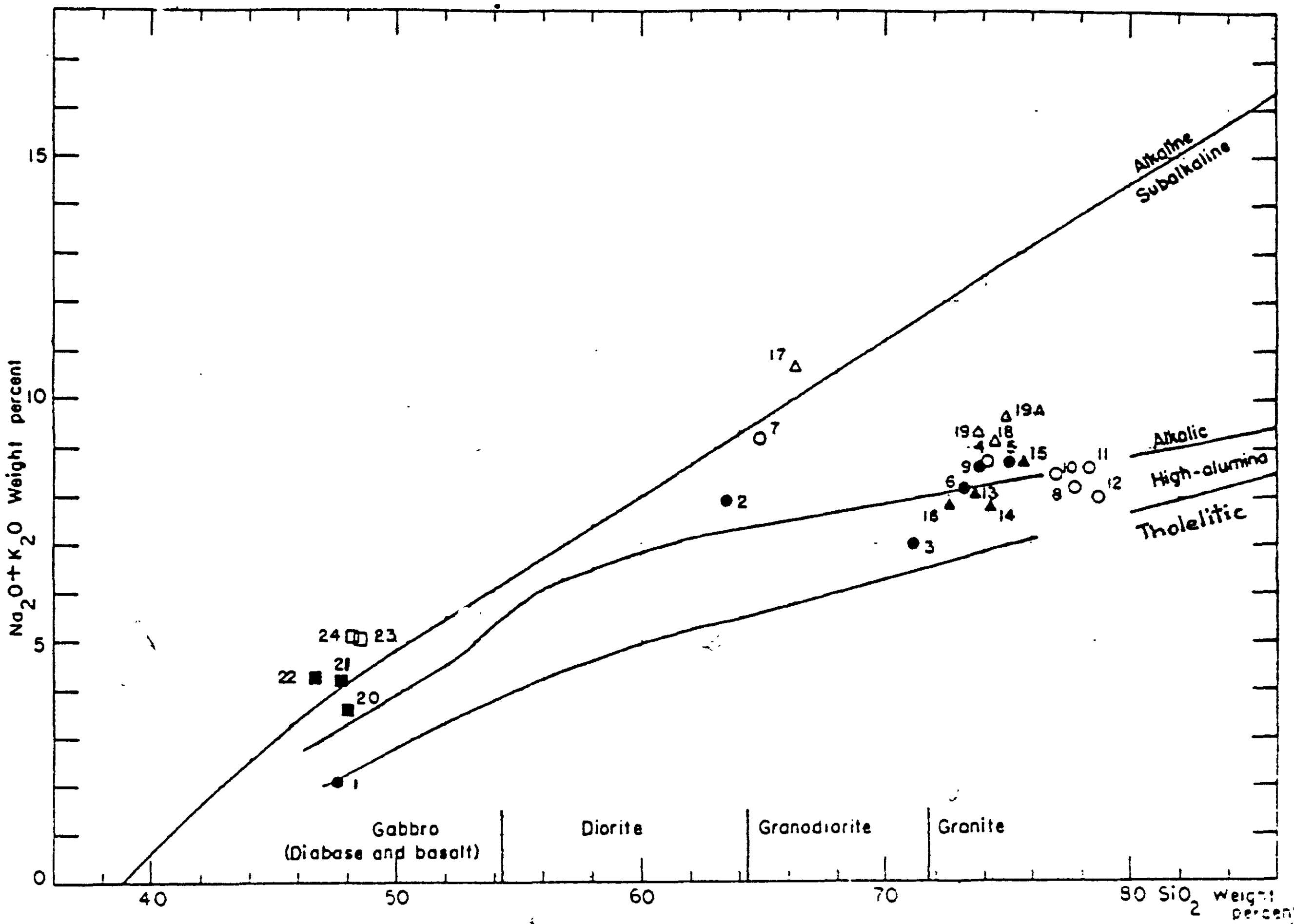
When the major-element compositions of the Precambrian granitoid rocks from the southeastern part of the YAR, shown in figures 3-6, are compared with the compositions of plutonic rocks from the Shield in the Kingdom of Saudi Arabia (Schmidt and Brown, in press, figs. 4, 8, and 11B), a strong similarity is apparent with the posttectonic rocks of Shammar age where alkali-feldspar granite is common (Schmidt and Brown, in press, fig. 8). In the AFM diagrams (fig. 5 of this report and fig. 8 of Schmidt and Brown, in press) the two samples of granodiorite from the YAR (fig. 5, samples 2 and 7) are similar to granodioritic batholiths of culminant-orogeny age, and the granitic rocks of figure 5 grade by increase in alkalis and decrease in total iron and MgO into the granite and alkali-feldspar granite of Shammar age. Thus, the possible range in age of these granitoid rocks may be from 660 Ma age to 560 Ma ago, most probably between 630 Ma ago and 560 Ma ago with the silica-rich rocks being toward the younger end (Schmidt and Brown, in press).



EXPLANATION
(Composition plotted at center of symbol)

Symbol	On figure	Field	Rock names from tables 3, 4, 5, and 6
		Precambrian igneous rocks (tables 3 and 4)	
●	1	MJG-76-41A	Diabase
●	2	MJG-76-54A	Granodiorite gneiss
●	3	MJG-76-16	Granite gneiss
●	4	MJG-76-21	Granite gneiss
●	5	MJG-76-25	Granite gneiss
●	6	MJG-76-28A	Granite gneiss
○	7	MJG-76-56A	Granodiorite
○	8	MJG-76-15	Granite gneiss
○	9	MJG-76-26B	Biotite granite
○	10	MJG-76-39A	Alkali-feldspar granite
○	11	MJG-76-39B	Alkali-feldspar granite
○	12	MJG-76-50	Riebeckite granite
		Precambrian igneous rocks (tables 3 and 4)	
▲	13	MJG-76-1A	Welded tuff
▲	14	MJG-76-1B	Welded tuff
▲	15	MJG-76-6	Vesicular welded tuff
▲	16	75-OT-26	Crystal lithic tuff
△	17	75-OT-27	Alkali granite
△	18	75-OT-28	Alkali granite
△	19	MJG-76-72A	Alkali granite
△	19A	ROJ-1	Alkali granite
		Pleistocene and Holocene extrusive rocks (olivine basalt of table 6)	
■	20	75-OT-2	Older lava
■	21	75-OT-1	Older lava
■	22	75-OT-9	Older lava underlying historical flo
□	23	75-OT-8	Historical flow-bottom
□	24	75-OT-7	Historical flow-top

Figure 3. -- Ternary diagram (NCK) showing the distribution of Na_2O-CaO-K_2O (molar data) in plutonic and volcanic rocks of various ages from the Yemen Arab Republic.



EXPLANATION
(Composition plotted at center of symbol)

Symbol	Sample numbers On figure	Sample numbers Field	Rock names from tables 3, 4, 5, and 6
		Precambrian igneous rocks (tables 3 and 4)	
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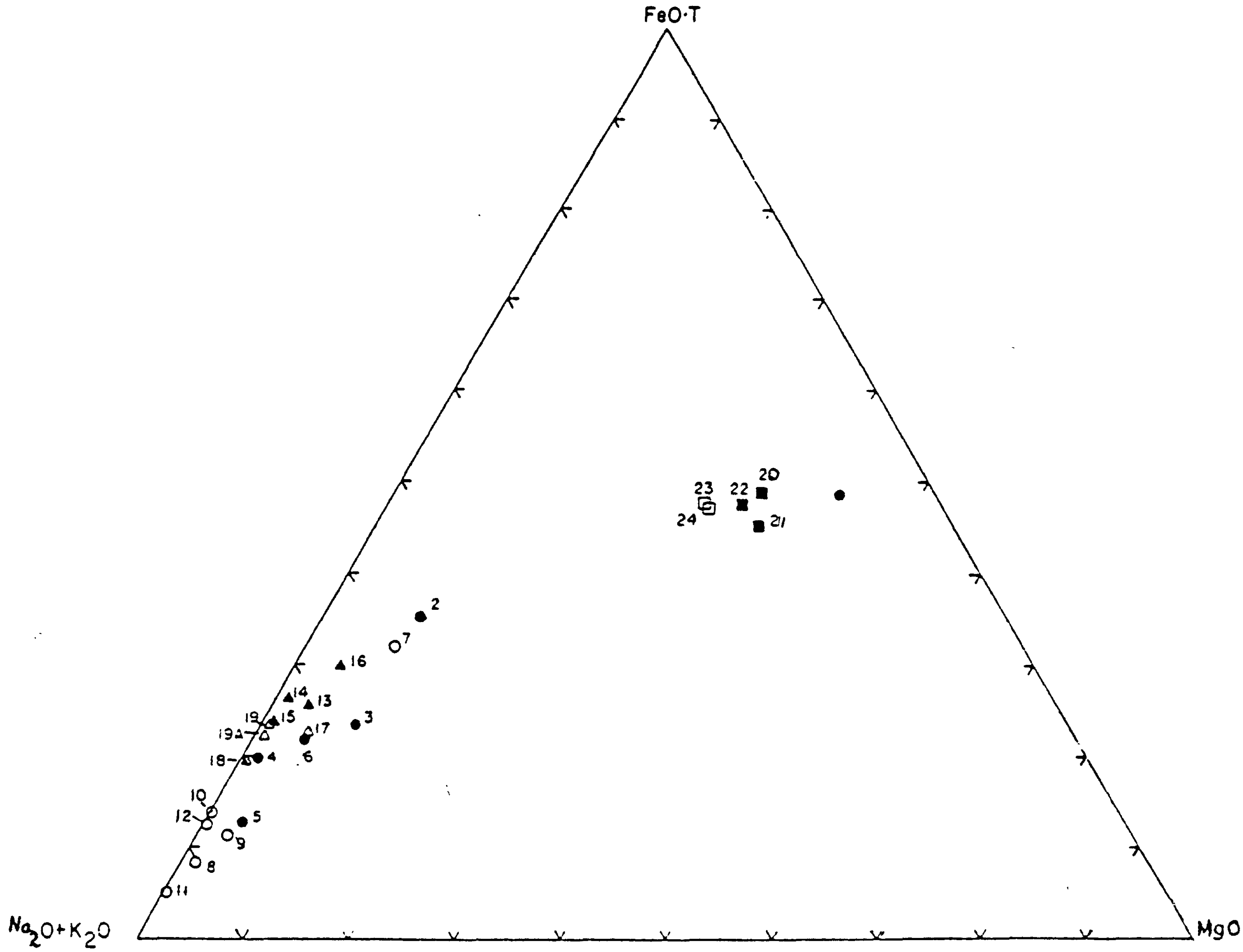
●	2	MJG-76-54A	Granodiorite gneiss
●	3	MJG-76-16	Granite gneiss
●	4	MJG-76-21	Granite gneiss
●	5	MJG-76-25	Granite gneiss
●	6	MJG-75-28A	Granite gneiss
○	7	MJG-76-56A	Granodiorite
○	8	MJG-76-15	Granite gneiss
○	9	MJG-76-26B	Biotite granite
○	10	MJG-76-39A	Alkali-feldspar granite
○	11	MJG-76-39B	Alkali-feldspar granite
○	12	MJG-75-50	Riebeckite granite

Symbol	Sample numbers On figure	Sample numbers Field	Rock names from tables 3, 4, 5, and 6
		Tertiary igneous rocks (table 5)	
▲	13	MJG-75-1A	Welded tuff
▲	14	MJG-75-1B	Welded tuff
▲	15	MJG-76-6	Vesicular welded tuff
▲	16	75-OT-26	Crystal lithic tuff
△	17	75-OT-27	Alkali granite
△	18	75-OT-28	Alkali granite
△	19	MJG-76-72A	Alkali granite
△	19A	ROJ-1	Alkali granite
		Pleistocene and Holocene extrusive rocks (olivine basalt of table 6)	
■	20	75-OT-2	Older lava
■	21	75-OT-1	Older lava
■	22	75-OT-9	Older lava underlying historical flo
□	23	75-OT-8	Historical flow-bottom
□	24	75-OT-7	Historical flow-top

Figure 4. Binary diagram showing the distribution of alkali (Na_2O+K_2O) and silica (SiO_2) contents in plutonic and volcanic rocks of various ages from the Yemen Arab Republic: alkaline-subalkaline division (single line) from Irvine and Baragar (1971) and threefold division of basalt (pair of lines) from Kuno (1966) are shown for reference for the volcanic rocks.



EXPLANATION
(Composition plotted at center of symbol)

Symbol	Sample numbers: On figure	Sample numbers: Field	Rock names from tables 3, 4, 5, and 6
		Precambrian igneous rocks (tables 3 and 4)	
●	1	MJG-76-41A	Diabase
●	2	MJG-76-54A	Granodiorite gneiss
●	3	MJG-76-16	Granite gneiss
●	4	MJG-76-21	Granite gneiss
●	5	MJG-76-25	Granite gneiss
●	6	MJG-75-28A	Granite gneiss
○	7	MJG-76-56A	Granodiorite
○	8	MJG-76-15	Granite gneiss
○	9	MJG-76-26B	Biotite granite
○	10	MJG-76-39A	Alkali-feldspar granite
○	11	MJG-76-39B	Alkali-feldspar granite
○	12	MJG-76-50	Riebeckite granite

Symbol	Sample numbers: On figure	Sample numbers: Field	Rock names from tables 3, 4, 5, and 6
		Tertiary igneous rocks (table 5)	
▲	13	MJG-76-1A	Welded tuff
▲	14	MJG-76-1B	Welded tuff
▲	15	MJG-76-6	Vesicular welded tuff
▲	16	75-OT-26	Crystal lithic tuff
△	17	75-OT-27	Alkali granite
△	18	75-OT-28	Alkali granite
△	19	MJG-75-72A	Alkali granite
△	19A	ROJ-1	Alkali granite
		Pleistocene and Holocene extrusive rocks (olivine basalt of table 6)	
■	20	75-OT-2	Older lava
■	21	75-OT-1	Older lava
■	22	75-OT-9	Older lava underlying historical flow
□	23	75-OT-8	Historical flow-bottom
□	24	75-OT-7	Historical flow-top

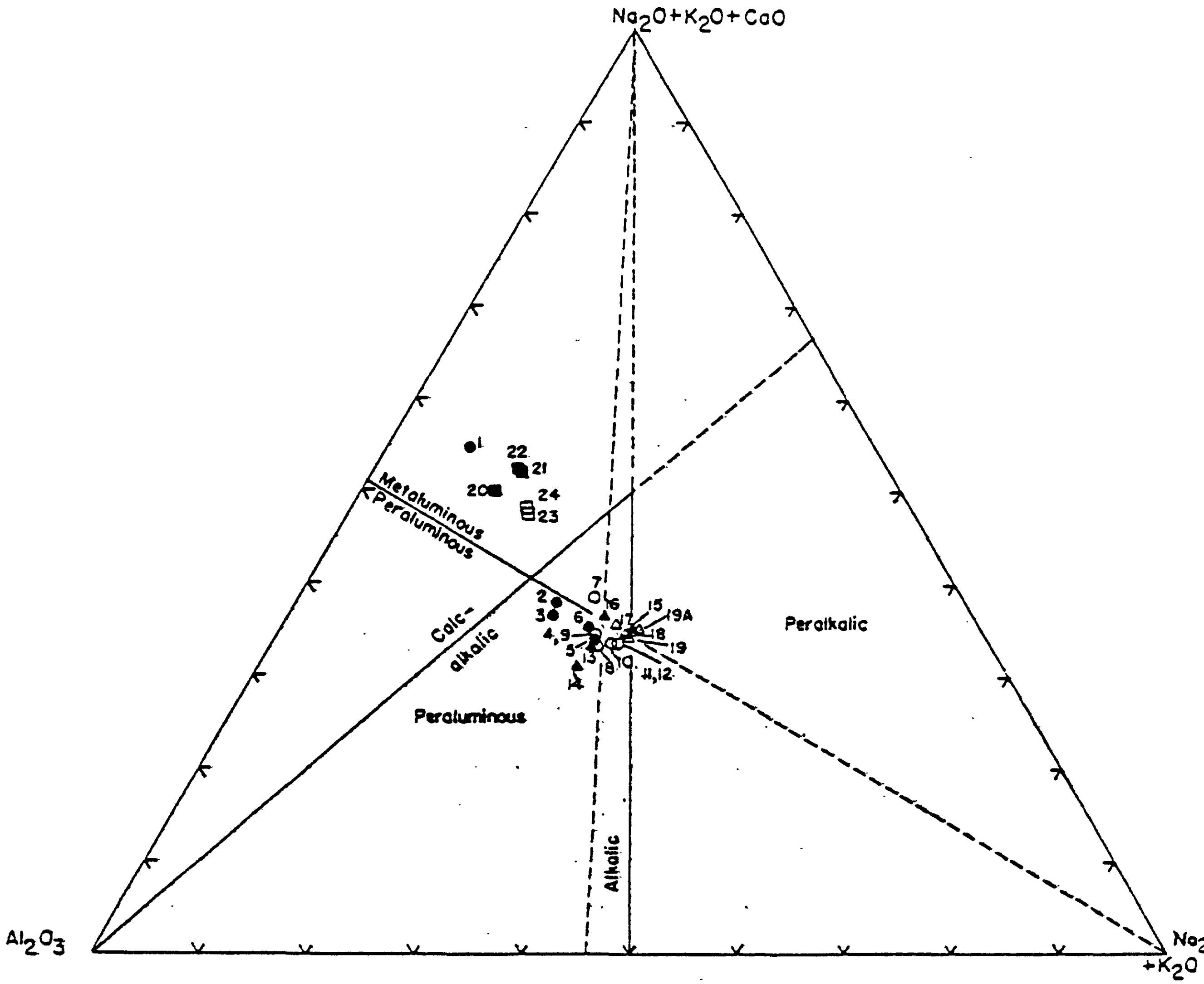
Figure 5.-- Ternary diagram (AFM) showing the distribution of (Na_2O+K_2O)-FeO.T-MgO (weight percent data) in plutonic and volcanic rocks of various ages from the Yemen Arab Republic; FeO.T is total iron as FeO.

The presence of riebeckite (table 7, sample MJG-76-50) generally indicates a peralkaline granite, and the presence of more the 1 percent of normative corundum (Appendices 1 and 2, samples MJG-76-16 and -15) generally indicates a peraluminous granite. However, the ratio of the molar percentages (Appendix 2) for Na_2O+K_2O/Al_2O_3 is 0.93 for sample MJG-76-50, which is well below that of ratios >1 that are typical of peralkaline granites (Shand, 1951). The ratio of the molar percentages (Appendices 1 and 2) for Al_2O_3/Na_2O+K_2O+CaO is 1.06 for sample MJG-76-16 and 1.10 for MJG-76-15 where ratios >1 are peraluminous, which confirms the indication from the normative corumdum. Except for the two samples of granodiorite (MJG-76-54A and -56A) all the Precambrian granitoid rocks have the ratios of peraluminous rocks as can be seen in figure 6:

Sample numbers On Fig. 6	Sample numbers Field	Rock names from tables 3 and 4	Ratios of molar percentages (Appendices 1 and 2) $\frac{Na_2O+K_2O}{Al_2O_3}$	$\frac{Al_2O_3}{Na_2O+K_2O+CaO}$
2	MJG-76-54A	Granodiorite gneiss	0.64	0.99
3	MJG-76-16	Granite gneiss	0.62	1.06
4	MJG-76-21	Granite gneiss	0.83	1.05
5	MJG-76-25	Granite gneiss	0.82	1.06
6	MJG-76-28A	Granite gneiss	0.78	1.03
7	MJG-76-56A	Granodiorite	0.80	0.89
8	MJG-76-15	Granite gneiss	0.83	1.10
9	MJG-76-26B	Biotite granite	0.81	1.06
10	MJG-76-39A	Alkali-feldspar granite	0.90	1.05
11	MJG-76-39B	Alkali-feldspar granite	0.92	1.04
12	MJG-76-50	Riebeckite granite	0.93	1.03

None have modal riebeckite except MJG-76-50 (table 7); none have normative acmite. Normative corundum is absent from the granodiorite gneiss (Appendix 1, sample MJG-76-54A), is present as <1 percent in the other samples except MJG-76-16 and -15 which contain >1 percent (Appendices 1 and 2). These data as well as the ternary diagram (fig.6) show that none of the Precambrian granitoid rocks described here from the YAR is peralkaline, but that all the probable posttectonic granites are peraluminous. These relations may indicate that for the posttectonic granites as a group in the YAR, fewer of the plutons are of peralkaline composition than would appear from the distribution of the unit called peralkaline granite (gp) on the geologic map (Grolier and Overstreet, 1978).

The ratios $(Na_2O+K_2O)/Al_2O_3$ and $Al_2O_3/(Na_2O+K_2O+CaO)$ in the posttectonic granites from the YAR described here are slightly higher than those reported for posttectonic granites from the northern part of the Arabian Shield (Stuckless, Knight, and others, 1983, table 1), where the values given for "Al/(Na+K)" are reciprocals of those given here for $(Na_2O+K_2O)/Al_2O_3$). In these respects, these posttectonic granites from the YAR do not conform fully in chemical composition with the granitoid rocks of Shammar age, which include some peralkaline granite (Schmidt and Brown, in press, fig. 8), but the YAR sample is small.



EXPLANATION
(Composition plotted at center of symbol)

Symbol	Sample numbers On figure	Sample numbers Field	Rock names from tables 3, 4, 5, and 6
		Precambrian igneous rocks (tables 3 and 4)	
●	1	MJG-76-41A	Diabase
●	2	MJG-76-54A	Granodiorite gneiss
●	3	MJG-76-16	Granite gneiss
●	4	MJG-76-21	Granite gneiss
●	5	MJG-76-25	Granite gneiss
●	6	MJG-75-23A	Granite gneiss
○	7	MJG-76-56A	Granodiorite
○	8	MJG-76-15	Granite gneiss
○	9	MJG-76-26B	Biotite granite
○	10	MJG-76-39A	Alkali-feldspar granite
○	11	MJG-76-39B	Alkali-feldspar granite
○	12	MJG-76-50	Riebeckite granite
		Tertiary igneous rocks (table 5)	
▲	13	MJG-76-1A	Welded tuff
▲	14	MJG-76-1B	Welded tuff
▲	15	MJG-75-6	Vesicular welded tuff
▲	16	75-OT-26	Crystal lithic tuff
△	17	75-OT-27	Alkali granite
△	18	75-OT-28	Alkali granite
△	19	MJG-76-72A	Alkali granite
△	19A	ROJ-1	Alkali granite
		Pleistocene and Holocene extrusive rocks (olivine basalt of table 6)	
■	20	75-OT-2	Older lava
■	21	75-OT-1	Older lava
■	22	75-OT-9	Older lava underlying historical
□	23	75-OT-8	Historical flow-bottom
□	24	75-OT-7	Historical flow-top

Figure 6. --Ternary diagram showing distribution in molar percent of Al_2O_3-(Na_2O+K_2O+CaO)-(Na_2O+K_2O) in plutonic and volcanic rocks of various ages from the Yemen Arab Republic.

The field description of the sample of granodiorite that occupies an anomalous position on the basis of modal composition (fig. 2, sample MJG-76-56A) identified the sample as representative of the central part of a pluton about 3.5 km across. The pluton was characterized by thick, strongly gneissic border zones. Although the modal data diverge from that of the other granitoid rocks from the southeastern part of the YAR, and the possibility arises that this granodiorite might be a much older primary crustal rock, the chemical data (figs. 3-5) appear to fit the distribution of the chemical components defined by the other granitoid rocks. It is, therefore, interpreted here to be a syntectonic intrusive associated with the culminate orogeny identified in the Precambrian rocks of Saudi Arabia (Schmidt and Brown, in press, fig. 8).

The single sample of Precambrian diabase (MJG-76-41A) was described in the field as fine-grained gabbro or coarse-grained diabase (Grolier and others, 1977, p. 18) constituting part of a sequence of layered mafic rocks ranging in composition from gabbro to diorite. Its modal composition is far removed from the syntectonic and posttectonic granitoid rocks (fig. 2). Nevertheless, the chemical data for this rock, shown on figures 3-5, fall in or near the fields shown by Schmidt and Brown (in press, figs. 4C, 8, and 11B) for layered gabbro of Shammar age in Saudi Arabia.

From this comparison of the major-element chemical data for the Precambrian granitoid rocks of the southeastern part of the YAR with the chemical data for plutonic rocks from the Precambrian Shield in Saudi Arabia as described by Schmidt and Brown in press, Stuckless, Knight, and others (1983), and Stuckless, Van Trump, and others (1983), the differences between the gneissic and the massive granitoid rocks are interpreted to reflect syntectonic and posttectonic emplacement with reference to the end of the Precambrian orogeny and final cratonization of the Shield. As the crust thickened with cratonization, the amounts of K_2O and SiO_2 of the magma increased, and the granite formed therefrom became increasingly more alkaline. No samples of primary crust are represented among the analyzed rocks from the southeastern part of the YAR.

Strict classification of the Precambrian plutonic rocks of the YAR will require definition of the stratigraphic succession of the metavolcanic and metasedimentary rocks, major-element geochemistry and geochronology of the metavolcanic and plutonic rocks, and an interpretation of the tectonic setting of the area. A long-term program of field and laboratory investigations will be needed to accomplish this.

Minor-element data.--The previously published minor-element data on the Precambrian granitoid rocks from the southeastern part of the YAR (Grolier and others, 1977, table 3) conforms generally with minor-element data on posttectonic granitoid rocks from the southeastern and eastern Shield in Saudi Arabia (du Bray, 1983, table 2; Stuckless, Van Trump, and others, 1983, table 4) and the northeastern Shield (Stuckless, Knight, and others, 1983, table 1-4). Relatively few minor elements determined by Stuckless and associates (1983) are duplicated in the data from the YAR, but 16 of the 28 minor elements discussed by du Bray (1983) are also ones sought in the spectrographic analyses of the granitoid rocks from the YAR (table 8). Many similarities exist either as identical values or as values within two laboratory reporting intervals in the spectrographic procedure used for the rocks from the YAR (Grolier and others, 1977, p. 32). Similar elements are Ti, Mn, Ba, Bi, La, Mo, Pb, Th, W, Zn, and Zr. Slightly greater dispersion

Table 8. Comparison of mean values for minor elements in nine samples of Precambrian posttectonic granites from the Yemen Arab Republic with mean values reported for Precambrian posttectonic granites from the southeastern, eastern, and northeastern parts of the Precambrian Shield in the Kingdom of Saudi Arabia (in ppm)

[dash = no data.]

Element	YAR (Grolier and others, 1977, table 3)	Arabian Shield: Southeastern and eastern (du Bray, 1983, table 1 and 2) 1/	Arabian Shield: Southeastern (Stuckless, Van Trump, and others, 1983, table 4)	Arabian Shield: Northeastern (Stuckless, Knight, and others, 1983, table 3)	Threshold values for eastern and southeastern Shield (du Bray and others, 1983)
Ti	1,500	100-1,700	900	--	--
Mn	500	200-800	300	--	--
Ba	700	<8-1,170	--	--	1,000
Be	2	<1-8	--	--	10
Bi	N(10)	N (10)	--	--	10
Co	L(5)	--	--	0.382	20
Cu	L(5)	<5-34	60.4	--	100
La	50	<13-42	--	54.3	70
Mo	N(5)	N(5)-5	--	--	15
Nb	N(20)	<1-100	--	--	100
Pb	30	<11-82	--	--	70
Sb	N(100)	--	--	0.218	100
Sc	L(5)	--	--	0.87	15
Sn	N(10)	<7-40	--	--	15
Sr	100	7-446	18.9	29.2	700
Th	N(20)	--	17.13	--	--
W	N(50)	N(20)-50	--	--	50
Y	30	4-181	39.9	--	150
Zn	N(200)	N(200)-L(200)	97.0	--	200
Zr	150	22-152	101.0	370	500

1/ Ranges in mean values for 17 different posttectonic plutons.

of the means is seen in table 8 for Be, Sn, and Y. Possibly similar values are represented for Co and Sc in the rocks from the YAR and those from the northeastern Shield, but a comparison of the data for Sb cannot be made owing to the high technically truncated value reported for the YAR. The greatest differences are for Cu and Sr in table 8. When only the posttectonic granites of the southeastern part of the Arabian Shield that were studied by du Bray (1983, table 1) are considered, the content of Cu is 13 ppm or less, which is quite close to the values from the YAR but is considerably less than the 60.4 ppm Cu reported for the southeastern Shield by Stuckless, Van Trump, and others (1983, table 3). Values for Sr in the southeastern Shield only are unchanged by discarding those given by du Bray (1983, table 1) for the eastern Shield; thus the great spread in means for Sr shown in table 8 is real. Individual values for Sr in the posttectonic granites from the southeastern part of the YAR (Grolier and others, 1977, table 3) include several that are similar to the low values shown for the Arabian Shield, but none is as high as the highest mean reported by du Bray (1983, table 1) unless the granodiorite (MJG-76-54A) is included. The general similarity in the abundances of the minor elements listed in table 8 is so great that the data pose no conflict in the assignment of the granites from the southeastern part of the YAR to a posttectonic Precambrian setting.

The granitoid plutons from the southeastern part of the Arabian Shield described by du Bray (1983, fig. 2L-2P) are far richer in modal plagioclase than the posttectonic granitic rocks from the YAR (fig. 2). Indeed, the close similarity between the posttectonic Precambrian granitic plutons in Arabia and in the southeastern YAR are found among the plutons of the eastern Shield, particularly the Huwail granite and the Huqban granite (du Bray, 1983, figs. 2D and 2H). The granitoid plutons in the southeastern part of the Arabian Shield are thought by du Bray (1983, p. 5) to have been emplaced earlier than those of the eastern Shield, with possible differences in age as great as from 670 Ma ago for the southern Shield and 590 Ma ago for the eastern Shield. The samples of granitoid rocks from the southeastern part of the YAR have a greater modal and geochemical similarity to the plutons in the eastern part of the Arabian Shield than to those in the southern part of the Shield. Possibly southward from the southeastern part of the Arabian Shield into the YAR, there is also a decrease in age of emplacement of the Precambrian granitoid rocks.

The threshold values shown in table 8 represent minimum concentrations of these elements found by du Bray (1983, p. 9, Table 5) to be present in Precambrian granitic plutons in Arabia having other geochemical, mineralogical, and textural characteristics associated with the possible presence of deposits of Sn, Mo or W, and other rare metals in the pluton or associated veins and wall rocks. Among the samples of granodiorite and granite from the southeastern part of the YAR for which both major and minor elements were determined, only the granodiorite (MJG-76-56A) from the small pluton at 14°04'01" N.; 45°29'46" E. contains threshold abundances for more than two or three of these minor elements (Grolier and others, 1977, table 3):

Element	Abundance in granodiorite sample MJG-76-56A (in ppm)
B	30
Be	5*
Co	20
La	200
Nb	30*
Pb	70
Sc	20
Sn	30
V	150
Y	100*
Zr	500

*Positive anomalous value for these granitoid rocks from the southeastern part of the YAR, but not a threshold value on the scale proposed by du Bray (1983, table 5).

Several of the mineralogical and chemical characteristics of this sample of granodiorite fail to fit the optimum conditions cited by du Bray (1983, p. 4 and 8) as indicative of potential mineralization. The rock lacks muscovite, contains antiperthite, and is neither peralkaline nor peraluminous. Nevertheless, it is an appropriate pluton for further petrographic and chemical study for the possible presence of Sn, Mo, W, or other rare metals.

The Sn-bearing granitic pluton exposed about 3 km to the east of Sa'dah in the northern part of the YAR was described by Schulze and Thiele (1978, p. 42-44, fig. 4) as young Precambrian alkali granite. Part of the pluton was shown on the geologic map of the YAR as Precambrian calc-alkaline granite of unit gr (Grolier and Overstreet, 1978). The presence of cassiterite and the subcircular plan of the pluton are here interpreted to indicate that the body is composed of posttectonic alkali or peralkaline granite similar to Sn-bearing granites identified in the eastern and southern Shield in Saudi Arabia (du Bray, 1983), and that the pluton belongs to the unit called gp on the geologic map (Grolier and Overstreet, 1978).

Miocene (?) alkali granite.--The results of modal analyses, age determinations, and major-element analyses show that the rock called Miocene (?) alkali granite in tables 5 and 7 after the description in Overstreet and others (1980, p. 10-12) is Early Miocene alkali-feldspar granite.

Modal data and K-Ar age.--The modal analyses given in table 7 yield the following percentages of minerals and mineral groups used in the IUGS classification (Streckeisen, 1976, p. 5-6) of plutonic igneous rocks (in percent):

Sample numbers		Q	A	P	F	M
Fig. 2	Field					
17	75-OT-26	20	70	--	--	10
18	75-OT-27	25	65	--	--	10
19	MJG-76-72A	25	70	1	--	4

Dash=less than 1 percent or absent.

Recalculated to QAP=100 percent and plotted on the ternary diagram (fig. 2), the modal composition of the Miocene (?) alkali granite fits the IUGS classification of alkali-feldspar granite (Streckeisen, 1976, fig. 1a). All three are fully within the field of peralkaline granites (fig. 2) adopted by Schmidt, Hadley, and Stoeser (1979, fig. 4) for granitoid rocks of Precambrian age. The color index derived from the values of M shown above is between 4 and 10; thus, the rock name is not modified by the dark minerals (Streckeisen, 1976, fig. 5).

The age of Miocene (?) was assigned originally (Grolier and others, 1977, fig. 2; Grolier and Overstreet, 1978) on the basis of a single K-Ar determination made on hornblende from the alkali granite at Jibal Sabir near Ta'izz, YAR, by R. F. Marvin and others, USGS, in 1974. That K-Ar analysis yielded an age of 22.0$\pm$0.7 Ma ago. Subsequently, two additional K-Ar ages have been published for the granite near Ta'izz: 21.0$\pm$0.6 and 20.9$\pm$0.6 Ma ago (Civetta and others, 1978, table 1). From these data the probable age of the alkali-feldspar granite at Jibal Sabir and at Jibal Hufash is here interpreted to be early Miocene (Van Eysinga, 1975) instead of Miocene (?) as shown on the geologic map (Grolier and Overstreet, 1978).

Major-element data.--Plots of the major elements (figs. 3-6) of the alkali-feldspar granite from Jibal Sabir and Jibal Hufash show that the rock is highly alkalic, which is confirmed by the molar ratios from the data in Appendix 3 showing that the ratio $(Na_2O+K_2O)/Al_2O_3$ is >1:

Sample numbers		Source	$\frac{(Na_2O+K_2O)}{Al_2O_3}$	$\frac{Al_2O_3}{(Na_2O+K_2O+CaO)}$
On figs. 3-6	Field			
17	75-OT-27	Jibal Sabir	0.92	0.95
18	75-OT-28	Jibal Sabir	0.97	0.96
19	MJG-76-72A	Jibal Hufash	0.99	0.96
19A	ROJ-1	Jibal Sabir	1.05	0.91

The presence of modal riebeckite in the three samples for which petrographic analyses are available (table 7, samples 75-OT-27 and -28, sample MJG-76-72A) and of normative acmite in sample ROJ-1 (Appendix 3) emphasizes the peralkaline tendency. Absence of normative corundum (Appendix 3) confirms that the early Miocene alkali-feldspar granite is not peraluminous despite the extremely close approach of the molar ratio $Al_2O_3/(Na_2O+K_2O+CaO)$ to values >1.

In a discussion of continental rift and the evaluation of the Red Sea in the southwestern part of Saudi Arabia, Schmidt, Hadley, and Brown (1982) evaluate the mineral and chemical composition and the K-Ar ages of the alkali-feldspar granites from Jibal Sabir and Jibal Hufash, YAR, using the chemical data given here in table 5 and in Appendix 3. They conclude that the granite in these plutons, and associated rhyolite (see below), were "...the ultimate magmatic products of continental rifting, and their production must indicate optimum high-temperature, low-pressure, and perhaps source-depletion conditions in the crust beneath the rift." They show that K_2O increases as the age of the rocks decreases, and that the high values for K_2O imply intrusion through thick continental crust at the approaching end of the continental-rift stage in the development of the Red Sea.

The early Miocene riebeckite-bearing alkali-feldspar granites (figs. 2 and 4, samples 17-19) are distinctly less silicic than the Precambrian riebeckite alkali-feldspar granite (fig. 2, sample 12), but in the NCK diagram (fig. 3), the relations of Na_2O, CaO, and K_2O are quite similar. In the AFM diagram (fig. 5) the Miocene granites are well separated from the Precambrian riebeckite-alkali-feldspar granite. Clear chemical differences are also evident in the previously published data on the minor elements in these rocks (Overstreet and others, 1976, table 2; Grolier and others, 1977, table 3).

Minor element	Abundance in ppm	
	Early Miocene riebeckite-alkali-feldspar-granite (mean of three 1/)	Precambrian riebeckite-alkali-feldspar-granite (MJG-76-50)
Ti	3,000	700
Mn	3,000	70
Ba	500	N(20)
Be	7	2
La	150	20
Mo	7	N(5)
Nb	70	N(20)
Zr	300	100

1/ Samples 75-OT-27, 75-OT-28, and MJG-76-72A. Variance among the other minor elements between the early Miocene and the Precambrian riebeckite--alkali-feldspar granites is very slight.

Minor-element data.--No chemical data are presently available to indicate if the early Miocene riebeckite-alkali-feldspar granites of the YAR are associated with metallic mineral deposits. A comparison of the mean values of the minor elements reported in five samples from the plutons at Jibal Sabir and Jibal Hufash (Overstreet and others, 1976, table 2; Grolier and others, 1977, table 3) with the threshold values for elements in Precambrian posttectonic granitic rocks having potential for mineralization (du Bray, 1983, table 5; this report, table 8) shows some similarity only for La, Nb, and Zn:

Element	Mean value (in ppm) in five samples of Miocene granite	Element	Mean value (in ppm) in five samples of Miocene granite
Ba	300	Sb	N(100)
Be	7	Sc	L(5)
Bi	N(10)	Sn	L(10)
Co	N(5)	Sr	L(100)
Cu	5	W	N(50)
La	150	Y	70
Mo	L(5)	Zn	200
Nb	100	Zr	300
Pb	50		

Individual samples exceeding both the mean and the threshold value reported by du Bray (1983, table 5) for Precambrian posttectonic granitic plutons in Saudi Arabia are (in ppm with sample number):

Jibal Sabir		Jibal Hufash	
Ba, 1,500;	75-OT-27	Be, 10;	MJG-76-72B
Be, 10;	75-OT-28	La, 200;	MJG-76-72A
La, 150;	75-OT-27	La, 100;	MJG-76-72B
La, 150;	75-OT-28	Nb, 150;	MJG-76-72A
La, 100;	ROJ-1	Nb, 100;	MJG-76-72B
Nb, 100;	ROJ-1	Sn, 15;	MJG-76-72A
Pb, 100;	ROJ-1	Sn, 15;	MJG-76-72B
Zr, 500;	75-OT-28	Zn, 300;	MJG-76-72A
		Zn, 500;	MJG-76-72B

No geochemical significance can be attached to this comparison between the abundances of individual elements in the Miocene granitic plutons in the YAR and the threshold values for the same elements in possibly mineralized Precambrian posttectonic granites in Saudi Arabia, because no connection has as yet been made in the YAR between the Miocene granitic plutons and metallic mineral deposits (El-Shatoury and Al-Eryani, 1977, p. 284-287; 1979, p. 122-125; Schulze and Thiele, 1978, p. 30-47). Nevertheless, geochemical investigations of the Miocene granitic plutons in the YAR along the lines followed for the Precambrian posttectonic granitic rocks in Saudi Arabia (du Bray, 1983) would be useful as a guide to possible mineral deposits associated with the Miocene plutons. Owing to the geologic youth of these rocks, they are not amenable to study by the methods of Stuckless, Van Trump, Christiansen, and associates (1983; oral communication, 1984) as sources for possible secondary uranium deposits in the younger sediments of the YAR. An evaluation of the uranium content of the Miocene granitic plutons and rhyolite tuffs of the YAR is, however, presented in a following section on minor elements in rocks, ores, and slags.

Yemen Volcanics.--Only the rhyolitic units from the Yemen Volcanics have been used for major-element analyses in the present work.

Relative ages and major-element data.--The relative ages of the four specimens from the Yemen Volcanics (table 5 and Appendix 3) are uncertain (Overstreet and others, 1976, table 1; Grolier and others, 1977, table 2). Using the stratigraphic divisions proposed for the Yemen Volcanics on the geologic map of the YAR (Grolier and Overstreet, 1978) samples MJG-76-1A and -1B are from the map unit TKy, an undivided sequence, and samples MJG-76-6 and 75-OT-26 are from relatively young parts of the Yemen Volcanics, respectively units TKy_3 and TKy_4. Samples MJG-76-1A and -1B are from a locality on the highway between San'a' and Al Hudaydah about 25 km to the east of Manakhah in a broad area shown as Yemen Volcanics undivided (TKy) grading into basal units TKy, and TKy_2 (Grolier and Overstreet, 1978). Owing to common faulting among these units, to the fact that unit TKy_1 is dominantly basaltic, and to the observation that the younger units from TKy_2 to TKy_5 are composed mainly of felsic volcanic rocks, it is possible that samples MJG-76-1A and 1B are at least as young as unit TKy_2 and are probably as young as units TKy_3 and TKy_4. The fields occupied by these samples in figures 3-6 show that they are not greatly different chemically, and that the compositions of samples MJG-76-1A and -1B tend to lie between those of the other two samples from the Yemen Volcanics.

On the basis of their normative color index and the composition of the normative plagioclase (fig. 7), the four tuffaceous rocks from the Yemen Volcanics (table 5 and Appendix 3) are rhyolite according to the scheme of Irvine and Baragar (1971, fig. 7A). A ternary plot (fig. 8) of the distribution of normative orthoclase + albite (OR+AB)-quartz(Q)-anorthite (AN) from Appendix 3 indicates that in the modal classification of the IUGS (Streckeisen, 1979, fig. 1) these samples of tuff are alkali-feldspar rhyolite. The molar ratios $Al_2O_3/(Na_2O+K_2O+CaO)$ show that sample MJG-76-6 is very close to peralkalic in composition:

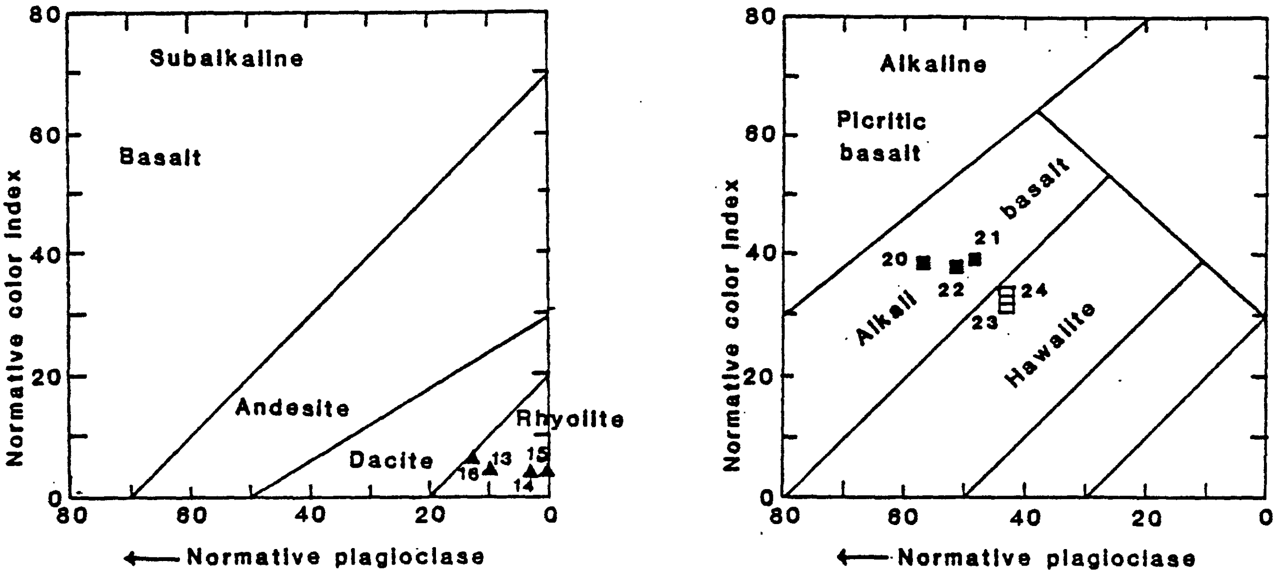
Sample numbers		Molar ratios	
On figs. 3-8	Field	$\frac{(Na_2O+K_2O)}{Al_2O_3}$	$\frac{Al_2O_3}{(Na_2O+K_2O+CaO)}$
13	MJG-76-1A	0.80	1.11
14	MJG-76-1B	0.75	1.28
15	MJG-76-6	0.99	1.07
16	75-OT-26	0.85	0.95

From these ratios and from figure 6, the rhyolite tuff of sample MJG-76-6 is alkalic (nearly peralkalic), the rhyolite tuff of sample 75-OT-26 is alkalic (nearly peraluminous), and the rhyolitic welded tuffs represented by samples MJG-76-1A and -1B are peraluminous (Shand, 1951, p. 228-229).

Stratigraphic and petrogenetic interpretations of the major-element composition of these four samples of rhyolite welded tuff from the Yemen Volcanics have been given in a review of Middle Tertiary continental rift in Southern Arabia (Schmidt, Hadley, and Brown, 1982). The analytical results for the rhyolite from the YAR were integrated with many analyses from Arabian rocks which afforded convincing evidence that the rhyolite tuffs in the YAR are correlative with the Liyyah Formation in Saudi Arabia. This formation, named for exposures in Wadi Liyyah near the border with the YAR, is part of the Jizan Group of late Oligocene and early Miocene age deposited between about 30 Ma and 20 Ma years ago along the coastal plain in southwestern Saudi Arabia. Thick sections of silicic volcanic rocks in the Liyyah Formation are thought by Schmidt, Hadley, and Brown (1982, p. 13) to have been deposited near erup-

The normative compositions of the rhyolitic tuffs from the YAR were reported by Schmidt, Hadley, and Brown (1982, p. 18) to fall "...in the projection of the low-temperature trough on the Ab-Q-Or face of the Ab-Q-Or-H_2O tetrahedron (Wyllie, 1977, p. 44)..." from which these authors infer that "...The magma equilibrated at a shallow crustal depth (1 to 2 kilobars, 4 to 7 km, fig. 11) in sialic crust beneath the continental rift. The rhyolites crystallized from water-saturated partial melts derived from the hot underlying crust."

Most of the rhyolites in the YAR have been shown by Civetta, La Volpe, and Lirer (1978, p. 308) to have been explosively erupted as ignimbrites with the total volume about equal to the thickness of the flood basalts in the Yemen Volcanics. These authors also note that rhyolite is more common in the upper part of the Yemen Volcanics than in the lower part. This observation accords with the interpretation followed on the geologic map of the YAR (Grolier and Overstreet, 1978). Schmidt, Hadley, and Brown (1982, p. 32)

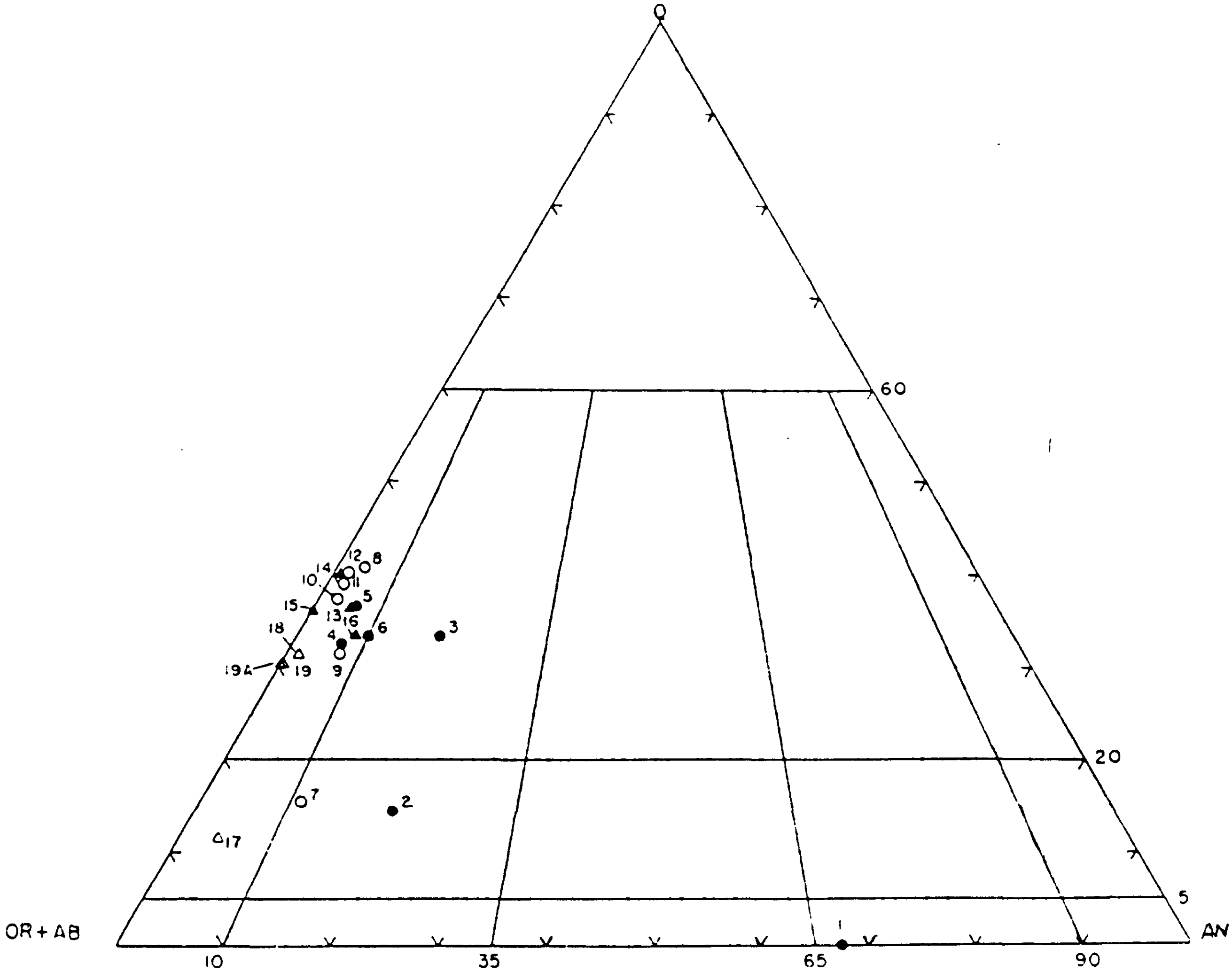


EXPLANATION

(Composition plotted at center of symbol)

Symbol On figure	Sample numbers Field	Rock names from tables 5 and 6
	Tertiary lavas (table 5)	
▲ 13	MJG-76-1A	Welded tuff
▲ 14	MJG-76-1B	Welded tuff
▲ 15	MJG-76-6	Vesicular welded tuff
▲ 16	75-OT-26	Crystal lithic tuff
	Pleistocene and Holocene extrusive rocks (olivine basalt of table 6)	
■ 20	75-OT-2	Older lava
■ 21	75-OT-1	Older lava
■ 22	75-OT-9	Older lava underlying historical flow
□ 23	75-OT-8	Historical flow-bottom
□ 24	75-OT-7	Historical flow-top

Figure 7. Plot of normative color index versus normative plagioclase composition for volcanic rocks of Tertiary to Holocene age, Yemen Arab Republic; classification for subalkaline rocks on left and for alkaline rocks on right after Irvine and Baragar (1971, fig. 7A, 10).



EXPLANATION

(Composition plotted at center of symbol)

Symbol	On figure	Sample numbers Field	Rock names from tables 3, 4, 5, and 6
		Precambrian igneous rocks (tables 3 and 4)	
●	1	MJG-76-41A	Diabase
●	2	MJG-76-54A	Granodiorite gneiss
●	3	MJG-76-16	Granite gneiss
●	4	MJG-76-21	Granite gneiss
●	5	MJG-76-25	Granite gneiss
●	6	MJG-76-28A	Granite gneiss
○	7	MJG-76-56A	Granodiorite
○	8	MJG-76-15	Granite gneiss
○	9	MJG-76-26B	Biotite granite
○	10	MJG-76-39A	Alkali-feldspar granite
○	11	MJG-76-39B	Alkali-feldspar granite
○	12	MJG-76-50	Riebeckite granite
		Tertiary igneous rocks (table 5)	
▲	13	MJG-76-1A	Welded tuff
▲	14	MJG-76-1B	Welded tuff
▲	15	MJG-76-6	Vesicular welded tuff
▲	16	75-OT-26	Crystal lithic tuff
△	17	75-OT-27	Alkali granite
△	18	75-OT-28	Alkali granite
△	19	MJG-76-72A	Alkali granite
△	19A	ROJ-1	Alkali granite

Figure 8.--Ternary diagram showing distribution of normative orthoclase + albite (OR+AB)-quartz(Q)-anorthite(AN) in plutonic and volcanic rocks of various ages from the Yemen Arab Republic; modal classification from Streckeisen (1979, fig. 1) for volcanic rocks overlain only for comparison.

observe that "Peralkalic granite and rhyolite were the ultimate magmatic products of continental rifting, and their production must indicate optimum high-temperature, low-pressure, and perhaps source depletion conditions in the crust beneath the continental rift...thus production of the ultimate peralkalic magma would suggest an approaching end to the continental rift stage." Increase in the K_2O contents of the Miocene alkali granite and of the rhyolitic tuffs in the YAR follows decreasing age (Civetta and others, 1978, table 1). These explosive episodes of rhyolitic volcanism may represent a time interval of only a few million years (Schmidt, Hadley, and Brown, 1982, p. 26), possibly mainly in the Miocene.

The age assigned to the Yemen Volcanics on the geologic map of the YAR (Grolier and Overstreet, 1978), Tertiary and/or Cretaceous, appears by comparison of major-element chemistry with equivalent rocks in Saudi Arabia (Schmidt, Hadley, and Brown, 1982), by K-Ar ages (Civetta and others, 1978), and by the fossil record (Geukens, 1966, p. B15-B16) to cover too great a span of geologic time. Although the base of the Yemen Volcanics has not been dated, and the top is eroded, the range in K-Ar dates obtained by Civetta and associates (1978, p. 309-312) for 15 samples of the volcanic rocks and for two samples of granite from Grolier and Overstreet (1978), the probable age of the Yemen Volcanics is Oligocene and early Miocene.

Minor-element data.--Previously published data on the minor-element composition of the rhyolite in the Yemen Volcanics (Overstreet and others, 1976, table 4; Grolier and others, 1977, table 3) give little indication of associated metallization. In ten samples the mean values for La, Zn, and Zr reached or exceeded the threshold abundances cited by du Bray (1983, table 5; this report, table 8) as indicative of possible mineraliation in Precambrian posttectonic granitic plutons in Saudi Arabia:

Element	Mean value (in ppm) for ten samples	Element	Mean value (in ppm) for ten samples
Ba	500	Sb	N(100)
Be	7	Sc	L(5)
Bi	N(10)	Sn	L(10)
Co	L(5)	Sr	L(100)
Cu	15	W	N(50)
La	150	Y	100
Mo	L(5)	Zn	200
Nb	70	Zr	1,000
Pb	30		

Except for Cu and Zr these means are the same as or are within one laboratory reporting interval of the means for the Miocene alkali-feldspar granite. As for the granite, no metallic mineral deposit has been observed to be genetically connected with the rhyolite of the Yemen Volcanics (El-Shatoury and Al-Eryani, 1977, p. 284-287; 1979, p. 122-125; Schulze and Thiele, 1978, p. 30-47). The uranium content of these rocks is discussed separately below.

Aden Volcanic Series (?).--The olivine basalt of the Aden Volcanic Series (?) was assigned Holocene and upper Pleistocene ages on the geologic map of the YAR (Grolier and Overstreet, 1978), as were the associated sedimentary rocks. New isotopic age determinations reported below indicate that some basalt of the Aden Volcanic Series (?) may be at least lower Pleistocene or upper Pliocene, which would bear importantly on the ages of the associated sedimentary deposits.

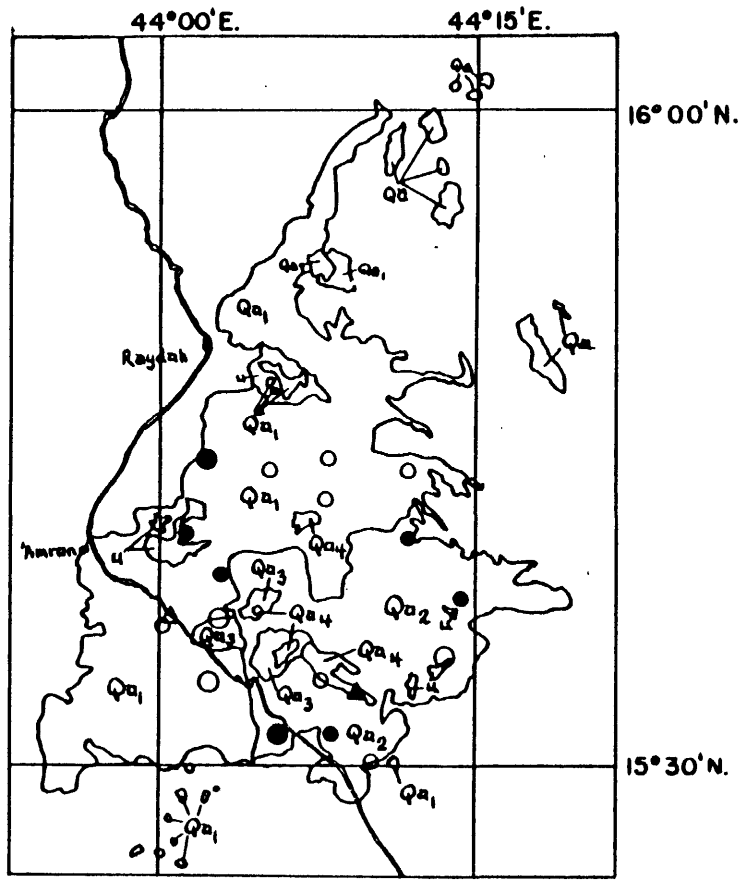
K-Ar ages.--Two samples of olivine basalt were taken from the Hamdan volcanic field (fig. 9, specimens 75-OT-1 and 75-OT-2) at a locality (15°36'45" N.; 44°00'35" E.) 8.7 km by road to the southeast of 'Amran in the YAR (Overstreet and others, 1976, table 1). Both are from the oldest unit of the Aden Volcanic Series (?), which is identified by the symbol Qa_1 on the geologic map of the YAR (Grolier and Overstreet, 1978). This unit consists of basalt flows that form a continuous mantle over older rocks. At the locality where the samples were taken the flow overlies Upper Jurassic limestone of the Amran Series. Sample 75-OT-1 came from a position 1.2 m above the base of the flow, and sample 75-OT-2 was taken 0.7 m above the base of the flow.

Potassium and argon measurements were made during 1979 in the laboratories of the U.S. Geological Survey using standard techniques of isotope dilution. Measurements of potassium were made by P. R. Klock, and measurements of argon and calculations of age were performed by B. M. Myers and S. E. Sims. The calculated ages for these samples of basalt are:

Stratigraphic position above base of flow (in meters)	Field sample number	Calculated age (millions of years)
1.2	75-OT-1	1.54 ± 0.12
0.7	75-OT-2	2.21 ± 0.13

The two samples are part of a massive flow lacking any stratigraphic break in the interval of 0.5m between samples. Possibly the younger age is the more precise. It is near the base of the Pleistocene (Van Eysinga, 1975). The older age is Upper Pliocene. Within the Aden Volcanic Series (?) volcanic activity has continued into geologically recent time with the historic flow, represented by major-element analyses for samples 75-OT-7 and 75-OT-8, being extruded about 1,700 years ago (Rathgens and Wissman, 1934, p. 105).

Major-element data.--The presence of modal olivine in the five samples of olivine basalt of the Aden Volcanic Series (?) from the Hamdan volcanic field in the YAR (Overstreet and others, 1980, p. 8-9) is reflected in the normative minerals derived from the major-element data (Appendix 4). These rocks fall in the field of olivine basalts as defined by the relation between the differentiation index of Thornton and Tuttle (1960, p. 670), and the normalized weight percentage of SiO_2 (fig. 10). The differentiation index of each sample is:



EXPLANATION

Rock units

Qa Qa, undivided Quaternary olivine basalt of the Hamdan volcanic field; divided on basis of reflectance on LANDSAT-1 image into four units, Qa_1-Qa_4 from oldest to youngest:

Qa_4, very dark lobate flows extruded in historic time

Qa_3, dark flows

Qa_2, thin flows, discontinuous over older rocks, appears lighter gray on LANDSAT-1 images than units Qa_3 and Qa_4

Qa_1, flows forming a continuous mantle over older rocks; Qa_1 and Qa_2 possibly part of only one eruptive phase

U Other rocks, undivided, including Quaternary alluvial sediments, Tertiary Yemen Volcanics, and Upper Jurassic limestone of the Amran Series

Symbols showing ranges in percentage of K_2O in olivine basalt and sources of analyses

▲ 1.12 percent, average of three, this report (75-OT-7, 75-OT-8, and 75-OT-9)

△ 0.83 percent, average of two, this report (75-OT-1 and 75-OT-2); also used for K-Ar age determinations

● 0.85-0.86 percent, Kabesh and Ghoweba, 1976, table 1 1/ and fig. 2

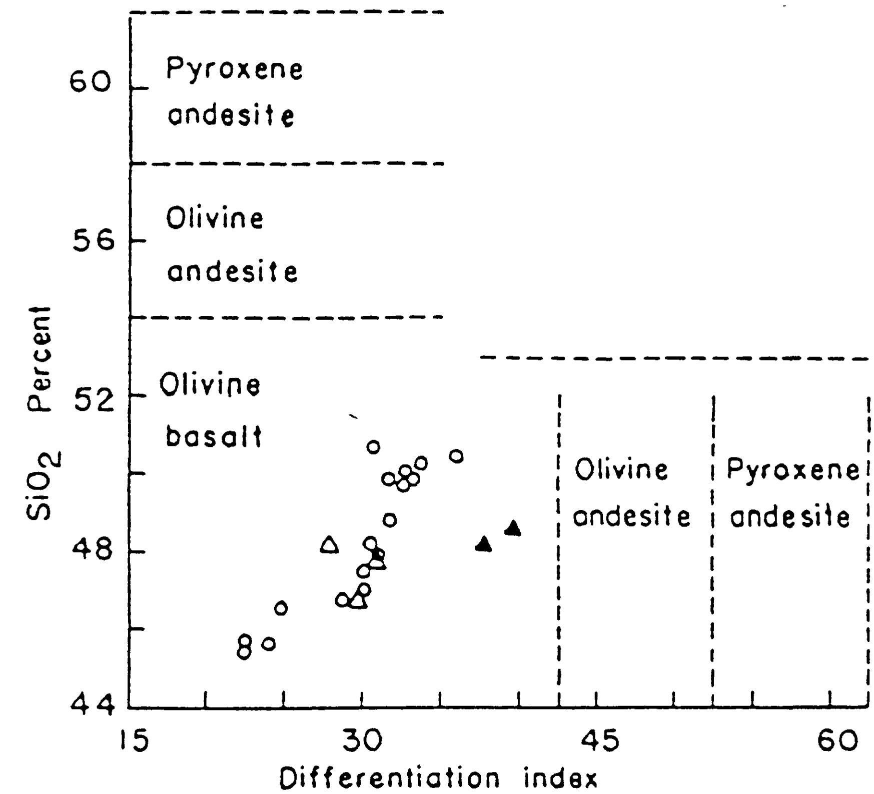
○ 0.80-0.82 percent, Kabesh and Ghoweba, 1976, table 1/ and fig. 2

• 0.78-0.79 percent, Kabesh and Ghoweba, 1976, table 1 1/ and fig. 2

∘ 0.72-0.77 percent, Kabesh and Ghoweba, 1976, table 2 1/ and fig. 2

1/ Rock analysis re-calculated here to H_2O-free basis.

Figure 9. Map showing location of Quaternary olivine basalt flows in the Hamdan volcanic field, Yemen Arab Republic, the site of samples taken for K-Ar age determinations, and the sites of chemically analyzed samples of basalt with the normalized percentages of K_2O in the lavas indicated; adapted from Grolier and Overstreet, 1978; Kabesh and Ghoweba, 1976.



EXPLANATION

o Data from Kabesh and Ghoweba, 1976, fig. 8

△ Data for older lavas, this report,samples 75-OT-1, 75-OT-2, 75-OT-9

▲ Data for historic flow, this report, samples 75-OT-7 and 75-OT-8

Figure 10.--Diagram showing the relation of the differentiation index (the sum of the percentages of normative quartz + orthoclase + albite; Thornton and Tuttle, 1960, p. 670) plotted against the weight percentage of SiO_2 in five samples of olivine basalt of the Aden Volcanic Series (?) from the Yemen Arab Republic compared with plots for other Quaternary basalt from the Yemen Arab Republic, after Kabesh and Ghoweba (1976, fig. 8).

Source	Sample number	Differentiation index (Sum of the percentages of normative quartz + orthoclase + albite)
Older lava	75-OT-1	31.31
Do.	75-OT-2	28.47
Do.	75-OT-9	30.06
Historic flow	75-OT-8	39.50
Do.	75-OT-7	37.64

The relation of (Na_2O+K_2O) to SiO_2 in these five samples of olivine basalt (fig. 4) shows that they are alkali-olivine basalt.

Chemical differentiation of the historic flow from the older lavas is clearly defined in the differentiation indices and in the data shown on figures 3-7 and 10. The classification of Irvine and Barager (1971) showing the relations between the normative color index and the composition of the normative plagioclase in figure 7 is particularly instructive; the older basalt flows are alkali basalt whereas the historic flows are differentiated to hawaiite.

On the basis of increasing content of the normalized percentage of K_2O (Appendix 4), the alkali-olivine basalt (75-OT-9) underlying the historic flow in the Hamdan volcanic field may be closer in age to the historic flow than it is to the basal lavas represented by samples 75-OT-1 and 75-OT-2 (fig. 9). The stratigraphic position assigned to sample 75-OT-9 is the unit Qa_3 in the upper part of the Aden Volcanic Series (?) (Overstreet and others, 1976, table 1; Grolier and Overstreet, 1978).

Through the courtesy of Dr. M. L. Kabesh of Sana'a University, the positions of the 17 samples of basalt collected by him and Dr. A. M. Ghoweba (1976, fig. 2; Grolier and others, 1977, fig. 1B) can be plotted on the stratigraphic units of the Hamdan volcanic field (fig. 9) as shown on the geologic map of the YAR (Grolier and Overstreet, 1978). A possible increase in the normalized percentage of K_2O with decreasing relative age of the flows is indicated on figure 9 and by the mean values:

Apparent stratigraphic position from youngest to oldest by unit in the Aden Volcanic Series (?) (Grolier and Overstreet, 1978)	Mean normalized percentage of K_2O (Kabesh and Ghoweba, 1976, table 1; this report)
Qa_4	1.12 1/
Qa_3	1.13
Qa_2	0.80
Qa_1	0.78

1/ In determining the mean values for Qa_2 and Qa_4, sample number 6 of Kabesh and Ghoweba (1976, table 1 and fig. 2), having 0.76 percent normalized K_2O could not be assigned because its location plotted on a boundary.

Minor elements in rocks, ores, and slags

Analyses for uranium were made on samples of the Tertiary granite and rhyolite to determine if the element was present in leachable phases that might be removed by solution during weathering and thus permit its secondary concentration in sedimentary rocks deposited in the Yemen Volcanics. Spectrographic analyses of samples of rocks, ores, and slags collected during 1979 (table 1) have been made for this report to expand the coverage of ancient mines in the northern part of the YAR over material previously presented and to add to the trace-element data on the Yemen Volcanics (Overstreet and others, 1976, tables 2 and 4; Grolier and others, table 3).

Methods and results of analyses

Uranium.--Radiometric analyses by Geiger counter were made on all samples from the YAR prior to spectrographic analysis, and none was found to be radioactive at a lower limit of determination of 250 ppm equivalent uranium (eU)(Grolier and others, 1977, p.39). This high lower limit is unsatisfactory for the evaluation of possible secondary deposits of U formed through the weathering of granitic rocks. In an earlier section of this report the recommendation was made to study the Precambrian intrusive rocks of the YAR by the methods of Stuckless, Van Trump, Christiansen, and associates (1983) to determine favorability for mineralization, including roles as possible source rocks for secondary deposits of U, but the methods are not applicable for U in igneous rocks as young as the Tertiary alkali-feldspar granite and the felsic rocks of the Yemen Volcanics. For the Tertiary rocks, special analyses were made by T. F. Harms, U.S. Geological Survey, using procedures to measure the easily soluble U and the total U in each sample (Grimaldi and others, 1954; Adams and Maeck, 1954) in order to determine the amount of U that might possibly be released from these rocks by weathering.

For the easily soluble U, 0.5g of sample was weighed, placed in a test tube, and 5 ml of concentrated HNO_3 was added. This was heated so that the HNO_3 refluxed and slowly evaporated over a period of 1-1/2 hours. The solid residue was moistened with 8 ml of 15 percent HNO_3, and this mixture was warmed to re-dissolve the solubilized salts. Aluminum nitrate was added to the 15 percent acid solution, heated to effect solution, and cooled to 20°-25° C. After cooling, 10 ml of ethyl acetate was added and the mixture was shaken for 2 minutes then centrifuged for 10 minutes at 1000 R.P.M. Five ml aliquots of blanks of the ethyl acetate and the standard U solutions and 5 ml aliquots of samples were pipetted and transferred to clean, dry, platinum dishes. After burning off the ethyl acetate the dish was ignited over an open flame to red heat for 5-10 seconds. Two grams of flux consisting of (in percent) 45.5 Na_2CO_3, plus 45.5 K_2CO_3, plus 9.0 NaF was added and the phosphor was prepared over Fischer burner for 3 minutes. The fluorescence of the cooled bead thus formed was measured in a Jarrell-Ash fluorometer and the results for the samples were compared with those obtained from the standards.

For total U, 0.2g of sample was weighed into a small Teflon jar with screw-cap Teflon lid. To the sample 4 ml of concentrated HNO_3 and 20 ml of 48 percent HF were added and this was allowed to stand overnight. Then the sample was refluxed for 24 hours with the lid on. After this, the sample was slowly evaporated to dryness. The residue was dissolved in 15 percent HNO_3, and the volume adjusted to 10.0 ml. A 5.0 ml aliquot was taken, aluminum nitrate added to it, and the sample was taken through the rest of the procedure. Conventionally, total U is the sum of the U in the HF digestion plus the U in the insoluble residue from the HF digestion which is later fused with Na_2CO_3. In the samples from the YAR no insoluble residue was found, probably because of the small weight of sample and the long time allowed for digestion.

The two samples of carbonaceous siltstone from the Yemen Volcanics (MJG-76-3 and MJG-76-5) contained fair amounts of organic carbon; therefore, they were ashed before the analytical procedures were begun. The amount of ash was 84 percent of sample MJG-76-3 and 91.5 percent of sample MJG-76-5. The determinations of easily soluble U and of total U were made on the ash.

The results of the analyses for U in 24 samples from the Tertiary rocks of the YAR are given in table 9.

Semiquantitative spectrographic analyses.--The minor elements were determined by James A. Domenico, USGS, using the method described by Grimes and Marranzino (1968). The sample was ground to <0.149 mm, weighed on a torsion balance, and mixed with graphite powder. The mixture was packed into the cavity of a preformed electrode and burned for 135 seconds at 12 amperes and 220 volts d.c. with the spectrum recorded on spectrographic film. Analytical results were reported as the approximate geometric midpoints of ranges in abundance the respective limits of which are:

Approximate geometric midpoint (reporting value)	Range in values represented by each midpoint
1	1.2-0.83
0.7	0.83-0.56
0.5	0.56-0.38
0.3	0.38-0.26
0.2	0.26-0.18
0.15	0.18-0.12
0.1	0.12-0.08

The accuracy of the reported values is ± 30 percent of the actual concentration of a given element. Under the uniform conditions of analysis in this investigation, 75-85 percent of the reported values are within two reporting units of the actual value. Where the upper or lower limits of reporting the results of the spectrographic analyses are exceeded by values in table 10, a letter symbol followed by the respective value is used:

N = Not detected at the lower limit of determination, or at value shown.

L = Detected, but below the lower limit of determination, or below value shown.

G = Greater than the upper limit of determination, or greater than value shown.

Table 9. Uranium in Tertiary alkali-feldspar granite and in alkali-feldspar rhyolite and carbonaceous sedimentary rocks of the Yemen Arab Republic (in ppm)

[Chemical analyses made by Thelma F. Harms, U.S. Geological Survey, 1984; descriptions of 75-OT series from Overstreet and others, 1976, table 1; descriptions of MJG-76 series from Grolier and others, 1977, table 2.]

Sample numbers: Field	Sample numbers: Laboratory	Location: North latitude	Location: East longitude	Description	Uranium content: Easily soluble	Uranium content: Total
			Tertiary alkali-feldspar granite (fresh)			
75-OT-27	MAM-604	13° 33' 45"	44° 02' 30"	Pluton at Jibal Sabir	0.08	0.5
75-OT-28	MAM-605	13° 33' 50"	44° 02' 10"	Do.	.22	4.0
MJG-76-72A	MAM-932	15° 11' 03"	43° 30' 42"	Pluton at Jibal Hufash	.23	3.0
MJG-76-72B	MAM-933	15° 11' 03"	43° 30' 42"	Do.	.20	4.0
			Yemen Volcanics (weathered)			
				Unit TKy4		
75-OT-13	MAM-591	14° 41' 35"	44° 20' 25"	Pink saprolite of lithic tuff	.60	5.0
75-OT-14	MAM-592	14° 41' 35"	44° 20' 25"	Dk. red saprolite of lithic tuff	.55	1.2
				Unit TKy2		
MJG-76-2	MAM-826	14° 43' 05"	44° 21' 50"	Grayish buff ignimbrite	.26	2.2
MJG-76-4	MAM-828	14° 13' 25"	44° 35' 15"	Felsic tuff	.26	3.0
				Unit TKy undivided		
MJG-76-73A	MAM-819	15° 11' 07"	43° 31' 07"	Yellow felsite	.08	9.0
MJG-76-73C	MAM-821	15° 11' 07"	43° 31' 07"	Crystal tuff	.10	5.0
MJG-76-74A	MAM-822	15° 10' 26"	43° 31' 03"	Felsite	.65	4.5
MJG-76-74B	MAM-823	15° 10' 26"	43° 31' 03"	Felsite	.20	8.0
			Yemen Volcanics (fresh)			
				Unit TKy4		
75-OT-15	MAM-593	14° 41' 35"	44° 20' 25"	Lithic tuff	.20	3.0
75-OT-17	MAM-595	13° 24' 00"	44° 19' 35"	Vesicular tuff	.14	1.5
75-OT-26	MAM-603	13° 54' 40"	44° 19' 40"	Black crystal lithic tuff	.08	1.5
				Unit TKy3		
MJG-76-6	MAM-830	14° 26' 44"	44° 34' 37"	Vesicular glassy tuff	.17	1.2
				Unit TKy1		
75-OT-30	MAM-607	15° 29' 40"	44° 28' 15"	Purple rhyolite tuff	.19	2.5
75-OT-31	MAM-608	15° 29' 40"	44° 28' 15"	Green rhyolite tuff	1.0	3.0
				Unit TKy undivided		
MJG-76-1A	MAM-824	15° 07' 50"	43° 55' 42"	Black obsidian	.16	2.5
MJG-76-1B	MAM-825	15° 07' 50"	43° 55' 42"	Pink ignimbrite	.19	1.7
MJG-76-72C	MAM-934	15° 11' 03"	43° 30' 42"	Grayish buff felsite	.70	1.7
MJG-76-72D	MAM-818	15° 11' 03"	43° 30' 42"	Purplish gray felsite	.42	4.0
			Carbonaceous siltstone interbedded in Yemen Volcanics (fresh)			
				Unit TKy3		
MJG-76-5	MAM-829	15° 12' 30"	44° 02' 40"	Carbonate minerals absent	.53	2.0
				Unit TKy2		
MJG-76-3	MAM-827	14° 15' 15"	44° 33' 15"	Carbonate minerals present	.46	1.0

Of the 31 elements sought in each of the 55 samples analyzed, six elements were found to be below their respective lower limits of determination in all samples (in ppm): As, N(200); Au, N(10); Bi, N(10); Cd, N(20); Sb, N(100); and Th, N(100). Several elements were detected at low abundances in a few samples:

Element	Sample number and abundance (in ppm)
Ag	79-OT-2, 2; 79-OT-10, L(0.5)
Mo	79-OT-1, 20; 79-OT-3, 30; 79-OT-10, 20; 79-OT-24, L(5); 79-OT-25, L(5); 79-OT-48, 5; 79-OT-49, L(5); 79-OT-50, L(5); 79-TK-1, L(5)
Sn	79-OT-23, L(10); 79-OT-50, L(10); 79-OT-51, L(10)
W	79-OT-25, L(50); 79-OT-29, 29, 50
Zn	79-OT-2, L(200); 79-OT-5, 300; 79-OT-18, 300; 79-OT-50, 300; 79-TK-3, 200

Abundances of the other 20 elements are listed in table 10.

Uranium in Tertiary granite and rhyolite

The mean values for easily soluble U and total U in the Tertiary alkali-feldspar granite, rhyolite of the Yeman volcanics, and carbonaceous siltstone of the Yemen Volcanics are low (table 9):

Rock	Uranium			
	Easily soluble		Total	
	Mean (in ppm)	Standard deviation	Mean (in ppm)	Standard deviation
Alkali-feldspar granite	0.18	0.07	2.88	1.65
Weathered rhyolite	.34	.23	4.74	2.70
Fresh rhyolite	.35	.3	2.26	0.89
Siltstone	.50	.05	1.50	.71
All rocks	.32	.24	3.10	2.07

The mean value for total U in all rocks is slightly greater than one-half the value given by Stuckless, Van Trump, and others (1983, table 4) for Precambrian postorogenic granites in the southeastern Arabia Shield (5.14 ppm) which themselves are not regarded as favorable sources for secondary deposits of U. Indeed, the carbonaceous siltstones of the Yemen Volcanics, which might be expected to be geochemical sinks for U in weathering products from the Tertiary igneous rocks, contain the least total U. They do, however, have more of the easily soluble U, but 0.5 ppm is minor compared to average values cited for black shales of 2-300 ppm U (Fix, 1958) or 3-1250 ppm (Levinson, 1980, p. 885). The low uranium content of the carbonaceous siltstones suggests that very little U has been released from the Yemen Volcanics during post-depositional weathering.

The weathered samples of rhyolite from the Yemen Volcanics contain essentially the same amounts of easily soluble U as the fresh rhyolite, but the weathered rocks have a mean content of U about twice that of the fresh rocks and include the two highest values for U in the set of analyses (table 9). Perhaps individual differences in original abundances of total U account for

Table 10. Results of semiquantitative spectrographic analyses of 55 samples of rocks, ores, and slag from the Yemen Arab Republic.

[Analyses by James A. Domenico, USGS, 1979; lower limits of determination shown in parenthesis below symbol for element.]

Sample numbers		Results in percent				Results in parts per million															
Field	Laboratory	Fe (0.5)	Mg (.02)	Ca (.05)	Ti (.002)	Mn (10)	B (10)	Ba (20)	Be (1)	Co (5)	Cr (10)	Cu (5)	La (20)	Nb (20)	Ni (5)	Pb (10)	Sc (5)	Sr (100)	V (10)	Y (10)	Zr (10)
Sa'dah area, Jebel Al Ma'dan open-pit iron mine																					
79-OT-1	MBC-486	3	0.5	0.7	0.3	300	30	500	1	10	100	30	N(20)	N(20)	50	30	15	300	200	50	150
79-OT-2	MBC-487	5	2	1.5	.3	700	10	300	1	10	50	50	N(20)	N(20)	20	30	15	300	200	30	100
79-OT-3	MBC-488	2	.3	20	.2	G(5000)	20	1000	3	20	30	30	N(20)	N(20)	500	20	10	150	100	70	70
79-OT-4	MBC-489	1	.07	3	.015	2000	N(10)	70	L(1)	N(5)	L(10)	10	N(20)	N(20)	15	N(10)	N(5)	N(100)	N(10)	N(10)	10
79-OT-5	MBC-490	20	.1	1	.05	1000	30	70	2	15	70	20	N(20)	N(20)	30	15	10	N(100)	150	20	70
79-OT-6	MBC-491	G(20)	.2	3	.01	G(5000)	30	200	2	15	10	10	N(20)	N(20)	30	20	L(5)	100)	30	50	N(10)
79-OT-7	MBC-492	15	.2	.3	.1	1500	30	50	2	20	10	10	N(20)	N(20)	50	10	15	N(100)	100	30	50
79-OT-8	MBC-493	G(20)	.5	.1	.02	G(5000)	30	20	2	7	20	10	N(20)	N(20)	20	15	L(5)	100	20	20	20
79-OT-9	MBC-494	G(20)	.3	.1	.1	G(5000)	30	100	2	20	50	15	N(20)	N(20)	50	N(10)	5	200	50	50	50
79-OT-10	MBC-495	3	1	.5	.3	300	30	200	2	N(5)	150	50	N(20)	N(20)	20	150	20	100	200	50	100
79-OT-11	MBC-496	7	2	5	.7	1000	30	150	1	30	200	30	N(20)	N(20)	70	N(10)	30	300	300	30	100
79-OT-12	MBC-497	G(20)	.15	2	.01	1000	30	50	1.5	10	10	5	N(20)	N(20)	20	10	N(5)	N(100)	20	L(10)	N(10)
79-OT-13	MBC-498	1	10	G(20)	.005	1500	N(10)	150	N(1)	N(5)	20	L(5)	30	N(20)	7	10	N(5)	200	30	N(10)	N(10)
Sa'dah area, Jabal Al Ma'aden open-pit iron mine																					
79-OT-25	MBC-510	15	.2	1.5	G(1)	G(5000)	50	700	2	50	100	50	50	20	30	30	70	500	300	70	70
79-OT-26	MBC-511	G(20)	.3	.1	.2	3000	30	500	3	30	70	20	N(20)	N(20)	70	10	10	N(100)	100	30	50
79-OT-27	MBC-512	10	.2	.5	.5	700	50	100	5	50	300	70	N(20)	N(20)	70	20	30	N(100)	500	20	70
79-OT-28	MBC-513	G(20)	.1	3	.1	700	10	300	15	50	100	30	N(20)	N(20)	100	20	7	N(100)	100	200	200
79-OT-29	MBC-514	15	.02	.2	.005	300	10	100	3	L(5)	50	5	N(20)	N(20)	20	L(10)	N(5)	N(100)	30	10	15
79-OT-30	MBC-515	G(20)	L(.02)	N(.05)	.003	300	10	L(20)	1	20	10	N(5)	N(20)	N(20)	30	L(10)	N(5)	N(100)	15	L(10)	N(10)
79-OT-31	MBC-516	G(20)	.05	.07	.02	200	20	150	5	10	20	15	N(20)	N(20)	30	10	N(5)	N(100)	100	15	70
79-OT-32	MBC-517	G(20)	.05	.05	.01	300	30	70	3	15	10	10	N(20)	N(20)	30	10	5	N(100)	50	30	20
79-OT-33	MBC-518	G(20)	L(.02)	.1	.002	700	30	150	2	20	10	L(5)	N(20)	N(20)	20	N(10)	N(5)	N(100)	30	10	N(10)
79-OT-34	MBC-519	1	10	G(20)	.007	1500	70	N(20)	N(1)	N(5)	10	N(5)	N(20)	N(20)	L(5)	N(10)	N(5)	N(100)	N(10)	N(10)	N(10)
79-OT-35	MBC-520	0.5	10	G(20)	.015	300	20	20	N(1)	N(5)	15	N(5)	N(20)	N(20)	L(5)	N(10)	N(5)	700	20	N(10)	N(10)
79-TK-7	MBC-540	G(20)	.02	.07	.007	700	20	50	2	7	70	5	N(20)	N(20)	20	N(10)	N(5)	N(100)	50	10	10
Sa'dah area, Jabal Ayub circular shaft mine																					
79-OT-14	MBC-499	.1	7	20	L(.002)	700	100	N(20)	N(1)	N(5)	N(10)	N(5)	30	N(20)	N(5)	10	N(5)	300	L(10)	N(10)	N(10)
79-OT-15	MBC-500	2	G(10)	5	.02	700	500	50	N(1)	10	N(10)	7	N(20)	N(20)	5	N(10)	N(5)	500	50	N(10)	N(10)
79-OT-16	MBC-501	15	3	10	.5	5000	10	500	L(1)	5	N(10)	5	N(20)	N(20)	L(5)	N(10)	30	500	100	50	30
79-OT-17	MBC-502	15	1	5	.7	2000	10	300	1.5	7	N(10)	7	N(20)	N(20)	L(5)	N(10)	50	700	100	50	150
79-OT-18	MBC-503	1	G(10)	7	.2	1500	150	70	1	N(5)	N(10)	N(5)	N(20)	N(20)	L(5)	N(10)	10	500	70	N(10)	70
79-OT-19	MBC-504	15	1	5	.7	2000	10	300	1	7	N(10)	10	N(20)	N(20)	5	N(10)	50	500	100	50	50
79-OT-20	MBC-505	.1	1.5	G(20)	.01	200	20	100	N(1)	N(5)	N(10)	N(5)	N(20)	N(20)	N(5)	N(10)	N(5)	2000	20	N(10)	10
79-OT-21	MBC-506	.7	G(10)	20	.05	1500	100	20	1	N(5)	N(10)	5	N(20)	N(20)	L(5)	15	N(5)	200	30	10	100
79-OT-22	MBC-507	10	5	5	1	1000	10	200	L(1)	30	150	20	N(20)	N(20)	15	N(10)	20	500	200	15	70
79-OT-23	MBC-508	2	.5	1	.3	700	20	1000	2	N(5)	10	N(5)	70	N(20)	5	50	5	300	30	30	150
79-TK-6	MBC-539	1	.5	1.5	.1	500	N(10)	1000	3	N(5)	10	N(5)	70	N(20)	N(5)	50	L(5)	200	20	20	100
Sa'dah area, vicinity of At Therwa in Wadi Agnam																					
79-TK-24	MBC-509	15	1	5	1	2000	10	300	1	10	15	10	30	L(20)	L(5)	N(10)	50	700	70	70	1000
79-TK-1	MBC-534	20	1	5	.7	3000	10	500	1	10	20	15	20	20	5	N(10)	70	700	100	70	G(1000)
79-TK-2	MBC-535	1	.2	.5	.015	200	N(10)	700	3	N(5)	N(10)	L(5)	30	N(20)	L(5)	70	5	100	20	30	70
Sa'dah area, slag pile at Al shatt																					
79-OT-38	MBC-521	G(20)	1.5	15	.1	G(5000)	50	300	2	L(5)	100	10	N(20)	N(20)	5	N(10)	10	700	100	30	100
79-OT-39	MBC-522	2	.2	2	.2	1500	70	150	1.5	N(5)	70	L(5)	50	N(20)	7	30	7	500	100	20	200
79-OT-40	MBC-523	G(20)	1	5	.05	G(5000)	50	200	3	5	70	7	N(20)	N(20)	10	N(10)	7	700	50	30	50
79-OT-41	MBC-524	G(20)	.7	5	.03	G(5000)	50	200	2	L(5)	50	10	N(20)	N(20)	10	N(10)	5	700	50	20	30
79-OT-43	MBC-525	G(20)	1	3	.05	G(5000)	50	200	5	N(5)	70	5	N(20)	N(20)	L(5)	N(10)	7	1000	70	30	70
79-OT-44	MBC-526	G(20)	1.5	5	.1	G(5000)	50	300	5	5	100	5	N(20)	N(20)	L(5)	N(10)	10	700	100	50	70
Manakhah area, Yemen Volcanics																					
79-OT-45	MBC-527	5	.3	.3	.5	2000	L(10)	500	1.5	N(5)	N(10)	L(5)	100	100	L(5)	30	10	100	70	70	500
79-OT-46	MBC-528	5	.7	.7	.5	1000	10	5000	2	N(5)	N(10)	L(5)	100	70	L(5)	30	15	150	30	70	500
79-OT-47	MBC-529	7.	1	.7	.5	1000	10	200	1.5	20	10	7	N(20)	20	5	10	15	100	150	50	100
79-OT-48	MBC-530	15	1.5	5	1	1500	20	300	1	50	50	20	N(20)	N(20)	10	10	30	200	500	50	100
79-OT-49	MBC-531	10	1	2	1	2000	20	500	2	15	10	10	70	50	5	20	10	200	200	70	200
79-OT-50	MBC-532	3	.5	.5	.5	2000	30	1000	3	N(5)	10	N(5)	100	70	L(5)	70	7	N(100)	10	70	500
79-OT-51	MBC-533	3	.7	1	.3	1000	20	200	5	L(5)	20	5	100	100	L(5)	30	5	N(100)	50	70	500
79-TK-3	MBC-536	5	.7	1	.5	1000	10	1500	3	N(5)	N(10)	L(5)	70	70	L(5)	30	10	N(100)	30	70	300
79-TK-4	MBC-537	7	.05	.3	.7	1500	10	500	2	N(5)	N(10)	L(5)	100	70	L(5)	30	7	N(100)	50	50	500
79-TK-5	MBC-538	7	1	.7	.5	700	15	200	5	5	100	5	100	100	5	30	5	L(100)	50	70	700

this relation. However, the general similarity in content of U from diverse sources over wide areas of the YAR for the Yemen Volcanics also may be interpreted to indicate that the high values for U in these weathered samples are attributable to adsorption or co-precipitation of the U with some relatively insoluble weathering product.

Sa'dah area

Jabal Al Maidan open-pit iron mine.--The Jabal Al Maidan ancient open-pit iron mine explores thick gossan of Quaternary age developed over sulfide-bearing metavolcanic rocks in a vertical sequence of northerly trending Precambrian metavolcanic and metasedimentary rocks exposed at Jabal Al Maidan (17°01'30" N.; 43°46'40" E.) about 9 km north of Sa'dah (fig. 1). Thirteen samples of wall rocks and gossan (used as ore) were taken in a traverse from east to west across the pit and its wall rocks (tables 1 and 10). Rocks represented are metavolcanics (79-OT-1, -2, -10, -11), carbonaceous schist (79-OT-3), and marble (79-OT-13). Weathering products from the pit include gossan (79-OT-7, -8, -9, -12), ferruginous collapse breccia (79-OT-5), ferruginous chert (79-OT-6), and white chert (79-OT-4). The gossan and other weathering products from the mined part of the deposit contain more Fe, Mn, and Be than the wall rocks, and they are also the sources of the only reported Ag and Zn (table 10.) Nevertheless, the sparsity of base metals, precious metals, and elements such as As, Bi, Cd, Mo, and Sb in the gossan, where secondary Fe and Mn oxides and hydroxides would tend strongly to have scavenged these elements, shows that they are indeed rare or absent from the source rocks from which the gossan formed.

The weathering products from the Jabal Al Maidan mine are somewhat leaner in Be, Co, Y and Zr than otherwise similar gossan exposed 8-9 km to the south (16°56'20" N.; 43°47'40" N.) near Jabal Abbelle (Overstreet and others, 1976, table 2).

Jabal Al Ma'aden open-pit iron mine.-- The ancient open-pit mine at Jabal Al Ma'aden (16°53'00" N.; 43°49'05" E.), situated 8 km by road to the northeast of Sa'dah, also exploited Quaternary gossan as an ore for iron, but at this locality the gossan is developed on gabbro and amphibolite of probable Precambrian age (Grolier and Overstreet, 1978). All 12 of the samples taken for analysis were from the gossan or adjacent spoil. Included among the samples are such secondary minerals as goethite, hematite, magnesite, calcite, clay, and chert (table 1). The goethite and hematite (samples 79-OT-26, -28, -30, -31, -32, -33, and 79-TK-7) all contain G(20) percent of Fe, but they are extremely poor in the other elements except for Be. Compared to the gossan overlying metavolcanic rocks at Jabal Al Maidan, the gossan formed on gabbro and amphibolite at Jabal Al Ma'aden contains less Mn and Sr and more Be, Co, Cr, and V (table 1). The samples of magnesite and calcite are enriched in Mg, Ca, and Sr, and depleted in Fe, Ti, Ba, Be, Co, Cr, Cu, Ni, Pb, Sc, V, Y, and Zr compared with the ferruginous gossan.

The gossan, exclusive of clay and carbonate minerals, at Jabal Al Ma'aden is less rich in Mn, Be, Ni, Sc, Y, and Zn and is richer in Ba than the gossan near Jabal Abbelle, where the source is layered metavolcanic rocks (Overstreet and others, 1976, table 2).

The only W detected among the 55 samples was reported as L (50) ppm in sample 79-OT-25 of clay, and as 50 ppm in sample 79-OT-29 of ferruginous chert. The clay was also the source for L(5) ppm Mo. These samples are from the southern and central parts of the gossan where a few small dikes of pink granite intrude the gabbro. The source for the W and Mo was not determined.

Jabal Ayub circular shaft mine.--At Jabal Ayub (17°01'00" N.; 43°48'00" E.) about 1 km to the east-southeast of the Jabal Al Maidan mine (Schulze and Thiele, 1978, fig. 4), a steeply inclined circular shaft at least 30 m deep and expanded by three short galleries 2-3 m in length, has been sunk on a vein of magnesite. A mafic dike rich in olivine crosses the collar of the shaft. Adjacent country rock is Precambrian hornblende granite and marble. No gossan is present at the surface, and no evidence of sulfide minerals was seen on the dump. It is not clear why ancient miners sunk the shaft. Perhaps they were after the white magnesite, which may have been used for decoration on buildings or for some metallurgical purpose in connection with the smelting of iron.

Results from spectrographic analyses of the 8 samples taken at the mine (tables 1 and 10) likewise fail to indicate anomalous metals that may have been sought. All samples from the circular shaft mine have distinctly sparse contents for Be, Co, Cr, Cu, Ni, Pb, Y, and Zr compared with other samples from the Sa'dah area (table 10). Among themselves, the samples of magnesite (79-OT-14,-15,-18) tend to have expectably high values for Mg, Ca, B, and Sr and low values for Fe, Ti, Ba, Co, Cr, Cu, Ni, Y, and Zr. Even lower concentrations of these depleted elements are found in the marble (79-OT-20-, -21). The mafic rocks at the mine (79-OT-16 and -17) are by comparison richer in Fe, Ti, Mn, Ba, Sr, V, and Zn, but even these values are ones characteristically associated with mafic rocks. The hornblende granite at the mine (79-OT-19) is excessively rich in Fe, Mg, and Ca, and contains more Mn, Sc, and V, and less La, Y, and Zr than the other samples of granite from the Jabal Ayub area (79-OT-23 and 79-TK-6). Petrographic description of the rock represented by sample 79-OT-19 was not made, but the chemical data suggest that the rock is more mafic than granite.

A sample of gabbro (79-OT-22) and two samples of granite (79-OT-23 and 79-TK-6) were collected from a locality (17°00'30" N.; 43°47'30" E.) to the south of Jabal Ayub and near the gabbro in Wadi Agnam discussed below. The granite forms a dike intrusive into the gabbro, and both samples came from the same dike. The granite is fine-grained, holocrystalline with hydpidiomorphic fabric and consists of major microcline which gives the rock a pinkish tint, quartz, biotite partly altered to cholorite, oligoclase (An_{26}), and accessory apatite. The chemical composition differs markedly from the hornblende granite (79-OT-19) at the Jabal Ayub mine (table 10). The sample of gabbro from this locality (79-OT-22) differs somewhat in minor element composition from both samples of mafic dikes at the Jabal Ayub mine (79-OT-16 and -17) and the pyrite-rich gabbro (79-OT-24 and 79-TK-1) in Wadi Agnam (table 10) principally in that it contains less Fe, Mn, Ba, Sc, and Y than the other mafic rocks as well as more Mg, Co, Cr, Cu, Ni, and V.

Pyritic andesine gabbro from Wadi Agnam.--Spoil from a dug well (16°59'00" N.; 43°48'00" E.) in Wadi Agnam about 1 km east of Ath Therwa was the source of two samples of andesine gabbro with bright coatings of pyrite on joints (79-OT-24 and 79-TK-1) and a specimen of red quartz syenite (79-TK-2) from a dike that strikes northward and dips steeply in the gabbro (table 1).

The dike that was the source for sample (79-TK-2) is exposed about 300 m east of the site from which the samples of gabbro were taken. All specimens were quite fresh, thus they provided excellent material for petrographic study.

The principal constituent of the andesine gabbro (79-OT-24 and 79-TK-1) is augite which, with the color indices of the two samples >70, support the mafic classification of the rock. The feldspar, however, is andesine (An_{45}), which is not calcic enough to fit a normal gabbro. Potassium feldspar and quartz are absent. From the mineralogical composition of the rock the name andesine gabbro is proposed.

A thin section of the red quartz syenite shows that the rock is composed principally of microcline. Andesine makes up about 30 percent of the rock, and quartz constitutes less than 10 percent. Some green biotite is present as an accessory mineral.

The values for Fe, Mg, Ca, Ti, Mn, B, Ba, Be, Ni, Pb, Sc, Sr, V, and Y are essentially the same for the pyrite-bearing andesine gabbro at Wadi Agnam (79-OT-24 and 79-TK-1) and the mafic dikes at Jabal Ayub (79-OT-16 and -17). Despite the lack of olivine in the andesine gabbro, Co, Cr, and Cu are a little more abundant in the andesine gabbro than in the mafic dikes at Jabal Ayub. Those elements may reflect the presence of the pyrite. Chemically, the greatest difference between the andesine gabbro and the mafic rocks at Jabal Ayub (table 10) is the rise in abundance of La, Nb, and Zr in the andesine gabbro.

The minor-element composition of the quartz syenite (79-TK-2) in Wadi Agnam closely resembles that of the biotite granite (79-TK-6) at Jabal Ayub (table 10), but both of these rocks differ greatly in composition from the so-called hornblende granite (79-OT-19) at Jabal Ayub.

The geochemical data suggest that the pyrite-bearing gabbro and the quartz syenite near Ath Therwa in Wadi Agnam lack economically useful metals.

Slag from iron smelting at Al Shatt.-- Six samples of slag from iron smelting at Al Shatt (17°01'45" N.; 43°46'15" E.) were taken to add to the data on the minor-element composition of iron slags from the YAR (Overstreet and others, 1976, table 2), to permit petrologic and mineralogic studies of the slag in order to estimate temperatures reached in pyrometallurgical industry in the YAR, and to allow comparison with old slags from the Warda iron mine, Ajlun district, Hashemite Kingdom of Jordan (Overstreet and others, 1982, p. 39-42). The ages of iron mining and smelling in the Sa'dah area have as yet not been reported, although Sa'dah and the village of Al Shatt, N'shur, Tawilah, and Gassaba overlie old piles (Schulze and Thiele, 1978, p. 32), and descriptions of the smelting of iron and of the manufacture of steel at Sa'dah have come down for a thousand years (Al-Hamdani, 945 A.D.). Evidently these activities were surviving as late as 200 years ago (Niebuhr, 1774-8, v. 2, p. 363).

The wide range in physical appearance of the slag from Al Shatt (table 1) may relate more to conditions of smelting and cooling than to a framework of technological development over time. When fragments of charcoal from the slag are dated by C-14 methods, and the results of age determinations are compared with the archaeological stratigraphy, petrography, and chemical composition of slags from the various sites identified by Schulze and Thiele

(1978, p. 32), then it will be known how the pyrotechnology of iron smelting developed over time in the YAR. Of equal interest would be the technological and historical reasons leading to the lack of exploitation of the large gossans in the Kingdom of Saudi Arabia at Wadi Wassat and Wadi Qatan (Jackaman, 1972; Dodge and Rossman, 1975) about 120 km to the north-northeast of Sa'dah.

Microscopic examination of sample 79-OT-38 of black, ropy slag with large gas bubbles showed a smooth-skinned, rounded surface with radial fibrous arrangement of olivine crystals. The interior is finely vesicular with a fine-grained nondirectional arrangement of olivine crystals. The dark-brown scoriaceous slag represented by sample 79-OT-40 consists of a surface composed of a "mush" of small, black crystals of olivine oxidized on their outer surfaces to brown. The interior part of the slag is black and glassy.

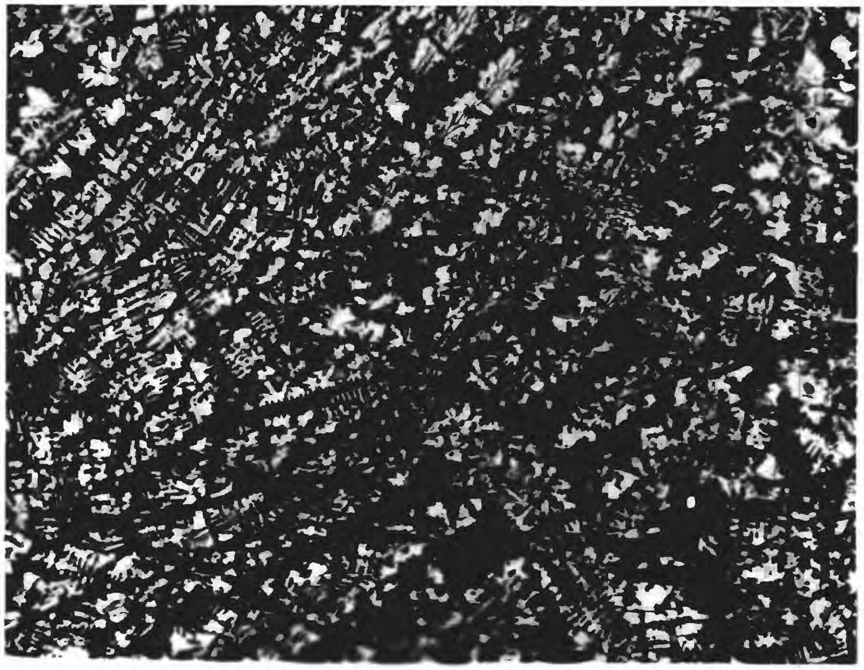
X-ray diffraction patterns and microscopic studies of two of the samples of slag from Al Shatt (79-OT-38, 79-OT-40) showed that they are olivine slags (fig. 11). Diffraction patterns of the crusts of the slags yield broad, wide peaks. Material from the centers of the specimens gives sharp, well-defined patterns of olivine. On the basis of spectrographic data (table 10) and X-ray diffraction patterns, which are somewhat different for the two samples, the olivines are intermediate between fayalite and kirschteinite but close to fayalite (fig. 12).

Powdered material from the crusts of these two samples of slag was heated to 1,100° C and cooled slowly several times in an effort to improve the crystallinity of the samples. Hematite was formed and the patterns for olivine deteriorated further, probably because of oxidation of the iron. Similar oxidation of the slag originally may be the reason for the poor crystallinity of the crust and for the brown oxidation of olivine on the surface of the slag.

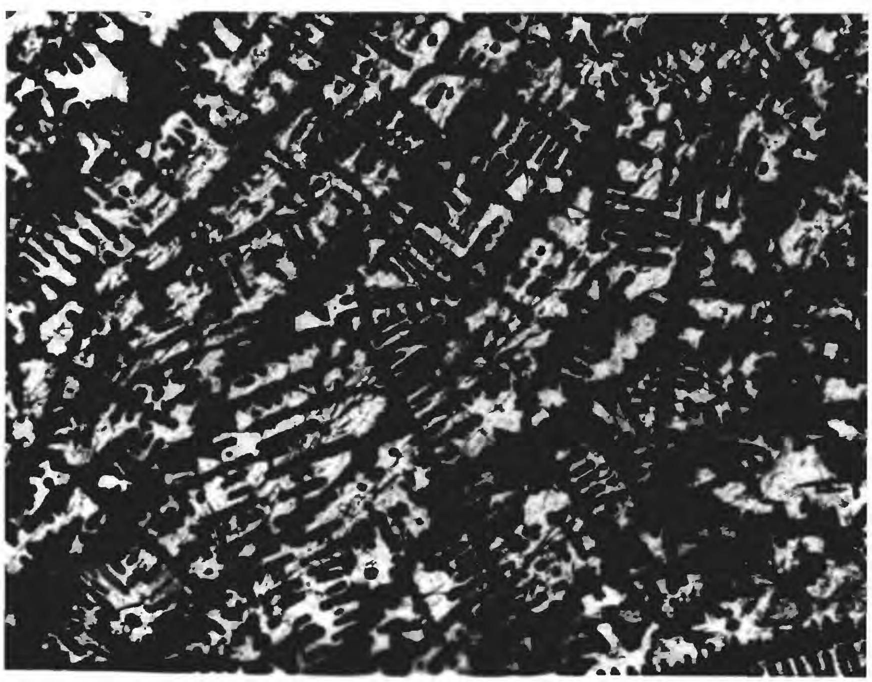
The composition of these olivine slags falls on either side of the minimum point E on the equilibrium diagram for the system Ca_2SiO_4-Fe_2SiO_4 from Bowen and others (1933, fig. 2), given here as figure 12. This minimum represents a composition of 81 percent of fayalite and a temperature of 1117° C. Bowen and associates (1933, p. 273) note that this equilibrium diagram is important to metallurgists..." because slags having such compositions are frequently used and are termed by them, monosilicate or singulo-silicate slags, following a system of naming silicates that has fallen into disuse in mineralogy." Thus, the slags at Al Shatt include mineralogical phases common in modern metallurgy.

Higher melting temperatures than 1117° C may have been reached (Conophagos and Papadimetriou, 1981, p. 367; Maddin, 1981, p. 311-312; Schmidt and Avery, 1983, p. 425-426), but the present data are inadequate to show what maximum temperatures were obtained in the old furnaces of the Sa'dah area. Considering the facts that samples 79-OT-38 contains 15 percent Ca and sample 79-OT-40 has 5 percent of Ca (table 10), that in both samples the abundance of Fe is reported as G(20) percent, and that the curve at the postulated minimum is relatively steep (fig. 12), temperatures on the order of 1200° C may have been reached.

The low-Fe sample 79-OT-39 (table 10) is an agglomerate composed mostly of particles of quartz sand and granule gravel cemented by slag. Its chemical



A. Olivine crystals, 40x.



B. Olivine crystals, 100x

Figure 11. Photomicrographs of dark-brown, scoriaceous slag (specimen 79-OT-40) from iron smelting at Al Shatt, Yemen Arab Republic. (Photomicrographs by Theodore Botinelly, USGS.)

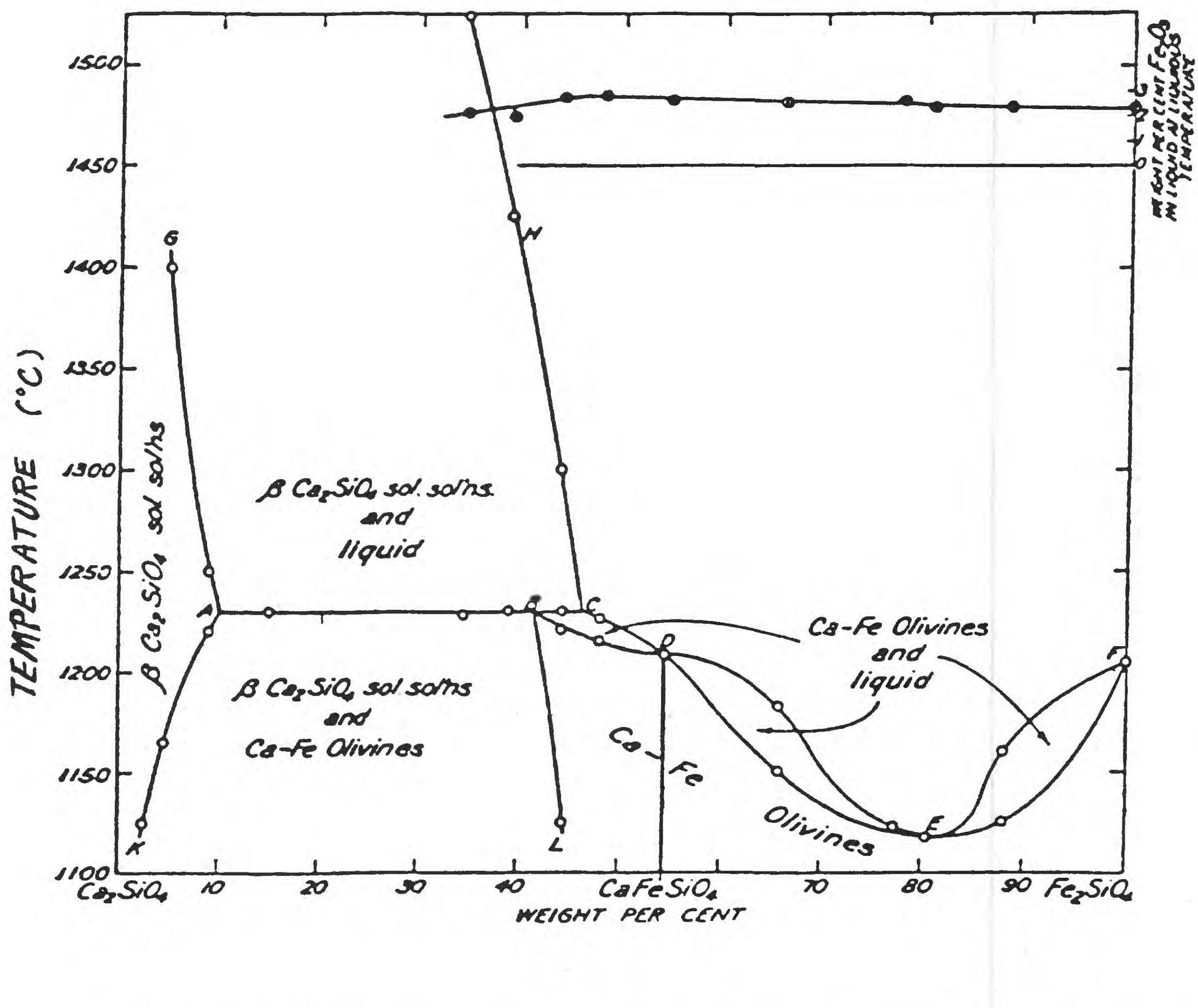


Figure 12. Equilibrium diagram of the system Ca_2SiO_4-Fe_2SiO_4 (after Bowen and others, 1933, fig. 2); the position of the olivine from the slag at Al Shatt, Yemen Arab Republic, fits E of the original diagram, indicating a temperature of crystallization of 1117° C.

composition is thus greatly modified from the typical Al Shatt slags, which contain G(20) percent of Fe, 5 percent of Ca, and rarely vary by more than three laboratory reporting intervals for the other determined elements (table 10). The Mn content of the slags, consistently G(5,000) ppm except in sample 79-OT-39, conforms with values found for Mn in the gossan, and suggests that the iron made from this ore would be Mn bearing. Indeed, the metal made at Sa'dah has been described as Mn steel (Wenner, 1967, p. 27).

The mean values of the elements sought in the slags produced during the smelting of iron ore at Al Shatt are nearly identical to the mean abundances in slag from iron smelting at Sa'dah (table 11). Inasmuch as the sources for the ore, flux, and fuel are essentially the same at these two archaeo-metallurgical centers, as probably were the techniques, this similarity is expectable. However, the similarity in composition of these slags from the YAR with the chemical composition of a slag from smelting at the Warda iron mine, Ajlun District, Hashemite Kingdom of Jordan, is, except for the content of Mn, also great. However, possible chemical differences may be obscured by the technical trancation of the upper and lower limits of determination for nearly two-thirds of the elements sought (table 11). Although the iron ore at Warda consists of aggregates of hematite and limonite that formed in Cretaceous limestone from late-magmatic epithermal metasomatism (Bender, 1974, p. 157-158), and Warda is 1,800 km to the north-northwest of Sa'dah, the minor-element composition of the iron ore at Warda (Overstreet and others, 1982, table 21) is very close to that of the gossan on Precembrian metavolcanic rocks at Sa'dah. The similarity of the compositions of the slags gives the appearance of convergent pyrotechnological processes during antiquity in the two areas.

Manakhah area

Field work in 1975 had disclosed that the Yemen Volcanics, then thought to be of Tertiary and/or Cretaceous age (Grolier and Overstreet, 1978) and here regarded as probably Oligocene and early Miocene in age, are generally little altered except somewhat by deuteric and by later weathering processes. Where these rocks are locally domed by unbreached plutons of Tertiary alkali-feldspar granite, colors of the Yemen Volcanics were thought to indicate possible hydrothermal alteration, and the Manakhah area (15°04'20" N.; 43°44'25" E.) was cited as one such area (Overstreet and other, 1976, p. 19). In that area the basal unit (TKy_1) of the Yemen Volcanics, described as predominantly basaltic but including green felsic conglomerate, porphyritic trachyte, and pink tuffs, overlies the Tawilah Group of Tertiary and/or Cretaceous age, and the Yemen Volcanics are intruded by plutons of Tertiary alkali-feldspar granite (Grolier and Overstreet, 1978).

In 1979 a traverse was made from the main Sana'a-Al Hudaydah highway southward through Manakhah, thence southwestward through Hajarah (15°03'50" N.; 43°41'25" E.) to Attarah (15°03'15" N.; 43°41'25" E.) to cross the basal unit of the Yemen Volcanics in a search for evidence of possible hydrothermal alteration. The route passed to the east of the pluton of Tertiary alkali-feldspar granite at Jabal Masar (15°04'45" N.; 43°40'35" E.) Great thicknesses of basalt overlain and interbedded with green conglomeratic tuff in lahar deposits, andesite tuff and porphyry, dacite porphyry, and green, buff to white tuff were observed, but no evidence for hydrothermal alteration was

Table 11. Comparison of mean compositions of slag from iron smelting at Al Shatt and Sa'dah in the Yemen Arab Republic with slag from the Warda area, Ajlun District, Hashemite Kingdom of Jordan.

[Sources of data: Al Shatt, table 10, this report; Sa'dah, Overstreet and others, 1976, table 1; Warda area, Overstreet and others, 1982, table 21.]

Element	Yemen Arab Republic		Jordan
	Al Shatt (5 samples)1/	Sa'dah (4 samples)	Warda iron nine (1 sample)
In percent			
Fe	G(20)	G(20)	G(20)
Mg	1	1	1
Ca	7	5	10
Ti	0.07	0.15	0.07
In parts per million			
Mn	G(5,000)	G(5,000)	300
Ag	N(.5)	N(.5)	N(.5)
As	N(200)	N(200)	N(200)
Au	N(10)	N(10)	N(10)
B	50	20	N(20)
Ba	200	500	150
Be	3	15	N(2)
Bi	N(10)	N(10)	N(10)
Cd	N(20)	N(20)	N(5)
Co	L(5)	30	L(5)
Cr	70	50	70
Cu	7	20	20
La	N(20)	N(20)	L(20)
Mo	N(5)	N(5)	N(5)
Nb	N(20)	N(20)	N(20)
Ni	5	30	L(5)
Pb	N(10)	L(10)	N(20)
Sb	N(100)	N(100)	N(100)
Sc	7	10	5
Sn	N(10)	N(10)	N(10)
Sr	700	1000	300
V	70	100	150
W	N(50)	N(50)	N(50)
Y	30	150	10
Zn	N(200)	N(200)	N(200)
Zr	70	50	30

1/ Sample 79-OT-39 not included in mean.

seen. Saprolitic weathering and thin paleosols are present, but they are climatic products. To the south of the Sana'a-Al Hudaydah highway and about 18 km east-southeast from Manakhah toward the head of Wadi Zawn (15°03' N.; 43°52' E.) and near Jabal Ahman (15°02' N.; 43°52' E.) general brown and yellow staining of the Yemen Volcanics was seen, but from a distance. The possibility for hydrothermal alteration and sulfide mineralization in the Yemen Volcanics near Jabal Ahman requires investigation.

The 10 samples from unit TKy_1 of the Yemen Volcanics from the Manakhah-Attarah area are described in table 1. Two of these specimens were studied petrographically.

Sample 79-TK-3 is from volcanic tuff that underlies the small settlement of Attarah (15°03'15" N.; 43°41'25" E.). The rock is purple, has a fine-grained texture, and is studded with altered feldspar, quartz phenocrysts, and clasts of tuffaceous rock. Much glassy material in the matrix shows a dense network of perlitic cracks.

Sample 79-TK-4 is from reddish lithic tuff that underlies the village of Hajarah (15°03'50" N.; 43°42'45" E.) where the rock is quarried for building stone and appears to be a principal construction material for the houses in Hajarah. Amethystine quartz in vugs in the tuff is collected for sale as semi-precious stones. This tuff is studded with clasts of other, darker-colored volcanic tuff, and some of the clasts have been flattened when hot by the weight of overlying rocks. Feldspar crystals in the tuff are too altered to permit identification. Shards of volcanic glass are common in the tuff.

The minor-element compositions of these 10 samples from unit TKy_1 of the Yemen Volcanics are listed in table 10 where it is seen that the greatest chemical differences are between the weathered rocks (saprolite samples 79-OT-47, -48, -49) as a group and the fresh rocks represented by the other samples. For most elements reported in the fresh rocks, the variation in abundance is generally within three laboratory reporting intervals, and, within this group, the most characteristic chemical difference is the tendency for Cr and Cu to be more abundant in the green-colored rocks (79-OT-50, -51, 79-TK-5) than in the others. Compared with the fresh rocks, some elements in the saprolite are depleted or enriched:

Depleted elements	Enriched elements	
Ba	Fe	Cu
Be	Mg	Mo
La	Ca	Ni
Nb	Ti	Sc
Pb	Co	Sr
Zr	Cr (?)	V

The depleted and the enriched elements in the samples of saprolite resemble those reported for chalcedony of secondary origin from unit TKy_3 elsewhere in the YAR (Overstreet and others, 1976, p. 19-21). Indeed, the composition of the fresh rocks from unit TKy_1 of the Yemen Volcanics exposed at Manakhah (table 10) is remarkably similar to the minor-element content of rocks from units TKy_1 and TKy_4 of the Yemen Volcanics exposed elsewhere in the YAR (Overstreet and other, 1976, table 4).

Lanthanum, Nb, and Pb are more consistently present in these samples from unit TKy_1 of the Yemen Volcanics than in any other material reported in table 10.

The minor-element data for the Yemen Volcanics in the Manakhah-Attarah area do not indicate the presence of hydrothermal mineralization.

MINERAL EXPLORATION IN THE SA'DAH AREA

The brief visit to the Sa'dah area, YAR, in 1979 confirmed the writers' earlier views (Overstreet and others, 1976, p. 33-55) that the gossan at Jabal Al Maidan was formed from the weathering of stratabound massive sulfides in volcaniclastic rocks of Precambrian age identical to deposits along strike in Saudi Arabia (Weissenborn and Earhart, 1968; Overstreet and Rossman, 1970; Jackaman, 1972; Dodge and Rossman, 1975; Overstreet and others, 1978; Roberts and others, 1978). This interpretation whose mapping and analyses was also adopted in the final report of the German Geological Advisory Group in the YAR (Schulze and Thiele, 1978, p. 30-40) for the deposit at Jabal Al Maidan, but the report noted chemical differences between groups of deposits in the Sa'dah area. The elements sought in that program were Cu, Pb, Zn, Co, Ni, Hg, Ba, As, Au, and Se (Schulze and Thiele, 1978, p. 38-39). The results show local high values in the gossan of the Jabal Al Maidan area of up to 200 ppm As, 200 ppm Ni, and 60 ppm Cu, and in the Jabal Al Ma'aden area of 60-550 ppm As, 300-1,000 ppm Ni, 6-300 ppm Co, and 3,0006,000 ppm Zn. It is possible, of course, that such high concentrations reflect co-precipitation with secondary Fe minerals during weathering, but at the Wadi Qatan gossan in Saudi Arabia, where the massive sulfides below the gossan have been tested by drilling, the surface gossan was shown to be depleted by factors of 5-10 relative to the unoxidized sulfides in Cu, Pb, Zn, Ni, and Co (Dodge and Rossman, 1975, p. 58). Therefore, exploration by drilling is justified at selected gossans in the Sa'dah area. Further search for sulfide deposits similar to those at the Kutam and Al Massane mines in Saudi Arabia near the border to the north of Sa'dah (Roberts and others, 1978; Blank and others, 1980) is justified.

Jabal Al Maidan mine

Surface features

A large, ancient, open-pit mine is located at Jabal Al Maidan (also reported as Jabal Al Maida, Jabal Al Maidah, and even known locally as Jabal Ahsen; 17°01'30" N.; 43°46'40" E.) about 9 km to the north-northeast of Sa'dah (fig. 13). The mine apparently was worked for iron as there is no visible evidence of other metals in commerical quantity at the outcrop nor in analytical results of samples taken from the outcrop (this report, table 10; Schulze and Thiele, 1978, p. 39). A substantial tonnage of gossan has been mined from the deposit, as is indicated by the dimensions of the open pit, which is about 300 m long, 30 m wide, and at least 10 m deep. The bottom of the pit is covered with rubble locally, and in those covered areas the pit appears to have been mined to greater depths. A much smaller and somewhat discontinuous pit 3-4 m wide and 1-2 m deep, is parallel to the principal open pit and about 50 m to the west. Slag piles at the outskirts of the nearby village of Al Shatt. indicate that some of the iron ore was probably smelted there. Larger piles of slag, however, underlie the eastern part of the city of Sa'dah. This slag

A. View toward north from south end of pit.

B. View of adits in pit.

Figure 13. Photographs of Jabal Al Maidan ancient open-pit iron mine 9 km to the north-northeast of Sa'dah, Yemen Arab Republic.

also probably was derived partly from iron ore mined at Jabal Al Maidan. Indeed, the position of the slag at Sa'dah indicates that the city may have originated as a smelting site for material mined from Jabal Maidan and other iron deposits in the area.

Minerals of the deposit

Hematite and goethite, secondary iron minerals derived from the oxidation of pyrite, together with ferruginous chert form the gossan at Jabal Al Maidan and were the principal materials mined (table 12). Unmined segments and fragmental masses of gossan remain in the pit. Many of these show brecciated hematite and goethite. The brecciated fragments are cemented together by

Table 12. Mineral composition of gossan from ancient iron mines at Jabal Al Maidan and Jabal Al Ma'aden near Sa'dah, Yemen Arab Republic.

[Descriptions based on X-ray diffraction studies by Theodore Botinelly, USGS, 1979.]

Sample number	Description
	Jabal Al Maidan
79-OT-8	Dark reddish-brown, medium soft pebbles of hematite, goethite, and quartz, from central part of gossan.
79-OT-9	Dark reddish-brown to black, hard gossan composed of hematite, goethite, and quartz, shows layered structure and inclusions, from west side of gossan.
79-OT-12	Dark brown gossan with strong boxwork structure, septa in boxwork have red centerline and are dark brown outside, consists of hematite, goethite, quartz, and carbonate(?).
	Jabal Al Ma'aden
79-OT-26	Massive greenish-brown gossan coated with granular yellow and white silt and with dark brown porous and white flakey material, goethite.
79-OT-27	Thoroughly leached white to yellow to ochre-colord clayey septum in gossan, yellow outside coating is mottled white and light-yellow clay, gossan consists of goethite and kaolinite.
79-OT-28	Limonitic gossan mottled red, yellow, and white with yellow coating, contains unidentified glassy mineral, gossan consists of goethite and carbonate mineral (?).
79-OT-31	Hard, dark brown gossan with botryoidal surface of radiating fibers around 5 mm in length, massive center, goethite, from north-central part of deposit.
79-OT-32	Hard, dark brown to black, irregularly banded gossan, agate-like banding in bright red, dark brown, and light brown with some fibrous inner layers, goethite, from northern end of deposit.

chert. These fragments are typical of collapse breccias. They appear to have formed by the oxidation of pyrite and the formation of secondary iron oxides leading to decrease in volume owing to removal of material. Gravity settling and compaction into the resulting voids formed the breccia. Dolomitic marble, conformable in strike and dip to the gossan, crops out along the east side of the large open pit (fig. 14), and north of the pit dolomite extends across the strike of the projected ore body. Although not seen in the pit, the dolomitic marble may be interbedded in the primary ore body. If it is, dissolution cavities in the dolomitic marble, caused by migrating ground water, also may have contributed to the decrease in volume of the original mass and contributed to the formation of the collapse breccia.

Geologic setting

The Jabal Al Maidan deposit is a stratabound, massive sulfide body interbedded in volcaniclastic rocks of Precambrian age. The brief visit to the deposit by the writers on the afternoon of January 25, 1979, did not allow time to map the geology of the locality; however, sketched and generalized geologic features at the mine are shown in figure 14. A thin unit of steeply dipping dolomitic marble and chert forms the east wall of the pit. Adjacent and conformable to the marble is thin-bedded, green, chlorite schist in which are thin interbeds of carbonaceous material which, in hand specimen, appears to be graphite. Schistose volcanic tuff underlies the eastern foot of the jabal. Tuffaceous greenschist extends along the western side of the open pit and interbedded in the schist, about 50 m from the large pit, is a smaller gossan that has been mined somewhat discontinuously in small pits. The west side of the jabal is underlain by massive metamorphosed basalt. Foliation in the metamorphosed volcanic rocks and conformable bedding in the enclosed marble strikes to the north and dips steeply.

Comparison with similar rocks in Saudi Arabia

Our interpretation of the Jabal Al Maidan deposit as a stratabound massive sulfide deposit is based not so much on our brief inspection of the mine as it is on our several years of experience in the geologic mapping and examination of mineralized localities in southern Saudi Arabia. At a number of nearby localities in that country, Precambrian host rocks and interbedded gossans are identical to the Jabal Al Maidan deposit in the YAR.

For example, along the highway leading westward from Najran to Khamis Mushayt in Saudi Arabia, at about long. 43°54' E., is a south-trending, steeply dipping cherty gossan some 30 m thick interbedded in a unit of tuffaceous greenschist that is bounded on the west and on the east sides by greenschist and interbedded carbonaceous material. Relict pyrite is to be seen in some broken fragments of the gossan. This gossan-bearing greenschist has been mapped southward to the border with the YAR, and inspection of LANDSAT imagery of the region shows the belt of schist to continue toward the south and to project into the Jabal Al Maidan area. This belt of schistose rocks has been mapped for about 90 km northward from the Najran-Khamis Mushayt highway to an area where it is terminated by intrusive rocks and regional faulting. Equivalent rocks, however, believed to be an extension of the belt, crop out to the east in the vicinities of Wadi Qatan and Wadi Wassat.

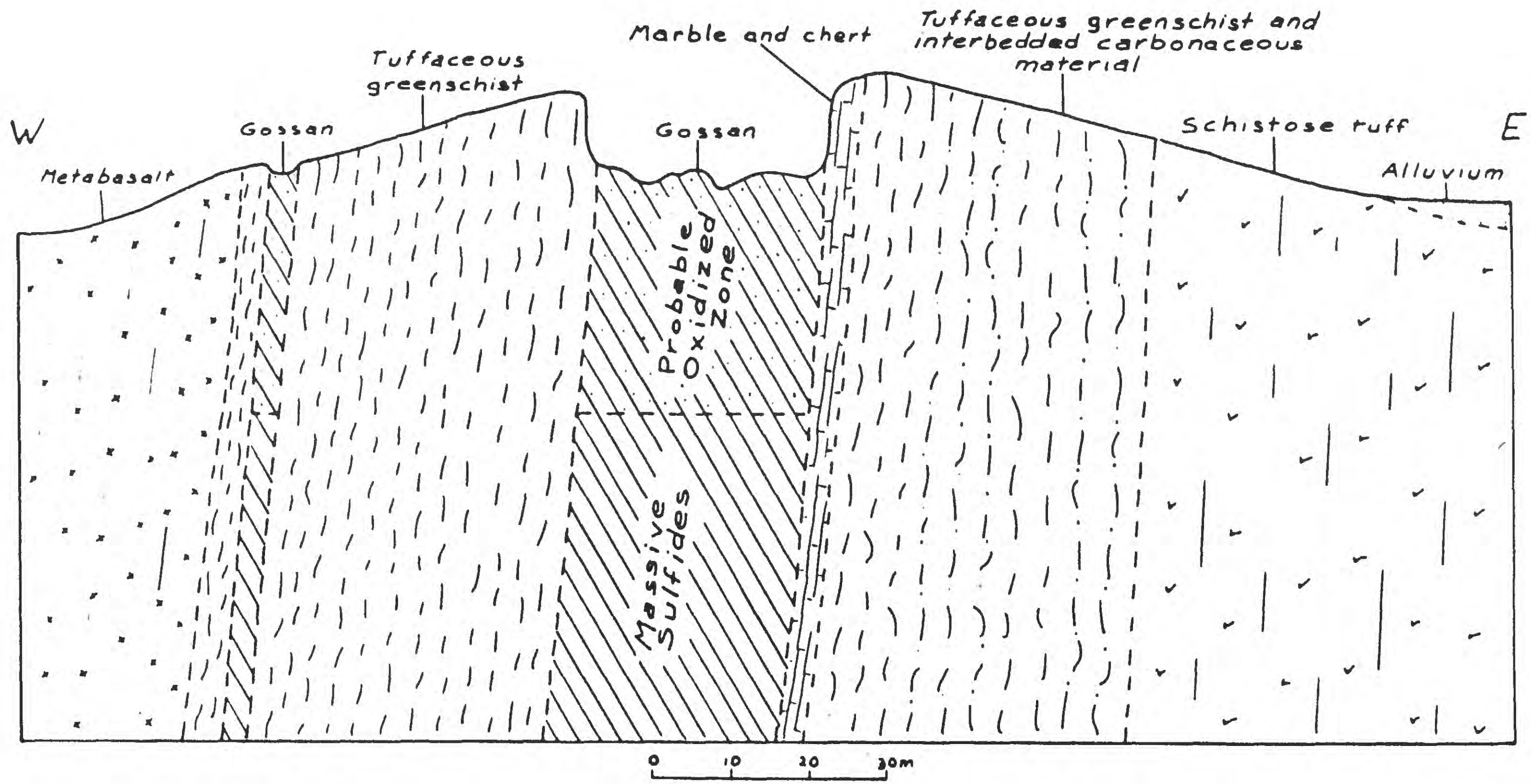


Figure 14. Sketched cross section across the south end of Jabal Al Maidan open-pit iron mine, looking north, Sa'dah area, Yemen Arab Republic.

Many diamond drill holes have been bored beneath gossans in the Wadi Qatan and Wadi Wassat area. Some of these have successfully passed through thick sequences of pyrite and pyrrhotite. At the Nahum gossan (18°07' N.; 44°08' E.) a drill hole disclosed a body of massive pyrite and pyrrhotite calculated to be 47 m thick. Several exposures of gossan, collectively referred to as the Hadbah gossan (18°09' N.; 44°09' E.), form a north-trending belt 2 km long. Several of these gossans have been tested by drilling, and some holes have intersected nickel minerals in commercial grade. Pentlandite intergrown with pyrrhotite is the principal nickel sulfide mineral. Core from the Arabian Shield Development Company's No. 3 hole assayed as much as 3.2 percent nickel (Dodge and Rossman, 1975). About 18 km to the north-northeast of Wadi Qatan, in the Wadi Wassat area, the U.S. Geological Survey Saudi Arabian Mission drilled 9 holes beneath gossans in country rock strikingly similar to that at Jabal Al Maidan in the YAR. The gossans crop out along a northerly-trending strike length of 17 km, and the massive sulfide deposits beneath them have been described (Overstreet and Rossman, 1970) as pyrite and pyrrhotite interbedded in tuffaceous metasedimentary rock of andesitic composition and associated andesite. Weissenborn and Earhart (1968) appraised the results of the drilling and described thicknesses of pyrite and pyrrhotite of 35-40 m. No copper or other metals of commercial value were found although the total aggregate of material indicated by drilling was calculated at about 125 million tons containing more than 80 percent of pyrite and pyrrhotite.

Along north-trending Wadi Bidah in Saudi Arabia, over a strike length of 45 km between 20°22' N. and 20°46' N. and 41°18' E. and 41°30' E., are many gossans, several of which have been explored by drilling. The gossans are bounded conformably by volcaniclastic schist, most of which is andesitic to dacitic in composition. Some of the schist contains interbedded carbonaceous materials. Some deposits have thin units of dolomitic marble along one side or even conformably within the deposit. Massive pyrite ranging in thickness from 1-47 m has been found by drilling beneath the gossan, as have mineralized bodies containing Cu and Zn with trace amounts of Ag and Au (Kiilsgaard and others, 1978). Study of the carbonaceous material, which was originally mapped as graphite interbedded in the volcaniclastic sedimentary rocks, showed that it probably originated as algae deposited on the sea floor in a rather shallow-water marine environment. The algal beds were covered from time to time by sediments and volcanic ash deposited in the sea. Subsequent metamorphism of the volcaniclastic sediments converted them to greenschist, a metamorphic rank not sufficiently high to convert the algal carbonaceous material to graphite. Drill cores show the carbonaceous material to be interbedded and conformable to the massive pyrite and other sulfide minerals, which indicates that these also were deposited on the sea floor. The sulfide minerals show evidence of having undergone the same metamorphic processes that affected the enclosing volcaniclastic rocks, which is further evidence for the early origin of the sulfides.

Many other massive sulfide deposits in Saudi Arabia could be described, all of which show geologic features similar to the Jabal Al Maidan deposit. The generalized features of these deposits, including the ones described above, can be summarized as deposits of massive pyrite interbedded conformably in volcaniclastic rocks in which carbonaceous material and dolomite are interbedded. Locally, concentrations of other sulfide minerals are intermixed with the pyrite at one or more stratigraphic horizons. Regionally, the enclosing rocks have been metamorphosed to the greenschist facies. Commonly, the suface expression of the massive sulfide deposits is deep gossan produced by weathering during Quaternary time.

Exploration techniques suitable for Jabal Al Maidan and similar deposits

Massive sulfide deposits of the type predicted to be present at Jabal Al Maidan are easily explored by diamond drilling. The sulfides core well, and good recovery of core is obtained, particularly from the larger core barrels of NX and BX sizes. Most Precambrian massive sulfide deposits in the Arabian Shield dip steeply and are commonly oxidized to a depth of at least 30 m below the ground surface. Inasmuch as scant information can be obtained from the oxidized zone, despite the importance of detailed studies of the gossan prior to drilling (Blanchard, 1968; Ryall and Taylor, 1981), it is necessary to position the drill holes so as to reach the deposits beneath the zone of oxidation at depths greater than 30 m. Very little information can be otained from drilling vertical holes. Either the hole tends to miss the steeply dipping deposit entirely, or, if sited on the gossan, simply will drill more or less down the dip of the deposit and thereby give false information on the thickness. Such a hole may completely miss mineralized beds that trend parallel to the walls of the deposit. In the Wadi Bidah area of Saudi Arabia, for example, bands of chalcopyrite follow traces of bedding that are marked by carbonaceous material, and some of these bands contain as much as 8 percent of Cu. These bands (beds) give the overall deposit values in Cu that attain commercial grade, yet had the vertically dipping deposit been explored by vertical holes, the holes could have passed through parallel and adjacent barren pyrite and given little, if any, indication of the chalcopyrite or of other minerals that are present.

Diamond drill holes bored in inclined sedimentary or layered rocks tend to divert from their originial inclinations and orient normal to bedding. Also, because the drill rod turns clockwise (to the right), the drill bit tends to deviate to the right away from the bearing on which the hole is drilled. To compensate for these deviations, any hole designed to test a deposit like that at Jabal Al Maidan should be sited so as to intersect the deposit at right angles to the strike of the deposit. The angle of inclination of the hole should be such that the hole would test the thickness of the deposit at a depth of at least 100 m below the surface. Thus, at Jabal Al Maidan, a hole located 100 m west of the west side of the open pit, drilled on a due east bearing and at an inclination of 45°, should intersect pyrite at a length of 135-150 m, and at a depth of about 120 m below the bottom of the open pit.

Jabal Al Ma'aden mine

The Jabal Al Ma'aden mine (16°53'00" N.; 43°49'05" E.) explores a massive gossan that crops out along the crest of a ridge 8 km by road to the northeast of Sa'dah, (fig. 15). The gossan strikes N.15° E., reaches widths of 30 m, and is about 500 m long. Much of the gossan is composed of hematite and chert, although locally masses of fibrous, botryoidal, black goethite of museum quality, magnesite, and kaolinite are present (table 12). Secondary copper minerals were not observed.

A. View looking north of rubble of gossan on east side of mine.

B. View looking northwest from east side showing gossan and magnesite near south end.

Figure 15. Photographs of east side of gossan at Jabal Al Ma'aden iron mine, Sa'dah area, Yemen Republic.

Gabbro and amphibolite form the wall rocks along the sides of the gossan, which at its northern and southern ends is enclosed in magnesite. The presence of the magnesite distinguishes the Jabal Al Ma'aden deposit from the various bodies of gossan over massive sulfide deposits of volcaniclastic origin in southwestern Saudi Arabia. Very large bodies of magnesite are known in Saudi Arabia, but they are in the northern and north-central part of the Precambrian Shield far from the border with the YAR (van Daalhoff, 1974, pl.2)

Several ancient pits have been excavated in the gossan, but no appreciable tonnage of ore appears to have been mined. No significant quantities of any metal of commercial value were detected in the samples (table 10), but very small amounts of Mo and W were detected, which chemically distinguish this deposit from gossan at Jabal Al Maidan.

Any investigation of the ore deposits in the Sa'dah area necessarily would require drilling into the deposit under the gossan to determine what the gossan was derived from.

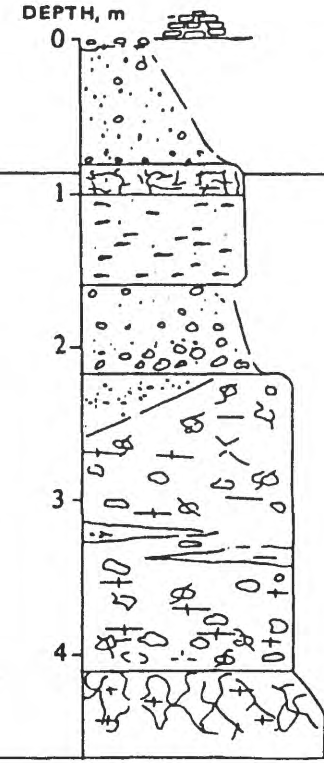
QUATERNARY ALLUVIAL STRATIGRAPHY OF SILT

Relations at auriferous placers in Saudi Arabia

The importance of Quaternary alluvial stratigraphy, of processes in the deposition of loessic silt, and of radiocarbon ages to an understanding of the economic geology of auriferous placers in the Arabian Peninsula has been made clear by detailed investigations in Saudi Arabia. There, at the Jabal Mokhyat placer area (Schmidt and others, 1982, p. 1), which occupies 30 km^2, gold has been found to be (fig. 16) "... sparsely distributed in locally derived, flood-deposited, immature gravels throughout a stratigraphic section that consists of 1) calichified, saprolitic bedrock of Precambrian age; 2) basal, intensely calichified, saprolitic gravel (0-3 m thick) of Pleistocene age; 3) disconformable, slightly consolidated gravel and sand (0-1 m thick) of late Pleistocene age; 3) disconformable, slightly consolidated gravel and sand (0-1 m thick) of late Pleistocene age containing sparse, disseminated caliche; 4) firm loessic silt (0-1 m thick) of early Holocene age; and 5) loose sand and gravel (0.3-1 m thick) of late Holocene age. The loessic silt accumulated during the Holocene pluvial. The top of the loessic silt unit is dated at about 6,000 years B. P. by using charcoal from hearths of ancient man. Following the Holocene pluvial, the climate became arid, and extreme dessication resulted in abundant eolian sand that progressively diluted the late Holocene gravels. The remnants of the pre-Holocene stratigraphy suggest similar climatic cycles during the Pleistocene."

General observations in the Yemen Arab Republic

All the features of the Quaternary alluvial stratigraphy described for the Jabal Mokhyat area (Schmidt and others, 1981) have been observed in the YAR. These include saprolite on Precambrian rocks; loessic silt containing fossils of molluscs and gastropods as well as carbonate layers and concretions



Climate	Geologic time	Carbon dates (years B.P.)	Thickness (in meters)	Description
		2,620±250		Placer mining
				Stone monuments (Early Dilmun(?) 5,000-3,800 yrs B.P.)
Extremely arid	–		0-0.05	Black desert patina, cobble pavement. Trace caliche
Arid	Late Holocene		0.25-1.0	Gray, washed sand and gravel, nonconsolidated. Reddish-buff, washed eolian sand, abundant
		5,930±300		Hearthsite, ancient man. Medium, buff gray humic soil, weakly developed
Pluvial 9,000-6,000 B.P.	Holocene (altithermal)	--	0.5-1.0	Buff loessic silt, washed, coherent
Arid	Late Pleistocene	--	0.5-1.0	Gray to buff gravel and sand, slightly consolidated, some white calcite-coated cobbles
Cyclical pluvial and arid	Pleistocene	--	1.0-3.0	Red and white calcified, saprolitic gravel and sand. Semicalcified red sand on top is washed eolian sand
				White and drab-green saprolitic bedrock, calcified

Figures 16. Quaternary stratigraphic column for the Jabal Mokhyat gold placer area, Kingdom of Saudi Arabia (from Schmidt and others, 1982, fig. 5; carbon-14 dating by Meyer Rubin, USGS.)

such as loess puppen (loess nodules), and dark gray to black humic layers rich in organic carbon; eolian sand; gravel with desert varnish; and artifacts (Overstreet and others, 1976, p. 22-30; Grolier and others, 1977, p. 59-65; Grolier and Overstreet, 1978). Large features such as the distributions of eolian sand, loess, and alluvial gravel heavily coated with desert varnish are discriminated on the geologic map of the YAR (Grolier and Overstreet, 1978), and the complex interrelations of the Quaternary sediments with the volcanic rocks of the Aden Volcanic Series (?) are shown. Notes made during field trips in 1975 and 1976 by Grolier and Overstreet comment on saprolitic boulders in Quaternary gravel near Jabal Abelle (16°56'20" N.; 43°47'40" E.), sequences of loessic silt up to 10 m thick and particularly well developed in the southern part of the YAR in the vicinity of Ibb (13°58'06" N; 44°11'42" E.; fig. 17A) and Ta'izz (13°34'05" N.; 44°01'24" E.) but also at the crest of the Red Sea Escarpment (fig. 17B) to the east of Wadi Da'ud (15°13'38" N.; 44°00'00" E.). Other large deposits of loessic silt were mapped (Grolier and Overstreet, 1978) at Dhamar (14°33'08" N.; 44°23'50" E.), Ma'bar (14°17'44" N.; 44°17'14" E.), Ma'rib (15°25'30" N.; 45°20'18" E.), and Sa'dah (16°56'44" N.; 43°45'25" E.). Those at Dhamar and Ma'rib are spatially associated with Quaternary volcanic rocks of the Aden Volcanic Series (?). Loessic silt is veneered with gravel, some coated with desert varnish, to the north of Ta'izz and in the vicinity of Bajil (15°03'16 N.; 43°16'48" E.). At Al Akhmah (figs. 17C and 17D) about 10 km from At Turbah (13°12'40" N.; 44°07'35" E.), an exposure of loess consists of a lower gray-brown unit in which loess puppen are strongly developed separated by a distinct disconformity from overlying buff loess lacking loess puppen. The older deposit appears to be naturally formed, whereas the younger is of historical age and was formed by impoundment of water behind man-made dams.

These sequences in the YAR have not been studied by the writers, nor have the writers visited the historically recorded alluvial gold placers near Sirwah (15°27.5' N.; 45°01' E.) on Precambrian rocks exposed about 35 km to the west of Ma'rib (Halevy, 1872, p. 53-54), but the impression from rapid reconnaissance is that the thick deposits of loess in the southern part of the YAR are older than the loessic silt in the Jabal Mokhyat area, but, in their upper parts may include loess of the same age as that at Jabal Mokhyat in Saudi Arabia.

The useful role of stone artifacts associated with Quaternary sedimentary deposits in the YAR has yet to be exploited in the correlation and dating of these deposits and surfaces, as has been done successfully in the Hashemite Kingdom of Jordan (Bender, 1968, p. 99-100). Typologically Paleolithic artifacts have been reported for the Sa'dah area (Overstreet and others, 1976, fig. 8), and pebble tools found by de Bayle des Hermens (1976) about 11 km north of Ma'rib and 1 km to the north of Ma'rib airport imply a Mousterian cultural stage at the latest and possibly a late Pleistocene (Wurm or earlier) age for the terrace surface on which they were found. The age of these tools would also assist in dating the lava flows of the Aden Volcanic Series (?) at this site (Grolier and Overstreet, 1978). Stone tools of Acheulean age, estimated to be 200,000-400,000 years old, are known at Jabal Tala and Qarn Qaimah in the PDRY (Doe, 1971, p. 137, 227). The possible range in age of stone tools in the YAR is great, and the study of these artifacts could contribute to the dating of Quaternary deposits and surface in the YAR.

A. View near Ibb showing fossiliferous loess over 10 m thick with black paleosols.

B. View near crest of Red Sea Escarpment on highway between Al Hudaydah and San'a of loessic silt held up by gravel bars.

Figure 17. Photographs of deposits of loessic silt in the Yemen Arab Republic.

C. View of fossiliferous loess near Al Akhmah.

D. View of fossiliferous loess near Al Akhmah showing collecting site.

Figure 17. Photographs of deposits of loessic silt in the Yemen Arab Republic--continued.

Detailed sequence at Ma'rib

A brief visit in 1976 to the townsite of Ma'rib and its famous ruined dam--Sadd Ma'rib (Hitti, 1956, p. 54) built across the water gap between Jabal Balak Al Qibli on the north and Jabal Balak Al Awsat on the south about 9 km upwadi from Ma'rib (Wissman, 1953, p. 85-86; Grolier and others, 1981, p. 21)--afforded Schmidt an opportunity to observe sedimentary deposits associated with these ancient structures. The older parts of Sadd Ma'rib were built about 2,700 years ago, and, although the dam was breached several times and repaired during its long life, its final destruction by catastrophic flood took place between 542-570 A.D. according to Hitti (1956, p. 64) or about 575 A.D. in the view of other writers (Dayton, 1975, p. 58; 1979; Wade, 1979). This collapse is the subject of verse 16 in chapter 34 Soorat-ul-Saba of the Koran

Various names appear in the literature in reference to the wadi: Wadi Adhanah upstream from the dam and Wadi as Sudd, also Wadi Saba, downstream from it (United Kingdom Ministry of Defence, 1971), Wadi Danah (Bowen and Albright, 1958, fig. 148), Wadi Dhana (Dayton, 1975, fig. 6), and Wadi Dana (Wade, 1979). The reach of the wadi below the water gap and dam and extending northeastward to Ma'rib takes its name of Wadi as Sudd or Wadi Saba in recognition of the great dam, or, alternatively, of the high Sabaean civilization responsible for Ma'rib. Farther toward the northeast the name Wadi Abrad is applied. Recent usage in the hydrologic literature retains the name Wadi Adhanah for the entire drainage basin to the confluence with Wadi Jawf, but this usage recognizes the names Wadi as Sudd in the reach at Ma'rib and Wadi Abrad downstream from Ma'rib to Wadi Jawf (Grolier and others, 1981, p. 53-54).

The sequence of sediments observed by Schmidt is at a natural exposure in the bank of Wadi as Sudd at the southern edge of Ma'rib townsite (15°25'30" N.; 45°20'18" E.).

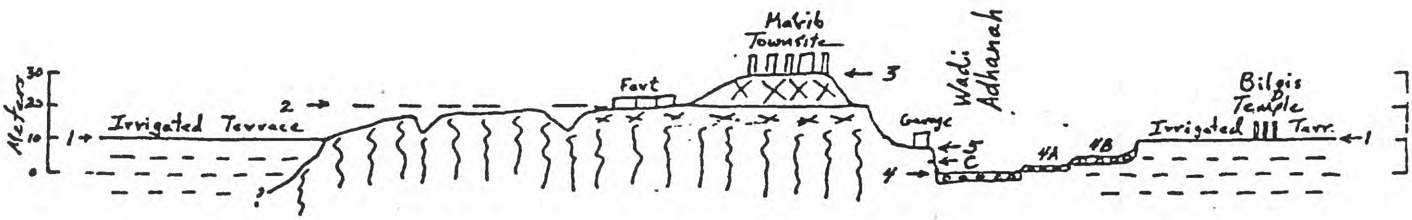
The Wadi Adhanah drainage basin is the largest system in the Wadi Jawf catchment area which, leading across the Ramlat as Sab'atayn to the Arabian Sea via the Wadi Hadramawt, is the largest catchment area in the YAR (Grolier and others, 1981, p. 49). In this report, owing to the need to refer to gradients within the entire drainage basin, the name Wadi Adhanah is used, but it is recognized that at the townsite of Ma'rib the conventional name for this intermittent stream is Wadi as Sudd.

The bank of Wadi Adhanah (Wadi as Sudd) was interpreted originally in terms of natural river-valley stratigraphy, but subsequent radiocarbon dating (see section below) afforded an alternative explanation of the stratigraphic section. Evidently the charcoal-bearing unit exposed in the bank is a low-level Sabaean tell and is associated with cultural development instead of natural alluvial stratigraphy. Nevertheless, cultural adaptation at Ma'rib is tied to the geomorphology and alluvial stratigraphy of Wadi Adhanah (Wadi as Sudd).

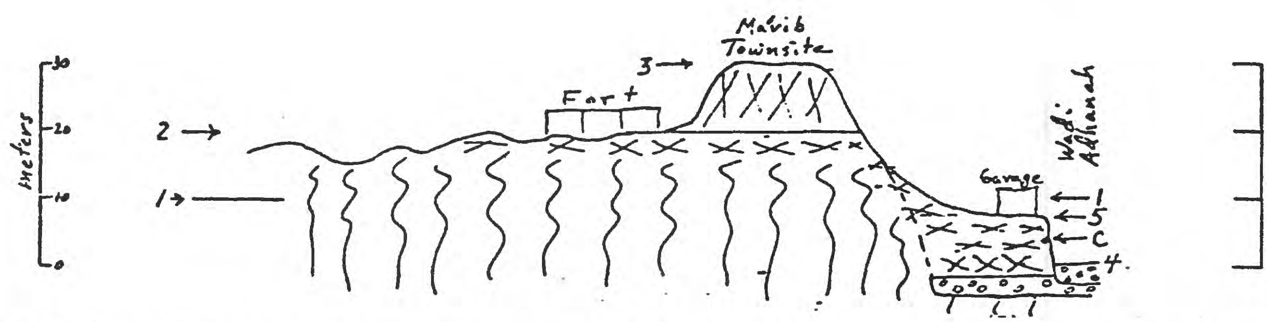
At and surrounding Ma'rib townsite are five levels of natural and man-made sedimentary deposits which are described in table 13 and in figures 18, 19, and 20. The deposit beneath the garage level (level 5), consisting of brown, water-lain silt and exposed at in situ ruins constitutes a subsidiary Sabaean tell according to the radiocarbon date from the charcoal. At this locality one distinct stratigraphic line of charcoal extends horizontally for several tens of meters and is well exposed about 4.5 m above the channel level. The dated charcoal, located in the bank of Wadi Adhanah (Wadi as Sudd) about 3 m above

Table 13. Surface levels at Ma'rib, Yemen Arab Republic.

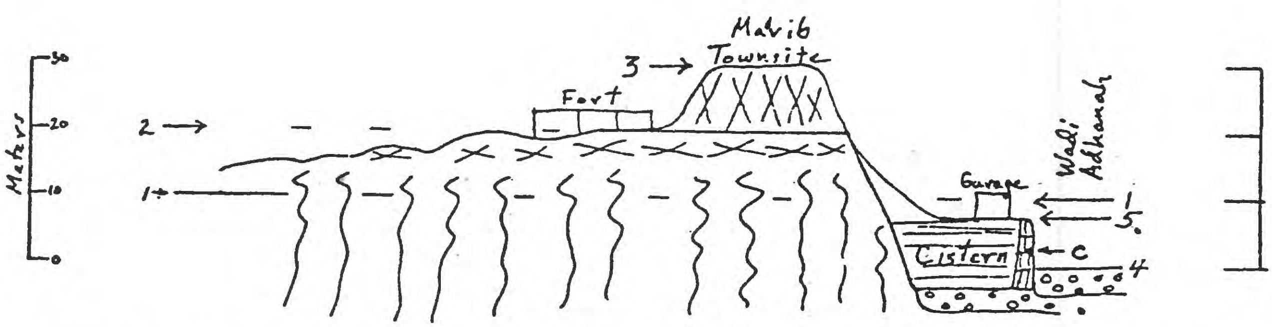
Level	Description
1.	An irrigated terrace or level lies to the north, west, and east of Ma'rib and consists of light-buff flood silt that was irrigated by water from Sudd Ma'rib. This terrace is about 10 m (not measured) above the modern channel of Wadi Adhanah (Wadi as Sudd). Similar Holocene silt terraces in the Najd of Saudi Arabia are dated about 6,000 years B.P. by charcoal (Schmidt and others, 1981, p. 22; this report fig. 16).
2.	The fort level, at and about Ma'rib and upon which the Turkish (?) fort is built, constitutes a higher, dissected silt deposit that may be the remnant of an older, late Pleistocene silt terrace. Alternatively, it could be an uplifted part of the Holocene irrigated silt terrace--uplifted by faulting, salt tectonics, or even subterranean volcanic swell--but such is improbable. This silt is of a darker light-buff color than that in level 1, and it is darkest at Ma'rib where it merges into an old, Sabaean (?) tell. The fort level is about 10 m (not measured) above the irrigated terrace of level 1. This local, natural height above the surrounding plain is doubtless the reason the place was chosen as the ancient Sabaean townsite. A comparison with the site at the airport where stone implements were found by de Bayle des Hermens (1976) is needed.
3.	Superposed on the fort level, i.e., upon the combined dissected silt deposit and old Sabaean tell is the tell of Ma'rib. This more recent (perhaps Islamic) tell deposit is a dark buff to brown color owing to its high content of organic material. The Ma'rib tell is estimated at 20 m (not measured) above the irrigated terrace of level 1. The modern, bombed-out and abandoned town of Ma'rib stands upon the Ma'rib tell.
4.	Wadi Adhanah (Wadi as Sudd) is incised about 10 m (not measured) below the irrigated terrace at level 1. The incised valley is about 2 km wide and is occupied by an annually flooded channel about 0.5 km wide and by terraces at various levels (fig. 18A, terraces 4A, 4B, etc.). No attempt was made to determine whether any of these terraces are natural fill terraces or perhaps related to the destruction of Sudd Ma'rib about 575 A.D. At the Ma'rib townsite, coarse cobble gravel is exposed in the lowest scour holes of the active channel, but most of the surface of the flood channel consists of fine sand.
5.	The garage level constitutes a small area less than 100 m wide between the Ma'rib tell and the incised Wadi Adhanah (Wadi as Sudd). This fifth level upon which the police garage is built is anomalous and is not easily interpreted. The fifth level is estimated to be 2-3 m (not measured) below the irrigated terrace of level 1; that is, 7-8 m above the channel of Wadi Adhanah (Wadi as Sudd). This is the source of the dated charcoal sample (laboratory number W-3457; field number Ma'rib 758) which was taken from a vertical exposure 7-8 m high on the northern bank of Wadi Adhanah (Wadi as Sudd) (figs. 19B and 19D). The deposit consists of brown, water-lain silt and *in situ* ruins of brick and block walls.



A.--Schematic cross section of the proposed surface levels at Ma'rib. (1) The irrigated silt terrace, (2) the Fort Level or older, dissected silt terrace, (3) tell of Ma'rib, and (4) the broad modern flood channel of Wadi Adhanah. (5) The garage level or terrace oddly does not seem to fit any of the above 4 categories; it contains the river bank ruins from which the 500 B.C. charcoal (C) date came.

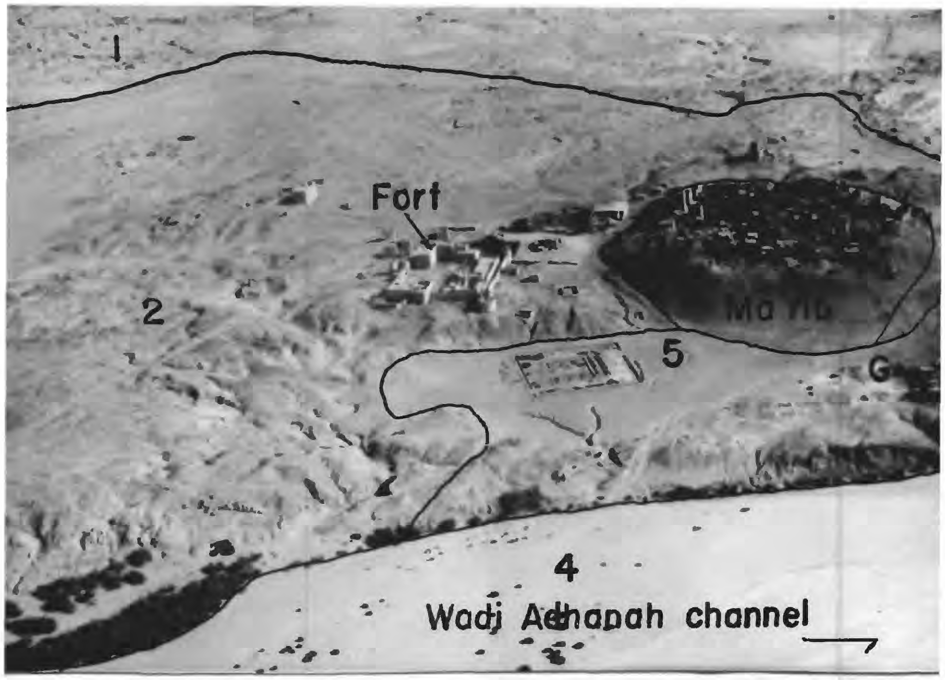


B.--Schematic cross section showing the river bank deposit (5) as a subsidiary Sabaean tell built on the flood channel of Wadi Adhanah about 500 yrs. B.C.

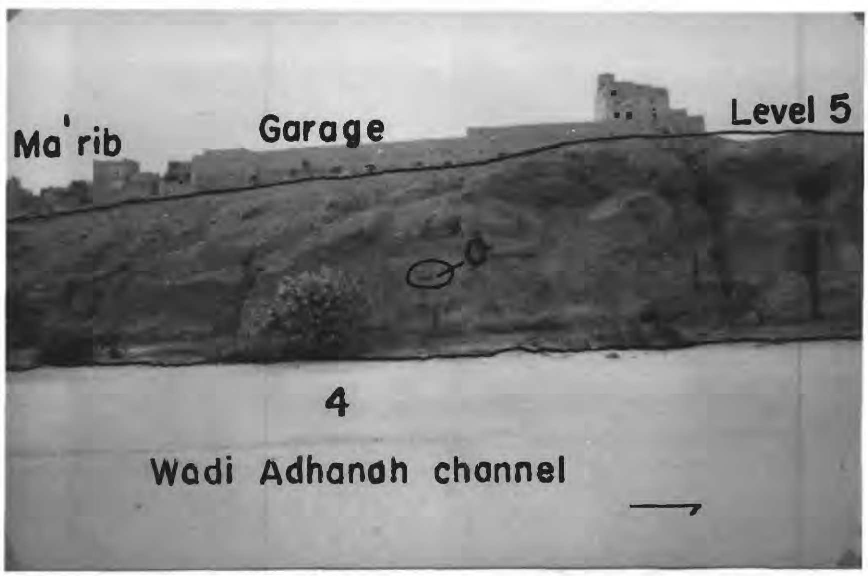


C.--Schematic cross section showing the river bank deposit (5) as a town reservoir during Sabaean time.

Figure 18. Schematic cross sections proposed for surface levels at Ma'rib, Yemen Arab Republic.



A. Oblique aerial view of Ma'rib northward over Wadi Adhanah (Wadi as Sudd). Numbers refer to levels described in table 13. Charcoal collection site (C, fig. 18) is off the right edge of the photograph in bank beneath partly visible garage (G).



B. Charcoal collection site in bank of Wadi Adhanah (Wadi as Sudd) beneath garage (G) and garage level 5. View toward the north shows moderately well stratified silt deposit (level 5) that comprises a Sabaean tell originally built on an ancestral flood plain of Wadi Adhanah (Wadi as Sudd).

Figure 19. Photographs showing surface levels and exposed sediments in the Ma'rib area, Yemen Arab Republic.

C. Irrigated terrace level 1; well-dissected silt terrace irrigated by water from Sudd Ma'rib during Sabaean time. Oblique aerial view looking toward the south; Ma'rib is off the left edge of the photograph.

D. Charcoal (C), dated 2,510±200 yr. B.P. in sediment about 4 m above Wadi Adhan̄ah (Wadi as Sudd) channel level. View looking to the north (see fig. 19B for locality) shows vague to moderate stratification of silt containing ruins. A rectangular pod of charcoal and silt about 2 m wide by 1 m high as exposed is 1 m above C.

Figure 19. Surface levels and exposed sediments in the Ma'rib area, Yemen Arab Republic--continued.

E. Ancient brick wall at the modern channel level of Wadi Adhanah (Wadi as Sudd) and probably extending below the channel level. This ancient wall is made visible by delicate water etching in gully. View looking toward the north about 20 m east of charcoal site (see fig. 19B for locality).

Figure 19. Surface levels and exposed sediments in the Ma'rib area, Yemen Arab Republic--continued.

A. Nonmortareds cut-stone towers at the northers and southern (foreground) sluiceways of the earth-banked dam; alluvial sediments fill reservoir to left, stone facing of earth-banked dam marked by sloping dark line on right. Modem channel of Wadi Adhanah low in foreground. Telephoto view.

B. Stone facing on reservoir side of earth-banked dam overlain by river silt of different thicknesses that filled the reservoir. View is partly seen on right edge of figure 20A.

Figure 20. Photographs showing construction and sediments at Sudd Ma'rib, Yemen Arab Republic.

C. Stone facing bonded with lime mortar on reservoir side of earth-backed dam, sandal shows size of stones; reservoir silt fill above; man-made fill of earth dam below, note two directions of man-dumped fill below stone facing; according to Wade (1979, p. 115) the dam is in cross section the shape of an isosceles triangle and was faced on both sides by stone bonded with lime mortar. The photographs in figure 20 show only the upstream side of the dam.

Figure 20. Photographs showing construction and sediments at Sudd Ma'rib, Yemen Arab Republic--continued.

channel level, consists of coarse fragments of massive charcoal in an irregularly shaped pod about 0.5 m long and 0.25 m high.

Radiocarbon age and interpretation of stratigraphy

The radiocarbon age of the charcoal was determined by Meyer Rubin, USGS, to be 2510±200 yr. B.P. (laboratory number W-3457; field number Ma'rib 758). The date is archaeologically significant in that it is later than the first high culture in Southern Arabia, which was between 1,600-1,200 B.C. (Van Beek, 1974, p. 43), and that it in general agrees with the ultimate development of South Arabian culture by roughly corresponding to the 2807±160 yr. B.P. date from a lower excavation, level (Q), at Hajar Bin Humeid (Van Beek, 1969a, p. 355) and the 7-8th century B.C. building of the finely cut stonework (fig. 19) in the sluices at Sudd Ma'rib (Doe, 1971, p. 76).

The deposit from which the charcoal was taken appears to be a subsidiary Sabaean tell, but the tell extends below the level of the modern channel of Wadi Adhanah (Wadi as Sudd) because the relict brick walls are in place and well preserved at channel level and lack any indication of a base (fig. 19E). Surprisingly few pot sherds are visible in the eroded bank. It is possible that the sediment which contains them has washed down, because the sherds are mixed, and most appear to be Islamic in age. One gray sherd with cord marking on the outer surface may be pre-Islamic, because it is somewhat similar to a Qatabanian mat-impressed sherd from Hajar Bin Humeid (Van Beck, 1969a, p. 87, pl. 24, c).

The date of the charcoal can be referred to the middle of an 8-meter-thick Sabaean tell that was built on the flood plain of Wadi Adhanah and that was subsidiary to the principal Sabaean tell upon the fort level (fig. 18B). Several suggestions are offered below to explain the apparently abnormal situation of Sabaean construction upon the flood channel.

Firstly, as Sabaean Ma'rib prospered after the superb dam was constructed in the 7-8th century B.C., the increasing population was forced to live on the dry flood channel because irrigated agrarian land surrounded Ma'rib on the other three sides (Dayton, 1975, fig. 6). Throughout the Arabian agricultural community today, the townsite is always built on nonarable land regardless of the inconvenience, because arable land is too precious to be used for habitations.

Secondly, successful control of water by Sudd Ma'rib would insure that the channel of Wadi Adhanah (Wadi as Sudd) would be relatively dry and free from floods for many generations. This flood-free period may have been long enough for a tell to rise to a relatively safe level above the flood channel (fig. 18B). More realistically, however, retaining and protective walls may have been needed at times; hence, the massiveness of some of the walls in the bank of the wadi may reflect techniques of construction for flood protection.

Thirdly, this small area against the wadi may have been a town reservoir or well in the bed of the wadi, like that presently used at Ad Darb (17°44' N.; 42°15' E.) in Saudi Arabia, made by building a retaining wall on the side toward the wadi (fig. 18C). As the reservoir filled during succeeding centuries, the retaining wall was raised until its level nearly reached that of the irrigated terrace; perhaps, the irrigation system instead of a dug well was the source of the water.

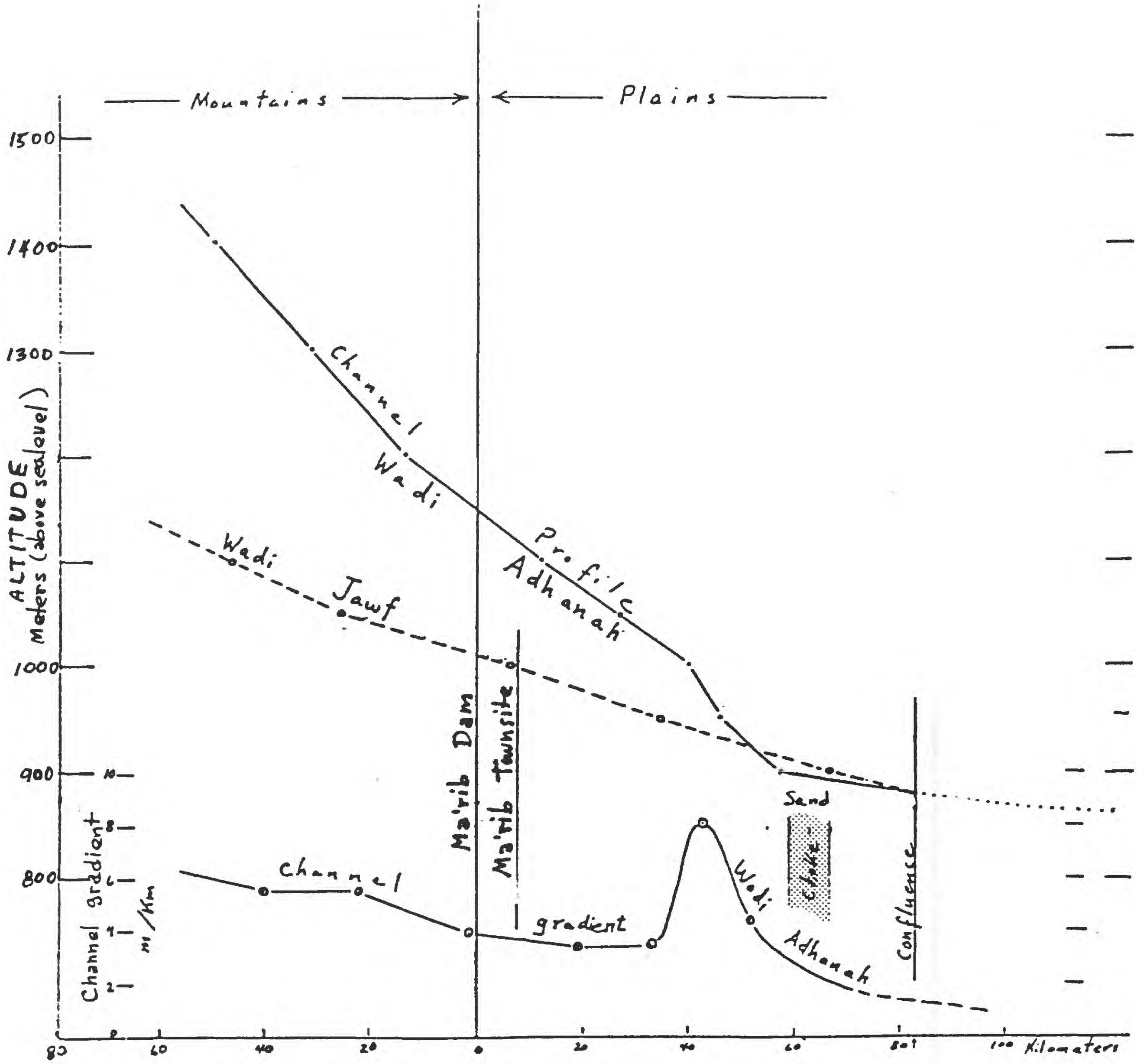
Two observations tend to favor the concept of a reservoir to explain level 5: (1) water sorting and horizontal stratification in the 8 m of the exposed deposit seem to be more pronounced than might be expected in a normal tell; and (2) the thick, massive, well-built wall exposed near the top edge of level 5 (the garage level) about 6-7 m above Wadi Adhanah (Wadi as Sudd) may have been needed to retain a reservoir but was certainly at that height not needed for protection against floods.

Fourthly, a catastrophic means might be used to explain the location in the wadi bank below the irrigation or living level of the Sabaeans of a wall and of charcoal having an age of 2510±200 yr. B.P. For example, Philby (1938, p. 127-128), impressed by the youthful volcanoes in the large lava field to the north of Ma'rib, suggested that earthquakes may have caused the destruction of the South Arabian civilizations and of the Sudd Ma'rib: "The eruption of volcanoes accompanied by earthquakes may have shaken Sheba to its foundations and overwhelmed it with ruin" (Philby, 1938, p. 128). This premise of destruction by earthquake seems undoubtful (Koran, 34:16; Van Beek, 1969b). To downfault or slump part of the Sabaean tell into the Wadi Adhanah (Wadi as Sudd) flood channel and preserve the wall is improbable despite the fact that Ma'rib is located in a structurally active area, as shown by the earthquake near Dhamar. Abundant structural lineaments, trending orthogonally toward the northeast and northwest in crystalline Precambrian rock are conspicuous on the 1:250,000-scale topographic maps of the YAR (United Kingdom Ministry of Defence, 1971) and LANDSAT images (Grolier and Overstreet, 1978). Some lineaments are likely faults, but to prove their age from the maps and images is not possible. Structurally, Ma'rib lies in the northwest-trending, Jurassic Al Jawf graben. Ma'rib also lies in the hinge zone between the Rub' al Khali downwarp and the Yemen highland uplift. To the extent that this hinge zone is related to the opening of the Red Sea, some modern faulting is to be expected. The alkaline basaltic volcanism of the recently active harrat to the north of Ma'rib, with conspicuous northeasterly alignment of the vents (Grolier and Overstreet, 1978) and overall northeasterly trend of the lava field, must somehow be related to deep-seated faults. The edge of the Ma'rib basalt field lies 5-10 km to the west and north of Ma'rib.

The topographic contours adjacent to Wadi Adhanah (Wadi Abrad) on the plain of the Ramlat as Sabatayn below the water gap and Ma'rib have the concave downstream form characteristic of basin fill rather than the conical, convex downstream, form of a stable piedmont. The channel profiles of Wadi Adhanah (Wadi Abrad) and its master stream, Wadi Jawf (fig. 21), as plotted from the 1:250,000-scale topographic maps, show a knickpoint or significant change of gradient for Wadi Adhanah (Wadi Abrad) about 40 km above the confluence with Wadi Jawf and about 35 km below Ma'rib. Topographic and stream slope evidence suggest that this 50 m knickpoint is not related to direct fault displacement. Hence, although recent faulting is to be expected in the Ma'rib area, evidence is not at hand that faulting has affected the Ma'rib tell or the modern channel of Wadi Adhanah (Wadi as Sudd) at Ma'rib.

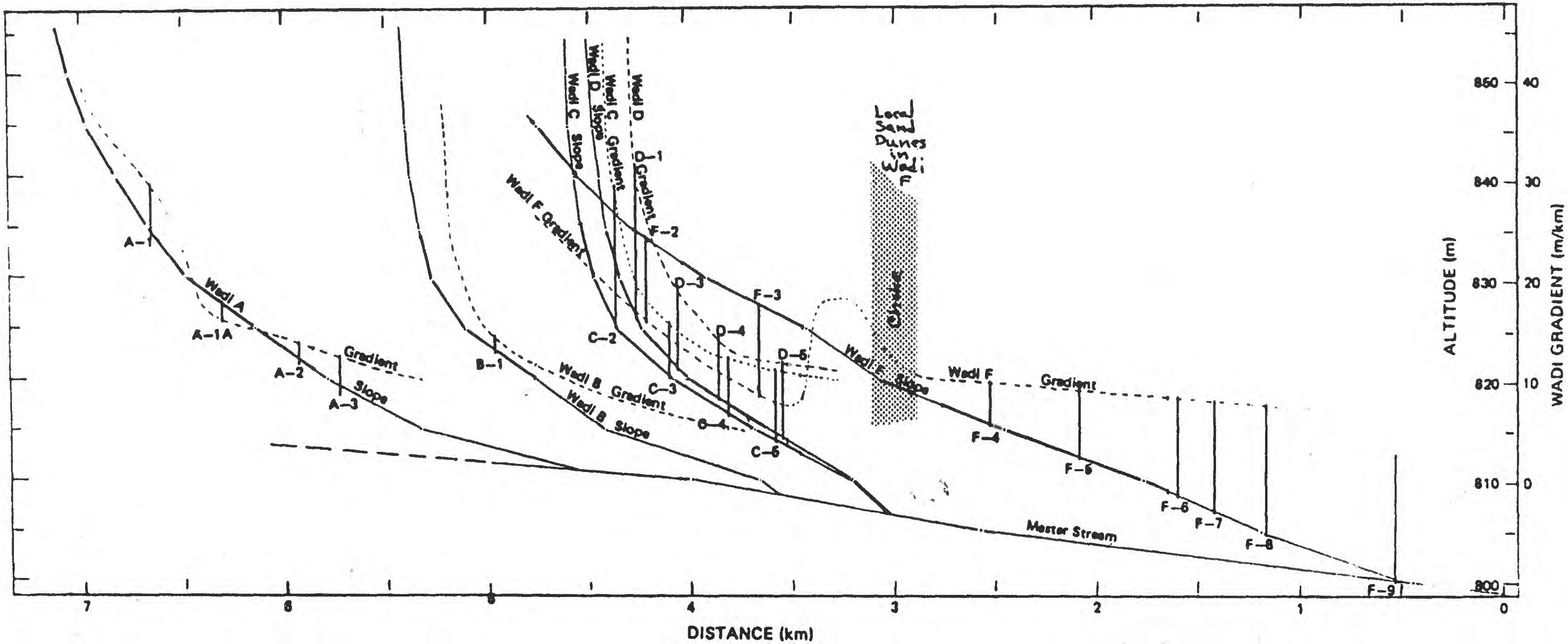
The large 50 m knickpoint, evident in the inflected slope on figure 21, might be caused by spring sapping of water bypassed underground from Wadi Jawf to Wadi Adhanah (Wadi Abrad), the more probable cause is to be found in depositional features first identified at the Jabal Mokhyat placer in the Kingdom of Saudi Arabia (Schmidt and others, 1982, p. 44-46, fig. 11). The small Wadi F (fig. 22) in the Jabal Mokhyat area shows the same gradient spike caused by an eolian sand choke in the bed of the wadi. The position of the sand choke in both wadis (figs. 21 and 22) is about the same, that is, just downwadi from the gradient spike. On Wadi Adhanah (Wadi Abrad) the spike is about 5 m/km whereas on Wadi F in the Jabal Mokhyat area the spike is about 9 m/km--values that are quite similar considering the many orders of magnitude difference in discharge. This gradient spike may be a more common response of wadis to a sand choke than is presently recognized.

Neither Wadi Adhanah (Wadi Abrad) nor Wadi F (Jabal Mokhyat area) appear to be aggrading at their respective sand chokes. Both wadis appear to be graded even through the sand choke. In a graded stream, a steeper gradient is caused by a greater load, which may mean coarser sediment or a greater volume of fine-grained sediment. A greater volume of fine-grained sediment must be



Channel profiles of Wadi Adhanah and Wadi Jawf from their mutual confluence (75 km below Ma'rib) to about 140 km above the confluence (60 km above Ma'rib on Wadi Adhanah). The channel gradient of Wadi Adhanah, lower curve, emphasizes a large 50 m knickpoint located about 40 km above the confluence (35 km below Ma'rib).

Figure 21. Diagram showing channel profiles of Wadi Adhanah and Wadi Jawf, Yemen Arab Republic, showing the position of the eolian sand choke.



Channel slopes and gradients of wadis sampled for placer gold. Vertical tielines locate sample trenches and connect the respective gradient and slope curves. Double line on channel-slope curves shows reaches of wadi that were placered by ancient miners. Most ancient placering was done on slopes between 10 and 30 m/km.

Figure 22. Diagram showing channel slopes and gradients in the Jabal Mokhyat gold placer area, Kingdom of Saudi Arabia, showing the position of the eolian sand choke in Wadi F (after Schmidt and others, 1982, fig. 11).

the cause at both Wadi Adhanah (Wadi Abrad) and Wadi F. For the streams to be graded, the supply of abundant fine material must be perpetual or permanent. Hence, the accumulations of eolian sand in their present positions on both wadis apparently date back to about the time of the incision of the wadis below the last pluvial terrace.

The presence of alluvial placers in the Jabal Mokhyat area of Saudi Arabia, and the eolian sand chokes there and at Wadi Adhanah (Wadi Abrad), suggest that traditional views of mean bed scour and fill during floods in ephemeral streams in semiarid climate (Leopold and others, 1964, p. 229) are not fully applicable (Foley, 1978) in the arid climate of the eastern part of the YAR. If the concept that stream channels are scoured at high flood stages and filled as discharge slacked was applied at the Jabal Mokhyat gold placer, then removal of the saprolitic gravel and sand diagrammed in figure 16, and possibly of the calcified layer of saprolitic bedrock, might be expected. The result would be the loss of detrital gold. The eolian sand chokes (figs. 21 and 22) have persisted long term. An implication is that, in parts of the YAR where lode deposits of gold are present (El Shatoury and Al Eryani, 1977, fig. 5), the possibility for proximate eluvial and alluvial gold placers must not be dismissed on theoretical concepts of scour and fill in arid climatic regimes.

Recent faulting and Quaternary geology

The destructive earthquake (magnitude $M_S = 6$) near Dhamar on 13 December, 1982, has greatly emphasized the reality of seismic activity in the YAR which Plafker and others (1983) and Langer and Merghelani (1983) associate with extensional surface fracturing above rising magma at depth. The significance of recent faulting in the Yemen is further emphasized in the compilation of historic earthquakes in Yemen by Ambraseys and Melville (1983). Extensional tectonism caused the structural formation of the continental rift valleys along the proto-Red Sea and proto-Gulf of Aden during late Oligocene and early Miocene time and during subsequent sea-floor spreading of the Red Sea and Gulf of Aden. The geologic map of the YAR (Grolier and Overstreet, 1978) well demonstrates that faulting was widespread during the Late Tertiary. The extent or even existence of regional extension during the Quaternary and today is not known.

The alinement of youthful volcanic vents (overlying dated upper Pliocene flood basalt) of the Aden Volcanic Series (?) in the Sirwah-Ma'rib and Dhamar-Rida' volcanic fields suggests deep, perhaps transcurrent (extensional transform?), faults as part of a conjugate fracture set associated with continental extension perpendicular to the Red Sea. Half of the 25 historic earthquakes dating back to 742 A.D. as plotted by Ambraseys and Melville (1983) are alined N60E along a narrow zone from Ma'rib through Ma'bar to Zabid. This is also the trend of Wadi Adhanah, but whether or not there is faulting or fault related slumping at Ma'rib and along Wadi Adhanah must await further study. The future study of recent faulting in the YAR is critical to the evaluation of earthquake risk and is important to the interpretation of many Quaternary geological problems.

INTERFACE OF ECONOMIC GEOLOGY AND CLIMATE

The geographic setting of the YAR between the deserts of the Rub'al Khali and Ramlat as Sab'tayn on the east, the Red Sea Escarpment (reaching over 3,000 m in height) and coastal plain (the Tihama) on the west, and the Gulf of Aden to the south of the People's Democratic Republic of Yemen (PDRP) controls the distribution of rainfall (fig. 23). The greatest annual precipitation exceeds 800 mm in the southern part of the country around Ta'izz and Ibb, but this declines in the interior plateau, and the isohyetal lines tend to follow the topographic grain of the country with less than 100 mm of rainfall in the eastern deserts and the western coastal plain. The high mountains of the Red Sea Escarpment may also receive locally as much of 1,000 mm of precipitation per year (Grolier and others, 1981, p. 18, fig. 4). These distributions of rainfall are clearly defined by patterns of vegetation in the YAR (Schoch, 1978).

Projections of the future patterns and intensity of precipitation are subject to many uncertainties (Ambroziak, 1980) and probably should be viewed on a worse-case basis in the short term. The relentless march of desertification in East Africa, abetted by human action and, since 1976 closely studied by the United Nations Environmental Program (Peipert, 1984), gives an example of what may have taken place in the historic past in the YAR as partial response to the use of wood for fuel in homes and in old pyrotechnological applications such as the burning of limestone for lime (Great Britain Naval Intelligence Division, 1946, fig. 275) and of gypsum for plaster of Paris (Bonnenfant and Bonnenfant, 1977, fig. 2; Schulze and Thiele, 1978, p. 48), the manufacture of bricks and pottery (Schulze and Thiele, 1978, p. 48), and the smelting and working of copper and iron (Overstreet and others, 1976). This long-term assault upon the forests of the YAR has even been continued in the 1970's when wood was used to melt tar for highways being constructed under the direction of advisors from the People's Republic of China (personal observations 1975, 1976, 1979), although as early as 1974 recommendations for reforestation in the YAR had been offered (Beskök, 1974).

Reduction of agriculturally based populations between Sabaean time and the present in the eastern part of the YAR was noted by Helfritz (1935, p. 405-406) among other examples attributed to the effects of reduced rainfall in the area. The importance to human populations of small changes in annual precipitation in regions such as the Arabian Peninsula over relatively short times was stressed by Dayton (1975, p. 33-34).

Historical aspects of geologically short-term climate change in the YAR are of less significance in the economic geology of the nation, except possibly for heavy-mineral placers and sedimentary deposits of clay, than the several episodes of rock weathering preserved in the geologic record and recognizable as laterite, saprolite, paleosols, and gossan. Nevertheless, some clear relations exist between the historic exploitation of mineral raw materials and trade routes, wells, and fuel.

Chemical weathering of rocks

The chemical weathering of some rocks in the YAR was recognized in early studies of the geology of the country when Geukens (1966, p. B15) commented on

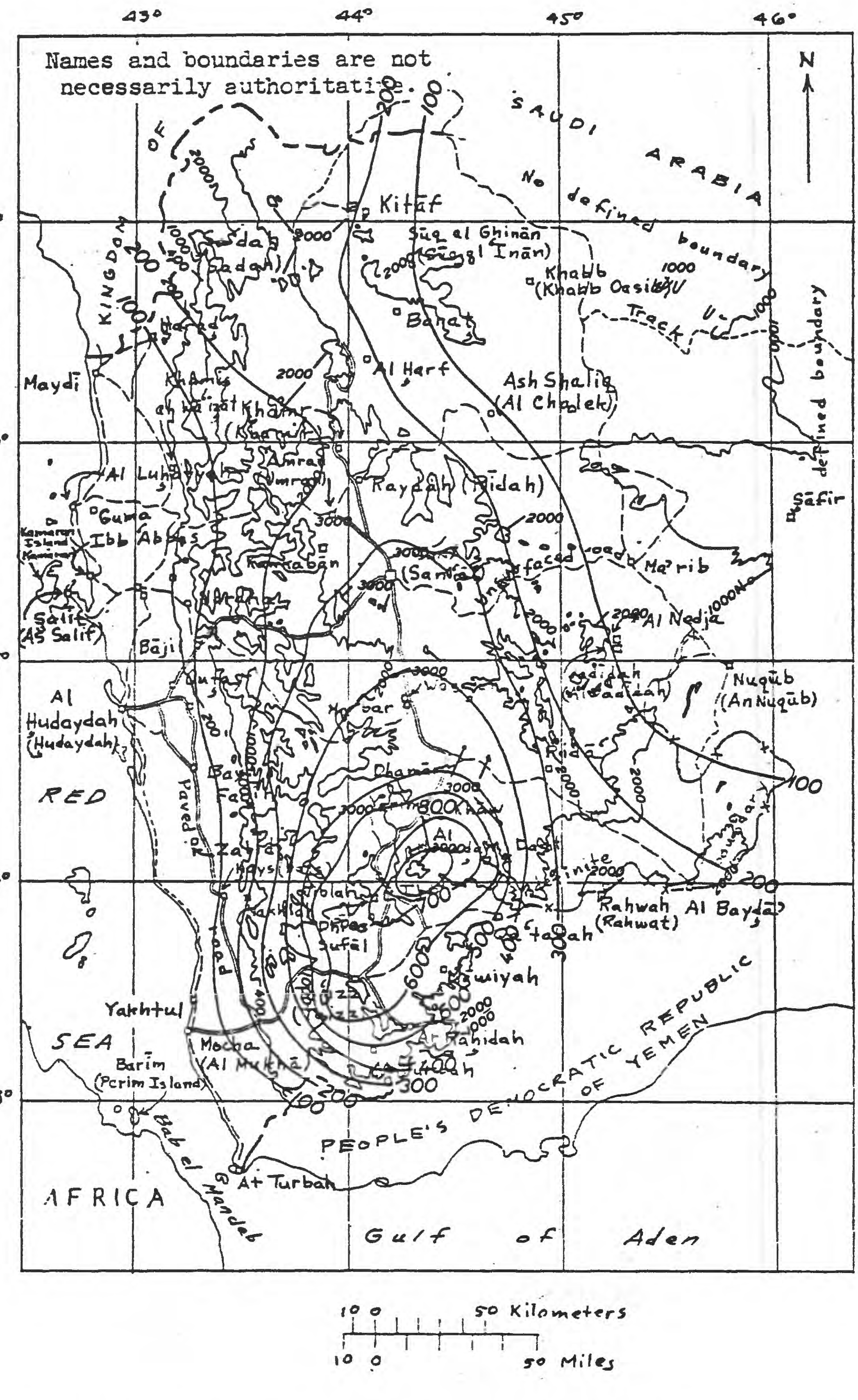


Figure 23. Rainfall map of the Yemen Arab Republic showing generalized annual precipitation in millimeters and topography generalized by 1000-meter contours (after Grolier, Tibbitts, and Ibrahim, 1981, fig. 4).

the development of laterite and paleosols as one product of quiescent periods during the deposition of the Tertiary and (or) Cretaceous Yemen Volcanics. These products of chemical weathering, as well as two other materials resulting from the same processes and found in the YAR--saprolite and gossan--have been discussed in terms of geologic setting, origin, and chemical composition (Overstreet and others, 1976, p. 22-26; Grolier and others, 1977, table 2).

The regional distribution of the major deposits of laterite in the YAR, from 10 km westward of Sa'dah to 75 km northwestward of that city, has been shown (Grolier and Overstreet, 1978), and two of these deposits have been evaluated as possible sources for kaolinite. They were found to be industrially unsuitable owing to the presence of as much as 50 percent of opaline silica and quartz (Schulze and Thiele, 1978, p. 61-63). The economic significance of gossans in the Sa'dah area were discussed above and also in earlier reports (Overstreet and others, 1976, p. 33-52; Overstreet and Grolier, 1980; Schulze and Thiele, 1978, p. 30-42, 81-82). Gossans associated with base- and precious-metal deposits in the YAR were noted by El Shatoury and Al Eryani (1977, p. 284-286). Evidence for the chemical weathering of rocks in the YAR has thus been extended in geologic time from the laterite of probable Eocene age under the Yemen Volcanics and saprolite and palesols as young as early Miocene in the Yemen Volcanics, to gossan of Quaternary age, and to small relicts of saprolite of pre-Ordovician age developed on Precambrian rocks underlying the Wajid Sandstone in the northern part of the YAR. Chemical weathering of possibly the same age as that which produced the Eocene(?) laterite has widely etched into a microkarst topography broad expanses of flat-lying limestone of the Amran Series of Upper Jurassic age between San'a and Sa'dah (fig. 24A and B). It is expected that solution caverns will be found in this limestone, possibly by access along the walls of great valleys such as Wadi Jawf, but none are known to the writers. In the vicinity of the Amran Valley near San'a, caves, sink holes, and smaller solution structures are reported to be rare (Tibbitts and Aubel, 1980, p. 15).

The common causative features shared by these products of rock weathering are adequate rainfall to provide the solvent, periods of reduced erosion to permit chemical weathering to advance over mechanical degradation, for example (fig. 24C) the widespread subaerial weathering of possible Oligocene age observed in Arabia (Brown, 1970, fig. 12), and sufficient cover or short time span since formation to insure preservation of the products of weathering. Deep chemical weathering is commonly regarded as the result of heavy rainfall (over 1,000 mm per year) in humid regions, and such an explanation is needed for the thick laterite preserved in the northwestern part of the YAR, but the composition of the rainwater and of mixtures of rainwater and soil water are also factors (Carroll, 1962; 1970, p. 19-21; Loughman, 1969, p. 67-74; Persons, 1970, p. 6). Hydrous oxides of Fe have precipitated within historic time in the open-pit mines at Jabal Al Maidan and Jabal Al Ma'aden near Sa'dah. These secondary minerals have formed on several man-made cut surfaces showing that chemical weathering can proceed where the rainfall is only 200-300 mm per year (fig. 23).

A. Microkarst topography developed by solution of flatlying Upper Jurassic limestone of the Amran Series between San'a and Sa'dah; may represent exhumed solution surface formed during quiescent period when the Eocene (?) laterite near Sa'dah was produced by chemical weathering of plutonic rocks.

B. Microkarst showing joint sets and shelter for plants.

Figure 24. Photographs showing relict Tertiary surfaces of weathering in the northern part of the Yemen Arab Republic.

C. Microkarst solution channels about 45 cm deep as exposed.

D. Mid-Tertiary erosion surface uplifted and dissected several thousand meters along the Red Sea Escarpment.

Figure 24. Photographs showing relict Tertiary surfaces of weathering in the northern part of the Yemen Arab Republic--continued.

Movement and processing of mineral raw materials

Spatial relations among ancient mines, wells, and routes of communication

The 98 localities in the YAR where metallic ores (44 sites) or industrial minerals and rocks (54 sites) have been or are being mined (El Shatoury and Al Eryani, 1977, figs. 4 and 5) conform well with the observations on location made by Sabir (1983, p. 11-12) for over 1,000 ancient mines and prospects in base- and precious-metal deposits in Saudi Arabia. That is, mines in the YAR are close to ancient water wells and to major routes of communication. Doubtless the field work undertaken since the compilation by El Shatoury and Al Eryani (1977) has led to the re-discovery of other ancient mines and prospects, and these sites no doubt strengthen the correlation with wells and routes. Owing to the vastly greater density of population in the YAR, with its concomitant needs for water and communication, the correlation on the basis of 98 mines would not have been perceived and the significance of the relation would have been lost in the overwhelming number of villages, wells, and routes in the YAR.

In commenting on the close spatial relation between ancient mines and ancient wells in Arabia, Sabir (1983, p. 11) noted that water wells are relatively more common where the ancient workings are extensive than where the workings are small, and he postulated that the water table may have been higher in Early Islamic time than it presently is. In that connection Sabir (1983, p. 11) cited an example, taken from the old book titled Mujam al Buldan (Yagut al Hamawi, 1178-1180 A.D.), of the ancient Arabian gold mine, An Najadi, which was abandoned because the excessive inflow of water could not be accommodated by available means. Reference to this old comment on ground water is also contained in a report by Fakhry (1935).

The role of water supply for the small community at the Jabal Mokhyat gold placer in Saudi Arabia, about 500 km to the north of Ma'rib in the YAR, was discussed by Schmidt and associates (1982, p. 60), who concluded that the miners brought in water from established wells from 10-26 km to the south. The more southerly wells are in Wadi Mellah where a perennial supply of water was reached from wells sunk in the active channel of the wadi. These perennial wells (Schmidt and others, 1982, p. 60)"...are protected from most floods by a broad accumulation of dung and sand, 4 m high, that has been well compacted by man and animals over many centuries. The climate during the period of placer mining was extremely arid, and the availability of water and food alone must have limited the mining force. The placer stratigraphy clearly indicates that the eolian sand accumulated during and before the ancient placering, as it does today. Extreme dessication came to Arabia before the ancient placering," which was probably about 2,600 years ago (fig. 16).

The main old caravan routes from South Arabia passed through Ma'rib and Sa'dah to converge at Najran in the Kingdom of Saudi Arabia at the border of the YAR. From Najran a main route led northward and northwestward to Qal'at Bishah (90 km west of the Jabal Mokhyat placer), thence west-northwestward to At Ta'if and Mecca where it joined the great Darb Zubaydah which reaches northward to Al Madinah and, ultimately, Baghdad. In segments of the route to the north of Najran large wells were noted (Overstreet and Rossman, 1970, p. 6; Overstreet, 1978, p. 4) at Al Husayniyah, Bi'r Idimah, and Bi'r Malah where elongate piles of dung up to 4 m deep protect the wells. Al Husayniyah, like Najran, is an important junction on this old route. At Al Hasayniyah a route branches northeasterly to skirt the Rub' al Khali along its northwestern edge by passing through the sandstone badlands of the Jibal al Wajid, turning eastward throught the mouth of Wadi ad Dawasir, thence passing northeastward to As Salamiyah, the oasis of Al Hufuf, and reaching the shore of the Arabian Gulf at Dhahran.

On the route north of Najran, the water of Bi'r Idimah presumably was a factor in travel over a long time. Just how long is unknown, but evidence for its importance is seen in the impressive size of the mound of dung that has accumulated around the well, the dimensions of which are about 70 m by 200 m. The vertical growth of the pile over the years has necessitated repeated raising of the stone collar of the well, so that each course of stone below the collar shows the grooves worn by ropes used to raise buckets of water. The pile is about 4 m thick. Trapped in this pile is an assortment of pollen and food grains that could provide clues to the fluctuation of climate in this part of the Arabian Peninsula during the life of the well, which might be determinable by radiocarbon dating.

Many but not all the ancient wells on the most important routes are surrounded by large dung piles like those at Bi'r Idimah, Bi'r Malah, Wadi Mellah, and Al Hasayniyah, but the writers have not observed similar wells in the YAR. That lack of observation must be attributed to the briefness of their visits and to the absence of traverses along the old caravan routes in the eastern part of the YAR, where large wells must be preserved. Similar wells with large dung piles have been noted south of Makkah at Ayn Zubaydah (Sabir, 1983, p. 12), at intervals along the Darb Zubaydah (MacKenzie and Al Helwa, 1980), and in south-eastern Jordan (Field, 1971, p. 28). These piles constitute important palynological reservoirs that could reach back several thousand years. Cores from them could be compared with palynological records from archaeological sites, including relicts preserved in such materials from pyrotechnological operations as pottery, slag, and lime mortar, and the knowledge of paleoclimate in the western part of the Arabian Peninsula, as interpreted from spores and seeds, could thereby be improved.

Effects of pyrotechnology on local environment

The chronology of pyrotechnological development in the YAR is inadequately known; hence, the effects of pyrotechnology on the local environment can only be considered against what has been reported for other parts of the Middle East. Kilns and furnaces must have been long established in the YAR as is attested by the presence of lime mortar at Sudd Ma'rib and of plaster of Paris, pottery, copper, and bronze in the Ma'rib area. Perhaps glass for personal adornment was manufactured in the YAR through introduction by the Persians in the 6th century A.D., because early glass-manufacturing centers are known in the PDRY (Doe, 1971, p. 134-137). The amounts of wood consumed for fuel in these operations, superimposed on domestic needs, must have had local, if not regional, effects on the environment. Where the history of lime burning and pyrometallurical operations in antiquity are well understood, as in the lands bordering the eastern Mediterranean, deforestation, erosion, and ecological changes began that are present to this day (Wertime, 1983). Early methods were enormously wasteful of fuel. For example, in Cyprus about

300 kg of charcoal are estimated to have been consumed to produce 1 kg of copper on average during the period 4,000-500 B.C. (Constantinou, 1981, p. 22) when primitive kilns required about 20 m^3 of wood to yield 1 ton of charcoal. Constantinou (1981, p. 22-23) estimated that a pine tree 80-100 years old yields 1 m^3 of wood. Thus over a period of 3,000 years when 200,000 tons of copper was produced on Cyprus, the forests on the island were destroyed at least 16 times for pyrometallurgical purposes alone. The fact that some copper slag piles, as among the more than 100 smelting sites in Oman (Ratnagar, 1981, p. 15-16) having from 25-100,000 tons of slag, were re-smelted, at some places with improved but at others with primitive methods, indicates that the tonnage of slag is not a certain basis for the amount of fuel consumed (Weisberger, 1981, p. 28-29). During antiquity the denudation of forests to supply fuel for copper smelting is thought by Doe (1983, p. 38) to have caused local climate change in northern Oman.

Pyrotechnological industries, including fire-breaking in mines, cease when the economic limit of transport for fuel is reached. Wertime (1981, p. 357) studied areas of provisionment by donkey transport and concluded that a perimeter of about 40 km was the economic limit. Transport by camel might double that; nevertheless, if the sources for wood within the economic perimeter failed of replenishment, as is highly likely under arid conditions, the industry would close for lack of fuel. This explanation has been offered for the cessation of metal mining and smelting in Saudi Arabia where slow-growing acacia was the main source of fuel (Overstreet, 1971). The old glass factory at Kawd Am-Sailah in the PDRY was situated where it had ample water, trees, and brushwood, but the glass-makers were thought by Doe (1971, p. 137) to have used re-forestation over the long term, because the area was comparatively well wooded as late as 1839, but thereafter was denuded of trees to supply Aden (Doe, 1971, p. 137).

As early as the 3rd century B.C., according to Hughes (1983, p. 441), Theophrastus noted local climate change resulting in the drying up of sources of water and the onset of warmer weather following the clearing of trees at Philippi in north central Macedonia, Greece. A search of old records in Sa'dah, YAR, might reveal something similar as having resulted from the cutting of trees to supply the iron smelting that produced the five large slag heaps within or adjacent to the walls of the city (Schulze and Thiele, 1979, fig. 4). However, the greatest ecological changes of antiquity may be those caused by the deforestation incident to the construction of agricultural terraces in the Red Sea Escarpment and re-forestation introduced along the margin of the eastern desert of the YAR through massive irrigation projects, as at Ma'rib, where orchards were cultivated.

CONCLUSIONS AND RECOMMENDATIONS

Recommendations from conclusions of the present investigation are made under the supposition that the many years of cooperation between the ongoing program of the Mineral and Petroleum Authority of the YAR and various outside geologic organizations will continue. Outside cooperative input has included geologic mapping, evaluation of selected mineral deposits, geochemical exploration, hydrologic surveys, evaluation of seismic hazards, and other aspects related to the geology and mineral resources of the YAR. The present investigation touches only parts of the Precambrian, Tertiary, and Quaternary geology of the YAR, but it is clear that basic geologic contributions are needed to support advances in economic geology in those parts of the stratigraphic column. Cooperative investigations with outside organizations could realize these recommendations.

Rock ages and geochemistry

Precambrian granitoid rocks

In the northern part of the YAR the stratigraphy of the Precambrian metavolcanic and metasedimentary rocks seems to be identical with that described in Kingdom of Saudi Arabia (Johnson, 1983, p. 2). From the major-element chemical composition of the late Precambrian granitoid plutonic rocks exposed as far south as Al Bayda near the border with the PDRY a nearly exact correpondence is seen with the posttectonic Precambrian plutonic rocks of Saudi Arabia. Chemical data on the older Precambrian plutonic rocks are scarce, but because of the similarity of the metavolcanic and metasedimentary host rocks, it seems probable that the origins, ages, and metallogeny of the older plutonic rocks will also be similar in the YAR.

The Precambrian granitoid rocks in the southeastern part of the YAR include a posttectonic suite of latest Precambrian age, probably between 620 Ma and 560 Ma (Schmidt and Brown, in press). They are among the youngest Precambrian rocks in the YAR, and they were so shown on the geologic map (Grolier and Overstreet, 1978). However, the most strongly gneissic members were mapped with the oldest of the Precambrian granitoid rocks in a unit called gneissic granite. It is probable that this unit includes some of the younger Precambrian gneissic rocks in other areas where the unit of gneissic granite was mapped. Among the younger Precambrian granites in Saudi Arabia that are chemically similar to the ones in the YAR are granitoid rocks significantly enriched in Be, Li, Mo, Nb, Sn, and W as well as rare-earth elements. Geochemical programs have been developed in Arabia to permit separation of the granitic plutons with highest potential for mineralization from those with the least potential (du Bray, 1983; Stuckless, Knight, and others, 1983; Stuckless, Van Trump, and others, 1983).

A similar program of geochemical investigations for rare metals is therefore recommended to be directed toward the youngest Precambrian peralkaline granite and syenite shown on the geologic map of the YAR as subcircular to circular plutons identified as the units "gp" and "sy" (Grolier and Overstreet, 1978). Each pluton should be mapped in detail, studied petrographically, and chemically analyzed for major and minor elements. In Saudi Arabia the geochemically anomalous granites have been found to be enriched, compared to global averages, in the minor elements Be, Pb, Li, F, Rb, Y, Nb, Bi, Ag, Sn, W, and Mo (du Bray, 1983, p. 5). These elements must, therefore, be included in the analyses of rocks from the YAR along with such other commonly determined minor elements as As, Au, B, Ba, Cd, Ce, Co, Cu, La, Nd, Ni, Sb, Sc, Sr, V, Zn, and Zr. Major-element determinations for SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5, and MnO are also necessary for petrologic classification and comparison with the minor-element data. Some, perhaps most, of these analytical requirements will have to be met outside the YAR, but the chemical data are necessary for an inventory of the rare-metal potential of the younger Precambrian granites in the YAR. For that reason, a cooperative program with an outside organization to inventory geochemically the younger Precambrian granites is recommended.

K-Ar age determinations should be done on selected plutons

Older units of the granitoid rocks in the YAR should also be studied for major and minor elements and K-Ar ages to complete a petrologic and tectonic understanding of their genesis and potential for economic minerals.

Tertiary volcanic rocks

The results of the major-element analyses of the rhyolites from the Yemen Volcanics give convincing evidence that the rhyolite tuffs in the YAR are correlative with the Liyyah Formation in the Jizan Group of Late Oligocene and Early Miocene age in Saudi Arabia (Schmidt, Hadley, and Brown, 1982, p. 13). The thick sections of silicic volcanic rocks in the Liyyah Formation are inter-interpreted by Schmidt, Hadley, and Brown (1982, fig. 2) to have been deposited near eruptive centers within the continental rift of the developing Red Sea structure, and most of the rhyolites in the YAR were shown to have been explosively erupted with a total volume about equal to the thickness of the flood basalts in the YAR (Civetta and others, 1978, p. 308).

The volcanic and sedimentary rocks of the Yemen Volcanics lack systematic study to identify the base and the top of the sequence, of which the top may have been lost (fig. 24D) throughout the country owing to erosion during the Middle Tertiary (Brown, 1970, p. 84). Sections close to major eruptive centers need to be measured. Many more major-element analyses of both the basaltic and rhyolitic phases of volcanism are necessary to permit petrologic, geochemical, and tectonic interpretations relating the deposition of the Yemen Volcanics to the development of the Red Sea Rift. Sedimentological and paleontological investigations of the sedimentary rocks in the Yemen Volcanics are needed to compare the stratigraphy with that being developed in Arabia. The margin of the Red Sea structure in the Tihama and Escarpment of the YAR deserves continuing detailed geologic and geophysical study; therefore, a long-term investigation of this problem is recommended.

Little is known of the potential for metallic mineral deposits in the Yemen Volcanics. The few data available appear to be unfavorable for uranium, but there may be a hydrothermally altered zone in the Yemen Volcanics to the east of Manakhah where base metals may be present. The recommended long-term study should include an evaluation of the possibility for deposits of base metals in the Yemen Volcanics.

<u>Aden Volcanic Series (?) of Quaternary and Pliocene age</u>

Alkali olivine basalt

The new total-rock K-Ar isotopic ages determined on old flows of alkaline olivine basalt of the Aden Volcanic Series (?) of 1.54 ± 0.2 Ma and 2.21 ± 0.13 Ma show that these rocks are at least as old as the Upper Pliocene in the YAR. The youngest flows in the YAR are historic. These results conform with ages assigned the late volcanic rocks in Saudi Arabia (Brown, 1970, p. 84-86; Coleman and others, 1975, p. 41-43) and show that the age of the unit is Quaternary and Pliocene. The geologic map of the YAR (Grolier and Overstreet, 1978) gives too short a geologic age for the Aden Volcanic Series (?).

Reflectance criteria from LANDSAT imagery used on the geologic maps of the YAR to discriminate the relative ages of the alkali olivine basalt of the Aden Volcanic Series (?) appear to have worked well, both where isotopic ages can be compared with the interpretation from reflectance, and where the normalized percentage of K_2O in the basalt can be compared with reflectance. The mean normalized percentages of K_2O increase with decreasing relative age where Qa_1 are the oldest and Qa_4 are the youngest flows (fig. 9):

Relative age of flow	Mean normalized percentage of K_2O
Qa_4	1.12
Qa_3	1.13
Qa_2	0.80
Qa_1	0.78

Further tests of these relations are recommended, including total rock K-Ar ages and major-element analyses of samples from flows in local stratigraphic sequence in the major lava fields of Quaternary and Pliocene age: (1) Ta'izz-Al Mukha area including flows to the south and southeast of Al Mukha near the border with PDRY, (2) between Rida' and Dhamar, (3) north and west of Ma'rib, and (4) east of the 'Amran-Raydah area (Grolier and Overstreet, 1978).

The economic geology of deposits of pumice and pumicites in the lava field east of Dhamar has been discussed by the German Geological Advisory Group in Yemen (Schulze and Thiele, 1978, p. 64-86). Recommendations given in that report are also applicable to other discoveries of this industrial raw material in the Aden Volcanic Series (?) elsewhere in the YAR.

Sedimentary rocks

Little is known about the ages, stratigraphic succession, and economic geology of the sedimentary rocks of Quaternary and Pliocene age in the YAR or of their relations with the igneous rocks of the Aden Volcanic Series (?). These sediments were the source of placer gold at Sirwah, and other proximate gold placers may be present in eluvial or alluvial sediments near exposed auriferous base-metal deposits in Precambrian hosts. Modern beach placers have been investigated in the YAR with negative results (Schulze and Thiele, 1978, p. 69-71). Sedimentary rocks of Quaternary age contain such nonmetallic industrial minerals as diatomite in Saudi Arabia (Whitney, 1982) and bentonite in the Hashemite Kingdom of Jordan (Overstreet, W. C., written commun., 1978). Silts of this age, either naturally deposited or accumulated under the influence of man (Dayton, 1975; 1979; Wade, 1979), are among the major agricultural soils of the YAR.

Several investigations of the sedimentary rocks are recommended.

Stratigraphy.--The broad outlines of the erosional history and surficial geology, as developed in Saudi Arabia (Chapman, 1971; 1974; McClure, 1976; Al-Sayari, 1978; Whitney, 1982; 1983; Whitney and others, 1983), are needed in the YAR to define the stratigraphic succession and effects of climate change in the Pliocene and Quaternary sedimentary rocks. Interrelated applications of geomorphology, sedimentology, palynology, paleontology, radiocarbon geochronology, and archaeology are required with emphasis on both the erosional and depositional history of the area. The work of Whitney in Saudi Arabia affords a model of the required approach (Whitney, 1982; 1983; Whitney and others, 1983).

Economic geology.--Except for possible gold placers, about which very little is presently known, the economic mineral deposits that could be expected in the Pliocene and Quaternary sedimentary rocks of the YAR are low-unit-value industrial materials such as heavy minerals in beach placers, diatomite in lake-bed deposits in the sand seas in the eastern YAR, and bentonite associated with sabkhah deposits adjacent to large lava fields.

Beach placers.--The most common industrial minerals mined from beach placers elsewhere in the world are ilmenite, rutile, zircon, monazite, and magnetite. Exploration for these minerals has been conducted along the Red Sea coast of the YAR (Schulze and Thiele, 1978, p. 69-71) and of Saudi Arabia (Skipwith, 1973, p. 123-125; Jacquin and others, 1983), with generally negative results, both in terms of concentration of these minerals and in terms of the chemical acceptibility for industry of the ilmenite and magnetite. Inasmuch as these investigations were restricted to visible black-sand deposits of the present storm beaches, they may not have fully reflected the composition or tenors of the wanted minerals in other geomorphic environments in the coastal plain, such as buried placers inland from the present beach. Nevertheless, the general conditions leading to the enrichment of titanium minerals, zircon, and monazite in beach placers are not met along the Red Sea. These conditions are the presence of Cretaceous or Tertiary sedimentary rocks backing the beaches and serving as a protore in which the industrially valuable heavy minerals have been previously concentrated and the unwanted heavy minerals such as amphibole, pyroxene, and epidote have been depleted by solution. Futher investigations of placer minerals along the coastal plain deserve a low priority, because the present data are inadequate.

Diatomite.--Fresh-water, fossiliferous, calcareous lake-bed deposits were first reported from inter-dunal areas in the Rub' al Khali by Philby (1933), and lake terraces have been described by others subsquently (Bramkamp and others, 1963; Powers and others, 1966, p.D99; McClure, 1976), but the first siliceous lake-bed sediments to be described were found on the southwestern edge of the An Nafud (Whitney, 1982; 1983, p. 65-66). This diatomite is 2.2 m thick and is of industrial grade. In Saudi Arabia the sand deserts were found by Whitney (1983, p. 64) to be more sensitive to variations in climate than the low-gradient, alluvial drainage systems on the Precambrian Shield. Thus, the possible presence of inter-dunal, lake-bed deposits of diatomite in the Rub' al Khali and the Ramlat as Sab'atayn in the northeastern and eastern parts of the YAR is a priority for study and could be investigated as part of a geomorphic and stratigraphic study of these sand deserts.

Bentonite.--Sites in the YAR suitable for exploration for possible bentonite deposits are the areas of loessic silt adjacent to extensive lava fields formed by the Aden Volcanic Series (?) in the vicinity of: (1) Ta'izz-Al Mukha area including flows and cones to the south and southeast of Al Mukha, (2) between Rida' and Dhamar, (3) north and west of Ma'rib, and (4) east of the 'Amran-Raydah area (Grolier and Overstreet, 1978). If the silts overlie khabra or sabkhah basin deposits, and are adjacent to crater fields, then the geologic similarity to the setting for bentonite deposits at Al Azrak in Jordan would be complete. At Al Azrak beds of bentonite 1-1.5 m thick are present at depths of 1.5-3 m in gypsiferous sand and silt of Quaternary age in large khabra deposits off the edge of a basalt plateau (Overstreet, W. C., written commun., 1978). The bentonite, which is a mixture of the minerals montmorillonite, beidellite, and nontronite, formed through the weathering of beds of volcanic ash. Ash falls from cones in the lava field appear to have been interspersed with periods of subaerial erosion and redeposition by sheetwash and flash floods. The thickest beds of bentonite are uncontaminated by erosional debris, but some thin beds of ash are disturbed and mixed with sand. Water flowing from the adjacent lava field caused the ash to weather to bentonite. In the YAR the areas of silt adacent to the lava fields east of Rida' and Dhamar and north and west of Ma'rib may offer the most suitable sites for testing.

Sulfide deposits of the Sa'dah area

The similarity of the stratigraphy of the Precambrian rocks and Quaternary gossan in the Sa'dah area, YAR, to these features at massive sulfide deposits in southwestern Saudi Arabia, combined with some high values reported for As, Ni, Cu, Co, and Zn in the gossan (Schulze and Thiele, 1978, p. 39) lead the authors to recommend that a high priority be given to the physical exploration of these deposits. Inclined diamond-drill holes should be sunk from offset sites on either side of the deposits to intersect the sulfide mineralization below the zone of weathering. Polished sections and thin sections of the core must be studied to identify the sulfide minerals and to establish their paragenetic sequence in order to determine the genesis of the ore and any effects of post-ore metamorphism. Major and minor elements in the ore should be determined by analysis, and the grade of the ore evaluated. Drilling should be done in two phases: (1) a first phase to determine if any deposits are of economic grade, and (2) a second phase of detailed drilling on deposits of commercial grade to permit the estimation of reserves to a vertical depth of 200 m.

Detailed geochemical exploration should be conducted to the west and north of Sa'dah as far as the border with Saudi Arabia to search for base- and precious-metal deposits in the Precambrian rocks.

REFERENCES

Adams, J. A. S., and Maeck, W. J., 1954, Fluorometric and colorimetric micro-determinations of uranium in rocks and minerals: Analytical Chemistry, v. 26, no. 10, pp. 1635-1639.

Al Hamdani, al Hasan ibn Ahmad, 945, Al Geoharatain [in Arabic].

Al-Sayari, S. S., and Zotl, J. G., 1978, Quaternary period in Saudi Arabia: New York, Springer-Verlag, 334 p.

Ambraseys, N. N., and Melville, C. P., 1983, Seismicity of Yemen: Nature v. 303, p. 321-323.

Ambroziak, Russel, 1980, Climate projections, in Barney, G. O., study director, The global 2000 report to the President: U.S. Government Printing Office, The global 2000 report to the President, v. 2, The technical report, p. 51-65.

Bayle des Hermens, R. de, 1976, Première mission de recherches préhistoriques en République Arabe du Yémen: L'anthropologie, v. 80, no. 1, p. 5-37.

Bender, Friedrich, 1968, Geologic von Jordanien: Beiträge zur Regionalen Geologie der Erde, v. 7, 230 p., Gebruder Borntraeger, Berlin.

_______________, 1974, Geology of Jordan: Berlin, Gebrüder Borntraeger, 196 p.

Beskök, T. E., 1974, Report to the Government of the Yemen Arab Republic on afforestation and quick-growing tree species: United Nations Food and Agriculture Organization Report, 47 p.

Blanchard, Roland, 1968, Interpretation of leached outcrops: Nevada Bureau of Mines, Bulletin 66, 196 p.

Blank, H. R., Flanigan, V. J., Gettings, M. E., and Merghelani, H. M., 1980, Geophysical investigations of the Kutam ancient mine and vicinity, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 80-1268, (IR)SA-278, 48 p.

Bonnenfant, Paul, and Bonnenfant, Guillemette, 1977, Les artisans du platre a Sanaa, Yemen: Revue des Etudes Islamiques, v. 45, no. 2, p. 247-262.

Bowen, N. L., Shairer, J. F., and Posnjak, E., 1933, The system, Ca_2SiO_4-Fe_2SiO_4: American Journal of Science, fifth series, v. 25, no. 148, p. 273-297.

Bowen R. L., Jr., and Albright, F. P., 1958, Archaeological discoveries in South Arabia: Baltimore, Md., The Johns Hopkins University Press, 315 p.

Bramkamp, R. A., Gierhart, R. D., Owens, L. D., and Ramirez, L. F., 1963, Geology of the western Rub al Khali quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geological Investigations Map I-218A, scale 1:500,000.

Brown, G. F., 1970, Eastern margin of the Red Sea and the coastal structures in Saudi Arabia: Philosophical Transactions of the Royal Society of London, ser. A., v. 267, p. 75-87.

Carroll, Dorothy, 1962, Rainwater as a chemical agent of geologic process--a review: U.S. Geological Survey Water-Supply Paper 1535-G, 18 p.

_____________, 1970, Rock weathering: New York, Plenum Press, 203 p.

Chapman, R. W., 1971, Climatic changes and the evolution of land forms in the Eastern Province of Saudi Arabia: Geological Society of America Bulletin, v. 82, no. 10, p. 2713-2728.

_____________, 1974, Calcareous duricrust in Al-Hasa, Saudi Arabia: Geological Society of America Bulletin, v. 85, no. 1, p. 119-130.

Civetta, Lucia, Volpe, Luigi La, and Lirer, Lucio, 1978, K-Ar ages of the Yemen Plateau: Journal of Volcanology and Geothermal Research, v. 4, p. 307-314.

Clifford, T. N., and Gass, I., eds., 1970, African magmatism and tectonics: Darien, Connecticut, Hafner and Company, 461 p.

Coleman, R. G., Fleck, R. J., Hedge, C. E., and Ghent, E. D., 1975, The volcanic rocks of southwest Saudi Arabia and the opening of the Red Sea: Saudi Arabian Directorate General of Mineral Resources Bulletin 22, p. D1-D30.

Comucci, Probo, 1929, Sopra alcune rocce volcanice della regione di Sanaa (Arabia): Mémoires della Societa Toscana di Scienze Naturali, no. 40, p. 70-78.

Conophagos, C., and Papadimitriou, G., 1981, La métallurgie du fer et de l'acier en Grèce, pendant la periode classique, in Muhly, J.D., Maddin, Robert, and Karageorghis, Vassos, eds., Early metallurgy in Cyprus, 4000-500 B.C.: ACTA of the International Archaeological Symposium, Pierides Foundation, Larnaca, Cyprus, 1-6 June 1981, p. 363-372.

Constantinou, G., 1981, Geological features and ancient exploitation of the cupriferous sulfide orebodies of Cyprus, in Muhly, J.D., Maddin, Robert, and Karageorghis, Vassos, eds., Early metallurgy in Cyprus, 4000-500 B.C.: ACTA of the International Archaeological Symposium, Pierides Foundation, Larnaca, Cyprus, 1-6 June 1981, p. 13-23.

Daalhoff, Hans van, 1974, Mineral locality map of the Arabian Shield, Kingdom of Saudi Arabia: Kingdom of Saudi Arabia Directorate General of Mineral Resources, Geologic Map GM-15, 2 pl., scale 1:2,000,000.

Dayton, John, 1975, The problem of climate change in the Arabian Peninsula: Proceedings for the Seminar for Arabian Studies, v. 5, p. 33-60.

____________, 1979, A discussion of the hydrology of Ma'rib: Proceedings of the Seminar for Arabian Studies, v. 9, p. 124-129.

Dodge, F. C. W., and Rossman, D. L., 1975, Mineralization in the Wadi Qatan area: U.S. Geological Survey Open-File Report 75-309, (IR)SA-190, 71 p.

Doe, Brian, 1971, Southern Arabia: New York, McGraw-Hill Book Company, 267 p.

____________, 1983, Monuments of South Arabia: Cambridge, England, The Oleander Press, 284 p.

du Bray, E.A., 1983, Mineral potential of selected felsic plutons in the eastern and southeastern Arabian Shield, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 83-370, (IR)SA-536, 58 p.

du Bray, E. A., Elliott, J. E., and Stoeser, D. B., 1983, Geochemical evaluation of felsic plutonic rocks in the eastern and southeastern Arabian Shield, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 83-369, (IR)SA-491, 53 p.

El-Hinnawi, E. E., 1964, Petrochemical character of African volcanic rocks Part I: Ethiopia and Red Sea region (including Yaman & Aden): Neues Jahrbuch fur Mineralogie Monatshefte, 1964, pp. 5-81, Stuttgart, Federal Republic of Germany.

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.

____________, 1979, Notes on the mineral distribution maps of the Arab Republic of Yemen, in Al-Shanti, A.M.S., ed., Evolution and mineralization of the Arabian-Nubian Shield: Institute of Applied Geology, King Abdulaziz Univeristy, Bulletin 3, p. 121-129, Jeddah, Kingdom of Saudi Arabia.

Fakhry, A., 1935, El Najadi: Kingdom of Saudi Arabia Directorate General of Mineral Resources Document, unnumbered, 1 p., Jiddah.

Field, Henry, 1971, Contributions to the anthropology of Saudi Arabia: Coconut Grove, Miami, Florida, Field Research Projects, 62 p.

Fix, C. E., 1958, Selected annotated bibliography of the geology and occurrence of uranium-bearing marine black shales in the United States: U.S. Geological Survey Bulletin 1059-F, p. 263-325.

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

Fleck, R. J., and Hadley, D. G., in press, Ages and strontium initial ratios of plutonic rocks in a transect of the Arabian Shield: Geological Society of London.

Foley, M. G., 1978, Scour and fill in steep, sand-bed ephemeral streams: Geological Society of America, Geology, April 1978, p. 229-230.

Gass, I. G., 1970, The evolution of volcanism in the junction of the Red Sea, Gulf of Aden, and Ethiopian rifts: Philosophical Transactions of the Royal Society, Trans. A, v. 267, p. 369-381, London.

Geukens, F., 1966, Geology of the Arabian Peninsula, Yemen: U.S. Geological Survey Professional Paper 560-B, 23 p.

Great Britain Naval Intelligence Division, 1946, Western Arabia and the Red Sea: Geographical Handbook Series B.R. 527, declassified.

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

Greenwood, J. E. G. W., Bleackley, D., and Beydoun, Z. R., 1967, Photogeologic map of the 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: Philosophical Transactions of the Royal Society, v. 280, p. 517-527, London.

Grimaldi, F. S., May, Irving, Fletcher, M. H., and Titcomb, Jane, 1954, Collected papers on methods of analyses for uranium and thorium: U.S. Geological Survey Bulletin 1006, 184 p.

Grimes, D. J., and Marranzino, A. P., 1968, Direct-current arc and alternating-current spark emission spectrographic field methods for the semiquantitative analysis of geologic materials: U.S. Geological Survey Circular 591, 6 p.

Grolier, M. J., Domenico, J. A., Donato, M. M., 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 Report 77-733, (IR)Y-12, 108 p.

Grolier, M. J., and Overstreet, W. C., 1978, Geologic map of the Yemen Arab Republic (San'a): U.S. Geological Survey Miscellaneous Investigations Series Map I-1143-B, 1:500,000 scale.

Grolier, M. J., Tibbitts, G. C., Jr., and Ibrahim, M. M., 1981, A qualitative appraisal of the hydrology of the Yemen Arab Republic from LANDSAT images: U.S. Geological Survey Open-File Report 80-565, 103 p.

Halévy, Joseph, 1872, Rapport sur une mission archéologique dans le Yémen: Journal Asiatique, 6th series, v. 19, p. 5-98.

Helfritz, Hans, 1935, The first crossing of southwestern Arabia: Geographical Review, p. 395-407.

Hitti, P. K., 1956, History of the Arabs from the earliest times to the present: London, Macmillan and Company, Ltd., 6th ed., 822 p.

Hughes, J. D., 1983, How the ancients viewed deforestation: Journal of Field Archaeology, v. 10, no. 4, p. 437-445.

Irvine, T. N., and Baragar, W. R. A., 1971, A guide to the chemical classification of common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, no. 5, p. 523-548.

Jackaman, Barry, 1972, Genetic and environmental factors controlling the formation of the massive sulfide deposits of Wadi Bidah and Wadi Wassat, Saudi Arabia: Kingdom of Saudi Arabia Directorate General of Mineral Resources Technical Record TR-1972-1, 244 p.

Jacquin, J. P., MacGaw, W., Quinet, P., and Sustrac, G., 1983, Allurial exploration along the Red Sea coast: reappraisal of results of 1968-1970 program, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report BRGM-OF-03-52, 83 p.

Johannsen, Albert, 1932, A descriptive petrography of the igneous rocks, Volume II, The quartz-bearing rocks: Chicago, The University of Chicago Press, 428 p.

___________, 1937, A descriptive petrography of the igneous rocks, Volume III, The intermediate rocks: Chicago, The University of Chicago Press, 360 p.

Johnson, P. R., 1983, A preliminary lithofacies map of the Saudi Arabian Shield: Kingdom of Saudi Arabia Deputy Ministry for Mineral Resources Technical Record RF-TR-03-02, 72 p.

Kabesh, M. L., and Ghoweba, A. M., 1976, Remarks on the petrochemistry of some Quaternary basaltic rocks, Hamdan volcanic field, Yemen Arab Republic: Chemie der Erde, v. 35, p. 344-355.

Karrenberg, Herbert, 1956, Junger Magmatismus und Volkanismus in Sudwestarabien (Jemen): International Geological Congress, 20th Session, Mexico, Section I - Vulcanologia del Cenozoico, p. 171-185.

__________, 1959, Junger Magmatismus in Sudwest Arabien (Jemen): Technische Mitteilungen Krupp, v. 17, no. 1, p. 33-36.

Kiilsgaard, T. H., Greenwood, W. R., Puffett, W. P., Naqvi, M., Roberts, R. J., Worl, R. G., Merghalani, H., Flanigan, V. J., and Gazzaz, A. R., 1978, Mineral exploration in the Wadi Bidah district, 1972-1976, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 78-771, (IR)SA-237, 89 p.

Kuno, Hishasi, 1966, Lateral variation of basalt magma type across continental margins and island arcs: Bulletin Volcanologique, v. 29, p. 195-222.

Langer, C. J., and Merghelani, H. M., 1983, Aftershocks of the Yemen earthquake of December 13, 1982: A detailed study from locally recorded data, abst.: Earthquake Notes, v. 54, no. 1, p. 20.

Leopold, L. G., Wolman, M. G., and Miller, J. P., 1964, Fluvial processes in geomorphology: San Francisco, W. H. Freeman and Company, 522 p.

Levinson, A. A., 1980, Introduction to exploration geochemistry: Wilmette, Ill., Applied Publishing Ltd., 924 p.

Lipparini, T., 1954, Contributi alla conoscenza vulcanologica dello Yemen: Bollettino del Servizio Geologico d'Italia, V. 76, p. 93.

Loughman, F. C., 1969, Chemical weathering of the silicate minerals: New York, American Elsevier Publishing Company, 154 p.

MacKenzie, N. D., and Al Helwa, S., 1980, Darb Zubaydah, 1979, a preliminary report: ATLAL, the Journal of Saudi Arabian Archeology, v. 4, p. 37-50.

Maddin, Robert, 1981, Early iron technology in Cyprus, in Muhly, J. D., Maddin, Robert, and Karageorghis, Vassos, eds., Early metallurgy in Cyprus, 4000-500 B.C.: ACTA of the International Archaeological Symposium, Pierides Foundation, Larnaca, Cyprus, 1-6 June 1981, p. 303-312.

McClure, H. A., 1976, Radiocarbon chronology of late Quaternary lakes in the Arabian desert: Nature, v. 263, p. 755-756.

Miclea, Pavel, 1973, Monographie geologico-miniera R.A. Yemen: Ministerul Minelor, Petrolului si Geologiei, Oficiul de Documentare si Publicatti Tehnice, Bucharest, 73 p.

Mohr, P. A., 1971, Ethiopian rift and plateaus: Some volcanic petrochemical difference: Journal of Geophysical Research, v. 76, no. 2, p. 1967-1984.

Niebuhr, Carsten, 1774-1778, Reisenbeschreibung nach Arabien und andern umliegende Lander: Copenhagen, 2 vols. [English edition published in 1972 at Edinburgh and reprinted in 1975 by Rare Books Reprints, Libraire du Liban, Beirut.]

Overstreet, W. C., 1971, Correspondence, in Field, Henry, Contributions to the anthropology of Saudi Arabia: Coconut Grove, Miami, Florida, Field Research Projects, p. 25-38.

____________, 1978, A geological and geochemical reconnaissance of the Tathlith one-degree quadrangle, sheet 19/43, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 78-1072, (IR)SA-230, 132 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 Report 76-274, 70 p.

Overstreet, W. C., Donato, M. M., Grolier, M. J., Domenico, J. A., Crenshaw, G. L., Tibbitts, G. C., Jr., and Ibrahim, M. M., 1980, Petrographic and trace-element data on rocks from the Yemen Arab Republic: U.S. Geological Survey Open-File Report 80-132, (IR)Y-15, 62 p.

Overstreet, W. C., Grimes, D. J., and Seitz, J. F., 1982, Geochemical orientation for mineral exploration in the Hashemite Kingdom of Jordan: U.S. Geological Survey Open-File Report 82-791, 246 p.

Overstreet, W. C., and Grolier, M. J., 1980, Iron ore near Sa'dah, Yemen Arab Republic: Geochemical implications for future economic development of an archeo-metallurgical site, in Prematilake, L., Gunawardane, W. T. T. P., and Silva, Roland, eds., P.E.P. Deraniyagala Commemoration Volume: National Museums Department, Colombo, Sri Lanka, p. 283-311.

Overstreet, W. C., Hubert, A. E., Crenshaw, G. L., and Mosier, E. L., 1978, Petrogenic significance of minor elements in pyritic core from the Wadi Wassat massive sulfide deposit, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 78-863, (IR)SA-214, 116 p.

Overstreet, W. C., and Rossman, D. L., 1970, Reconnaissance geology of the Wadi Wassat quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 78-863, (IR)SA-117, 68 p.

Peipert, J. R., 1984, Desert marches on relentlessly: The New Mexican, April 8, 1984, p. A-13, Santa Fe, N.M.

Persons, B. S., 1970, Laterite, genesis, location, use: New York, Plenum Press, 103 p.

Philby, H. St J. B., 1933, The Empty Quarter: New York, Henry Holt and Company, 433 p.

_____________, 1938, The land of Sheba: The Geographical Journal, v. 92, no. 1, p. 1-21, 107-132, London.

Pilger, A., and Rosler, A., eds., 1975, The Afar Depression of Ethiopia: Volume 1 of International Symposium on the Afar Region and Related Rift Problems, Schweizerbart, Stuttgart, 416 p.

Plafker, George, Agar, Robert, Al-Thahiri, A. A. H., and Hanif, Mohammed, 1983, Surface effects and tectonics of the 13 December 1982 Yemen earthquake, abst.: Earthquake Notes v. 54, No. 1, p. 20.

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

Rathjens, Carl, and Wissman, Herrmann von, 1934, Sudarabien Reise, v. 3, Landeskundliche Ergebnisse: Hamburg, Friedrichsen, de Gruyter and Co., 229 p.

_____________, 1942, Beobachtungen in Yemen: Geologische Rundschau, v. 33, p. 248-279.

Ratnagar, Shereen, 1981, Encounters, the westerly trade of the Harappa civilization: Delhi, Oxford University Press, 294 p.

Roberts, R. J., Rye, R. O., and Mawad, M. M., 1978, Preliminary sulfur isotope investigations of mineral deposits in the Precambrian Shield, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 78-776, (IR)SA-246, 19 p.

Roman, D. R., 1926, Petrographical studies in Yemen (Arabia): Institutuli Geologic and Romaniei Anuaral, v. 21, p. 301-348.

Ryall, W. R., and Taylor, G. F., 1981, Gossan evaluation manual for use in the Kingdom of Saudi Arabia: Kingdom of Saudi Arabia Deputy Ministry for Mineral Resources Technical Record RF-TR-01-3, 146 p.

Sabir, Hussein, 1983, Ancient mining activity and its relationship to modern mineral exploration in Saudi Arabia: Report from the Arab Seminar on Ancient Mining Exploitation and Its Effects on Modern Mining Technology, Jiddah, Saudi Arabia, Rajab 1403 (April 1983), 35 p.

Schmidt, D. L., and Brown, G. F., in press, Major-element chemical evolution of the Late Proterozoic Shield of Saudi Arabia: The First Symposium of Pan-African Crustal Evolution in the Arabian-Nubian Shield, IGCP Project 164.

Schmidt, D. L., Hadley, D. G., and Brown, G. F., 1982, Middle Tertiary continental rift and evolution of the Red Sea in southwestern Saudi Arabia: U.S. Geological Survey Open-File Report 83-641, (IR)SA-503, 56 p.

Schmidt, D. L., Hadley, D. G., and Stoeser, D. B., 1979, Late Proterozoic crustal history of the Arabian Shield, southern Najd Province, Kingdom of Saudi Arabia, in Al-Shanti, A.M.S., ed., Evolution and mineralization of the Arabian-Nubian Shield, Volume 2: Institute of Applied Geology, King Abdulaziz University, Bulletin 3, p. 41-58, Jeddah, Kingdom of Saudi Arabia.

Schmidt, D. L., Puffett, W. P., Campbell, W. L., and Al-Koulak, Z. H., 1982, Gold placer and Quaternary stratigraphy of the Jabal Mokhyat area, southern Najd Province, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 82-414, (IR)SA-375.

Schmidt, P. H., and Avery, D. H., 1983, More evidence for an advanced prehistoric iron technology in Africa: Journal of Field Archaeology, v. 10, no. 4, p. 421-434.

Schoch, Rudolph, 1978, Land evaluation and classification from LANDSAT-imagery in the Yemen Arab Republic: Department of Geography, University of Zurich, in cooperation with the Swiss Technical Co-operation Service, map, 1:1,000,000 scale.

Schulze, K. H., and Thiele, Joachim, 1978, German Geological Advisory Group in Yemen Arab Republic final report for the period 24 April 1974 to 30 April 1977: Hannover, Federal Institute for Geoscience and Natural Resources Report, 86 p.

Shand, S. J., 1951, Eruptive rocks: New York, John Wiley, 488 p.

Shapiro, Leonard, 1975, Rapid analyses of silicate, carbonate, and phosphate rocks--revised edition: U.S. Geological Survey Bulletin 1401, 76 p.

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

____________, 1955b, A classification of the pyroclastic rocks of Yaman: L'Institut d'Egypte Bulletin, v. 36, p. 165-175.

Skipwith, Sir Patrick, 1973, The Red Sea and coastal plain of the Kingdom of Saudi Arabia, a review: Kingdom of Saudi Arabia Directorate General of Mineral Resources Technical Record TR-1973-1, 149 p.

Stacey, J. S., and Hedge, C. E., in press, Direct evidence for early Proterozoic crust in the eastern Arabian Shield: "Nature"

Stacey, J. S., and Stoeser, D. B., 1984, Distribution of oceanic and continental leads in the Arabian-Nubian Shield: Contributions to Mineralogy and Petrology, v. 84, p. 91-105.

Stoeser, D. B., and Elliott, J. E., 1979, Post-orogenic peralkaline and calcalkaline granites and associated mineralization of the Arabian Shield, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 83-674, (IR)SA-265, 42 p.

Stoeser, D. B., Fleck, R. J., and Stacey, J. S., in press, Geochronology and origin of an early tonalite gneiss of the Wadi Tarib batholith and the formation of syntectonic gneiss complexes in the southeastern Arabian Shield, Kingdom of Saudi Arabia: Proceedings, First Symposium on Pan-African Crustal Evolution in the Arabian-Nubian Shield, IGCP Project 164.

Streckeisen, A. L., 1976, to each plutonic rock its proper name: Earth-Science Reviews, v. 12, no. 1, p. 1-33.

__________, 1979, Classification and nomenclature of volcanic rocks, lamprophyres, carbonatites, and melilitic rocks: Recommendations and suggestions of the IUGS Subcommission on the Systematics of Igneous Rocks: Geological Society of America, Geology, v. 7, p. 331-335.

Stuckless, J. S., Knight, R. J., Van Trump, George, Jr., and Budahn, J. R., 1983, Trace-element geochemistry of postorogenic granites from the northeastern Arabian Shield, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 83-287, (IR)SA-497, 34 p.

Stuckless, J. S., Van Trump, George, Jr., 1979, A revised version of Graphic Normative Analysis Program (GNAP) with examples of petrologic problem solving: U.S. Geological Survey Open-File Report 79-1237, 115 p.

Stuckless, J. S., Van Trump, George, Jr., Christiansen, E. H., Bush, C. A., Bunker, C. M., and Bartel, A. J., 1983, Preliminary assessment of the geochemistry and mineral favorability of the postorogenic granites of the southeastern Arabian Shield, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report 83-486, 41 p.

Thornton, C. P., and Tuttle, O. F., 1960, Chemistry of igneous rocks I. Differentiation index: American Journal of Science, v. 258, p. 664-684.

Tibbitts, G. C., Jr., and Aubel, James, 1980, Groundwater resources investigation in the Amran Valley, Yemen Arab Republic: U.S. Geological Survey Open-File Report 80-774, 138 p.

United Kingdom Ministry of Defence, 1971, Ma'rib sheet: Director of Military Survey, Ministry of Defense, United Kingdom, topographic map, 1:250,000 scale, sheet ND38-2, London.

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

Van Beek, G. W., 1969a, Hajar Bin Humeid: Investigations at a pre-Islamic site in South Arabia: Publications of the American Foundation for the Study of Man, v. 5, 421 p., The John Hopkins University Press, Baltimore.

__________, 1969b, The rise and fall of Arabia Felix: Scientific American, v. 221, no. 6, p. 36-46.

__________, 1974, The land of Sheba, _in_ Pritchard, J.B., ed., Solomon and Sheba: London, Phaidon Press Limited, p. 40-63.

Van Eysinga, F. W. B., 1975, Geological time table: Amsterdam, Elsevier Scientific Publishing Co., chart, 3d ed.

Wade, Rosalind, 1979, Archaeological observations around Ma'rib 1976: Proceedings for the Seminar for Arabian Studies, v. 9, p. 114-123.

Weisberger, G., 1981, Towards a history of copper mining in Cyprus and the Near East: possibilities of mining archaeology, in Muhly, J.D., Maddin, Robert, and Karageorghis, Vassas, eds., Early metallurgy in Cyprus, 4000-500 B.C.: ACTA of the International Archaeological Symposium, Pierides Foundation, Larnaca, Cyprus, 1-6 June 1981, p. 25-32.

Weissenborn, A. L., and Earhart, R. L., 1968, Appraisal of the Wadi Wassat and Wadi Adhbat pyrite deposits, Asir quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Open-File Report SA(IR)-101, 22 p.

Wenner, M. W., 1968, Modern Yemen, 1918-1966: Baltimore, The Johns Hopkins University Press, 257 p.

Wertime, T. A., 1981, Cypriot metallurgy against the backdrop of Mediterranean pyrotechnology: energy reconsidered, in Muhly, J.D., Maddin, Robert, and Karageorghis, Vassas, eds., Early metallurgy in Cyprus, 4000-500 B.C.: ACTA of the International Archaeological Symposium, Pierides Foundation, Larnaca, Cyprus, 1-6 June 1981, p. 351-361.

__________, 1983, The furnace versus the goat: the pyrotechnologic industries and Mediterranean deforestation in antiquity: Journal of Field Archaeology, v. 10, no. 4, p. 445-452.

Western, S., 1972, The classification of arid zone soils: the classification of sedosols in South Arabia: Journal of Soil Science, v. 23, no. 3, p. 279-290.

Whitney, J. W., 1982, Preliminary geological investigation of the B'ir Hayzan diatomite deposit, Kingdom of Saudi Arabia, with a section on Selected physical properties and implications for future geophysical investigations, by M. E. Gettings: U.S. Geological Survey Open-File Report 82-1046, (IR)SA-432, 25 p.

__________, 1983, Erosional history and surficial geology of western Saudi Arabia: Available from Saudi Arabia Deputy Minister for Mineral Resources.

Appendix 1. Normalized oxide values, normative minerals, and adjusted molar oxide values based on the chemical composition of six samples of older Precambrian igneous rocks from the Yemen Arab Republic (in percent).

[Dash=no entry.]

Petrologic parameters	Rock type and field number					
	Diabase	Granodiorite gneiss	Granite gneiss			
	MJG-76-41A	MJG-76-54A	MJG-76-16	MJG-76-21	MJG-76-25	MJG-76-28A
Normalized oxide values						
SiO_2	47.71	63.47	71.46	73.87	75.50	73.22
Al_2O_3	16.34	17.62	14.97	13.81	12.89	13.58
Fe_2O_3	4.35	1.57	1.06	1.56	0.40	1.04
FeO	7.19	3.56	1.48	0.76	0.96	1.50
MgO	9.65	1.30	0.93	0.18	0.39	0.55
CaO	11.17	3.59	2.64	0.96	0.88	1.42
Na_2O	1.85	4.77	3.22	3.87	2.13	3.20
K_2O	0.24	3.11	3.76	4.68	6.55	4.94
TiO_2	1.18	0.59	0.30	0.21	0.19	0.38
P_2O_5	0.13	0.24	0.10	0.04	0.08	0.11
MnO	0.19	0.17	0.08	0.05	0.02	0.05
Total	100.00	99.99	100.00	99.99	99.99	99.99
Normative Minerals						
Quartz	--	12.803	30.917	31.218	35.280	31.533
Corundum	--	0.461	1.060	0.726	0.894	0.658
Orthoclase	1.408	18.352	22.196	27.660	38.687	29.196
Albite	15.688	40.363	27.255	32.778	18.038	27.076
Anorthite	35.570	16.233	12.414	4.491	3.833	6.316
Nepheline	--	--	--	--	--	--
Acmite	--	--	--	--	--	--
Wollastonite	7.909	--	--	--	--	--
Enstatite	20.103	3.235	2.313	0.452	0.981	1.378
Ferrosilite	6.692	4.591	1.500	--	1.149	1.359
Fosterite	2.760	--	--	--	--	--
Fayalite	1.012	--	--	--	--	--
Magnetite	6.307	2.281	1.537	1.989	0.586	1.503
Hematite	--	--	--	0.192	--	--
Ilmenite	2.242	1.118	0.575	0.402	0.365	0.726
Titanite	--	--	--	--	--	--
Rutile	--	--	--	--	--	--
Apatite	0.319	0.577	0.239	0.096	0.091	0.262
Total	100.009	100.015	100.006	100.003	100.004	100.006
Molar data adjusted oxides						
SiO_2	50.54	70.13	77.68	80.74	82.05	79.72
Al_2O_3	10.20	11.47	9.59	8.90	8.26	8.72
Fe_2O_3	1.73	0.65	0.43	0.64	0.17	0.42
FeO	6.37	3.29	1.35	0.69	0.87	1.37
MgO	15.24	2.14	1.51	0.30	0.64	0.90
CaO	12.67	4.25	3.07	1.12	1.02	1.66
Na_2O	1.90	5.11	3.39	4.10	2.25	3.38
K_2O	0.16	2.19	2.60	3.26	4.54	3.43
TiO_2	0.94	0.49	2.25	0.17	0.16	0.31
P_2O_5	0.06	0.11	0.05	0.02	0.04	0.05
MnO	0.17	0.16	0.07	0.05	0.02	0.05
Total	99.98	99.99	99.99	99.99	100.02	100.01

Appendix 2. Normalized oxide values, normative minerals, and adjusted molar oxide values based on the chemical composition of six samples of younger Precambrian igneous rocks from the Yemen Arab Republic (in percent).

[Dash=no entry.]

Petrologic parameters	Rock type and field number					
	Granodiorite	Granite gneiss	Biotite granite	Alkali-feldspar granite		Riebeckite granite
	MJG-76-56A	MJG-76-15	MJG-76-26B	MJG-76-39A	MJG-76-39B	MJG-76-50
Normalized oxide values						
SiO_2	64.88	77.67	74.19	76.95	78.36	78.65
Al_2O_3	15.46	12.49	14.26	12.51	12.10	11.67
Fe_2O_3	1.67	0.64	0.32	1.16	0.33	0.80
FeO	3.41	0.17	0.85	0.34	0.15	0.43
MgO	1.30	0.13	0.31	0.01	0.03	0.05
CaO	2.70	0.53	1.04	0.38	0.32	0.28
Na_2O	4.40	2.58	3.79	3.59	3.07	3.86
K_2O	4.76	5.64	4.94	4.90	5.57	4.17
TiO_2	1.05	0.10	0.20	0.12	0.04	0.07
P_2O_5	0.26	0.02	0.06	0.02	0.02	0.01
MnO	0.11	0.02	0.03	0.02	0.01	0.01
Total	100.00	99.99	99.99	100.00	100.00	100.00
Normative Minerals						
Quartz	13.269	39.812	30.231	36.549	38.547	39.595
Corundum	--	1.228	0.922	0.657	0.495	0.327
Orthoclase	28.151	33.348	29.209	28.940	32.902	24.627
Albite	37.203	21.791	32.089	30.378	25.938	32.678
Anorthite	8.392	2.513	4.770	1.764	1.464	1.298
Nepheline	--	--	--	--	--	--
Acmite	--	--	--	--	--	--
Wollastonite	1.400	--	--	--	--	--
Enstatite	3.227	0.326	0.773	0.025	0.075	0.127
Ferrosilite	3.348	--	1.023	--	--	0.022
Fosterite	--	--	--	--	--	--
Fayalite	--	--	--	--	--	--
Magnetite	2.426	0.325	0.464	0.818	0.402	1.167
Hematite	--	0.419	--	0.592	0.054	--
Ilmenite	1.996	0.919	0.380	0.229	0.076	0.135
Titanite	--	--	--	--	--	--
Rutile	--	--	--	--	--	--
Apatite	0.604	0.048	0.142	0.048	0.048	0.024
Total	100.015	100.001	100.003	100.001	100.001	100.001
Molar data, adjusted oxides						
SiO_2	71.62	84.08	80.61	83.47	84.53	84.55
Al_2O_3	10.06	7.97	9.13	8.00	7.69	7.39
Fe_2O_3	0.69	0.26	0.13	0.47	0.13	0.33
FeO	3.15	0.15	0.77	0.31	0.14	0.38
MgO	2.13	0.21	0.50	0.02	0.05	0.08
CaO	3.20	0.62	1.21	0.44	0.37	0.32
Na_2O	4.70	2.70	3.99	3.78	3.21	4.02
K_2O	3.35	3.90	3.43	3.39	3.83	2.86
TiO_2	0.87	0.08	0.16	0.10	0.03	0.06
P_2O_5	0.12	0.01	0.03	0.01	0.01	0.00
MnO	0.10	0.02	0.03	0.02	0.01	0.01
Total	99.99	100.00	99.99	100.01	100.00	100.00

Appendix 3. Normalized oxide values, normative minerals, and adjusted molar oxide values based on the chemical composition of eight samples of Tertiary igneous rocks of the Yemen Arab Republic (in percent).

[Dash=no entry.]

Petrologic parameters	Rock type and field number							
	Welded tuff		Vesicular welded tuff	Crystal lithic tuff	Alkali granite			
	MJG-76-1A	MJG-76-1B	MJG-76-6	75-OT-26	75-OT-27	75-OT-28	MJG-76-72A	ROJ-1
Normalized oxide values								
SiO_2	73.72	74.26	75.69	72.63	66.32	74.53	73.82	74.89
Al_2O_3	12.23	13.82	11.58	12.74	16.31	12.64	12.64	12.53
Fe_2O_3	2.02	2.89	3.03	2.63	2.07	1.46	2.68	2.39
FeO	1.09	0.21	0.04	1.16	1.44	1.28	0.51	--
MgO	0.39	0.12	0.13	0.52	0.74	0.12	0.10	0.10
CaO	0.73	0.24	0.46	1.42	1.25	0.49	0.33	0.36
Na_2O	3.33	3.55	3.67	4.16	6.14	4.31	4.40	4.83
K_2O	4.71	4.17	5.05	3.68	4.49	4.76	4.92	4.78
TiO_2	0.55	0.58	0.25	0.82	0.84	0.23	0.40	--
P_2O_5	0.06	0.03	0.03	0.12	0.21	0.03	0.03	--
MnO	0.15	0.13	0.07	0.11	0.18	0.13	0.19	0.11
Total	99.98	100.00	100.00	99.99	99.99	99.98	100.02	99.99
Normative Minerals								
Quartz	34.368	37.049	34.308	31.099	10.479	29.880	28.928	28.667
Corundum	1.483	3.113	--	--	--	--	--	--
Orthoclase	27.828	24.632	29.856	21.733	26.542	28.128	29.044	28.240
Albite	28.155	30.046	31.062	35.217	51.960	36.491	37.198	37.860
Anorthite	3.222	0.973	0.191	5.228	3.667	1.081	0.237	--
Nepheline	--	--	--	--	--	--	--	--
Acmite	--	--	--	--	--	--	--	2.650
Wollastonite	--	--	0.613	0.425	0.488	0.477	0.492	0.739
Enstatite	0.980	0.308	0.327	1.283	1.839	0.304	0.253	0.254
Ferrosilite	--	--	--	--	--	1.003	--	--
Fosterite	--	--	--	--	--	--	--	--
Fayalite	--	--	--	--	--	--	--	--
Magnetite	2.412	--	--	1.733	2.791	2.124	1.121	0.366
Hematite	0.356	2.892	3.025	1.432	0.149	--	1.903	1.226
Ilmenite	1.050	0.721	0.236	1.565	1.595	0.444	0.754	--
Titanite	--	--	0.313	--	--	--	--	--
Rutile	--	0.197	--	--	--	--	--	--
Apatite	0.151	0.073	0.072	0.293	0.503	0.072	00.072	--
Total	100.005	100.003	100.002	100.008	100.013	100.003	100.004	100.001
Molar data, adjusted oxides								
SiO_2	80.69	81.82	82.79	79.34	73.65	81.17	81.06	81.82
Al_2O_3	8.54	8.97	7.46	8.20	10.67	8.11	8.18	8.07
Fe_2O_3	0.83	1.20	1.25	1.08	0.87	0.60	1.11	0.98
FeO	1.00	0.19	0.04	1.06	1.33	1.17	0.47	--
MgO	0.64	0.20	0.21	0.84	1.22	0.20	0.17	0.17
CaO	0.86	0.28	0.54	1.66	1.49	0.57	0.38	0.42
Na_2O	3.53	3.79	3.89	4.41	6.61	4.55	4.68	5.12
K_2O	3.29	2.93	3.53	2.56	3.18	3.31	3.44	3.33
TiO_2	0.45	0.48	0.21	0.68	0.70	0.19	0.33	--
P_2O_5	0.03	0.01	0.01	0.06	0.01	0.01	0.01	--
MnO	0.14	0.12	0.07	0.10	0.17	0.12	0.18	0.10
Total	100.00	99.99	100.00	99.99	99.90	100.00	100.01	100.01

Appendix 4. Normalized oxide values, normative minerals, and adjusted molar oxide values based on the chemical composition of five samples of Quaternary extrusive rocks from the Yemen Arab Republic--olivine basalt of the Aden Volcanic Series (?), (in percent).

[Dash=no entry.]

Petrologic parameters	Rock type and field number				
	Older Lava			Historic flow	
	75-OT-2	75-OT-1	75-OT-9	75-OT-8	75-OT-7
Normalized oxide values					
SiO_2	48.00	47.74	46.70	48.54	48.22
Al_2O_3	16.93	16.18	16.59	17.16	17.27
Fe_2O_3	4.94	3.12	3.04	3.92	3.37
FeO	6.48	7.63	8.10	7.31	7.79
MgO	7.79	8.37	7.57	6.81	6.89
CaO	9.29	9.92	10.32	8.18	8.32
Na_2O	2.79	3.36	3.13	3.94	4.02
K_2O	0.82	0.85	1.13	1.12	1.11
TiO_2	2.30	2.18	2.44	2.26	2.26
P_2O_5	0.48	0.47	0.77	0.57	0.57
MnO	0.18	0.18	0.20	0.18	0.18
Total	100.00	100.00	99.99	99.99	100.00
Normative Minerals					
Quartz	--	--	--	--	--
Corundum	--	--	--	--	--
Orthoclase	4.851	5.025	6.699	6.16	6.536
Albite	23.618	26.279	23.362	33.335	31.098
Anorthite	31.246	26.543	27.863	25.803	25.820
Nepheline	--	1.170	1.706	0.018	1.573
Acmite	--	--	--	--	--
Wollastonite	4.875	8.197	7.627	4.601	4.904
Enstatite	16.585	5.455	4.880	3.047	3.115
Ferrosilite	3.728	2.142	2.249	1.221	1.475
Fosterite	1.971	10.789	9.800	9.746	9.841
Fayalite	0.488	4.668	4.978	4.303	5.139
Magnetite	7.157	4.521	4.408	5.688	4.885
Hematite	--	--	--	--	--
Ilmenite	4.366	4.134	4.639	4.291	4.298
Titanite	--	--	--	--	--
Rutile	--	--	--	--	--
Apatite	1.142	1.103	1.831	1.362	1.346
Total	100.027	100.026	100.042	100.032	100.032
Molar data, adjusted oxides					
SiO_2	52.10	50.94	50.31	52.89	52.38
Al_2O_3	10.83	10.17	10.53	11.01	11.05
Fe_2O_3	2.02	1.25	1.23	1.61	1.38
FeO	5.88	6.81	7.30	6.66	7.08
MgO	12.60	13.31	12.16	11.06	11.15
CaO	10.80	11.34	11.91	9.55	9.68
Na_2O	2.94	3.48	3.27	4.17	4.23
K_2O	0.57	0.58	0.78	0.78	0.77
TiO_2	1.88	1.75	1.98	1.85	1.85
P_2O_5	0.22	0.21	0.35	0.27	0.26
MnO	0.17	0.16	0.18	0.17	0.17
Total	100.01	100.00	100.00	100.02	100.00