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Cenozoic volcanic rocks of Saudi Arabia

by

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CENOZOIC VOLCANIC ROCKS OF SAUDI ARABIA

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ABSTRACT

The Cenozoic volcanic rocks of Saudi Arabia cover about 90,000 km^2, one of the largest areas of alkali olivine basalt in the world. These volcanic rocks are in 13 separate fields near the eastern coast of the Red Sea and in the western Arabian Peninsula highlands from Syria southward to the Yemen Arab Republic.

The initial phase of rifting of the Arabian Plate from the African Plate began as a wide zone of continental-crust extension manifested by basin and range topography. Freshwater lakes, northwest-trending marine gulfs, and alkali olivine basalt flows occupied these basins. Extensive dike swarms intruded parallel to the proto-Red Sea and marked the first phase of new mafic crust formed by volcanic processes. After a hiatus in volcanic activity, counterclockwise rotation of the Arabian Plate during middle Miocene time changed the stress pattern in the plate and a second phase of extrusion of alkali olivine basalt commenced along north-trending fractures. This stress pattern continues to influence Holocene volcanism.

The earliest (pre-uplift) basalts to erupt on the Arabian Plate were predominantly undersaturated picrite and ankaramite, whereas those to erupt near the axis of the proto-Red Sea rift zone were tholeiite. The within-plate volcanic rocks evolved from picrite-ankaramite to alkali olivine basalt with minor volumes of fractionated, under-saturated felsic rocks. Continued crustal thinning and dike intrusion along the proto-Red Sea were accompanied by melting of the continental crust to produce silicic magma as part of a bimodal volcanic suite (tholeiite-rhyolite). These magmas were emplaced as dikes, sills, layered bodies, and flows that mark the early construction of the Red Sea crust. Second-phase lavas are predominantly fractionated hawaiites and alkali olivine basalts. Because undersaturated and

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oversaturated silicic magmas represent the second phase of activity, both fractional crystallization of the basaltic magma and melting of the crust are believed to have occurred.

The historical record of volcanic activity in Saudi Arabia suggests that volcanism is dormant. The harrats should be evaluated for their potential as volcanic hazards and as sources of geothermal energy. The volcanic rocks are natural traps for groundwater; thus water resources for agriculture may be significant and should be investigated.

INTRODUCTION

One of the largest areas of predominantly alkali-olivine basalt in the world is in Saudi Arabia, the Yemen Arab Republic, and Ethiopia (fig. 1; plate 1). Eruption of these lavas is closely tied to the history and evolution of the Red Sea basin. In Saudi Arabia, these lava fields (harrats) are restricted to the eastern coast of the Red Sea and to the adjacent western Arabian highlands. Harrats extend intermittently northward from the Yemen volcanic series (covering some 35,000 km^2)to the Jabal Druse volcanic field of comparable size (45,000 km^2) in Syria. The 13 separate volcanic areas in western Saudi Arabia cover 89,670 km^2 (table 1). The total volume of eruptive material in western Saudi Arabia is estimated to be 10^3 to 10^5 km^3.

The eruptive history of these rocks apparently spans from Oligocene time to the present. The first major pulse occurred during the early Miocene and was followed by a hiatus at the end of the early Miocene. Volcanic activity resumed during the middle Miocene and continues to the present.

The purpose of this report is to synthesize the published data on the Saudi Arabian Cenozoic volcanic rocks and to develop a program of study to establish the geothermal-energy, ground-water, and volcanic-hazards potential of the harrats.

The authors visited all of the volcanic fields of Saudi Arabia during 63 days between January 1981 and January 1982. In some areas, detailed studies have already been published, but, in others, little work has been completed. As part of this project, a computerized catalog of all chemical analyses and standard petrographic calculations has been developed to facilitate future data manipulation (Coleman and others, 1982). All of the radiometric age data are collected in the present report and these have been recalculated using standardized decay constants for K-Ar age determinations (Steiger and Jäger, 1977).

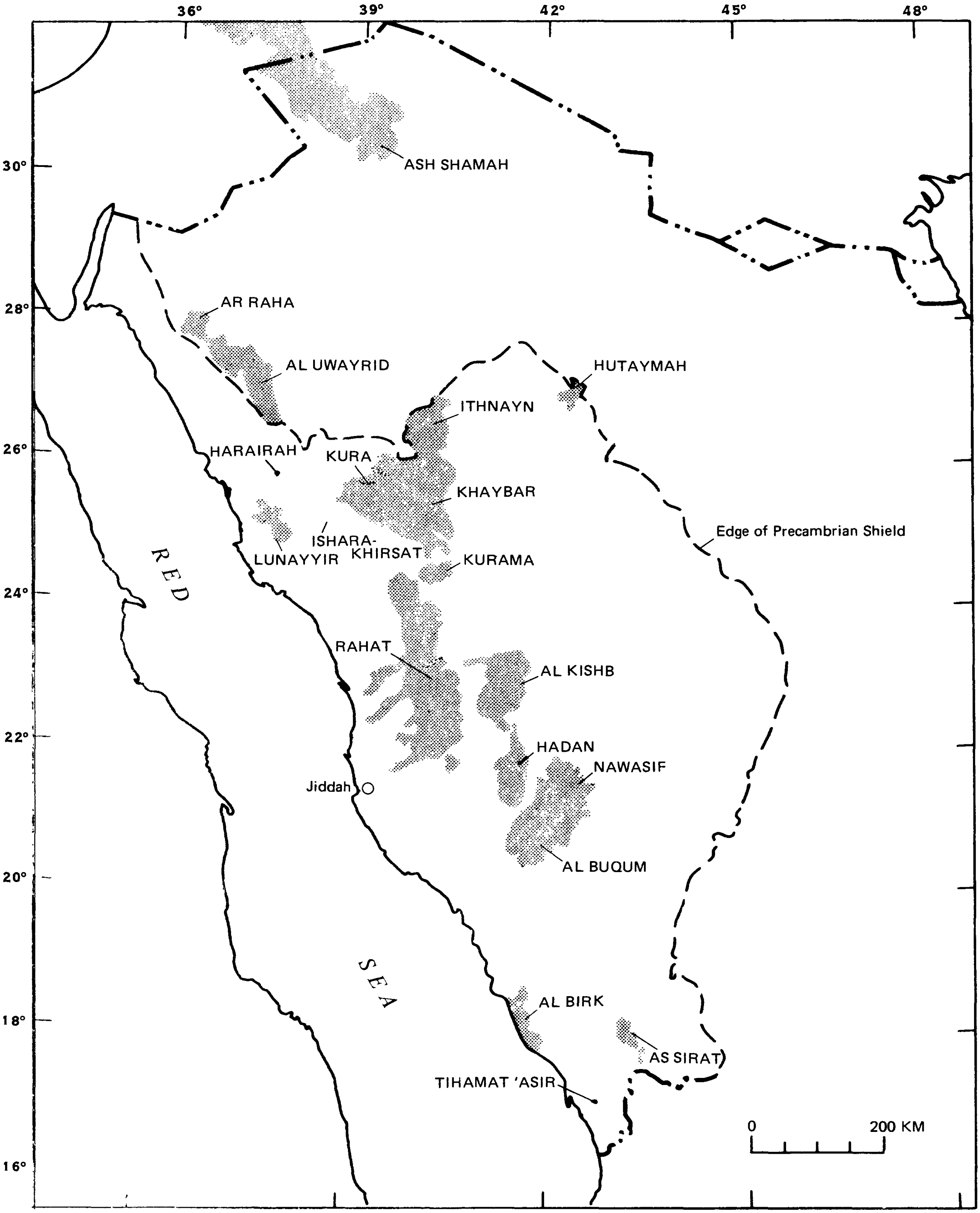

Figure 1.--Index map of western Saudi Arabia showing Cenozoic volcanic fields referred to in this report.

Table 1.--Cenozoic volcanic fields in western Saudi Arabia

Harrat	Area (km^2)	Structural trends	Nodule* distribution	Eruptive** modes	Silicic magmas
Khaybar-Ithnayn-Kura	21,400	N. 30° W., N.	L,D,H	F,T,S,P,D	Yes
Rahat	18,100	N. 10° W., N. 25° W.	L,D,H	F,P,D,S	Yes
Al Harrah	15,200	N. 30° W., N. 7° W.	L,H,D	F,T,S,P	No
Nawasif-Buqum	10,800	N. 30° E.	L,D	P,F,S	No
Rahat-Uwayrid	7,150	N. 30° W., W.	L,D,H,W	P,S,T,D	Yes
Kishb	6,700	N. 10° E.	L,D,C,W	P,T,F,S,D	Yes
Hadan	3,700	?	--	F?	No
Al Birk	1,800	N. 30° W.	H,D,G,C,W	P,F	No
Lunayyir	1,750	N. 30° W.	--	P,F	No
Kurama	1,100	?	?	--	No
Hutaymah	900	N. 10° E.	L,D,C,K	P,T,	No
As Sirat	750	N. 30° W.	--	F?	Yes
Jabal Jilan	320	?	?	?	?

* L-lherzolite, D-dunite, K-kaersutite, H-harzburgite, C-crust, G-gabbro, W-websterite
** F-fissure eruptions, T-tuff rings, S-shields, P-pyroclastic cones, D-domes

A general synthesis of the harrats was made by Brown (1972) during his work on the tectonic map of Saudi Arabia. In the southern Shield, Coleman and others (1977, 1979) concentrated on Harrat al Birk and Harrat as Sirat as well as the Tihamat 'Asir complex. Greene (in press) described the basalts of the Harrat Nawasif and Harrat al Buqum, and Smith (1980) studied the basalts of the southern half of Harrat Rahat. In the northern Shield, Harrat Khaybar has been studied with detailed petrologic work by Baker and others (1973), and regional mapping with K-Ar age determinations by Dhellemmes and Delfour (1980).

ACKNOWLEDGMENTS

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VOLCANIC FIELDS OF SAUDI ARABIA

Harrat as Sirat

Harrat as Sirat, having an area of about 750 km^2 along the Red Sea escarpment from Al Jawf to the Yemen border, is transected by the paved highway between Khamis Mushayt and Zahran (fig.2). Harrat As Sirat is deeply eroded and forms a series of mesas and buttes along the edge of the erosional escarpment of the Asir region, one of the highest areas in Saudi Arabia (2,784 m; Brown and Jackson, 1959).

The lavas were extruded on an extensive laterite formed on Precambrian basement. The laterite is similar to the laterites underlying the Ethiopian Trap Series (Mohr, 1962) and at the top of the Umm Himar formation of Eocene age northeast of At Taif (Madden and others, 1979/1980). To the south near the Yemen border, As Sirat volcanic rocks rest unconformably on the Wajid Sandstone of Cambrian and Ordovician (?) age. Northwest of the Harrat As Sirat, where deep erosion has completely removed the flows, volcanic feeder pipes are exposed along a northwest trend parallel to the Red Sea. These pipes are as much as 15 m in diameter and show columnar jointing normal to their margins. Exposure of the pipes for a distance of 65 km to the northwest suggests that Harrat As Sirat originally extended this far north. Because only rare basaltic dikes can be related directly to the

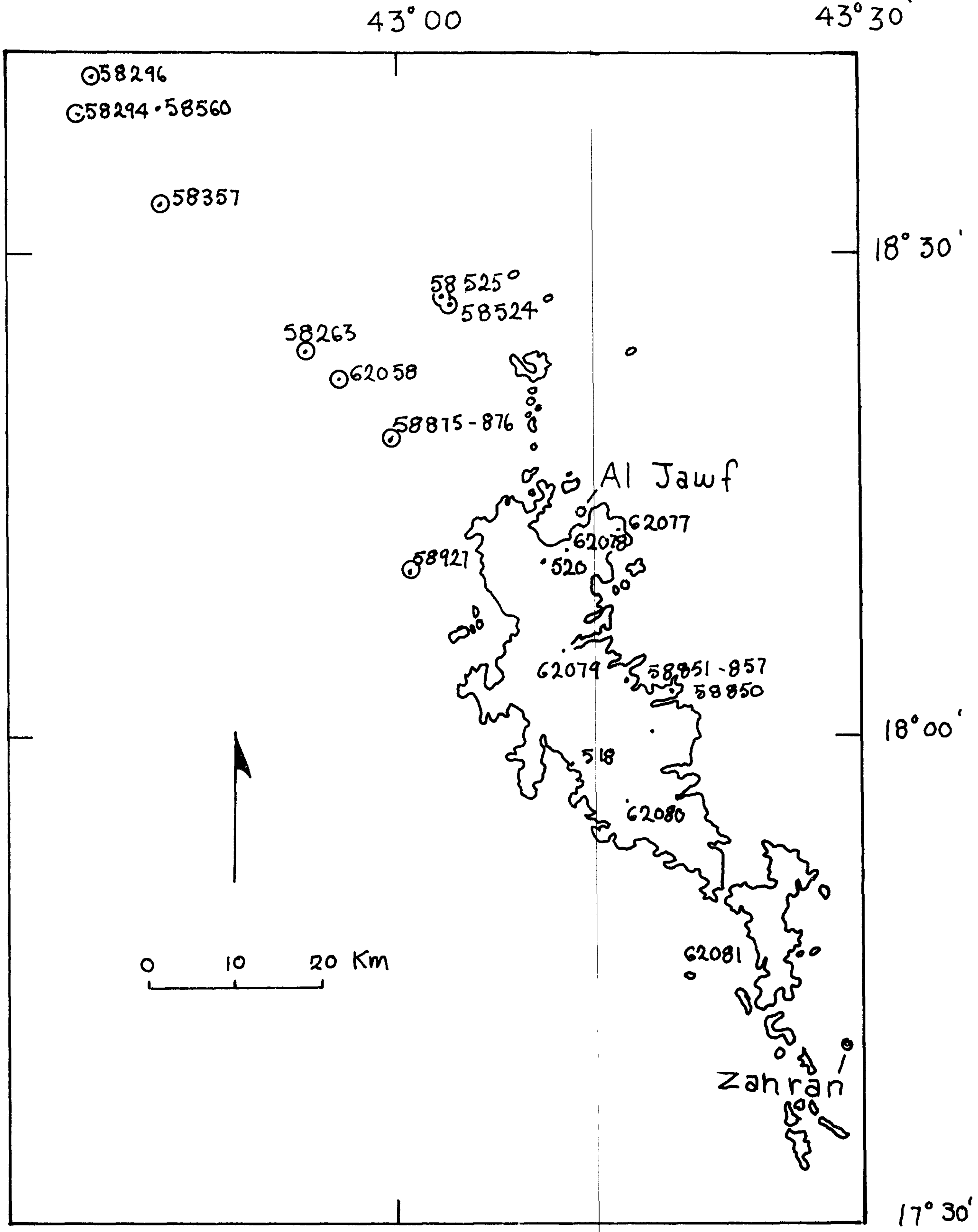

Figure 2.--Map of Harrat as Sirat. Circles with dots show locations of volcanic necks and numbers are of analyzed samples.

harrat, the lavas are believed to have erupted mainly through these pipes. A small plug of trachyte in the center of the harrat appears to intrude the basalt flows (Overstreet and others, 1977).

The As Sirat flows have a maximum total thickness of 580 m, and approximately 20 separate flows have been recognized. Individual flows are 6 to 13 m thick and characteristically have columnar joints in the massive lower and middle sections and platy subhorizontal jointing in the upper sections. No extensive breccia or soil zones are known to separate the flows and no local cinder cones or interlayered pyroclastic rocks were found. Although vesicular textures are present at the tops and bottoms of the flows, the generally massive lavas apparently were extruded rapidly with only minor amounts of volatiles. No folding or warping of the As Sirat flows is apparent, but minor north-trending faults have produced small offsets along the northern boundary of the harrat. No reliable evidence of the flow direction was observed. The absence of As Sirat lavas overlying Wajid sandstone on the coastal plain indicates that these lavas did not flow toward the Red Sea.

Harrat al Birk

Harrat al Birk (fig. 3) is situated on the Red Sea coastal plain, mainly between Wadi Hali and Wadi Nahb. Between these two wadis, the Al Birk volcanic rocks almost completely cover the coastal plain from the foothills to the shoreline (Brown and Jackson, 1958; Hadley, 1975). The flows form an irregular elongate volcanic field of approximately 1,800 km^2. Further inland, two separate cones (Jabal al Haylah and Jabal Baqarah) and associated flows may belong to the same period of volcanism. Many small cinder cones and associated flows are present southward to Jizan; however, south of the Ad Darb transform fault (pl. 1) these smaller eruptive centers have not coalesced to produced extensive lava fields.

The lavas cover paleotopographic features such as river valleys and pediment surfaces and are aggregated into a nearly level plateau surface just above sea level. At Jabal al Haylah, the lava covers gravel terraces that contain Acheulian implements (W. C. Overstreet, written commun; Overstreet and others, 1977). In Europe, Acheulian implements are suggestive of lower-Paleolithic age between the second and third interglacial periods - 500,000 years. On the east side of northern Harrat al Birk, lavas overlie Precambrian basement that is intruded by Tertiary diabase dikes. To the south, the Al Birk lavas rest unconformably upon the Miocene Jabal at Tirf dike swarm and on Wajid Sandstone. On the

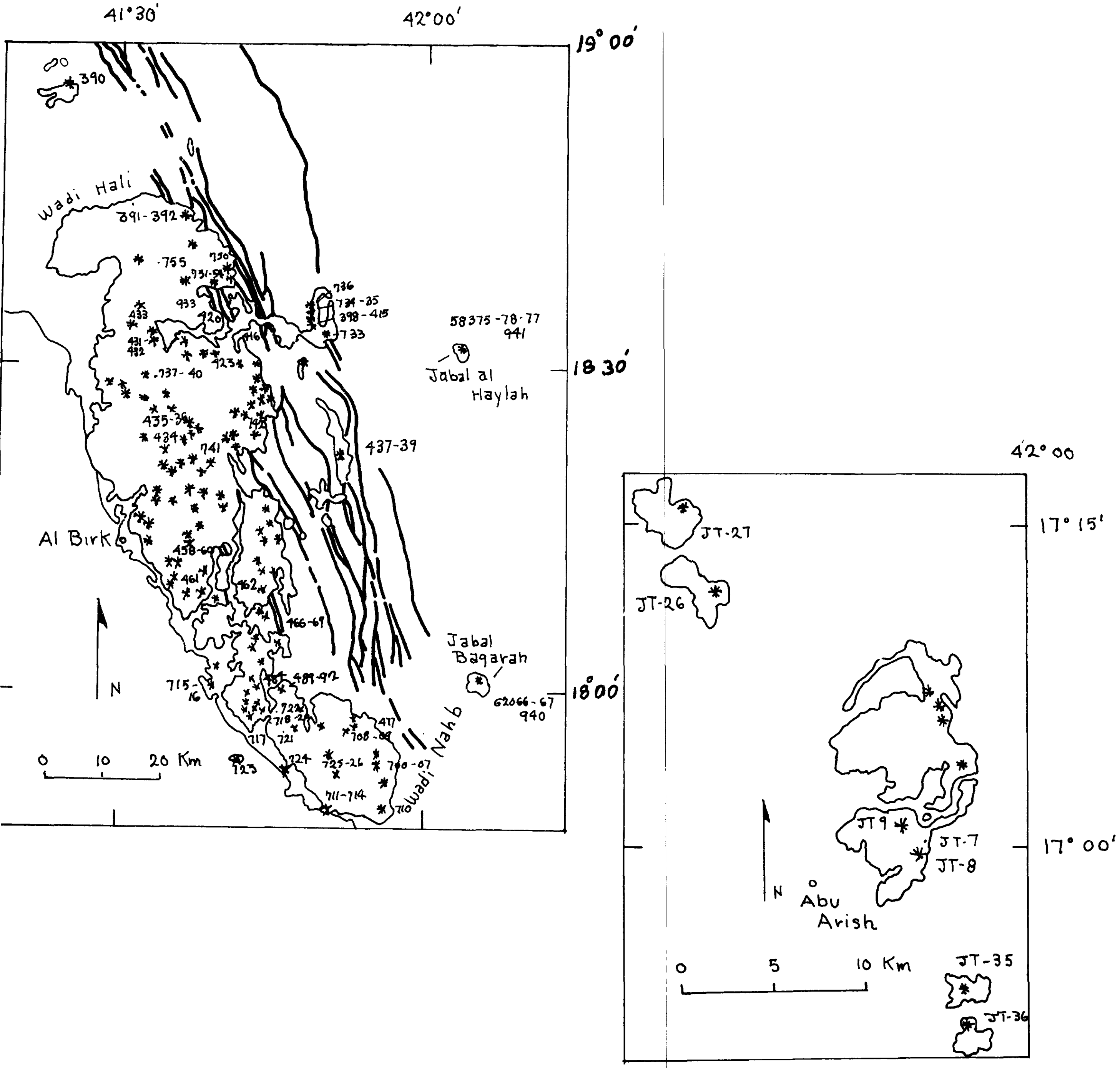

Figure 3.--Map of Harrat al Birk. Asterisks show locations of volcanic eruptive centers and numbers are of analyzed samples. Heavy dark lines show locations of continental dikes. A, northern area; B, southern area.

coastal side, the Al Birk lavas overlie exhumed coral reefs that were formed along the former Red Sea shoreline. All of these contact relations indicate that the Al Birk field is post-Miocene.

More than 200 cinder cones within the main volcanic field have a general northerly trend rather than the northwesterly trend of the Red Sea axis. Nearly all of the lava flows erupted from these cinder cones and the individual volume of any one eruption is not large. The cinder cones are now deeply dissected, but originally most of them appear to have been less than 150 m high and 800 to 1,500 m in diameter at the base. Most of the cones have small craters that were breached by central-vent lava flows. These flows are small, generally blocky on their upper surfaces, and locally interbedded with pyroclastic material. Where the Al Birk volcanic rocks are exposed by erosion in Wadi Amq and Wadi Dhahaban, the flows are columnar in the lower half and grade upward to a zone of knobby rock that is overlain by a zone of platy, horizontally fractured rock. The lavas must have been very fluid and most flowed toward the Red Sea. Locally, multiple flows formed barriers that forced new lava to flow away from the coast.

Xenoliths, common in the cinder cones and within the solidified flows, appear to reflect the lower crustal composition beneath the Al Birk volcanic field. South of the Ad Darb transform fault, where the lavas erupted through attenuated crust that was about 20 km thick (Healy and others, 1982/1983), the inclusion suite is mostly harzburgite and dunite with some gabbro and Wajid Sandstone. In contrast, north of the Ad Darb transform fault, where the Al Birk kavas overlie a 40-km-thick continental crust (Healey and others, 1982/1983), the more heterogenous inclusion suite contains harzburgite, dunite, lherzolite, gabbro, websterite, and megacrysts of spinel, clinopyroxene, and plagioclase (Ghent and others, 1980).

Harrat Nawasif-Harrat al Buqum

The basalts of Harrat Nawasif-Harrat al Buqum (fig. 4) form an elongate lava field situated east of Turabah and southeast of Khurmah (Brown and others, 1963; Jackson and others, 1963). The harrat forms a somewhat sloping plateau that has a maximum altitude of approximately 1,400 m near lat 20°20' N. and a minimum elevation of 1,000 m about 150 km to the northeast. The harrat is the fourth largest lava field (10,300 km^2) in the Kingdom, and it rests entirely on the Precambrian rocks of the Hijaz Mountains and the Najd Plateau. North-trending faults within the Precambrian basement extend to the southern edge of the harrat and, near

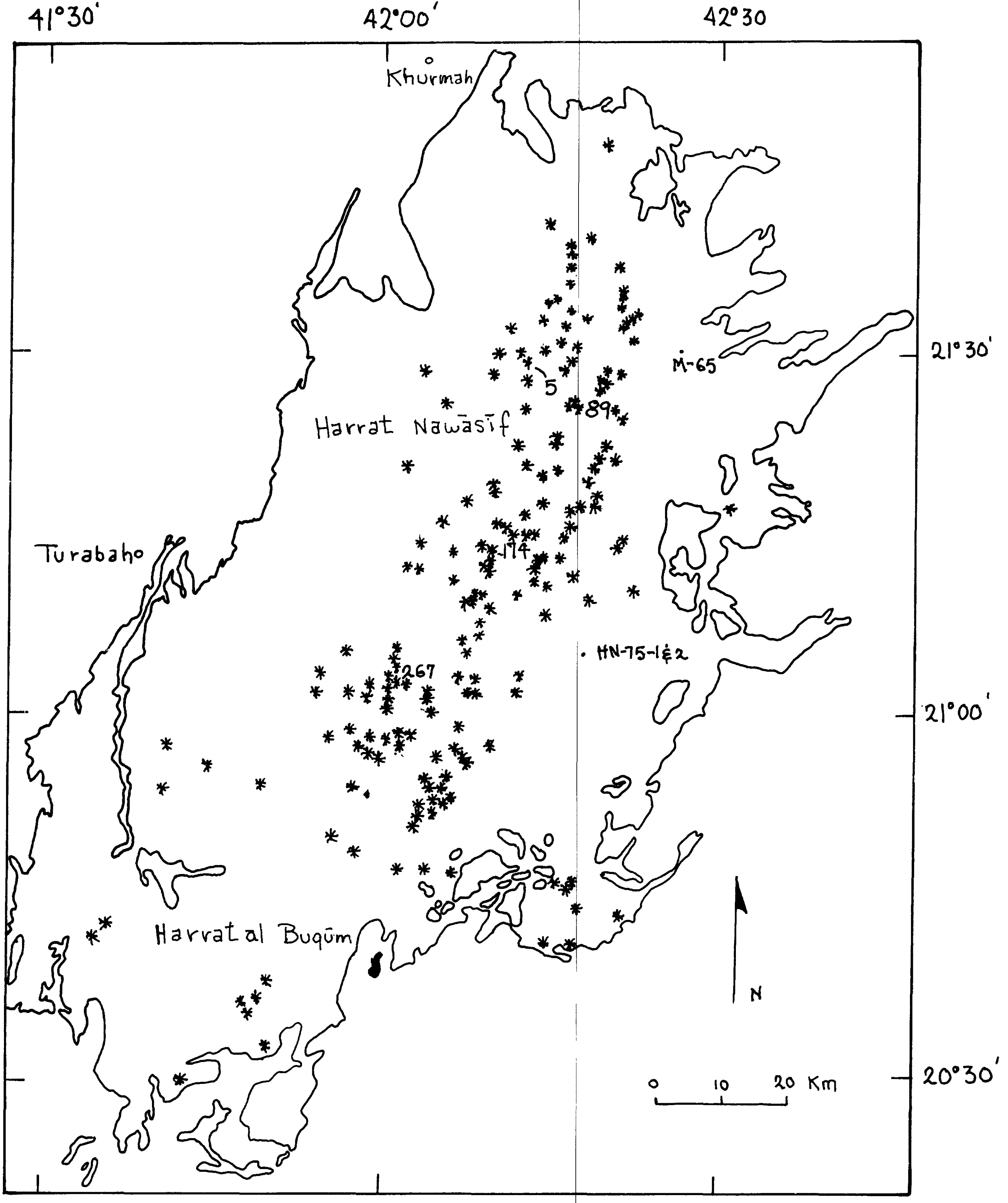

Figure 4.--Map of Harrat al Buqum and Harrat Nawasif. Asterisks show locations of eruptive centers and numbers are of analyzed samples.

Ranyah, northwest-trending Najd system faults extend beneath the eastern edge of the vocanic field. The regional trend of the cones within the field is northeasterly and does not appear to be controlled by the underlying Precambrian faults (Greene, in press), The basal flows rest directly on eroded basement and no evidence of interlayering of Phanerozoic sediments has been discovered. Physiographic evidence suggests that the initial eruptions were Quaternary and probably continued into the Holocene.

The earliest flows, as much as 10 m thick, are exposed in the deep wadis draining eastward. The main part of the harrat, a subtle volcanic highland having a northeasterly trend, is a series of coalescing flows that emanated from more than 350 cones and small vents. The relative degree of cone erosion and the fresh appearance of some of the lavas suggest a northeasterly progression of the volcanic activity; the most recent eruptions are concentrated in the northeastern corner of the field. Most of the lavas appear to have issued from central vents in small cinder cones. Some of the larger eruption centers include small, shallow calderas. The older flow surfaces of Harrat Nawasif-Harrat al Buqum contain numerous man-made stone stripes that may have been built during the period 3,000 to 5,000 years B.C. (see section on Age).

There appear to have been three eruptive episodes that are represented by: (1) flows that are exposed only in the deep, east-draining wadis; (2) the volcanic highland of central-vent volcanic origin that dominates the N. 30° E.-trend of the harrat; and (3) the most recent eruptive material that is concentrated in the northeastern end of the volcanic field and that is volumetrically least important.

Harrat Hadan

The lavas of Harrat Hadan (fig. 5) occupy an elongate area (3,700 km^2) extending northward from Turabah for about 125 km and form the eastern barrier of the great Sahl Rakbah (Arabic for 'easy passage'), one of the largest open plains in the southern Hijaz (Brown and others, 1963). Ninety kilometers across Sahl Rakbah west of Harrat Hadan, an erosional scarp near Taif marks the edge of Hijaz plateau, an eastward-sloping peneplain of Precambrian rock. Harrat Hadan separates the Hijaz plateau and the Sahl Rakbah from the Najd plateau to the east.

Harrat Hadan is a deeply eroded remnant of a prominent lava plateau above the Sahl Rakbah whose west-facing erosional escarpment has about 300 m of relief. East-flowing

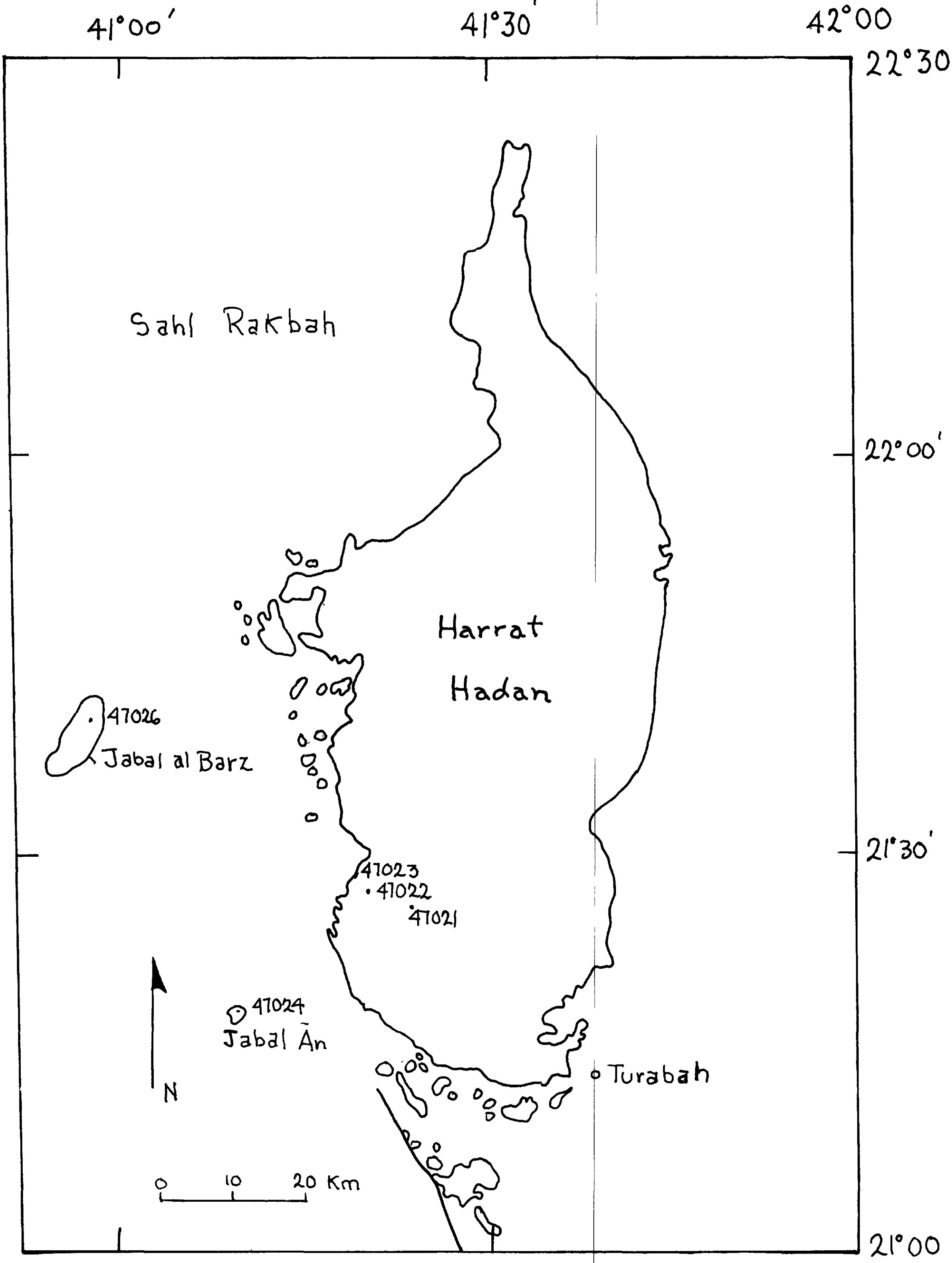

Figure 5.--Map of Harrat Hadan. Numbers are of analyzed samples and heavy dark line is a fault.

wadis have deeply dissected the lava plateau, whose eastern flank is subdued as a result of tilting to the east. The lava flows of Harrat Hadan formed a barrier to streams flowing east from the Red Sea scarp; thus, Sahl Rakbah is a basin with no apparent drainage outlet.

The lavas at Harrat Hadan have been deposited on a laterite, and the lower basalt flows are interbedded with mudstone and limestone (Madden and others, 1979/1980). Underlying the laterite is the Umm Himar formation of Paleocene age. The Umm Himar formation appears to be an estuarine deposit formed in a shallow seaway extending eastward from Jiddah and At Taif.

The deep erosion of the west side of the Harrat Hadan has exposed numerous feeder necks distributed along a northerly trend that may have formed the original axis of the volcanic pile. A dike swarm on the north tip of Harrat Hadan has a northerly orientation. North-trending faults in the Precambrian basement extend toward Harrat Hadan from the south; however, there is insufficient evidence that extrusion of the lava was controlled by these structures. Approximately 30 km west of Harrat Hadan, there is a small isolated volcanic center (Jabal al Barz) that may be related to the Harrat Hadan lava, but further work is needed before this relationship can be established.

The lava flows are typically 8-10 m thick. The lower flows are most intensely weathered and are exposed as knobby, recessive outcrops. The upper flows have columnar joints at the base and platy joints at the top, which are similar to joint patterns in other area. The erosion of Harrat Hadan is similar to that of As Sirat, and thus it is difficult to establish the morphology and extent of single flows and eruptive styles. The exposed feeder pipes on the west side and the dike swarm to the north suggest that the flows may have been fed either from dikes or pipes.

The lower flows of Harrat Hadan have a regional dip of about 10 degrees to the east, whereas the upper four or five flows appear to be horizontal. This unconformity can be seen within the erosional re-entrants along the west side of the harrat. At least some of the uplift and tilting east of the Red Sea escarpment took place after the earliest flows were extruded onto the lateritized surface of the Paleocene Umm Himar formation. The deep erosion of Harrat Hadan and the internal unconformities indicate that it is one of the older lava plateaus in Saudi Arabia; it may be equivalent in age to the As Sirat volcanic field.

Harrat Rahat

Harrat Rahat (fig. 6) extends southward from Al Madinah (lat 24°30' N.) to Wadi Fatimah near Makkah (lat 21°40' N.), a distance of 310 km. The average width is 60 km and the area is 18,100 km^2 (Brown and others, 1963; Smith, 1980). Near Al Madinah, the basalt has filled the upper valley of Wadi Hamd, whose ancestral course may have extended from the confluence of the ancient Wadi Hamd and Wadi Aqiq northwestward to Wadi Jizl. The crest of the volcanic field is 650 m above sea level at Al Madinah, 1,570 m in the southern part, and a maximum of 1,640 m at lat 23° N. The southeast edge of the harrat forms the western barrier for Sahl Rakbah, and extensive sabkhah deposits abut the eastern edge of these lava flows. The high points of the crest are linear clusters of cinder cones, craters, and domes that represent four centers of eruptive activity that have coalesced to form Harrat Rahat. From north to south, the centers are named Harrat Madinah (contiguous with Harrat Abu Rashid to the south), Harrat Bani Abdullah, Harrat Turrah (the highest part of the crest), and Harrat ar Rukhq. These four centers of volcanic activity form N. 20°-25° W.-trending segments, each 50 to 75 km long, and each offset about 10 km from the other segments in a right lateral sense. On the western margin of Harrat Rahat, numerous flows from the three southernmost volcanic centers have flowed through passes in the Hijaz mountains and down the westward-draining wadis. These highly fluid basalts flowed onto a pediment where they are preserved about 75 m above the present surface of the coastal plain (Brown and others, 1963).

On the western edge of Harrat Rahat, westward-flowing streams have cut gorges as much as 50 m deep through as many as 15 flows that had earlier filled the same wadis. Volcanic rock abuts the eastern flank of the Hijaz Mountains and is interbedded with conglomerate derived from the surrounding mountains. These sections of basalt and interbedded fanglomerates indicate that there were several hundred meters of relief in the area at the time of the early eruptions. Farther to the west in Wadi Faydah and Wadi Qudaya, the Harrat Rahat lava rests on carbonaceous sediment of the Oligocene Shumaysi formation. To the south, at the head of Wadi Shamiyah, gravel and red marl crop out under the basal flows. In contrast, on the eastern margin of Harrat Rahat, the wadis are not deeply incised and as many as 30 m of section are rarely exposed. This low relief appears to be primarily the result of deflation of the sabkhah and sand surfaces that flank the southeastern part of Harrat Rahat.

Drilling near Adh Dhumariyah (100 km southeast of Al Madinah) revealed the following section in ascending order: Precambrian basement, red marl, gravel, and interbedded marl and basalt (Daessle and Durozoy, 1972; Durozoy., 1972).

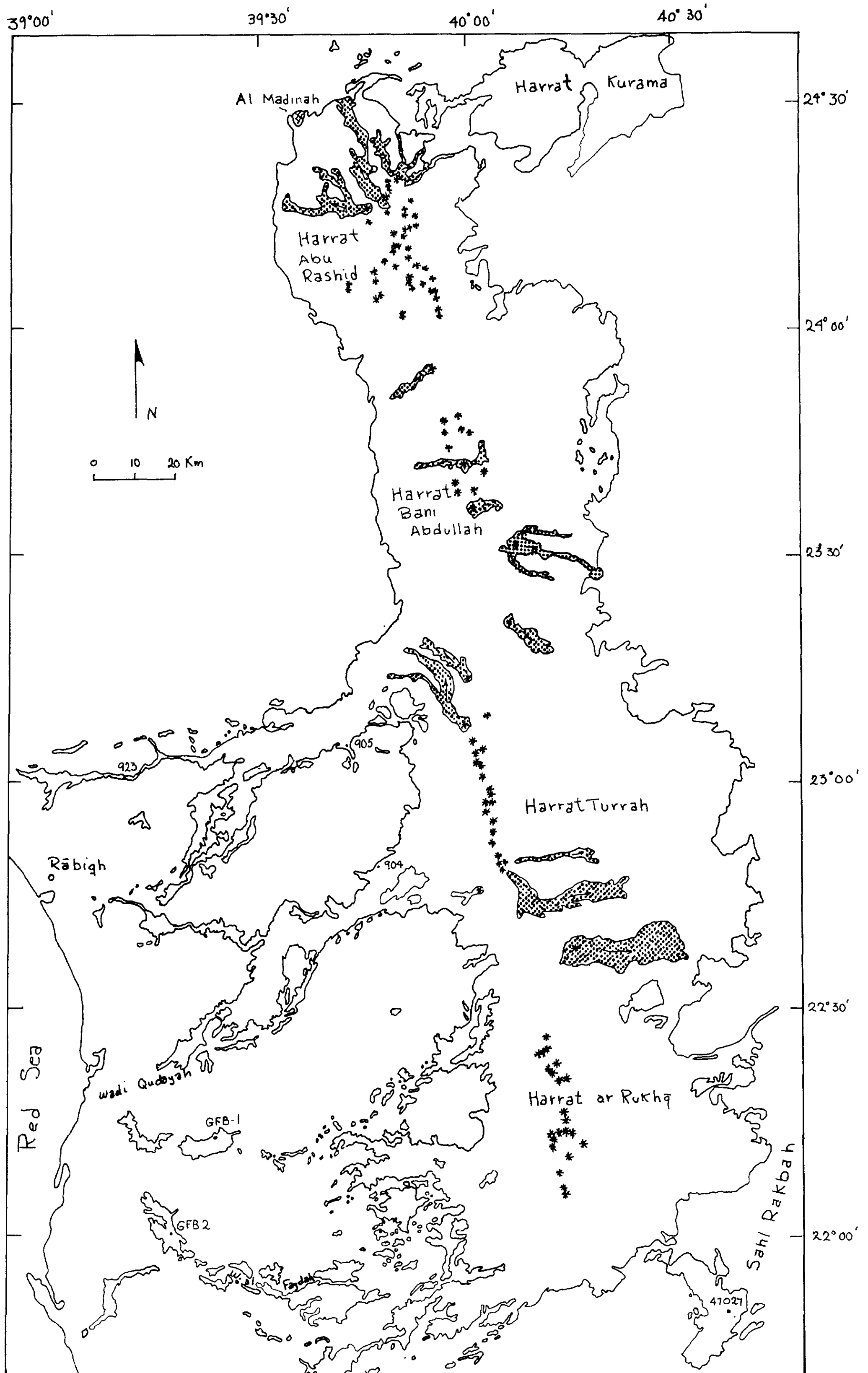

Figure 6.--Map of Harrat Rahat that encompasses Harrat ar Rukhq, Harrat Turrah, Harrat Bani Abdullah, Harrat Abu Rashid, and Harrat Kurama. Asterisks show locations of eruptive centers and stipple shows locations of recent flows. Numbers are of analyzed samples.

Fossils from the intercalated sediments indicate a Miocene age for the lowest flows (Durozoy, 1972).

In the central and northern parts of the harrat, recent activity has been fissure basalt and pyroclastic eruptions, explosive eruptions of silicic magma forming tuff rings, and relatively quiet eruptions of lava that formed steep-sided domes called tholoids. The youngest historically recognized eruptive center is just east of Madinah, where the Chada flow was extruded about 1,256 A.D. (Doughty, 1888). Thus Harrat Rahat preserves a volcanic record that began in the Miocene with sporadic activity continuing up to historical times.

Harrat al Kishb

Harrat al Kishb (fig. 7) forms the northern boundary of Sahl Rakbah and lies east of Harrat Rahat (Brown and others, 1963). The lava fields coalesce to form a somewhat elongate volcanic plateau whose axis trends almost northerly and whose area is approximately 6,700 km2. The lavas apparently were extruded initially onto a peneplain of Precambrian rock and effectively formed a barrier to northward drainage from the Sahl Rakbah. Sabkhah deposits on the southeastern edge of Harrat al Kishb near Al Muwayh are the result of this barrier. In Harrat al Kishb, Tertiary sediments do not underly or interlayer with the lava flows as at Harrat Hadan to the south or at Harrat Rahat to the west. The underlying Precambrian rock has a general north to northwesterly grain and is cut by faults having a similar trend. These faults, some of which can be related to the Najd fault system, cannot be related to the location of vents and cinder cones of Harrat al Kishb that in general have a northerly trend.

Harrat al Kishb appears to have two dintinct parts: a southern area that is partly covered by aeolian deposits of sand, and the central and northern areas that are relatively free of sand. This relationship may suggest a younger age for the central and northern parts of Harrat al Kishb. However, because the sand and gravel plain of the Sahl Rakbah borders Harrat al Kishb to the south, the apparent age difference may be more of a reflection of the prevailing wind direction and the availability of sand to the south.

Eruptive styles appear to be similar for both parts of Harrat al Kishb with as many as five north-trending chains of volcanic centers to the south and two prominent chains to the north. There are approximately 150 cinder and scoria cones within the whole field. Lava flows, most of which are less than 10 m thick, emanate from the volcanic centers and generally flow either to east or the west from the central volcanic highland.

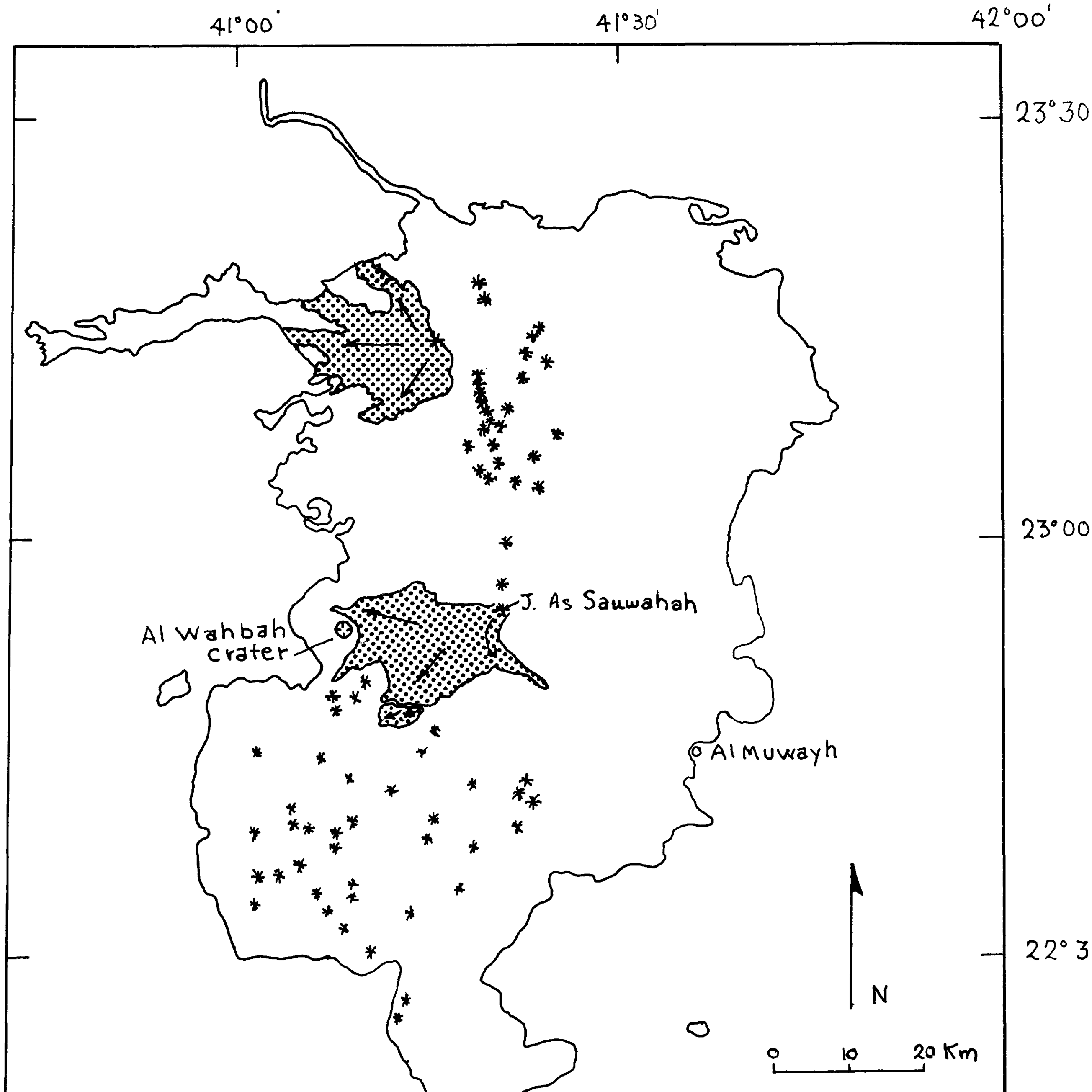

Figure 7.--Map of Harrat al Kishb. Asterisks show locations of eruptive centers and stipple shows locations of recent flows.

The central volcanic highland of northern Harrat al Kishb is dominated by two northward-trending chains of volcanic centers: a western chain comprised of shield volcanoes and pyroclastic cones of basaltic composition, and an eastern chain composed of silicic tuff rings with central resurgent domes some of which have been breached by silicic flows. In contrast, there are several chains of basaltic cones in the south and only a few isolated silicic flows to the northeast of these cones.

The northern and southern parts of Harrat al Kishb are separated by the Holocene volcano, Jabal as Sauwahah. Flows from Jabal as Sauwahah abut the eastern margin of a spectacular crater known as Al Wahbah. Al Wahbah is 2 km in diameter and 270 m deep. The flat floor of the crater is covered by sabkhah deposits and the vertical walls expose Precambrian andesites. Rimming the crater are basal basalt flows that are capped by a basaltic tuff ring bearing peridotite inclusions and megacrysts of spinel, clinopyroxene, and amphibole. On the northern rim, a pyroclastic cone has been bisected by a a north-trending reverse fault. Tuff was apparently extruded along this feature because the ejecta blanket is thickest at the northern and southern ends of the crater. Southeast of Al Wahbah, the youngest volcanic activity is represented by an obsidian flow that moved westward. This obsidian flow may represent the youngest silicic activity in Saudi Arabia, and it is unusual because the obsidian contains peridotite inclusions. Other Holocene activity was near the northwestern corner of Harrat al Kishb west of the prominent basaltic chain of the northern highland. This activity apparently began as a fissure eruption that sent pahoehoe and aa flows to the west, followed by pyroclastic activity that brought a mantle-assemblage of inclusions to the surface.

Eruptions of Harrat al Kishb appear to have begun in the south and migrated northward; the most recent activity occurred in the central and northern parts of the harrat. Although no radiometric age determinations are available, physiographic evidence indicates that volcanic activity began in the Pliocene-Pleistocene and continued to the Holocene.

Harrat Khaybar, Harrat Ithnayn, Harrat al Kura, and Harrat Kurama

Harrats Khaybar, Ithnayn, and Al Kura (fig. 8), covering about 21,000 km^2, are the largest contiguous exposure of volcanic rocks in Saudi Arabia. Harrat Kurama (fig. 6), also known as Harrat Hirmah (Pellaton, 1981), covers about 1,100 km^2 and is an outlier 20 km south of Harrat Khaybar. Volcanic rocks can be traced from Harrat Khaybar to Harrat Ithnayn across an easterly trending topographic low. Harrat

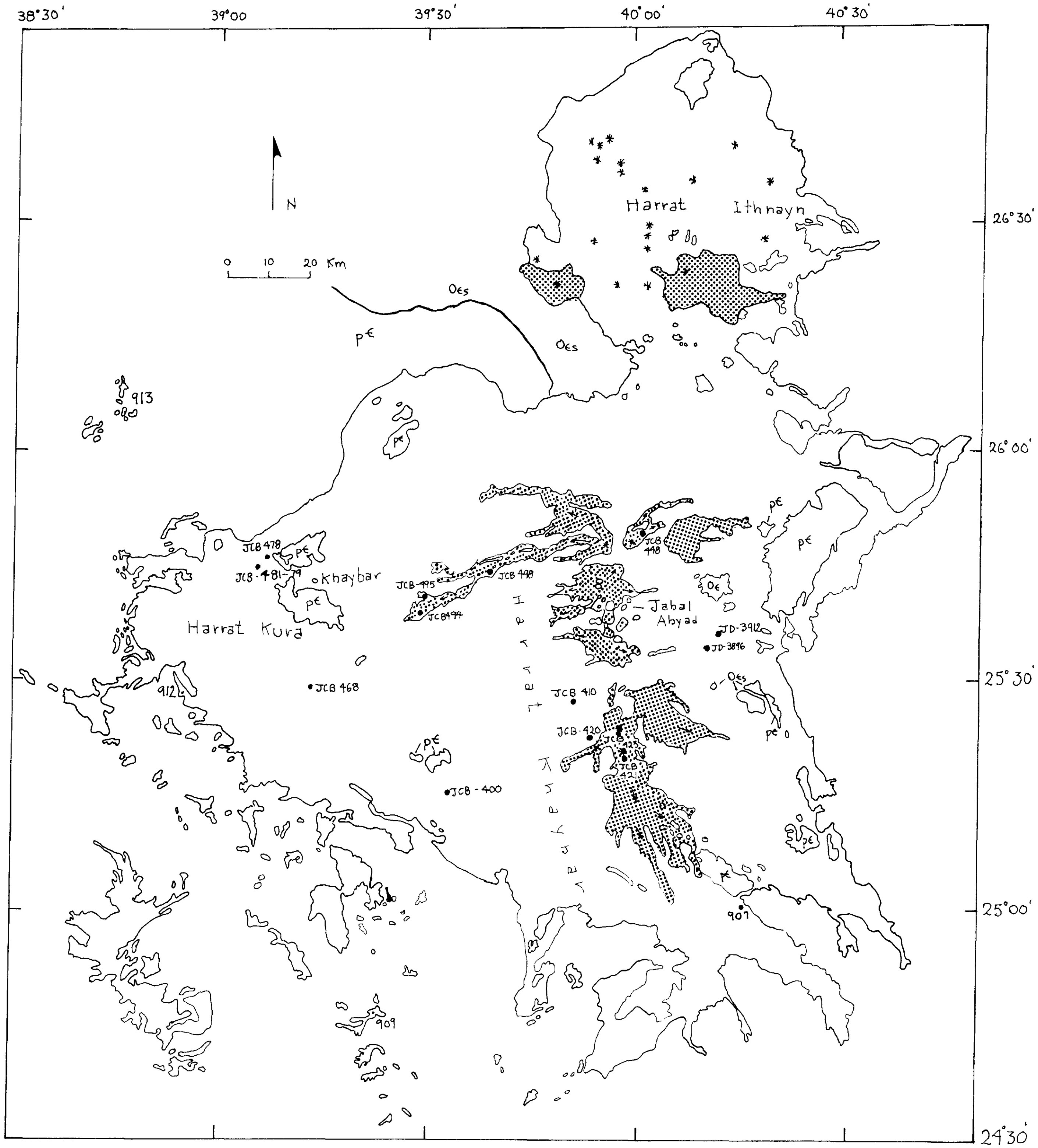

Figure 8.--Map of Harrat al Kura, Harrat Khaybar, and Harrat Ithnayn. Asterisks show locations of eruptive centers and stipple shows locations of recent flows. Numbers are of analyzed samples. Jabal Abyad in the central part of Harrat Khaybar is the largest silicic volcanic center in Saudi Arabia.

al Kura, which crops out west and southwest of the city of Khaybar, is much older than both the younger part of Harrat Khaybar and all of Harrat Ithnayn. The northern part of Harrat Khaybar and Harrat Ithnayn contain very young eruptive centers, some of which have disrupted Neolithic rock monuments.

Harrat Khaybar rises gently toward the east from the basalt plateau at the town of Khaybar. Along its axis, the harrat contains several volcanic peaks that have altitudes in excess of 1,900 m. The crest of the range contains two prominent, intersecting belts: (1) a young, north-trending chain of cones that include basaltic shields, silicic tuff rings and domes, and intermediate-composition tholoids, and (2) an older, N. 25° W.-trending chain of basaltic pyroclastic cones. The two belts are approximately 10 to 20 km wide and contain several hundred volcanic centers.

Jabal Abyad ("white mountain"), a prominent peak within the younger belt, is located about 20 km north of the older belt. The Jabal Abyad area is one of the largest and best preserved areas of Cenozoic silicic rock in all of Saudi Arabia. The intermediate and silicic rocks are tuff rings and domes; Jabal Abyad is a composite dome and tuff ring complex. The SiO_2 content of the lavas of the Jabal Abyad area is bimodal with a gap between 50 and 56 weight percent (Baker and others, 1973; Dhellemes and Delfour, 1980).

The youngest volcanic activity on Harrat Khaybar was basaltic fissure eruptions in the northern part. Jabal al Qidr (Dhellemmes and Delfour, 1980), 7.5 km north-northwest of Jabal Abyad, is a shield volcano that abuts the silicic rocks of the Jabal Abyad area at the southern terminus of a north-trending fissure. Flows from an eruption north of Jabal al Qidr partially cover man-made stone monuments southeast of the city of Khaybar.

Harrat Ithnayn, also known as Harrat Hutaym, (Brown, 1972; Brown and others, 1963) is north of Harrat Khaybar and is composed of a 40 km-wide belt of volcanic centers aligned in north-trending chains. The western chain of craters of Harrat Ithnayn is on strike with the main axis of Harrat Khaybar, and thus most of the volcanic features of Harrat Ithnayn are offset from that of Harrat Khaybar in a right-lateral sense. In Harrat Khaybar, there is evidence of abundant silicic activity and a paucity of lavas containing mantle inclusions, whereas, in Harrat Ithnayn, silicic rocks are absent and numerous pyroclastic cones contain peridotite nodules. Thus, different sources of magma and (or) different plumbing systems appear to have been involved.

At both Harrat Ithnayn and Harrat Khaybar, Tertiary sediments do not appear to be interlayered with basal flows. Basalt of Harrat Ithnayn overlies Paleozoic sandstone on the southeastern margin of the Al Hisma plateau (Brown, 1960) and cascades over sandstone bluffs near the northern, eastern, and southern margins of the harrat. These relations suggest that the flows of Harrat Ithnayn are a thin veneer no more than 100 m thick covering the Paleozoic sandstone. Southwest of Harrat Ithnayn, the Al Hisma plateau terminates in a 300-m-high erosional escarpment of Paleozoic sandstone that marks the boundary between the Precambrian Shield and younger platform sediments. The escarpment is buried by lava of Harrat Khaybar, which suggests that this harrat may locally exceed 600 m thickness. Partially-covered Paleozoic sandstone found on the eastern margin of Harrat Khaybar suggests that the basalt section thins to the east. The lavas are thought to have been extruded onto basin and range topography because remnants of structurally-controlled (N. 50° W.) ranges of Precambrian volcanic rocks interrupt the gently sloping surface of Harrat Khaybar. Further evidence of paleotopographic basement relief is present to the west at Harrat Kura.

Harrat al Kura forms a sloping highland area that is deeply incised on its western margin. The walls of these drainages expose a series of flows extruded on the Precambrian basement that had as much as 100 m of relief. The lavas flowed down existing paleostream channels and are interbedded locally with stream gravels. The basalt of Harrat al Kura forms a gently sloping surface of varying dip around a series of eroded pyroclastic cones having a N. 30 W. trend. later flows from Harrat Khaybar and Harrat Ithnayn have flowed across Harrat al Kura and down the incised canyons of its northwestern margins.

Harrat Ishara-Khirsat and Harrat Harairah

Harrat Ishara-Khirsat (Kemp, 1982) and Harrat Harairah (fig 9) occupy a highland area extending along the southwestern margin of Wadi al Jiz'l and Wadi Hamd from lat 26°15' to 24°30' N. (Brown and others, 1963). Eroded volcanic necks define a N. 30° W. trend that is nearly parallel to the structurally controlled courses of these two wadis. The two harrats range in thickness from 30 m to as much as 400 m; the variation of thickness indicates moderate topographic relief at the time of volcanic activity. Harrat Harairah is thickest at lat 26°10' N. and thins to the southeast; Harrat Ishara-Khirsat is thickest at lat 24°40' N. Both fields are deeply eroded and basal sections are well exposed in many wadis. The surface morphology of these harrats is similar to the southernmost portion of Harrat Uwayrid to the north and to Harrats Hadan and As Sirat to the south; all are probably similar in age.

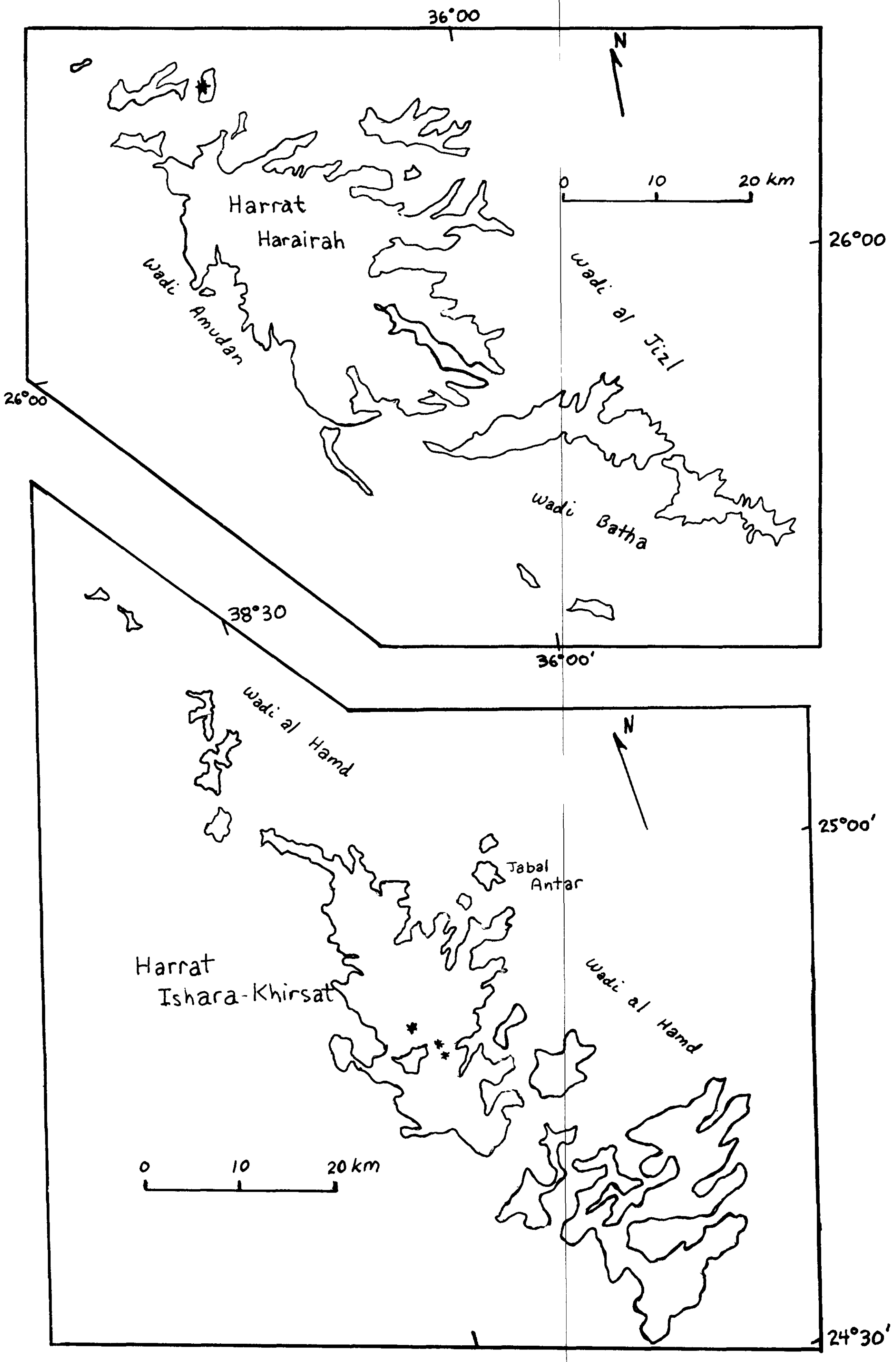

Figure 9.--Map of Harrat Ishara-Khirsat and Harrat Harairah. Asterisks show locations of eruptive centers.

The sections of both Harrat Ishara-Khirsat and Harrat Harairah are variable in thickness due to the paleotopography. However, because of the relatively continuous exposure in the wadis, a consistent picture emerges of the sequence of events associated with the formation of each harrat. The basalt section records an early history dominated by picrite-ankaramite deposition, followed by the deposition of peridotite nodule-bearing olivine basalt, and then diktytaxitic alkali olivine basalt. At Harrat Harairah, locally underlying the basalt are lag deposits of silicified coquina and pebbles and cobbles of chert. These lag deposits are significant because they are similar to lag deposits to the north under Harrat ar Rahah, and to widespread deposits of lag chert in the region surrounding Turayf near the Jordan border. Similar deposits also underlie Harrat Hadan. The lag deposits represent a post-Eocene surface developed upon marine sedimentary rocks whose age may span from the Paleocene to Eocene. Locally, conglomerates consisting of Precambrian basement rocks are interbedded with the lowermost flows. To the south at Jabal Antar of Harrat Ishara-Khirsat, at least four fanglomerate sequences underlie the basal picrite-ankaramite member (Kemp, 1982). Each of these sequences is finer-grained toward the top and each is capped by a red-brown bentonite horizon; one such horizon contains petrified logs. These bentonite layers indicate pyroclastic activity that predates eruption of the basalts.

Harrat Lunayyir

Harrat Lunayyir (fig. 10) crops out over an area of about 1,750 km^2 north of Yanbu and east of Umm Lajj at lat 25° N. (Brown and others, 1963). The harrat is composed of relatively old flows in the southwestern part and very young pyroclastic cones and flows to the northeast. Harrat Lunayyir occupies the crest of the Red Sea scarp (Hijaz) mountains flanked by the Red Sea to the west and Wadi al Hamd to the north and east. The crest of the range in the vicinity of Harrat Lunayyir is at 1,500 m altitude and altitudes decrease to less than 400 m at the bottom of Wadi Hamd. All of the Harrat Lunayyir flows postdate the formation and uplift of the Red Sea escarpment and these flows extend in all directions from the range crest. Harrat al Qalib to the west (Brown and others, 1963) is a single flow that reached the Red Sea.

The older lavas occupy less than 20 percent of the harrat and, because they resemble morphologically the older flows of Harrat Khaybar and Harrat al Kishb, they may be of similar age. Regardless of apparent age, all volcanic centers on Harrat Lunayyir define a northward trend. The younger lavas are among the most recent in Saudi Arabia; at least a half-

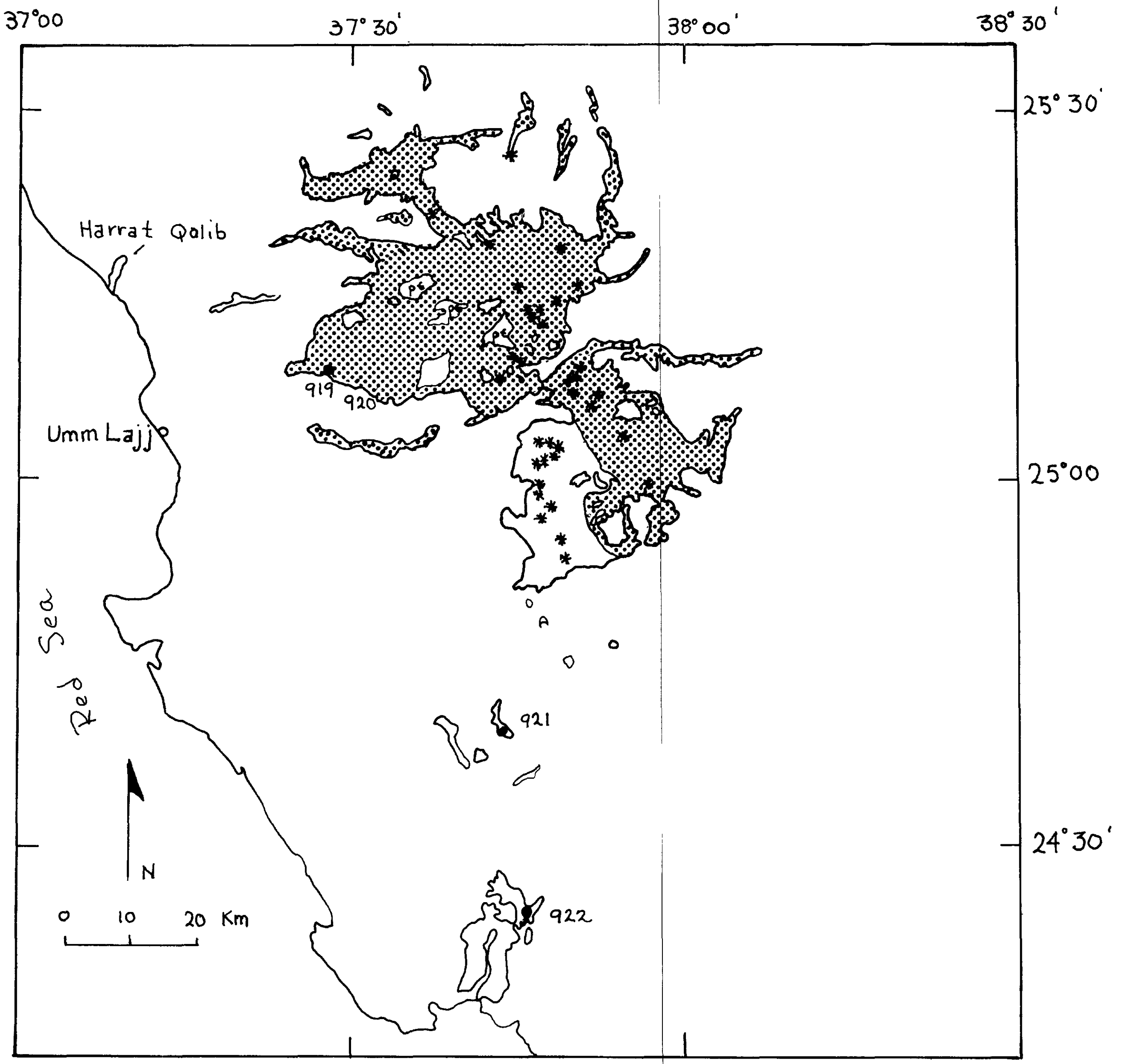

Figure 10.--Map of Harrat Lunayyir. Asterisks show locations of eruptive centers and numbers are of analyzed samples. Stipple shows the younger part of the harrat.

dozen cinder cones show no erosional degradation.

Harrat Hutaymah

Harrat Hutaymah (fig. 11) covers an area of 900 km^2 between lat 26°45' and 27°20' N. and is farther from the Red Sea (550 km) than any other Cenozoic volcanic field of Saudi Arabia (Bramkamp and others, 1963). Harrat Hutaymah consists of a thin veneer of basaltic rock in an area of low relief that is typical of the northeastern Shield. Tuff ring craters expose Precambrian basement rock beneath basalt flows less than 100 m thick.

Harrat Hutaymah consists of two major chains of volcanic centers. Both chains have a northerly trend; the westernmost chain is dominated by the tuff rings and the easternmost chain by pyroclastic cones. Harrat Hutaymah is significant because several of the tuff rings and pyroclastic cones contain a wide variety of felsic and ultramafic xenoliths that are samples of the crust and upper mantle. The inclusions from the upper mantle are similar to those of the other harrats and are discussed below. The suite of crustal inclusions that is unique to Harrat Hutaymah contains an unfoliated quartz-biotite rock that may represent metasedimentary rock from the lower crust.

Harrat al Uwayrid and Harrat ar Rahah

This composite volcanic field (fig. 12) forms a plateau of about 7,200 km^2 extending from lat 28°05' N. southeastward to lat 26°30' N., a distance of 225 km (Brown and others, 1963). Harrat ar Rahah and Harrat al Uwayrid consist of 50 km-long chains of volcanic centers. Summit altitudes are in excess of 1,900 m above sea level and near Al Ula the approximate altitude of the plateau is 550 m above the flood plains of Wadi Jiz'l and Wadi al Ula. The Ar Rahah centers, spectacularly exposed in the face of the retreating, west-facing escarpment, consist of domes and plugs connected by feeder dikes that trend N. 30° W.

The stratigraphic sections for Harrats ar Rahah and al Uwayrid are similar to those of the older harrats As Sirat, Hadan, Kura, Kurama, Harairah, and Ishara-Khirsat. The basal lavas consist of eucrystalline picrite-ankaramite. To the west, these lower lavas were extruded onto a tilted platform of Paleozoic sandstone, and the contact between the lava and the sedimentary rock is an angular unconformity. Thus, the lower Al Uwayrid-Al Rahah lavas postdate the initiation of a tilting event that affected the northern Shield in middle Tertiary time (Brown, 1960). Erosion of the escarpment has

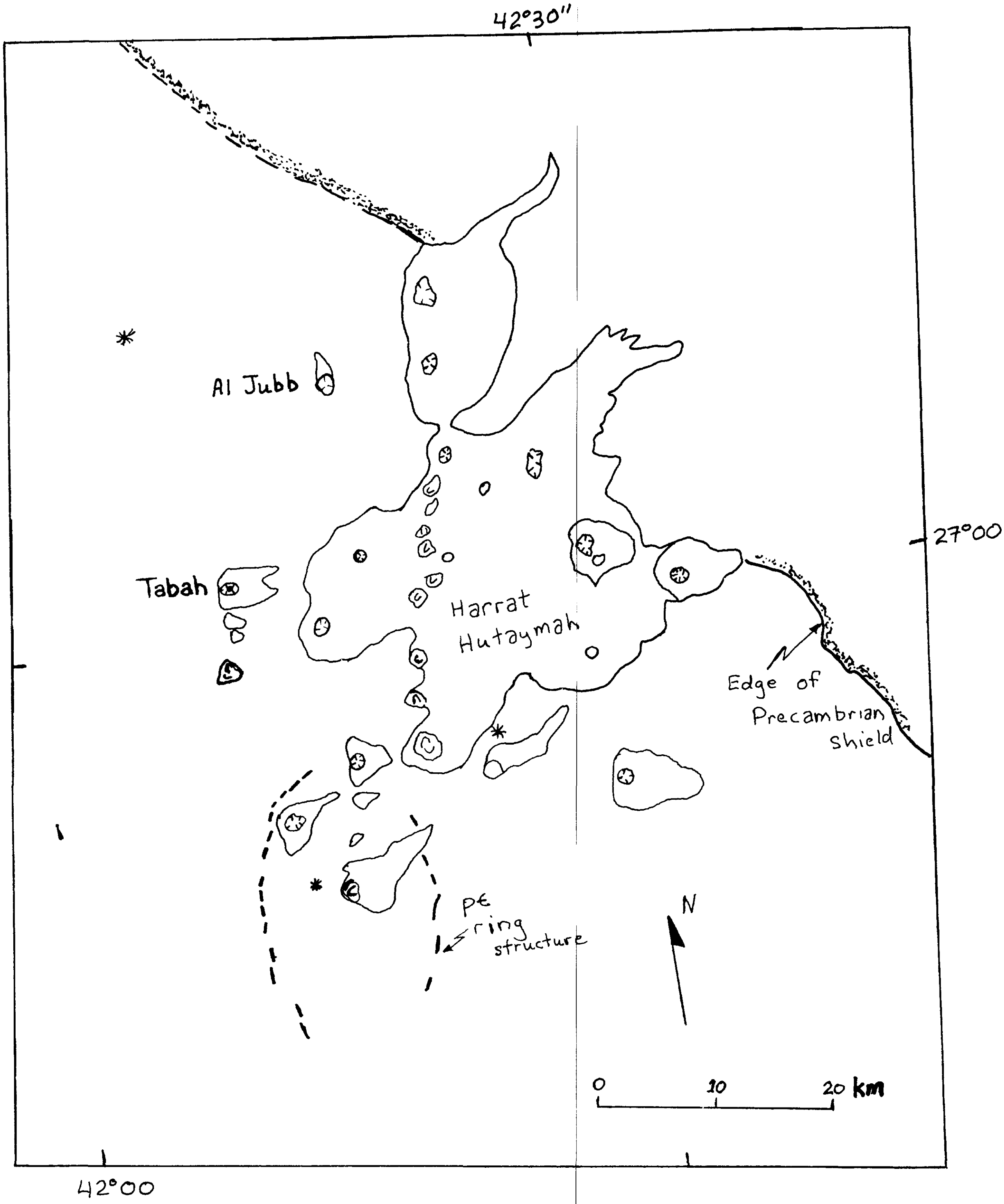

Figure 11.--Map of Harrat al Hutaymah. A N. 10° E.-trending chain of pyroclastic cones that dominates the harrat terminates to the north at three tuff rings. Hachures show locations of large tuff ring craters.

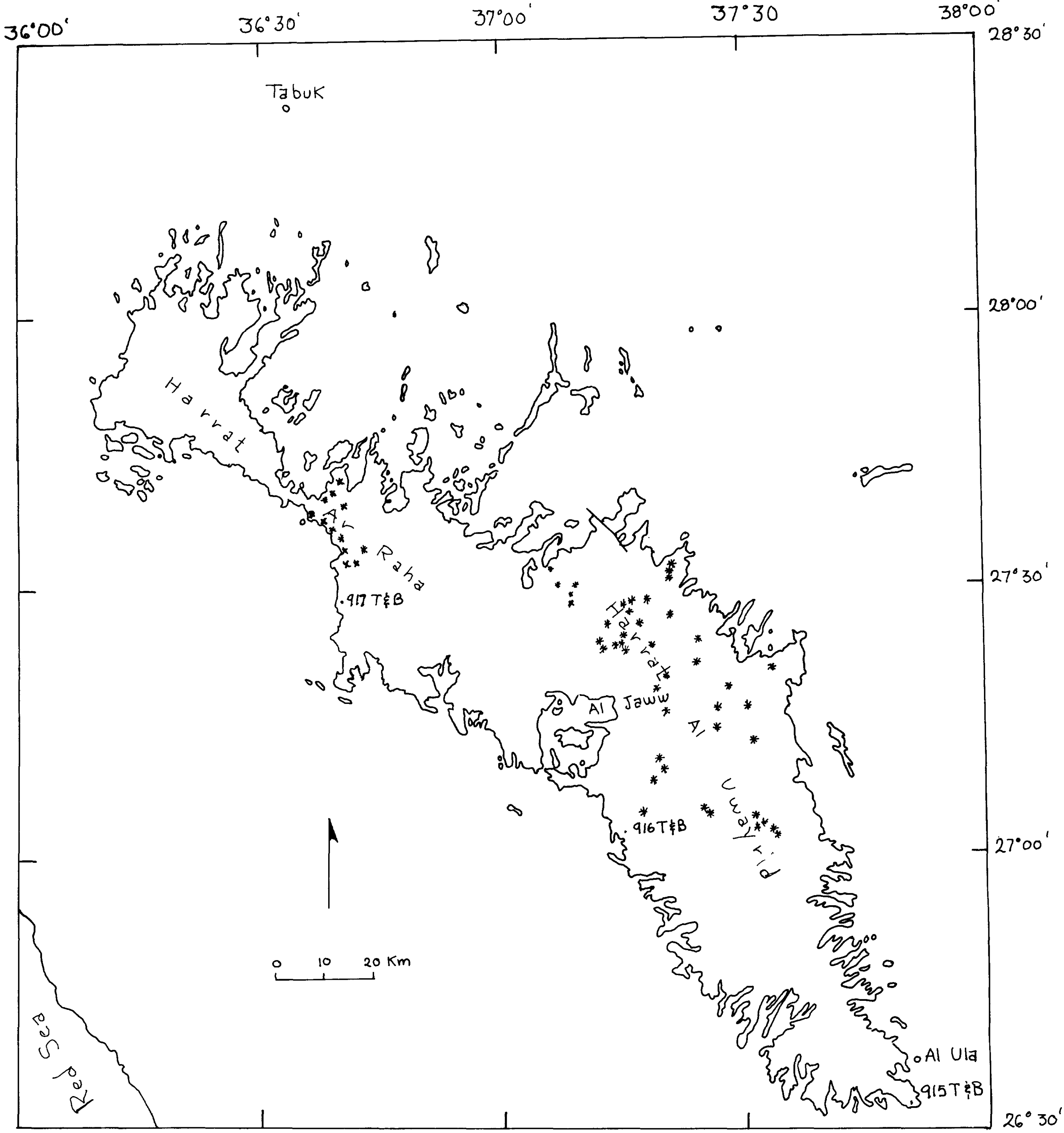

Figure 12.--Map of Harrat al Uwayrid and Harrat ar Rahah. Asterisks show locations of eruptive centers and numbers are of analyzed samples.

exposed silicic flows that were contemporaneous with the picrite-ankaramite lavas. Several silicic centers were buried by later diktytaxitic alkalic basalts. This stratigraphy at Harrat ar Rahah and Harrat al Uwayrid indicates that volcanism in some of the harrats has been bimodal throughout the Cenozoic era.

The most recent volcanic activity in Harrats ar Rahah and al Uwayrid is concentrated in the region called Al Jaww (Fig. 12), a depression that partially separates the two lava fields. Most of the younger lavas flowed in a northeasterly direction. However, a flow that contains numerous peridotite nodules is exposed within the northwesterly course of Wadi Jiz'l west of Al Uwayrid, at an altitude 300 m below the top of the lava plateau; therefore, uplift continued subsequent to the onset of volcanic activity.

The lavas of Harrats ar Rahah and Al Uwayrid are a bimodal suite of basalt and silicic rocks, and numerous domes and necks of silicic rock form the crest of Harrat ar Rahah. The composition of the basalts appears to range from picrite-ankaramite to alkali olivine basalt. The lavas of Harrat al Uwayrid are particularly rich in ultramafic inclusions and numerous pyroclastic eruptions have brought harzburgite, dunite, lherzolite, and pyroxenite nodules to the surface. Harrat ar Rahah and Al Uwayrid have a history similar to Harrat Rahat and may serve as an older analog for geothermal assessment of Harrat Rahat.

Harrat ash Shamah (al Harrah)

The northernmost volcanic field Harrat ash Shamah, crops out continuously from Syria, across Jordan, and into Saudi Arabia (Bramkamp and others, 1963). About one-third of this harrat's 15,000 km^2 area is in Saudi Arabia (fig. 13). The exposures of volcanic rock trend northwesterly and are truncated at the Dead Sea Rift and at the Syrian arc (plate 1). To the southwest, the harrat is bounded by Wadi Sirhan at altitudes between 600 and 700 m above sea level. Drill holes in Wadi Sirhan penetrated basalt beneath as much as 200 m of sediment. Along this wadi, basalts are interbedded with Miocene shallow-water marine sediments. To the northeast, the basalts rest uncomformably on eroded lower Tertiary marine sediments at 700 to 800 m altitude above sea level. The youngest volcanoes are also the highest at about 1,100 m above sea level.

Approximately 500 volcanic centers lie along either older northwest-trending faults or younger north-trending faults. The older volcanic centers found along the southeastern and southwestern margins, follow fault structures that trend N.

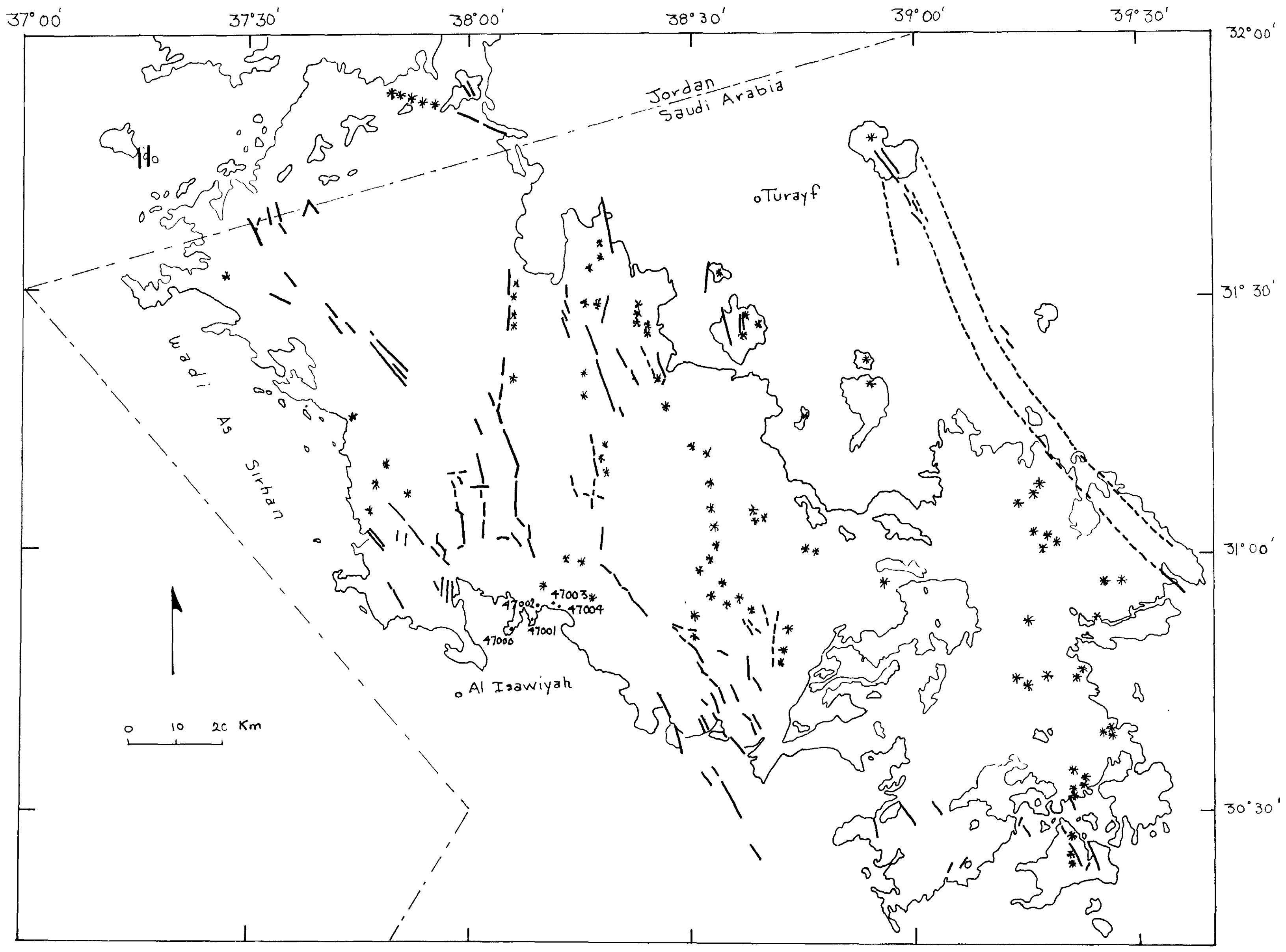

Figure 13.-- Map of Harrat ash Shamah (Al Harrah). Asterisks show locations of eruptive centers, heavy lines show locations of normal faults, and numbers are of analyzed samples.

20° to 30° W. whereas the youngest centers south of Turayf follow apparently later structures that trend north to N. 10° W. Numerous fault scarps are well preserved and as many as five flow units are exposed. Southwest-facing fault scarps predominate, although northeast-facing scarps with lesser offsets are also present. The faults bound asymmetric grabens with the greater displacement on the northeastern side. Numerous tuff rings are present along the graben structures. The presence of dry lake beds and probable Pleistocene to Holocene shorelines along some of the fault scarps suggest that the tuff rings formed where basaltic magma encountered the water table close to the graben surface. In the highland areas between grabens, pyroclastic cones, shield volcanoes, and composite volcanoes are dominant.

For both the older and younger basalts, the predominant mode of eruption appears to have been fissure eruptions followed by pyroclastic cone building. Many cones appear to have been breached by flows during the final stages of eruption. Both pahoehoe and aa flows are present, but most flows have been mechanically weathered and many of the primary features have been destroyed. Along Wadi Sirhan the older parts of the harrat are covered by sand, ventifacts are common, and the prevailing wind direction appears to be N. 70° W. to N. 80° E.

Tuff rings are common in both the older margins of the harrat and in the younger interior south of Turayf. The youngest, best-preserved tuff ring and collapse crater is approximately 80 m deep and 1.5 km in diameter. The older collapse craters are filled with reworked tuff and windblown sand. Several rings are present in which all of the basaltic tuff has been removed by mechanical weathering. At the southeastern margin of the harrat, the former presence of some tuff rings is indicated by the erosional remnants of ring dikes. Most of the tuffs contain peridotite nodules, megacrysts of hornblende and olivine, and inclusions of Cretaceous and Tertiary sedimentary rocks. Harzburite, dunite, and lherzolite are the most common ultramafic nodules.

Dike swarms, layered gabbros, and granophyres

On the eastern side of the Red Sea, 40 km east of Jizan, a dike complex (Tihamat 'Asir complex; Coleman and others, 1979) intrudes Phanerozoic sedimentary rock and Precambrian rock along a northwesterly trend that is parallel to the present-day axial trough of the Red Sea (pl. 1, fig. 14). The dike swarm is exposed discontinuously for about 200 km from the Yemen border northward to Ad Darb where it is

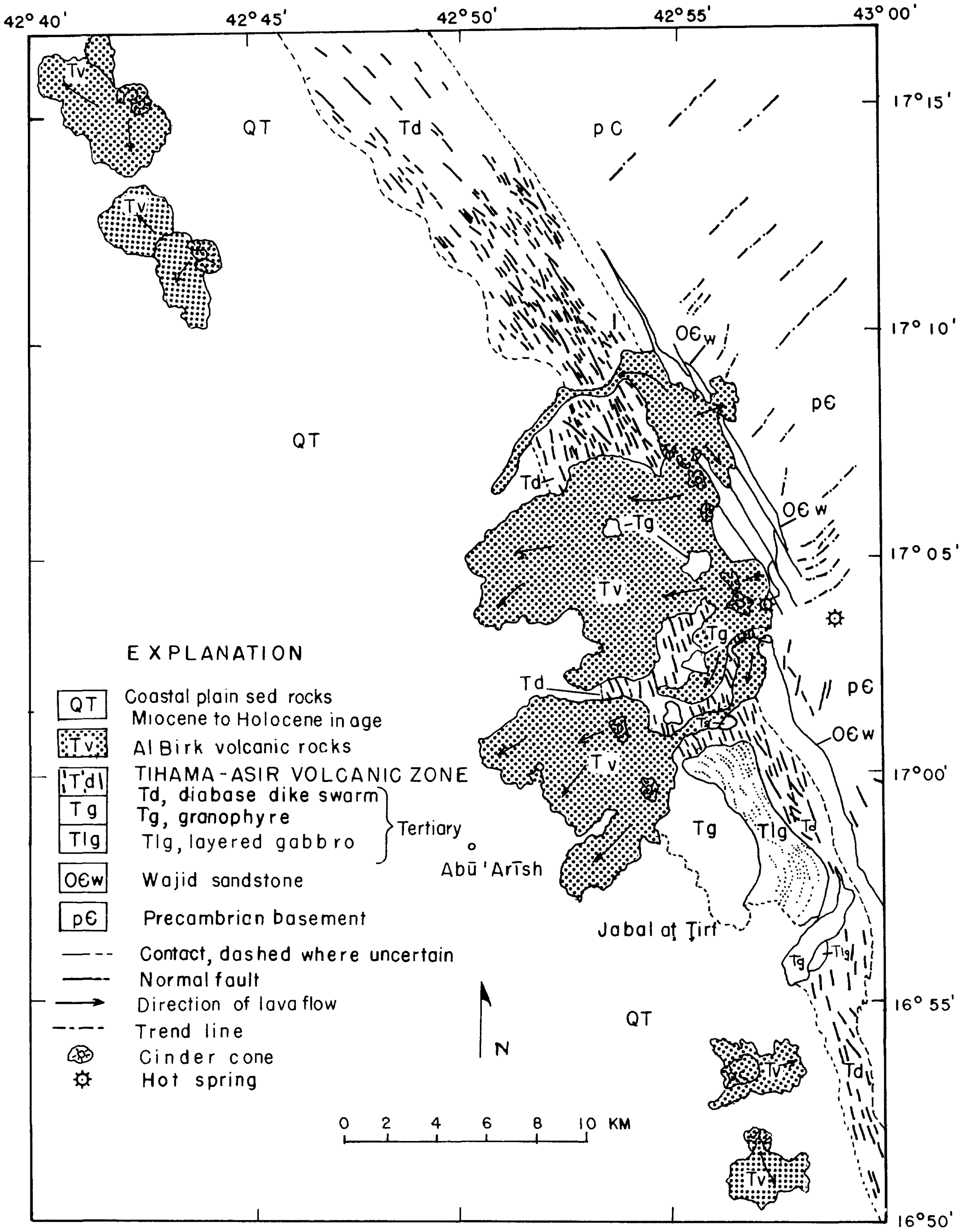

Figure 14.--Geologic map of the Tihamat 'Asir complex. (after Coleman and others, 1979).

terminated by a northeast-trending fault that may be the landward extension of an older transform fault related to the opening of the Red Sea (pl. 1). late Miocene tilting toward the axial trough and subsequent erosion have exposed this initial continental-oceanic crust boundary along a narrow zone of the Tihamat 'Asir (coastal plain).

West of the Precambrian crust, new oceanic crust consists of a 4-km-wide zone of closely-spaced subparallel dikes that are separated by Precambrian mafic and silicic volcanic rock. Circular-shaped, layered gabbro masses within the dike complex represent small magma reservoirs that developed during the initial stage of rifting. Granophyric sills and dikes are products of partial melting of the continental crust during the early stages of rifting. North of the Ad Darb fault, the sheeted dike swarm gives way to single, isolated dikes of hypabyssal quartz gabbro, quartz monzogabbro, quartz monzonite, and quartz syenite (Blank, 1977). These dikes are characteristically coarse-grained and have chilled margins adjacent to Precambrian country rock. Individual dikes have been traced without interruption for 50 km. Blank (1977) used north-northwest-trending aeromagnetic lineaments to trace dikes to the Gulf of Aqaba (Blank, 1977), and Bartov and others (1980) demonstrated that these dikes extend across the Gulf of Aqaba and are found as far north as the Central Sinai-Negev shear zone. Sinistral strike-slip movement on the western shore of the Gulf of Aqaba that can be related to the continued opening of the Red Sea has offset these dikes a total of 24 km (Bartov and others, 1980). Even though these dikes have the same compositional range as the sheeted dikes to the south of the Ad Darb transform fault, the former are not dense conjugate systems and they represent less than 20 percent distension of the Precambrian basement. Magnetic anomalies north of the Ad Darb fault show that the oceanic crust-Precambrian crust boundary must lie several kilometers west of the present shoreline. Furthermore, sub-horizontal Paleozoic sandstone north of Ad Darb and vertical dikes indicate that rotation toward the Red Sea did not take place.

Thus, two separate types of dikes can be distinguished on the eastern side of the Red Sea: (1) dike swarms that formed during continuous spreading and contain conical-shaped, layered-gabbro bodies, granophyric sills, and screens of Precambrian basalt and rhyolite; and (2) large individual dikes of coarse-grained quartz monzonite or quartz gabbro that cut Precambrian rock. Gradations between these two types may have occurred in various stages of the opening of the Red Sea and it seems possible that the floor of much of the Red Sea is a mosaic of the two types.

Nearly all of the rocks making up the Tihamat 'Asir complex have undergone low-temperature (less than 400°C) hydrothermal alteration. The resulting secondary mineral assemblage is similar to that developed under conditions of zeolite to greenschist-facies metamorphism, although original igneous textures are preserved. This hydrothermal alteration apparently was caused by hot meteoric water that began circulating within the Tihamat 'Asir complex shortly after its formation and that may be continuing at present (Taylor and Coleman, 1977). The presence of hot springs and abnormally high heat flow demonstrates considerable current thermal activity.

STRUCTURAL SETTING

The volcanic fields of Saudi Arabia (plate 1) have two major structural trends. The older fields have eruptive centers that roughly follow a N. 30° W.-trend parallel to the Red Sea axis. The younger fields have vents and chains of cones that are oriented between N. 20° W. and N. 10° E. with the exception of Harrats Nawasif and Al Buqum that display a N. 30° E. trend. The older northwesterly trend is displayed in Harrats Al Rahah, Al Uwayrid, Harairah, Al Kura, Ishara-Khirsat, As Sirat, and Ash Shamah. The younger northwesterly trend characterizes the more recent vents of Harrats Khaybar, Al Ithnayn, Hutaymah, Ash Shamah, and Lunayyir. From these northerly vent systems, erupted lavas cascaded down escarpments along the Red Sea and down escarpments of Paleozoic cover rocks on the Shield. Thus, the volcanic fields that display the younger fissure systems clearly postdate the first opening of the Red Sea and the initial development of the Red Sea scarp.

The older harrats having the N. 30° W. structural trend are generally deeply incised, and thus provide evidence for the middle-to-late Tertiary history of the Arabian Shield. Marine sedimentary rocks ranging in age from Eocene to Miocene underlie the basal lava flows, and Miocene sediments (Bramkamp and others, 1963) are locally (Harrat ash Shamah) interbedded with the basal lava flows. Either well-preserved, shallow-water marine sediments or lag deposits of fossiliferous siliceous concretions are exposed underlying the Harrats (from north-to-south) ash Shamah, Ar Rahah, Al Uwayrid, Harairah, and Hadan. In addition, marl has been found in drill core from beneath Harrat Rahat near Al Madinah (Durozoy, 1972). The widespread occurrence of marine sediment underlying the harrat suggests that parts of the Shield were at sea level during the early stages of volcanic activity associated with the opening of the Red Sea. This seaway was probably connected to the Mediterranean Sea because uplift in the north, near Jordan, did not begin until post-Miocene time whereas to the south, in Yemen it appears to have begun in the late Cretaceous (Brown, 1972).

The presence of fanglomerate underlying and interbedded with the basal flows of Harrats al Kura, Ar Rahat, Al Uwayrid, Ar Rahah, Harairah, and Ishara-Khirsat suggests that the areas below sea level were probably restricted to basins bounded by fault-block mountains. The fault blocks were aligned both parallel to the trend of the Red Sea axis and to older reactivated Najd structures.

In the Tihamat 'Asir area, the early stages of volcanic and intrusive activity are related to structures that follow the general trend of the axial trough of the Red Sea. Fresh-water sediments of the late Oligocene-early Miocene Baid formation are interlayered with bimodal volcanic rocks of the Jizan group and these were presumably deposited on Precambrian crust (Schmidt and others, 1982). Emplacement of dike swarms parallel to the present Red Sea coast northward to the Gulf of Aqaba and within these proto-Red Sea sediments and volcanic rocks represent early extensional tectonism.

These areas of crustal extension are not uniform in character. For instance, in the sector south of Ad Darb, the Baid formation is preserved as screens between the dikes, whereas locally (for example, the Jabal at Tirf complex and at Wadi Jizan) the dikes constitute sheeted swarms. Funnel-shaped layered gabbro bodies have formed within these dike swarms and preserve evidence of shallow magmatic fractionation in the extension zone. To the north of Ad Darb, singular, thick, continental dikes mark a distinctly different regime of crustal extension and magma emplacement. Here, northwest-trending dikes were emplaced in zones up to 25-50 km wide. Radiometric ages indicate that the continental dikes, the Jabal Tirf dike swarm, and the layered gabbros were emplaced during the early Miocene, nearly contemporaneous with deposition of the Baid formation and Jizan group of bimodal volcanic rocks. Left-lateral offset of the continental dikes along the Dead Sea rift marks the beginning of the final phase of the Red Sea extension. Subsequent to the movement along the Dead Sea rift, the younger continental volcanic centers follow a N. 20° W. to N. 10° E. orientation, and the earlier-formed proto-Red Sea assemblage of dike swarms, layered gabbro, and associated sediment was rotated on a horizontal axis toward the Red Sea. Similar faulting and tilting are observed seaward in the Red Sea basin where seismic reflection profiles indicate that evaporites are block-faulted and rotated (Ross and Schlee, 1973).

The structural development of the Arabian Plate during separation from the African Plate can be divided into two phases, beginning with a wide zone of crustal extension and basin-range topography characterized by northwest-trending fractures that controlled the alignment of dikes, dike swarms, and early volcanic centers. Uplift began in the south and migrated northward. In late Miocene time, initiation of the Dead Sea Rift marks the beginning of the second phase of activity and the rotation of the Arabian Plate changed the stress pattern in the plate that reactivated older, northerly basement trends. Thus, the extrusion of the main volume of basalt appears to have been in structural lows produced by the early extension. Tilting of the harrat surfaces appears to be a very late aspect of the volcanic evolution.

AGE

The age of volcanism in Saudi Arabia sometimes can be established by stratigraphic evidence and by structural relationships discussed above. Our ability to establish age relationships is limited because of the scarcity of Tertiary sediments interlayered with basalt units and between the Precambrian basement and the basalt. Thus, in order to determine age relationships within the entire volcanic province, both geologic and radiometric age evidence must be considered.

Stratigraphic evidence

Perhaps the best documented stratigraphic relationships of the lower Tertiary are at the base of Harrat Hadan east of At Taif (pl. 1; Madden and others, 1979/1980; Gonzales, 1973). Here the basal Umm Himar formation comprises approximately 20 m of ferruginous limestone, interlayered mudstone and shale, and dolomitic limestone that unconformably overlie quartzose sandstone that rests on the Precambrian basement. Fossil sharks, catfish, lungfish, turtles, and crocodiles indicate a late Danian or early Tanetian age (Paleocene) and an estuarine depositional environment (Madden and others, 1979/1980). After the regression northward of this Paleocene sea, laterite formed on the slightly eroded surface. The early flows of Harrat Hadan rest on this laterite with no apparent angular unconformity. Similarly, the basal flows of the As Sirat volcanic field rest on a laterite that is considered to be Paleocene or late Cretaceous in age (Overstreet and others, 1977). Diabase dikes of the Jabal Tirf complex cut the late Cretaceous Anatolo limestone just north of the Yemen border and limit the possible maximum age of the igneous activity. The Shumaysi formation, a clastic ironstone produced by denudation of the Paleocene laterite, contains interlayered basalt from Harrat Rahat that is Miocene according to K-Ar measurements. To the north near Jordan, basalt of Harrat ash Shamah is interlayered with Miocene marine sedimentary rock (Bramkamp and others, 1963).

The stratigraphic relationships point to a possible late

Oligocene-early Miocene initiation of the volcanic activity. Perhaps just as important is the inferred northward migration of the uplift from Yemen toward Jordan. The laterite of As Sirat suggests that the southern area was above sea level prior to the initiation of volcanism, whereas the basal Miocene marl of the north suggests that the northern area was still close to sea level long after volcanic activity and uplift began in the south.

Results of our recent studies indicate that marine sedimentary rock may extend northward from Harrat Hadan to Turayf (Harrat ash Shamah). Isolated outcrops of sedimentary rock or silicified lag deposits that contain marine fossils have been found at Harrats ash Shamah, Harairah, and Ar Rahah. At each locality, the earliest flows were deposited conformably on the remnants of these sedimentary rocks. Fossil assemblages have not yet been identified for all of these rocks and their ages are poorly known, but they have similar stratigraphic settings. The presence of basal terrestrial sedimentary rock and the data listed above suggest that the marine connection from Turayf southward was along a fault-bounded seaway parallel to, but not necessary connected with, the Red Sea (pl. 1). The presence of both marine and coarse terrestrial sedimentary rock beneath the lowermost basalt suggests that the early eruptions at Harrats al Uwayrid, Harairah, Ishara-Khirsat, Al Kura, and Hadan were controlled by basin-range faulting and that lavas filled the basins that now form topographic highs due to drainage inversions.

Radiometric age determinations

Within the last 15 years, numerous K-Ar whole-rock age-determinations have been made of the basaltic rocks of Saudi Arabia and surrounding countries (table 2). Because these determinations were made in different laboratories at different times, there is no way to evaluate and compare the results; therefore, we would like to caution the reader in using these age determinations (fig. 15).

As more K-Ar ages have become available, it is increasingly apparent that nearly all the volcanic rocks around the Red Sea and the Dead Sea Rift are spatially and temporally related to the development of the Red Sea and to the movement of the Arabian Plate away from Africa.

The oldest radiometric age, about 30 Ma, comes from the basal flow in the As Sirat volcanic field (Brown, 1972). Similar ages have been determined for basal flows in Yemen and at the base of the Ethiopian Trap Series (Jones, 1976, Civetta and others, 1978). Kohn and Eyal (1981) used

Table 2.--Potassium-argon ages of Cenozoic volcanic rocks in western Saudi Arabia. Data from Brown (1972), Fleck and others(1973/1976) and Coleman and others (1979)

Sample Number	Sample location	Percent K_2O	Moles $^{40}Ar^*$/Gm ($X 10^{-12}$)	Percent $^{40}Ar^*$	Age	Rock type	Source	Laboratory
907	Isolated flow south end H. Khaybar	.269	.008	1	1.1 ± 1.0	Alkaline Basalt	Brown	Geochron
		.254	.002	0.1				
908	Harrat Kurama	.665	.2152	8	20.0 ± 2.0	Alkaline Basalt	Brown	Geochron
		.641	.2277	10				
			.2402	8				
905	W. flow Harrat, Turrah (Rahat)	.416	.0926	3	12.6 ± 2.5	Alkaline Basalt	Brown	Geochron
		.393	.0851	3				
904	W. flow Harrat, Turrah (Rahat)	.216	.050	4	13.2 ± 1.5	Alkaline Basalt	Brown	Geochron
		.196	.045	4				
GFB1	W. flow Harrat Rahat } Ar Rukha	.35	.0270	12	4.4 ± .4	Alkaline Basalt	Brown	Isotopes Inc.
		.37	.0283	10				
GFB3	W. flow Harrat Rahat } Ar Rukha	.45	.0353	16	4.2 ± .8	Alkaline Basalt	Brown	Isotopes Inc.
		.44	.0295	14				
GFB2	W. flow Harrat Rahat } Ar Rukha	.61	.2019	48	19.1 ± .6	Alkaline Basalt	Brown	Isotopes Inc.
		.61	.2056	59				
902	Hadat ash Sham, Harrat Rahat	.381	.1776	3	25.8 ± 5.0	Alkaline Basalt	Brown	Geochron
		.351	.1526	2				
47027B	S end Harrat Rahat	.493	.0450	2	8.7 ± 2.0	Alkaline Basalt	Brown	Geochron
		.494	.0851	7				
			.0926	2				
47026	Isolated center Al Jarad	1.121	.1676	9	8.0 ± .5	Hawaiite	Brown	Geochron
		1.150	.1501	8				
47024	Feeder neck Jabal An	4.187	1.596	14	22.2 ± 3.5	Trachyte	Brown	Geochron
		4.166	1.841	14				
			1.409	11				
47023	West side Harrat Hadan B. flow	.854	.2477	18	16.6 ± 1.5	Alkaline Basalt	Brown	Geochron
		.861	.2477	19				
47022	West side Harrat Hadan T. flow	.912	.0550	1	3.4 ± .5	Alkaline Basalt	Brown	Geochron
		.876	.0500	1				
47021	West side Harrat Hadan	.796	.2702	24	16.2 ± 1.8	Alkaline Basalt	Brown	Geochron
		.774	.1927	21				
			.2027	31				
47000	SW edge Harrat Al Harrah	.88	.1891	41	12.0 ± .4	Alkaline Basalt	Brown	Isotopes Inc.
		.99	.1824	40				
47001	SW edge Harrat Al Harrah	.50	.0982	31	11.4 ± .4	Alkaline Basalt	Brown	Isotopes Inc.
		.50	.1003	34				
47002	SW edge Harrat Al Hanah	.49	.1144	36	13.4 ± .4	Alkaline Basalt	Brown	Isotopes Inc.
		.49	.1140	39				
47003	SW edge Harrat Al Hanah	.73	.1508	38	12.0 ± .4	Alkaline Basalt	Brown	Isotopes Inc.
		.70	.1477	39				
47004	SW edge Harrat Al Hanah	.58	.1310	35	12.9 ± .6	Hawaiite	Brown	Isotopes Inc.
		.56	.1248	50				

Table 2.--Potassium-argon ages of Cenozoic volcanic rocks in western Saudi Arabia. Data from Brown (1972), Fleck and others (1973/1976) and Coleman and others (1979)--Continued

Sample Number	Sample location	Percent K_2O	Moles $^{40}Ar^*$/Gm ($X 10^{-12}$)	Percent $^{40}Ar^*$	Age	Rock type	Source	Laboratory
93379	Jabal Haylan, Al Birk				.18 ± .06	Alkaline Basalt	Fleck	USGS Menlo Park
					.25 ± .04			
93415	Wadi Halicone, Al Birk				.28 ± .04	Alkaline Basalt	Fleck	USGS Menlo Park
					.25 ± .04			
93435	Wadi Hali, Al Birk B. flow				1.19 ± .24	Alkaline Basalt	Fleck	USGS Menlo Park
93452	Wadi Dahaban, Al Birk B. flow				0.94 ± .39	Alkaline Basalt	Fleck	USGS Menlo Park
					1.51 ± .39			
93454	Wadi Dahaban, Al Birk Oldest				2.61 ± .20	Alkaline Basalt	Fleck	USGS Menlo Park
93484	Wadi Urayk, Al Birk				.57 ± .00	Alkaline Basalt	Fleck	USGS Menlo Park
93718	Wadi Urayk, Al Birk				.80 ± .08	Hawaiite	Fleck	USGS Menlo Park
					.83 ± .11			
93721	Wadi Urayk, Al Birk				.54 ± .10	Hawaiite	Fleck	USGS Menlo Park
93722	Wadi Urayk, Al Birk				.66 ± .30	Hawaiite	Fleck	USGS Menlo Park
					.67 ± .10			
JT-8	Wadi Jizan, Al Birk	1.976	2.608	3.9	.99 ± .23	Basalt	Fleck	USGS Menlo Park
		1.953						
JT-9	Wadi Jizan, Al Birk	1.770	0	0	Recent	Basalt	Fleck	USGS Menlo Park
		1.816						
JT-26	Jibal Akhwah, Al Birk	1.394	0.650	1.0	.31 ± .32	"Picrite"	Fleck	USGS Menlo Park
		1.431						
JT-35	Jabal Ummal Qumm, Al Birk	1.877	1.496	11.8	.53 ± .08	Hawaiite	Fleck	USGS Menlo Park
		1.925						
518	Bottom flow As Sirat	.52	.2773	36	30.0 ± 1.0	Basalt	Brown	Isotope Inc.
		.54	.2799	32				
725-BA	Feeder neck J. Qarn As Sirat	1.005	36.862	11.0	24.7 ± 2.0	Basalt	Fleck	USGS Menlo Park
725-BD	Feeder neck Bani Thwar, As Sirat	1.002	35.579	8.8	25.4 ± 2.7	Basalt	Fleck	USGS Menlo Park
520	Top flow As Sirat	1.34	.5901	92	25.3 ± .5	Basalt	Brown	Isotope Inc.
		1.32	.5865	93				
743-4P	Flow interlayered with Baid Fm	.518	13.78	7.9	18.4 ± 3.1	Basalt	Fleck	USGS Menlo Park
743-4S	Flow interlayered with Baid Fm, Ad Danb	.499	14.01	24.0	19.4 ± 1.1	Basalt	Fleck	USGS Menlo Park
743-4T	Flow interlayered with Baid Fm, Ad Danb	.493	14.07	37.2	19.7 ± 1.0	Basalt	Fleck	USGS Menlo Park
93770	Flow interlayered with Shumaysi Jidda	.714	20.82	28.9	20.1 ± 0.7	Basalt	Fleck	USGS Menlo Park
514-5	Layered gabbro Jabal Tirf	.14	5.506	19	23.0 ± 2.0	Gabbro	Coleman	Isotopes Inc.
		.14	5.952	15				
516-C	Layered gabbro Jabal Tirf	.093	2.903	13	20.0 ± 2.0	Gabbro	Coleman	Isotopes Inc.
		.080	3.265	18				
515-A	Granophyre Jabal Tirf	3.17	117.0	43	20.6 ± .06	Granophyre	Coleman	Isotopes Inc.
		3.13	114.2	43				
515-B	Granophyre Jabal Tirf	1.71	72.06	26	23.3 ± 1.0	Granophyre	Coleman	Isotopes Inc.
		1.70	70.45	29				
517-C	Hornfels Jabal Tirf	3.12	135.0	26	24.3 ± 1.0	Granophyre	Coleman	Isotopes Inc.
		3.15	137.1	27				

Table 2.--Potassium-argon ages of Cenozoic volcanic rocks in western Saudi Arabia. Data from Brown (1972), Fleck and others (1975/1976) and Coleman and others (1979)--Continued

Sample Number	Sample location	Percent K_2O	Moles $^{40}Ar^*$/Gm (X 10^{-12})	Percent $^{40}Ar^*$	Age	Rock type	Source	Laboratory
917 T	W. edge Harra Rahah	1.054	.2102	26	1.9 ± 1.1	Hawaiite	Brown	Geochron
		1.053	.1902	31				
917 B	W. edge Harra Rahah	.388	.0701	15	9.4 ± 2.5	Alkaline Basalt	Brown	Geochron
		.349	.0500	8				
916 T	W. edge Harrat Uwayrid	.630	.0976	8	7.4 ± 1.5	Hawaiite	Brown	Geochron
		.597	.0600	8				
916 B	W. edge Harrat Uwayrid	.689	.3753	7	26.7 ± 2.6	Alkaline Basalt	Brown	Geochron
		.670	.2577	6				
915 T	S. tip Harrat Uwayrid	1.208	.2177	4	7.8 ± 1.0	Alkaline Basalt	Brown	Geochron
		1.271	.1176	2				
915 B	S. tip Harrat Uwayrid	1.081	.1826	13	9.4 ± 1.0	Alkaline Basalt		Geochron
		1.138	.1801	14				
920	W. edge Harrat Lunayir	.775	.0901	20	6.2 ± .8	Alkaline Basalt	Brown	Geochron
		.764	.0751	17				
913	Isolated flow N. of Harrat Khaybar	1.270	.2052	4	7.4 ± .8	Hawaiite	Brown	Geochron
		1.286	.1301	2				
912	W. edge Harrat Khaybar	1.015	.2477	11	11.5 ± 2.3	Alkaline Basalt	Brown	Geochron
		1.006	.1576	8				
911	Harra Al Jarf	.713	.2902	18	21.2 ± 2.1	Hawaiite	Brown	Geochron
		.729	.2427	18				
910	Harra Al Jarf	.606	.3628	13	28.3 ± 2.9	Alkaline Basalt	Brown	Geochron
		.593	.2302	18				
907	S. end Harrat Khaybar	.269	.008	1	1.1 ± 1.0	Alkaline Basalt	Brown	Geochron
		.254	.002	.1				

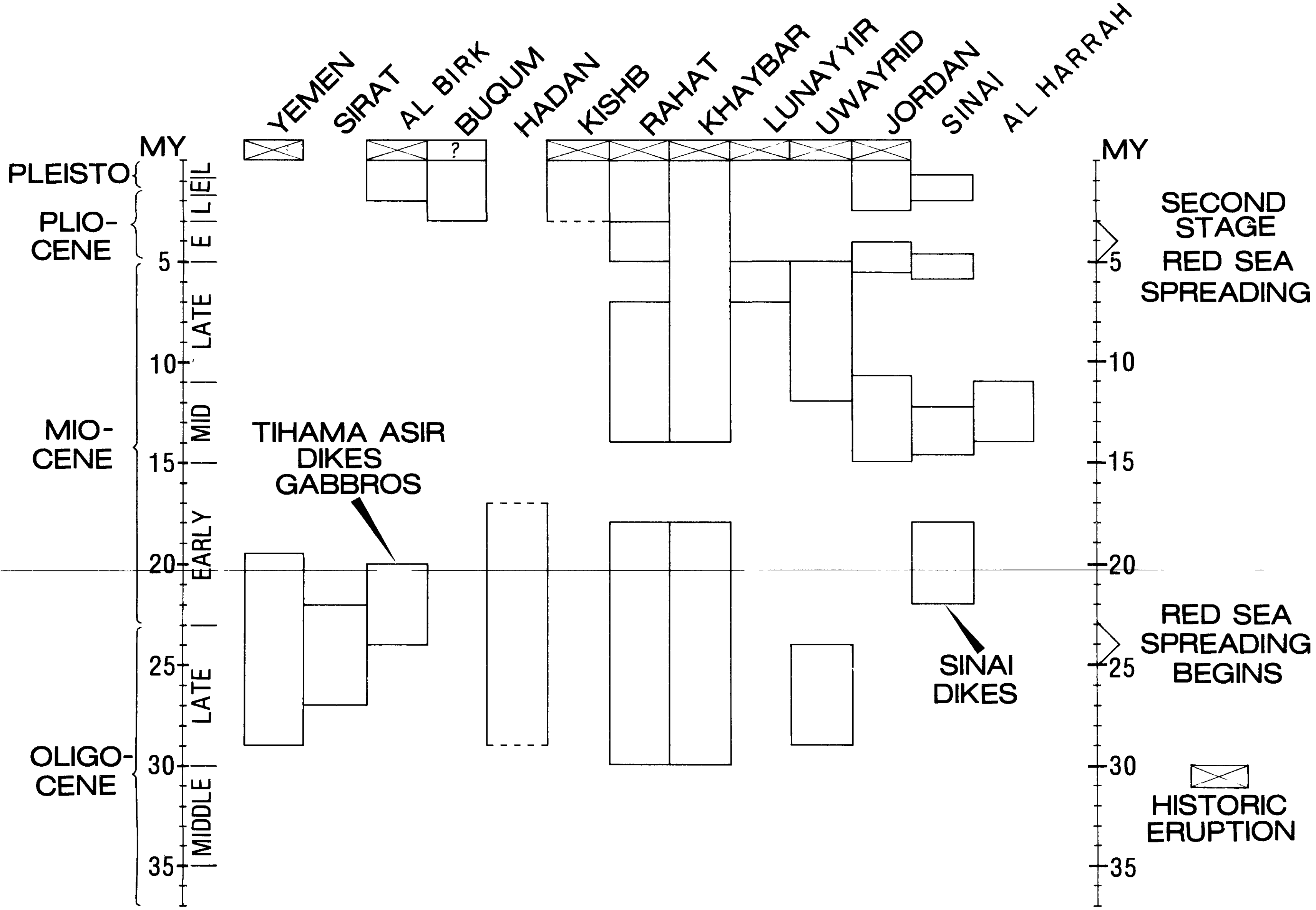

Figure 15.--Age relationships for Cenozoic volcanic rocks of the Arabian Peninsula. Data taken from table 2. Siedner (1973), Siedner and Horowitz (1974), Jones (1976), Coleman (1977), Civetta and others (1978), Steinitz and others (1978), Bartov and others (1980), Kohn and Eyal (1981), and Simkin and others (1981). Ranges are approximate and encompass possible ranges due to experimental error.

fission-track dating of thermally sensitive apatite to establish that domal uplift commenced on the Sinai Peninsula about 26 Ma ago. Sills and layered gabbros at Jabal at Tirf, considered to represent new oceanic crust developed in the first stage of the Red Sea opening, have K-Ar ages between 24.5 and 20 Ma (Coleman and others, 1979). Similar dikes in the Sinai Peninsula have K-Ar ages of approximately 22 Ma (Steinitz and others, 1978) that, with the other ages, indicate a widespread rifting as early as the beginning of the Miocene. The bimodal volcanic rocks of the Jizan group (including the Baid formation) probably represent the first volcanic activity related to lithospheric thinning and the development of the proto-Red Sea. According to Schmidt and others (1982), the Baid formation is older than the Tihamat 'Asir complex, and the Baid formation contains continental mammalian remains of early Miocene affinity. However, in the Shumaysi and Baid formations, interlayered basalt ranges in age from 21 to 18 Ma (Coleman and others, 1979). Thus, radiometric ages for the Shumaysi and Baid formations are in conflict with the Tihamat 'Asir complex (25 to 20 Ma). Because these early events of crustal thinning and volcanism were rapid and overlapped in time, the K-Ar ages should be interpreted with caution. There is no strong geologic evidence to indicate a hiatus between the sedimentation and volcanism of the Jizan group and the intrusive events of the Tihamat 'Asir complex. It is clear that all of these units are unconformably overlain by the evaporites of the Red Sea.

These early Miocene events were followed by a period of sporadic basalt eruptions on the Arabian Plate through middle to late Miocene time when eruptions in Harrats ash Shamah, Al Uwayrid, Khaybar, Rahat, Hadan, and Jabal Druse (Jordan) were widespread. Although eruption of basalt continued on the western side of Saudi Arabia, volcanic activity in the Yemen and Ethopian plateau areas virtually ceased.

Evidence from Deep Sea Drilling Program (DSDP) Leg 23 in the Red Sea indicates that from middle Miocene to late Miocene evaporites continued to accumulate in the Red Sea basin (Ross and others, 1973). At about 4 to 5 Ma ago, an abrupt change in sedimentation within the Red Sea basin marked the beginning of vigorous, renewed spreading in the axial trough (Ross and others, 1973). K-Ar ages for basalt indicate that volcanism also increased at that time and continues to historic-time. This Pliocene volcanism is represented by flows in Yemen and in Harrats al Birk, Rahat, Khaybar, Lunayyir, Ar Rahah, Al Kishb, Hutaymah, Ithnayn, and Jabal Druse (Jordan).

Historical evidence

Accounts of historical eruptions are common in the Middle East and are related in religious books. Perhaps the best known historical eruption in Saudi Arabia is the Chada flow east of Al Madinah, which is reported to have erupted 1256 A.D. A recent publication on volcanoes of the world (Simkin and others, 1981) lists historic eruptions in Saudi Arabia and vicinity (fig. 16). The most recent eruptions in Saudi Arabia are recorded from Jabal Yar (1810 A.D.; Tihamat 'Asir complex) near Abu Arish and from Harrat Ithnayn (1800 A.D.). Historic eruptions are also recorded on Harrats Lunayyir, Khaybar, and Ar Rahah. Even younger eruptions are recorded in Yemen. No clear time and space progression is apparent from the distribution of historic eruptions. The lack of good records prohibits any systematic analysis of the periodicity of these eruptions. Comparisons between areas of known historic eruptions and such remote areas as Harrat al Kishb and Harrat Nawasif suggest that other unrecorded historic eruptions have taken place.

Many eroded flows that lack primary extrusive morphology are covered by man-made stone stripes that form geometrical patterns. These stripes are locally covered by young and much fresher lava, particularly at Harrats al Kishb, Rahat, Ash Shamah, Al Uwayrid, and Lunayyir. These stripes are thought to be constructions made by ancient dwellers of the Arabian Peninsula; however, no one is sure of the age of these stripes. Recent studies of Jawa, a lost city on Harrat ash Shamah along Wadi Sirhan, Jordan, provide important clues (Helms, 1981). The excavations of Jawa indicate a shortlived civilization that existed between the 5th and 3rd millenia (5000 to 3000 B.C. or about 7000 years ago). The Jawa ruins are stratigraphically above the stone stripes and, therefore, it is possible that most flows with stone stripes are probably older than about 7,000 years. Many K-Ar age determinations for basalts from young flows did not yield measurable argon, and these flows probably belong within the group having ages between 5000 B.C. and 700 A.D., characterized by the Chada flow near Al Madinah.

PETROGRAPHY

The Cenozoic volcanic rocks have such similar characteristics thoughout Saudi Arabia that it is possible to characterize the most important rock types by general petrographic descriptions. For this purpose, we have divided the rocks into six main lithologies: (1) picrite-ankaramite, (2) alkali olivine basalt (basanite), (3) hawaiite-mugearite, (4) trachyte-phonolite-comendite, (5) xenoliths, and (6) diabase-gabbro-granophyre.

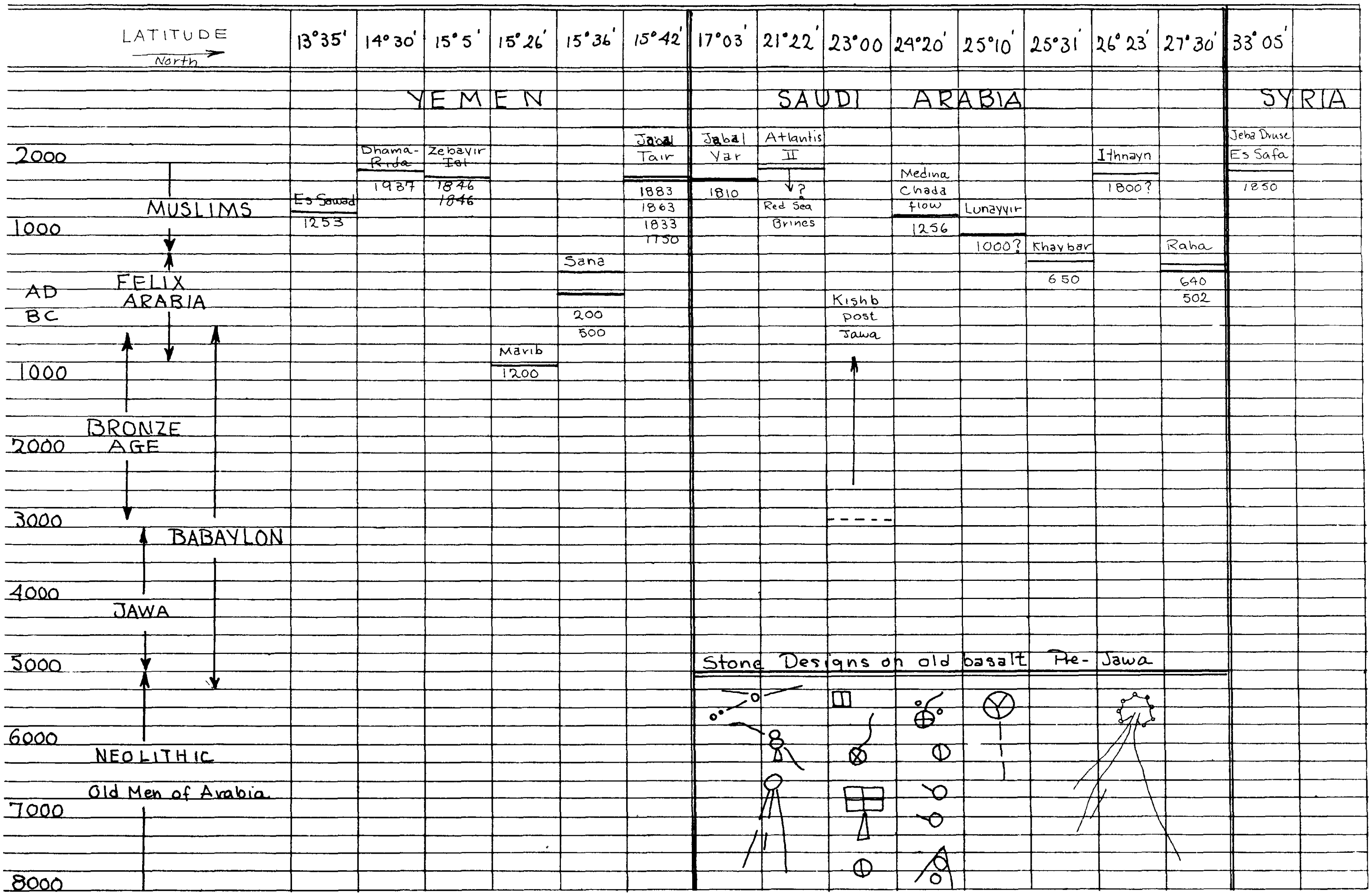

Figure 16.--Holocene volcanic records. Data taken mostly from Simkim and others (1981) and Helms (1981). Stone designs are representative only; 1 cm about 12 m.

In an attempt to identify fine-grained nepheline in the basalts, low-density minerals (less than 2.65 gm/cm3) were scanned by x-ray diffraction techniques.

Picrite-ankaramite

The earliest phases of eruption in the older volcanic fields such as As Sirat and Harrats Hadan, Al Kura, Kurama, Harairah, Ash Shamah, Al Uwayrid, and Ar Rahah contain basal flows of picrite basalt. The rocks are dark, have a typical knobby weathered surface, and contain more than 60 percent olivine and clinopyroxene. In some cases, 30 percent by volume of basalt is olivine phenocrysts, but generally the olivine and clinopyroxene form intergranular mixtures. The olivine is commonly zoned and the rims enriched in iron. The clinopyroxene is a mauve, titanium-rich diopside. Nepheline was identified by X-ray diffraction. Plagioclase forms groundmass laths and microlites intergrown with the mafic minerals, but it does not form individual phenocrysts in the picrite. Plagioclase has a composition of An_{55-60} and is slightly zoned. Mixtures of magnetite and ilmenite are 10 to 15 percent of the rock.

Alkali olivine basalt (basanite)

Alkali olivine basalt, the predominant rock type in all of the harrats, has a very uniform mineralogy and texture. Basalt flows are 1 to 10 m thick, and are generally dark gray to black. Textures vary from nonvesicular to vesicular, trachytic to diktytaxitic. These rocks contain 10-20 percent olivine, 20-25 percent clinopyroxene, 50-60 percent plagioclase, 5-10 percent opaque minerals, and minor nepheline and potassium feldspar.

The alkali olivine basalts generally contain olivine phenocrysts that show zoning from cores of Fo_{85-90} to rims of Fo_{80-75}. The more fayalitic olivine rims are typically altered to iddingsite, particularly in those flows that are more vesicular and have trachytic textures. Clinopyroxene phenocrysts are less abundant than olivine, are zoned, and are characteristically mauve. Phenocrysts of clinopyroxene are commonly ragged, and have a moth-eaten appearance that indicates that they have reacted with the melt. These clinopyroxene phenocrysts and groundmass crystals are titanium-rich diopside.

The groundmass consists mainly of plagioclase laths (more calcic than An_{50}), ophitic to intergranular clinopyroxene, and opaque iron-titanium oxides. Nepheline is locally coarse enough to identify optically, but in most cases its presence can be verified only by X-ray diffraction. Analcite, chabazite, and carbonate minerals are typically present in amygdules, and, in some instances, the carbonate appears to be a magmatic phase within the groundmass. The olivine with deep reddish-brown iddingsite was probably oxidized (Baker and Haggerty, 1967) during eruption. Glass is rare in the alkali olivine basalt lava, and is generally preserved in small interstitial areas in the groundmass.

Hawaiite-mugearite

A highly-evolved hawaiite-mugearite basalt is less abundant than alkali olivine basalt and it appears to have been extruded mainly in the later phase of volcanic activity. Hawaiites have been positively identified in the Harrats al Birk, Rahat, Al Kishb, Khaybar, and Lunayyir. This rock, in contrast to alkali olivine basalt, is lighter gray and tends to be more viscous and vesicular. Typical textures are trachytic to diktytaxitic. Olivine, commonly less than 5 percent of the rock, has an intergranular relationship to plagioclase and clinopyroxene in the groundmass. Flows containing plagioclase megacrysts (An_{10-50}) are common. Pinkish clinopyroxene is apparently a titanium-rich diopside. Opaque minerals are abundant and nepheline is a common accessory mineral. Chabazite is a common secondary mineral in hawaiite.

Trachyte-phonolite-comendite

Restricted volumes of volcanic rock of intermediate to silicic composition are present in the Harrats Khaybar, Rahat, As Sirat, Ar Rahah, Al Uwayrid, and Al Kishb. These rocks generally form tholoids or solid pluglike extrusions that have flat tops and nearly vertical walls. Many of the tholoids were intruded up through tuff ring craters.

The buff to pale-gray trachyte and phonolite are easily distinguished from the much darker alkali olivine basalt but are gradational in color to the hawaiite and mugearite. The trachyte has phenocrysts of both potassium feldspar and plagioclase in a flow-aligned groundmass of feldspar and interstitial aegerine-augite and magnetite. The phonolites are generally microphyric and consist of aegerine-augite, fayalitic olivine, and magnetite in a matrix of sodic plagioclase, potassium feldspar, and traces of nepheline and (rarely) nosean.

Jabal Abyad is a spectacular center of silicic volcanism that is constructed of tholoids, tuff rings, and pumice-breccia deposits. The predominance of domes or tholoids indicates that the silicic magmas were relatively dry and viscous. The major rock types are pale-gray, flow-banded, glassy flows that contain partly welded pumice, vent agglomerates, and pyroclastic debris of uncemented tuff and lapilli. The fragmental rocks display no flow textures and consist of devitrified glass and fresh obsidian. Most rock types are cryptocrystalline, but some contain phenocrysts of anorthoclase and smaller grains of potassium feldspar, quartz, aegerine, riebeckite, katophorite, crossyrite, apatite, and zircon. These rocks are classified as comendites according to Baker and others (1973).

Xenoliths

Ultramafic inclusions from the mantle are common in the alkali olivine basalts of Saudi Arabia, and these are locally accompanied by fragments of gabbro and Precambrian crustal rock. Table 1 shows the distribution of inclusion types for the individual volcanic fields.

The principal mantle-rock inclusions are harzburgite, dunite, lherzolite, and websterite and megacrysts of clinopyroxene, plagioclase, amphibole, and spinel.

The harzburgite and lherzolite are coarse grained and consist of a mosaic of subhedral to anhedral olivine, orthopyroxene, green clinopyroxene, and minor chromian spinel. The texture of most of these rocks is xenomorphic granular, although rocks exhibiting a tectonite fabric are also present. Olivine is generally Fo_{90-91} and shows very little variation in composition. Orthopyroxene is also magnesium-rich and has the same magnesium/iron ratio as the olivine. Based upon its emerald-green color, the clinopyroxene appears to be chromian diopside. The harzburgite has an average mode of 80 percent olivine, 17 percent orthopyroxene, 2 percent clinopyroxene, 1 percent spinel (when clinopyroxene exceeds 5 percent, the name lherzolite applies). Neither plagioclase nor garnet is present in harzburgite or lherzolite nodules. Cumulate websterite and gabbro commonly contain plagioclase.

The websterite, gabbro, and megacrysts of spinel and amphibole appear to be products of fractional crystallization of basalt. The clinopyroxene in websterite and in megacrysts contain more aluminum and titanium than the chromian diopside of the harzburgite and lherzolite.

The inclusions of Precambrian rock are metasandstone, granite, and other rock types. No high-grade (granulite-facies) metamorphic rocks have been found.

Diabase-gabbro-granophyre

The Tihamat 'Asir complex (ophiolite) of southwestern Saudi Arabia is a distinct suite of rocks that contrasts strongly with the volcanic rocks previously described.

The most important rock is diabase that forms the dike swarms of the complex exposed south of the Ad Darb line. These dikes are two types: fine-grained diabase and leucocratic rhyolite in the proportion of about 2:1. The diabase consists primarily of calcic plagioclase, clinopyroxene, and iron-titanium oxides. The texture is marked by ophitic clinopyroxene surrounding plagioclase laths. An average mode for the diabase is 52 percent plagioclase, 37 percent clinopyroxene, and 10 percent iron-titanium oxides; olivine and hypersthene are not present. The rhyolite consists principally of lath-shaped potassium feldspar, plagioclase, and quartz. Granophyric intergrowths of potassium feldspar, plagioclase, and quartz compose the mesostasis. Minor amounts of brown hornblende, pyroxene, and opaque minerals are present. The leucocratic dikes characteristically have a trachytic texture that gives some dikes a flow-banded appearance.

Rifting north of the Ad Darb transform fault has produced hypabyssal dikes of partially differentiated mafic magma. These dikes are medium to coarse grained, and exhibit wide variations in modal composition from quartz gabbro to quartz monzonite. All contain quartz and plagioclase, and potassium feldspar is commonly an important constituent. These minerals form hypidiomorphic textures. The plagioclase is zoned from An_{60} to An_{30}, and graphic intergrowth of quartz and potassium feldspar is rare. Biotite, clinopyroxene, and amphibole are present in nearly all of these dikes and are 10 to 30 percent of the rock. Opaque minerals are 2 to 7 volume percent.

The gabbro that forms the conical bodies within the Tihamat 'Asir complex is generally medium to coarse grained, and gray to dark gray. Rhythmic layering reflects the accumulation of plagioclase, clinopyroxene, and olivine crystals in layers as thick as 1 m. Most layers are clinopyroxene-olivine-plagioclase cumulate rocks and locally orthopyroxene-plagioclase or olivine-plagioclase cumulate rocks are present. Ultramafic layers and evidence of extreme upward differentiation are absent. Plagioclase forms cumulus textures in all of the specimens examined, but visible layering is not apparent everywhere. Plagioclase composition ranges from An_{62} to An_{72}, but individual grains rarely show zoning. Neither variation in calcium content nor modal abundance of plagioclase is systematically related to stratigraphy. Anhedral clinopyroxene grains are commonly heteradcumulus material, and they produce a pseudo-ophitic texture. The fact that no exsolution lamellae were detected in the clinopyrox-ene is evidence for shallow crystallization of gabbro. Minor olivine (Fo_{67-69}) is present in nearly all layers and con-stitutes a maximum of 30 percent of the lower parts of the sequence. The abundance of olivine decreases irregularly whereas that of clinopyroxene increases from the bottom to the top of the layered sequence. In layers with mesocumulate texture, olivine grains have rare reaction rims of orthopyroxene. Opaque minerals appear to be a mixture of magnetite and ilmenite and are as much as 11 volume percent.

The granophyre that forms a thick carapace over the layered gabbro and dike complex is a medium-grained, leucocratic rock consisting mainly of graphic intergrowths of quartz and potassium feldspar. Zoned plagioclase is rimmed by granophyric intergrowths. A pale-green clinopyroxene (hedenbergite) is present as are rare grains of riebeckite, but these phases never exceed 2 volume percent of the rock. Opaque minerals are common and are probably intergrowths of magnetite and ilmenite. Vugs, as large as 1 cm in diameter, contain clots of epidote, sphene, green amphibole, and opaque minerals, and all seem to have formed during the late stages of cooling.

CHEMICAL PETROLOGY

The Cenozoic volcanic rocks of Saudi Arabia represent one of the largest and most widespread occurrences of alkali olivine basalt in the world, and knowledge of the chemical variation can provide important clues regarding their origin. The chemical data used in this discussion were compiled from published and unpublished sources (table 3; Coleman and others, 1982). Unfortunately, the data are not evenly distributed on a geographical basis; therefore conclusions derived from these studies must be considered preliminary. All of the analyses were normalized to 100 weight percent from which CIPW norms and other chemical parameters and ratios were calculated. Before the norms were calculated, the FeO-Fe_2O_3 was redistributed according to the formula: $Fe_2O_3=TiO_2+1.5$, and excess Fe_2O_3 was converted to FeO (Irvine and Baragar, 1971). The analyses used in this study were made in various laboratories over a period of about 10 years, and the degree to which these data may be compared is highly uncertain. Most of the Cenozoic basalts in Saudi Arabia contain either olivine or clinopyroxene phenocrysts in a groundmass consisting mainly of calcic plagioclase, clinopyroxene, olivine, magnetite, glass, and xenoliths. The major-element chemistry discussed below is not corrected for the presence of phenocrysts and xenoliths; thus it may not reflect true liquid compositions.

Table 3.--Chemical and CIPW normative compositions of fourteen representative samples of Cenozoic volcanic rock, western Saudi Arabia

[Analyses in weight percent. Explanatory notes for samples are shown below table]

SAMPLE	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	45.9	46.6	47.9	49.4	50.5	53.0	58.3	61.5	71.5	49.9	48.8	70.2	44.5	51.3
Al_2O_3	14.2	16.2	16.5	16.5	18.3	16.5	18.5	18.0	11.8	13.2	17.9	12.8	.80	5.4
Fe_2O_3	1.6	3.4	1.4	8.07	3.4	8.81	3.27	2.3	2.51	4.7	2.4	3.7	.54	3.4
FeO	9.9	7.7	9.0	2.82	7.6	2.15	2.61	2.4	1.17	8.8	6.4	2.0	7.6	5.3
MgO	12.1	7.6	9.0	5.51	2.8	1.91	.64	.15	<.1	4.8	8.0	.47	45.2	18.1
CaO	9.0	9.7	10.7	8.53	6.3	5.13	2.26	1.3	.28	8.8	11.7	1.7	.80	14.5
Na_2O	2.2	3.0	3.3	4.60	5.0	5.91	7.50	6.8	6.03	2.7	2.5	4.5	.04	.73
K_2O	.51	1.1	.54	1.65	1.8	2.51	3.87	4.6	4.16	.78	.22	2.8	.07	.04
H_2O+	2.1	1.1	.44	.30	.64	.83	1.45	1.2	1.29	2.3	1.1	.25	.32	.39
H_2O-	.48	.35	.09	16	.30	.56	1.04	.4	.14	.21	.12	.39	.96	.07
TiO_2	1.6	2.2	1.69	1.84	1.7	1.42	.26	.11	.14	3.1	.65	.53	.04	.53
P_2O_5	.22	.53	.30	.49	.90	.83	.22	.10	.12	.30	.07	.13	.04	.04
MnO	.17	.23	.17	.19	.20	.25	.17	.17	.10	.24	.17	.14	.07	.12
CO2	<.05	.11	--	--	.08	--	--	.95	--	<.05	<.05	<.05	<.05	<.05
Total	99.98	98.72	100.99	100.06	99.52	99.81	100.09	99.98	99.34	99.83	100.03	99.61	100.98	99.92
Q	--	--	--	--	--	--	--	.6	24.7	1.7	--	25.8	--	
Or	3.1	6.6	3.2	9.8	10.8	15.1	23.4	27.9	25.1	4.8	1.3	16.8	.4	.2
Ab	19.1	25.8	22.1	33.5	42.6	50.6	54.3	59.1	38.3	23.6	21.5	38.6	.3	6.2
An	28.1	28.0	28.7	19.6	22.5	11.3	5.5	5.1	--	22.3	37.5	6.5	1.8	11.4
Ne	--	.02	2.9	3.0	.2	.1	5.8	--	--		--	--	--	--
Ac	--	--	--	--	--	--	--	--	7.4		--	--	--	--
Na_2SiO_3	--	--	--	--	--	--	--	--	1.2		--	--	--	--
Di	13.2	14.1	18.1	15.3	2.7	7.1	3.8	.7	.5	17.5	17.1	1.0	1.5	47.66
Hy	6.9	--	--	--	--	--	--	2.7	2.1	23.4	5.3	10.0	20	25.98
ol	23.6	15.0	19.1	4.7	10.7	1.1	1.3	--	--	--	15.9	--	74.6	2.1
mt	2.4	5.0	2.0	4.4	5.0	3.6	4.9	3.4	--	--	--	--	.78	4.9
Il	3.1	4.2	3.2	3.5	3.3	2.7	.5	.2	.3	6.1	1.3	1.0	--	1.0
Ap	.5	1.3	.7	1.2	2.1	2.0	.5	.2	.3	.7	.2	.3	.10	.1
H	--	--	--	5.1	--	6.4	--	--	--	--	--	--	--	--

Table 3.--Chemical and CIPW normative compositions of fourteen representative samples of Cenozoic volcanic rock, western Saudi Arabia--Continued

Sample	Rock type and location	Reference
1.	Alkali picrite (58851). Basal flow, Harrat as Sirat	Coleman and others, 1977
2.	Alkali olivine basalt (58378). Basal flow, Jabal Haylah, Harrat al Birk	Coleman and others, 1977
3.	Alkali olivine basalt (G-28). Young flow, Jabal Abyad, Harrat Khaybar	Baker and others, 1973
4.	Hawaiite (6-38). Flow from small cone northeast of Jabal Abyad, Harrat Khaybar	Baker and others, 1973
5.	Hawaiite (93722). Young flow, Wadi Uvayk, Harrat al Birk	Unpublished data, USGS
6.	Mugearite (G-11). Flow north of Jabal Abyad, Harrat Khaybar	Baker and others, 1973
7.	Phonolite (B-18). Flow from small cone east of Jabal Abyad, Harrat Khaybar	Baker and others, 1973
8.	Trachyte (62079). Small neck in Harrat as Sirat	Coleman and others, 1977
9.	Comendite (G-17). Small cone northeast of Jabal Abyad, Harrat Khaybar	Baker and others, 1973
10.	Diabase (JT-31). Dike east of Jabal Abyad, Harrat Khaybar	Coleman and others, 1977
11.	Clinopyroxene-olivine gabbro (JT-42). Ten m from base of Jabal at Tirf gabbro, Tihamat 'Asir complex	Coleman and others, 1977
12.	Granophyre (JT-1). Sheet overlying layered gabbro at Jabal at Tirf, Tihamat 'Asir complex	Coleman and others, 1977
13.	Harzburgite (JT-26A). Inclusion in basalt from Jabal Akwah, Harrat al Birk	Ghent and others, 1980
14.	Websterite (58377). Inclusion in basalt from Jabal Haylah, Harrat al Birk	Ghent and others, 1980

Major elements

All available analyses of the volcanic rocks have been plotted on a total alkali versus silica diagram (fig. 17). Most basalts are part of the alkali-olivine-basalt series. Analyses that plot in the subalkaline field are typically picritic-ankaramitic basalt containing very small amounts of alkalis. The picritic varieties are characteristic of the pre-uplift basal sections of the older harrats such as As Sirat and Hadan, whereas the initial eruptive rocks of both the post-Miocene and post-uplift fields are less mafic and are much more strongly enriched in alkalis relative to silica. All of the Saudi Arabian volcanic rock samples belong to the sodic-alkali-olivine basalt series because sodium predominates over potassium. (Irvine and Baragar, 1971). The normative plagioclase content and the normative color index indicate that the Saudi Arabian samples characterize a progression from picrite, to alkali basalt (basanite), hawaiite, and (rare) mugearite (rare) (fig. 18; Irvine and Baragar, 1971). Also, minor vol-umes of silicic volcanic rock are present at certain eruptive centers. These rocks are mainly trachyte, phonolite, and comendite and have agpaitic indices (Na+K/Al) that are slightly greater or equal to 1.00. These silicic rocks probably developed from peralkaline magma.

Alkali olivine basalt is Miocene to Holocene in age, whereas picritic lavas tend to dominate in the early stages of this time period. The later magmas (hawaiite)tend to be less mafic and apparently they can be derived, in terms of their major elements, from primary undersaturated picritic melts (see below). Peralkaline and silica-rich volcanic bodies present in some of the post-Pliocene fields such as Khaybar, Al Kishb, and Rahat are associated with hawaiite. The oldest volcanic fields in Saudi Arabia, Harrat Hadan and Harrat as Sirat, have virtually no fractionated silicic rocks except for a small trachyte plug in As Sirat.

The diabase-gabbro-granophyre of the Tihamat 'Asir complex is distinctly different from basalts in the harrats. Previous publications (Coleman and others, 1977, 1979) have shown that the dike swarms, gabbros, and continental dikes have definite tholeiitic affinities. The dike swarms have a trend of slight iron-enrichment and silica-enrichment that is very similar to basalts from Thingmuli, Iceland (Coleman and others, 1979). The total alkalis are low and sodium/potassium ratios are high, typically greater than 4. All rocks of this complex contain normative hypersthene and rare phenocrystic olivene, whereas only the continental basalts tend to contain normative nepheline. The chemical composition of the continental dikes is slightly more evolved

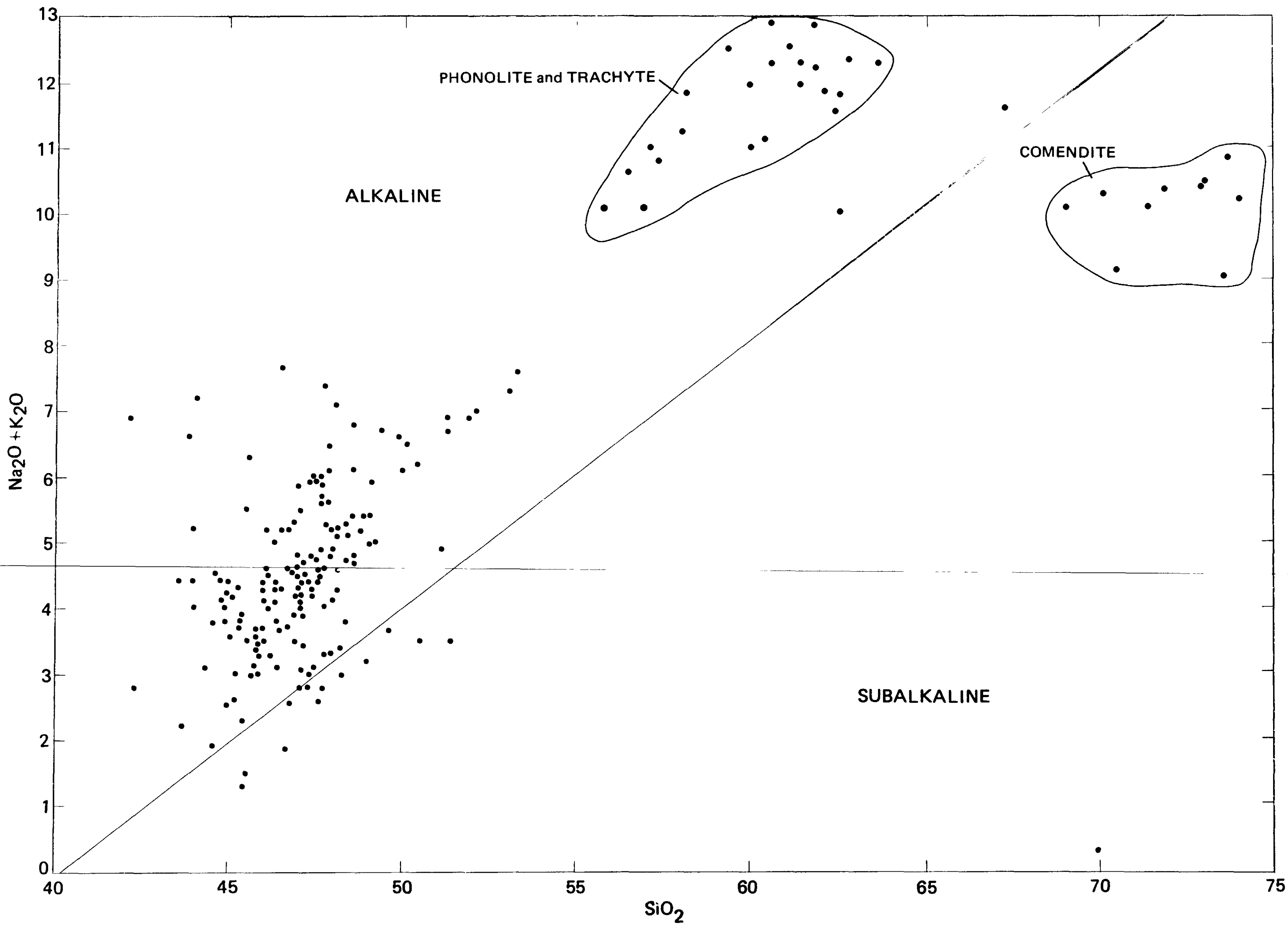

Figure 17.--Harker diagram, SiO_2 versus Na_2O+K_2O of analyzed samples from harrats of Saudi Arabia; in weight percent.

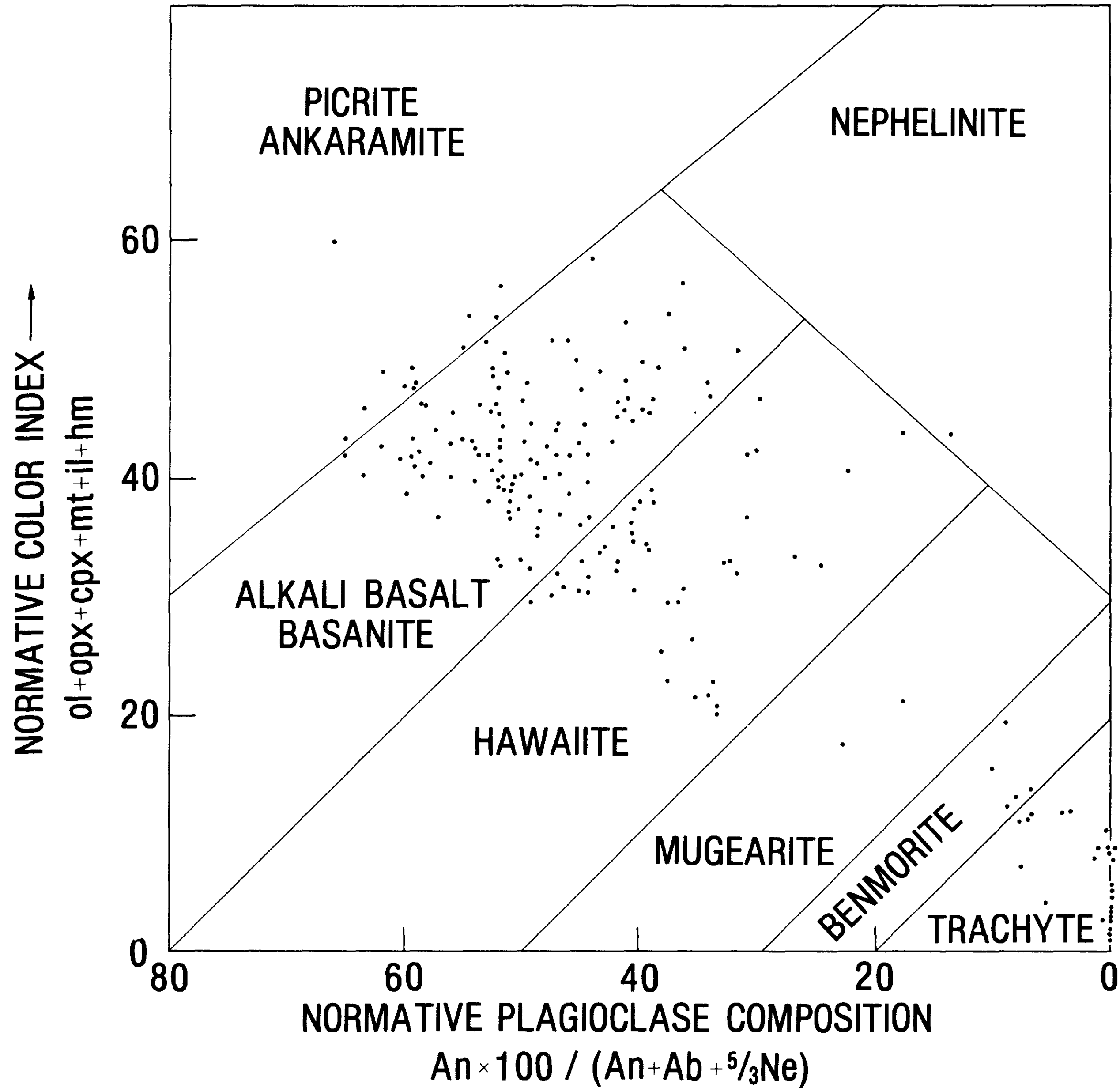

Figure 18.--Irvine and Baragar classification diagram. Normative color index versus normative plagioclase for analyzed samples from the harrats of Saudi Arabia. Values for minerals derived from CIPW normative calculation.

than that of the dike-swarms from the Tihamat 'Asir complex, but their chemical parameters indicated that they evolved from a tholeiitic parent similar to the basalt of the present-day Red Sea spreading center (Coleman and others, 1979). The gabbro from the layered conical bodies is characteristically low in silica and potassium and high in alumina and calcium, an indication of the cumulate or residual mineralogy of the gabbro. Most of the layered gabbro is slightly under-saturated but typically hypersthene-normative with modal orthopyroxene. The layered gabbro bodies do not exhibit progressive fractionation (from bottom to top) of the solid-solution minerals, apparently because successive batches of new magma were introduced during the formation of the gabbro bodies. The fact that layered gabbro plutons both cut and are cut by the dike swarms suggests that similar liquid produced both the dikes the gabbroic magma chambers.

Rhyolite dikes and granophyric sheets are contemporaneous with the Tihamat 'Asir dikes and gabbro bodies, but they have a distinctive chemical composition, silica typically being in excess of 65 percent. All of these rocks contain potassium feldspar and exhibit granophyric textures, and their compositions plot near the ternary minimum in the system orthoclase-albite-silica. Thus, the Tihamat 'Asir assemblage is chemically and lithologically bimodal and is chemically similar to the pre-rift volcanic rocks of the Jizan group (Schmidt and others, 1982).

Trace elements

Because trace-element data are incomplete for the Cenozoic igneous rocks of Saudi Arabia, it is difficult to make exact comparisons (table 4). The correlation between rubidium, barium, and K_2O in these rocks is positive and the rubidium and barium contents are high in the trachyte samples. The granophyre from the Tihamat 'Asir complex, however, contains much less rubidium. The alkali olivine basalts have potassium/rubidium ratios from 350 to 600, which is somewhat higher than the ratio (300) for the Tihamat 'Asir dike swarm. Fractionation of the basalt toward trachyte increases both potassium and rubidium, however the potassium/rubidium ratio declines to about 100. Strontium is strongly enriched by a factor exceeding two in the alkali olivine basalts and the hawaiites (600-1150 ppm), over the subalkaline lavas such as the diabase dikes and gabbros from the Tihamat 'Asir complex that typically contain less than 300 ppm strontium. Zirconium abundances in the alkali basalts range from 130 to 300 ppm. The titanium/zirconium ratio is 40 to 100 for the alkali olivine basalt and about 80 for the diabase dikes of the Tihamat 'Asir complex. The

Table 4.--Minor and trace element compositions of eleven samples representing the main types of Cenozoic igneous rocks in western Saudi Arabia

[K_2O, TiO_2, and P_2O_5 in weight percent; others in parts per million. Leader indicates analysis not performed. N.D. indicates elements not detected]

	1	2	3	4	5	6	7	8	9	10	11
K_2O	0.86	1.4	1.4	0.51	0.78	0.92	4.6	4.1	0.7	0.18	2.5
TiO_2	2.2	2.3	2.4	1.5	2.1	2.1	.11	.37	2.3	.72	.76
P_2O_5	.40	.57	.70	.25	.32	.48	.10	.08	.4	.06	.22
Ba	248	426	550	155	240	372	700	12	218	37	467
Co	51	50	38	55	64	48	N.D.	--	49	64	5
Cr	456	518	359	500	500	400	N.D.	--	39	273	<1
Cu	91	92	61	50	45	34	5	--	71	59	9
Ni	253	241	244	162	132	150	N.D.	--	23	260	N.D.
Sr	604	653	746	600	1040	1150	163	~8	315	231	145
V	205	213	192	150	150	152	N.D.	--	433	371	~20
Y	29	30	47	30	39	48	80	163	69	16	150
Zr	131	155	227	150	221	316	700	2000	160	~25	650
Rb	14	25	31	--	--	--	347	212	17	~6	85

Sample	Rock type and location	Samples
1.	Basalt flows, Harrat as Sirat	12
2.	Basalt feeder pipes, Harrat as Sirat	11
3.	Basalt flows, Harrat al Birk	13
4.	Basalt flows, Harrat Rahat	4
5.	Basalt flows, Harrat Khaybar	7
6.	Basalt flows, Harrats Uwayrid, Lunayyir, and Rahah	9
7.	Trachyte, Harrat as Sirat	1
8.	Comendite, Jabal Abyad, Harrat Khaybar	4
9.	Diabase dikes, Jabal at Tirf, Tihamat 'Asir complex	23
10.	Layered gabbro, Jabal at Tirf Tihamat 'Asir complex	7
11.	Granophyre sheet, Jabal at Tirf Tihamat 'Asir complex	4

chromium content of the alkali basalt is generally in excess of 400 ppm. In contrast, the chromium content of the gabbro and diabase from the Tihamat 'Asir complex is generally less than 200 ppm and reflects the fractionated nature of these mafic rocks. Nickel generally follows the same pattern as chromium in the contrasting rock types. Vanadium in the alkali olivine basalt varies from 150 to 200 ppm and is considerably below the average for tholeiite (330 ppm) and for the Tihamat 'Asir diabase dikes (433 ppm). The copper content in the alkali olivine basalt (30 to 90 ppm) is somewhat less than that for the average basalt (about 120 ppm), but not noticeably different from that for the diabase dikes (71 ppm) of the Tihamat 'Asir complex.

The rubidium content of granophyre and rhyolite of the Jabal at Tirf complex is significantly high when compared to that of the diabase dikes of the Tihamat 'Asir but all contain nearly the same levels of strontium. The alkali basalt of the harrats generally has higher concentrations of both rubidium and strontium. The highly fractionated, felsic volcanic rock of the harrats has relatively high rubidium and low strontium contents.

Strontium-isotope ratios ($^{87}Sr/^{86}Sr$) for the Red Sea axial-trough basalt are 0.7026 to 0.7027, which is considerably less than the 0.7037 to 0.7033 ratios for alkali basalt in Harrats al Birk and As Sirat (table 5). However, the close similarity between the strontium-isotope ratios for the Tihamat 'Asir layered gabbro and diabase dikes (0.7031 to 0.7036) and those of the alkali basalts indicates that the Tihamat 'Asir complex may have been derived from similar upper mantle material or contamination may have occurred during the ascent of magma of Harrat al Birk, Harrat as Sirat, and the Tihamat 'Asir complex through the Precambrian crust. In contrast, the granophyre may represent melted older continental crust rather than the differentiation product of the layered gabbro because the granophyre has strontium-isotope ratios of 0.7041 to 0.7057.

Rare-earth elements

Rare-earth element (REE) analyses available for a limited number of samples from Harrats al Birk and As Sirat provide some insight into the evolution of the magmas (table 6; fig. 19). The samples are divided into geographic and lithologic groups in order to discuss their respective REE patterns: (1) Harrat al Birk eruptive centers south of the Ad Darb transform fault, (2) Harrat al Birk north of the Ad Darb transform fault, (3) Harrat as Sirat feeder necks, and (4) Harrat as Sirat flows. The high light-REE content and the low magnesium values relative to iron of samples from the Al

Table 5.--Rubidium, strontium, and strontium isotopic data for Cenozoic volcanic rocks from Saudi Arabia**

[*Concentration by isotope dilution; all others by X-ray fluorescence]

Sample number	Rb (ppm)	Sr (ppm)	Rb/Sr	Sr^{87}/Sr^{86}
As Sirat, volcanic rocks (25-29 Ma)				
58851	9.2	334	0.028	0.7034
58856	9.5	715	.013	.7033
62080	26.0	801	.033	.7036
As Sirat, feeder pipe (25 Ma)				
58524	25	606	.042	.7036
Jabal at Tirf granophyre (22 Ma)				
JT-1	83	116	.715	.7046
JT-2	85	93	.917	.7057
JT-5	58	179	.324	.7041
Jabal at Tirf layered gabbro (22 Ma)				
JT-42	0.9	247	.004	.7034
JT-45	1.5*	258	.0058	.7031
514-4	0.98*	226	.0043	.7034
Jabal at Tirf diabase dikes (22 Ma)				
JT-11	17.1	210	.082	.7036
JT-23 (Chill)		364		
JT-29	14.6	234	.062	.7034
Al Birk basalt				
JT-9 0 Ma	63	934	.067	.7036
JT-26 0.31 Ma	28	763	.037	.7037
JT-36 0.5 Ma	68	964	.071	.7035
58377 5.0 Ma	26	581	.045	.7033
Hail Arch basalts				
Haddat ash Sham 902, 25.1 Ma	4.2*	897	.0047	.7044
Jabal Antar 910, 20.4 Ma	11.3	478	.024	.7030
Harrat Kurama 908, 19.4 Ma	13.0	448	.029	.7036
Harrat Rahat 905, 12.5 Ma	8.8	369	.024	.7039
Harrat Khaybar 907, 1.0 Ma	3.0*	396	.0076	.7034

** from Coleman and others, 1977

Table 6.--Barium and rare-earth-element concentrations in samples of volcanic rock from Harrat al Birk

[Concentrations in parts per million. Leader indicates analysis not performed. Explanatory notes for samples are shown below table]

	Ba	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu
South of Ad Darb Transform Fault									
JT-7	700	64	137	--	8.9	3.0	0.8	3.9	0.41
JT-8	600	65	142	90	9.7	3.0	1.3	3.4	.36
JT-9	700	61	137	80	9.1	2.9	1.1	3.2	.50
JT-12	500	54	116	--	10.0	2.7	1.2	4.7	.50
JT-26	600	52	141	40	8.4	2.6	1.0	2.8	.36
JT-27	600	59	132	40	9.3	2.7	.9	3.8	.40
JT-35	800	70	148	70	10.2	2.6	1.1	3.2	.42
JT-36	700	69	140	170	9.7	2.8	1.2	2.6	.41
	650	62	137	82	9	3	1.1	3.5	.42
North of Ad Darb Transform Fault									
62066	400	31	72	--	6.4	2.4	.7	2.1	.35
62067	500	37	92	--	7.6	2.6	.7	2.7	.31
58375	200	30	81	--	6.7	2.1	1.0	2.3	.36
58378	400	28	71	--	6.2	2.2	1.0	2.5	.40
58377	400	26	67	--	6.3	2.2	1.0	3.9	.57

Volcanic rocks south of Ad Darb transform fault		
JT-7	Hawaiite flow, Jabal at Tirf, Tihamat 'Asir Complex	Coleman and others, 1977
JT-8	Alkali olivine basalt, Jabal at Tirf, Tihamat 'Asir Complex	Coleman and others, 1977
JT-9	Alkali olivine basalt, Jabal at Tirf, Tihamat 'Asir Complex	Coleman and others, 1977
JT-12	Alkali olivine basalt, Jabal at Tirf, Tihamat 'Asir Complex	Coleman and others, 1977
JT-26	Alkali picrite (contaminated), Jabal Akwah, Harrat al Birk	Coleman and others, 1977
JT-27	Alkali olivine basalt, Jabal Akwah, Harrat al Birk	Coleman and others, 1977
JT-35	Hawaiite, Jabal at Tirf, Tihamat 'Asir Complex	Coleman and others, 1977
JT-36	Alkali olivine basalt, Jabal at Tirf, Tihamat 'Asir Complex	Coleman and others, 1977
Volcanic rocks north of Ad Darb transform fault		
62066	Alkali olivine basalt, basal flow, Jabal Baqarah, Harrat al Birk	Coleman and others, 1977
62067	Hawaiite, upper flow, Jabal Baqarah, Harrat al Birk	Coleman and others, 1977
58375	Alkali olivine basalt, Jabal Haylah, Harrat al Birk	Coleman and others, 1977
58378	Alkali olivine basalt, Jabal Haylah, Harrat al Birk	Coleman and others, 1977
58377	Alkali olivine basalt, Jabal Haylah, Harrat al Birk	Coleman and others, 1977

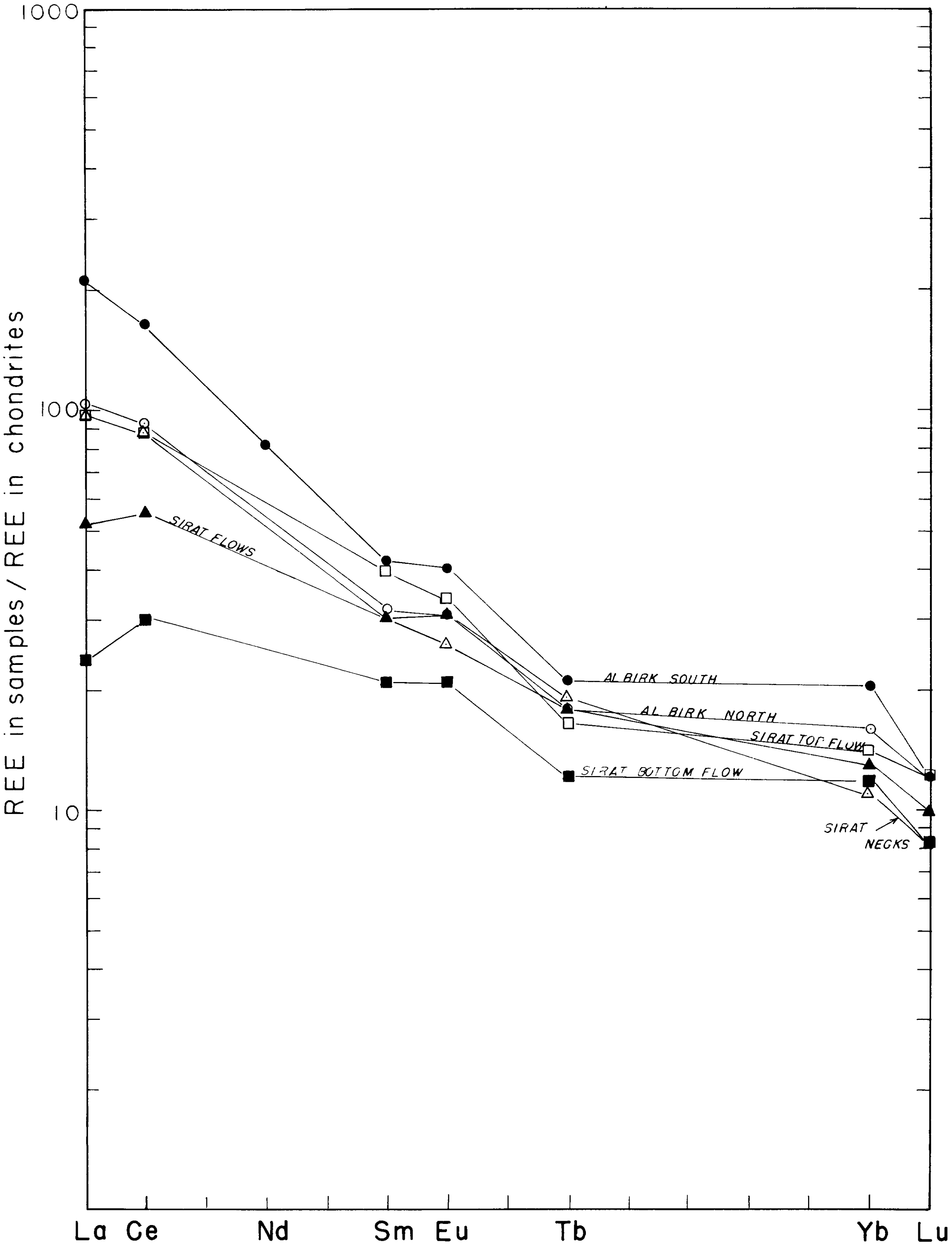

Figure 19.--Chondrite-normalized rare-earth-element (REE) patterns for volcanic rocks from Harrat as Sirat and Harrat al Birk.

Birk volcanic centers south of the Ad Darb transform fault imply that these rocks may be the most fractionated. Similar average light-REE contents of the Al Birk volcanic rocks both north and south of the Ad Darb transform fault indicate a similar fractionation pattern. Because the Al Birk lavas are mantle-nodule bearing, this fractionation probably occurred under mantle conditions. The light-REE data for the As Sirat flows also indicate crystal fractionation. The most primitive basalt flow at the base of the As Sirat field is the least-fractionated rock with the lowest light-REE content and perhaps this rock best represents the primary mantle magma. If a phase such as clinopyroxene is fractionated out of the liquids at high pressure, then the top flows of a lava sequence should show an increase in light-REE. The relatively high light-REE contents of both the top flows and the late trachyte plug of the As Sirat field support the hypothesis that there was differentiation of the As Sirat lavas as the field developed. Similar enrichment-patterns in the Al Birk lavas that contain mantle nodules suggest that the fractionation occurred under mantle conditions.

Stable isotope geochemistry

Stable-isotope analyses were performed on more than 60 mineral separates and whole rocks from Jabal at Tirf in the Tihamat 'Asir complex (Taylor, 1980). Samples from the three major units (layered gabbro, sheeted dikes, and granophyre) were analyzed. The stable-isotope data were obtained in order to characterize the hydrothermal solutions that interacted with the Tihamat 'Asir complex at the time of its formation.

The results, summarized in figures 20 and 21, are almost identical to those obtained for the Skaergaard intrusion and East Greenland coastal dike swarm (Taylor and Forester, 1979). The Jabal at Tirf $\delta^{18}O$ data indicate that isotopically light, meteoric water rather than seawater exchanged with the dike swarm, the granophyre, and the layered gabbro. These data support the inference that the Red Sea rift had not developed into an ocean basin filled with seawater at the time of Jabal at Tirf complex (early Miocene).

The mineral $\delta^{18}O$ data indicate the gabbro and the granophyre crystallized from distinct $\delta^{18}O$ reservoirs. The gabbros which have a primary whole-rock $\delta^{18}O$ value of about 6 are clearly mantle-derived. The granophyre, which appears to be somewhat younger than the gabbro, has quartz $\delta^{18}O$ values suggestive of remelted, hydrothermally altered lower crust. The oxygen data compliments $^{87}Sr/^{86}Sr$ data (Coleman and others, 1977) that show that the granophyre has more radiogenic strontium (0.7041 to 0.7057) than the gabbro

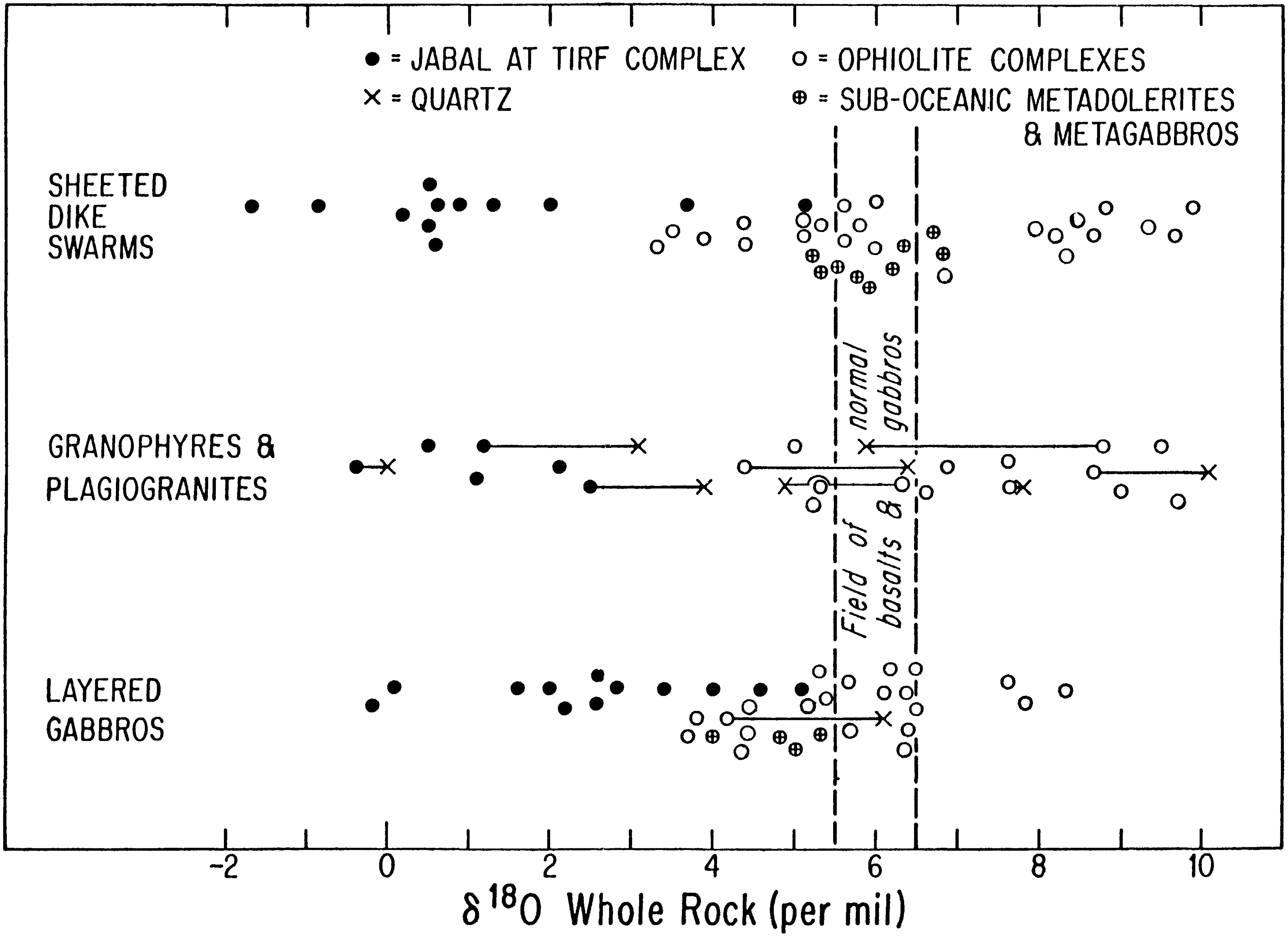

Figure 20.--Comparison of the stable-oxygen-isotope data from the Jabal at Tirf complex with data from ophiolite complexes, submarine basalts, and continental rift basalts. Data from Javoy (1970), Spooner and others (1974), Magaritz and Taylor (1974, 1976), Heaton and Sheppard (1977), Steinitz and others (1978), Taylor and Forester (1979), Taylor (1980), and Gregory and Taylor (1981).

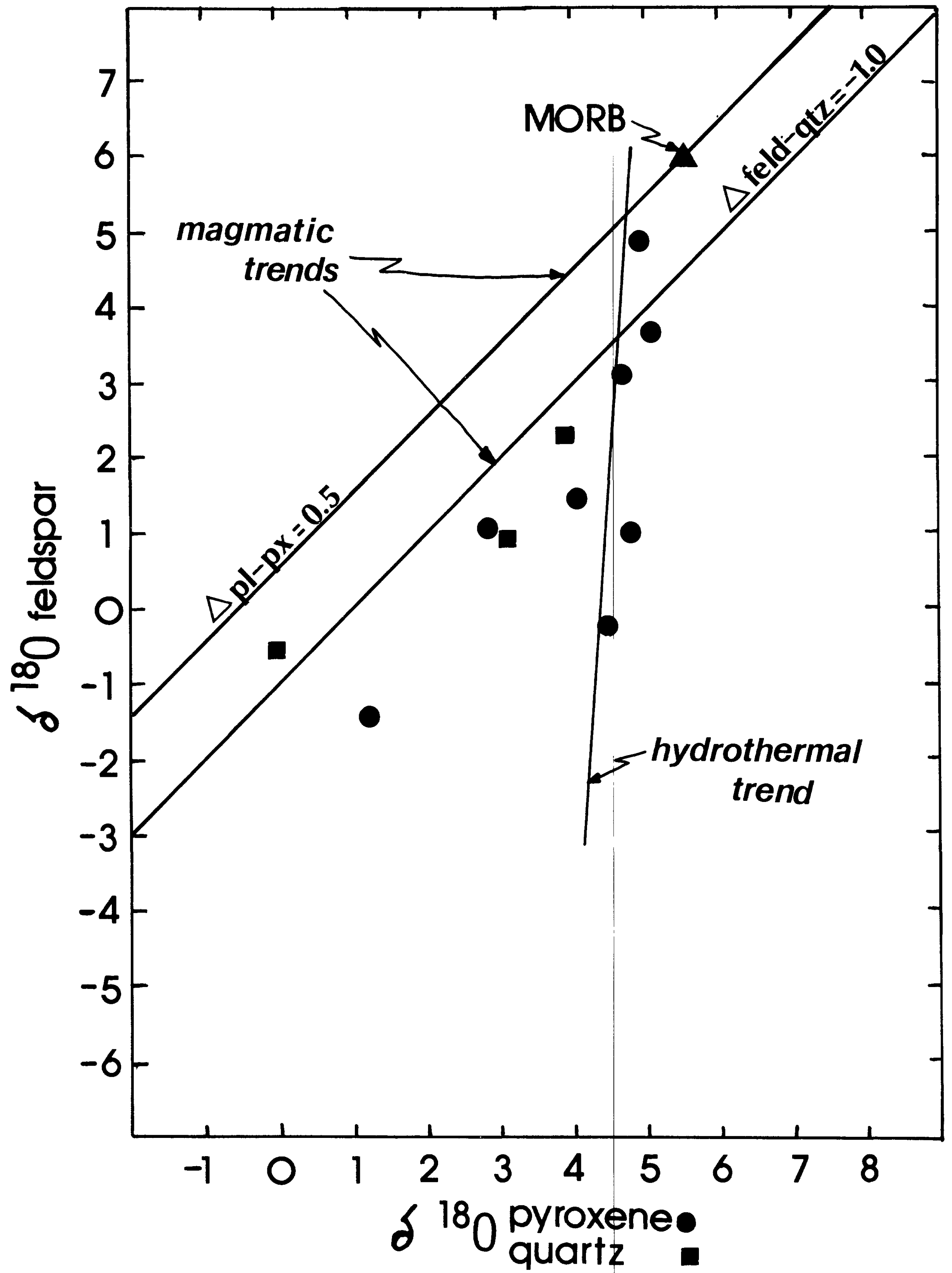

Figure 21.-- $\delta^{18}O$ feldspar versus $\delta^{18}O$ pyroxene or $\delta^{18}O$ quartz for the Jabal at Tirf complex. The layered gabbro plagioclase-pyroxene pairs exhibit a steep hydrothermal alteration trend and appear to have crystallized from a magma that may have been contaminated by interaction with hydrothermally altered crust. The granophyre mineral pairs have $\delta^{18}O$ values that suggest they originated from low $\delta^{18}O$ magmas. Data from Taylor (1980).

or diabase (0.7031 to 0.7036).

PETROGENESIS

The evolution of the basaltic rock of the harrats of Saudi Arabia appears to follow a general trend over geologic time. The late Oligocene and early Miocene extrusions are characterized by early outpourings of picrite-ankaramite lavas that have a very primitive composition. Repeated eruptions produced fractionated lavas of basanite and hawaiite, both of which commonly contain normative nepheline. The eruptions of middle Miocene to Holocene time follow similar trends of development except that fractionation produced more silica-rich varieties and primitive picrite-ankaramite is absent.

Existing experimental work on basaltic magma is sufficient to allow us to somwhat constrain hypotheses for the evolution of such magmas. The association of mantle xenoliths with alkalic basalt is typical throughout the world. The most common mantle xenolith is harzburgite (75 percent olivine, 25 percent orthopyroxene, and minor clinopyroxene and spinel). Therefore, it can be assumed that transport of these xenoliths in the basalt was rapid enough to preserve these original mantle asemblages. It is not clear, however, that these peridotite inclusions represent the depleted source that gave rise to the associated basalt. Earlier work by Ghent and others (1980) suggests that the Al Birk alkalic basalt could have been in equilibrium with the harzburgite at a temperature near 1250°C and a pressure near 19 kb.

Recent attempts to establish the nature of primary liquids by constructing pseudoliquidus phase diagrams have been partially successful in understanding the nature of primary magma and its origin in the mantle. In order to utilize this approach for the basalt of Saudi Arabia, two methods of projection have been used: 1) nepheline-forsterite-quartz plane of the basalt tetrahedron (fig. 22) and 2) the diopside-silica-olivine plane projected from plagioclase (fig. 23). Superimposed on the former diagram are the experimental data of Kushiro (1968) at 20 kb with the main field boundaries shown. A small amount of melting of a lherzolite at the 20 kb invariant point Fo-En-Ne will generate a basalt with normative nepheline. With decreasing pressure, this invariant point will migrate along the trace of the critical plane, and low-pressure melting will produce hypersthene-normative liquids. The lack of hydrous phases in the basalt indicates that H_2O was not an important component in the magma. The abundance of carbonate as a primary phase in some lavas indicates that the partial

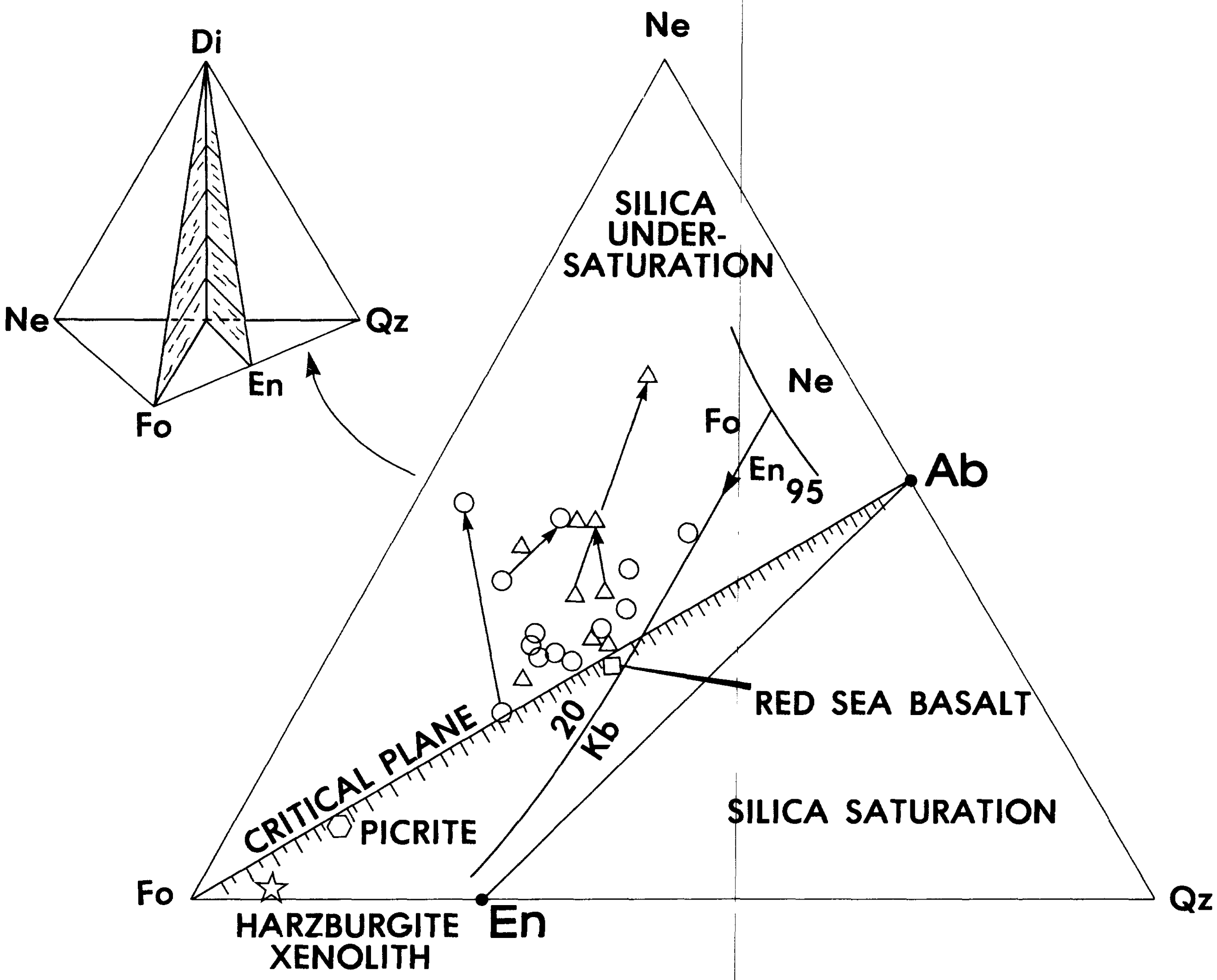

Figure 22.--Pseudoliquidus diagram in the system Fo-Ne-Di-Qz at 20 Kb. Fo-Ne-Qz represents the base of the basalt tetrahedron. 20 Kb high-pressure boundary after Kushiro (1968) and other parts of the diagram from Morse (1980). Open circles represent analyzed samples from Harrat al Birk and Harrat as Sirat, and triangles represent analyzed samples from the northern harrats. Tie lines connect bottom and top flows and show a progression away from the thermal divide during evolution of single volcanic areas. Star indicates composition of harzburgite xenolith associated with the lavas and the picrite plotted is typical for lavas of this composition.

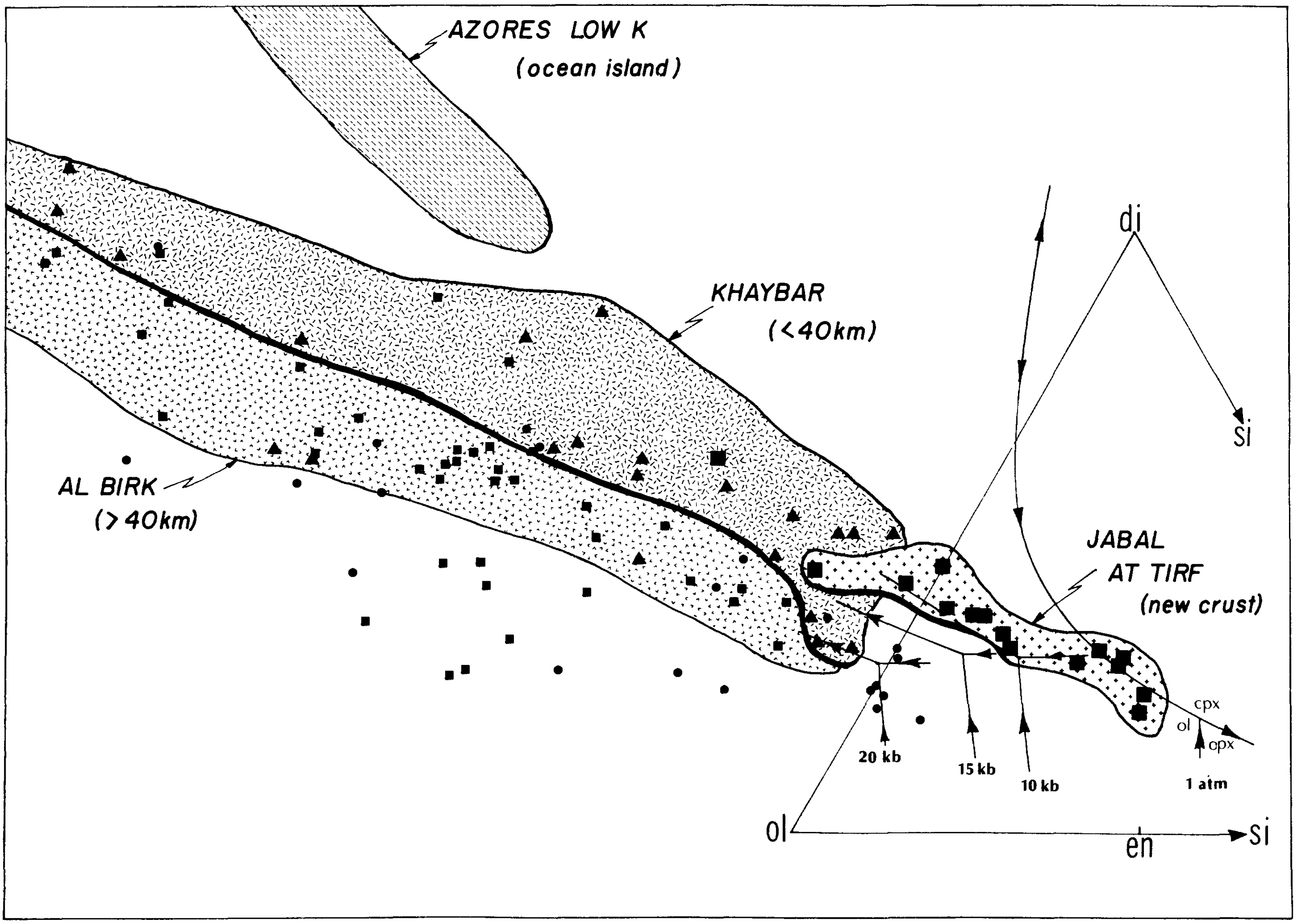

Figure 23.--Major element data for Cenozoic volcanic rocks of Saudi Arabia projected from plagioclase onto the diopside-olivine-silica surface after the method of Walker and others (1979). In this projection system, Ne normative rocks lie in the negative silica field. Shown are Harrat al Birk (small squares), Harrat Khaybar (triangles) and Jabal at Tirf dike swarm (large squares). All other Saudi Arabian volcanic rocks shown as dots. Mg-values of the Khaybar and Al Birk samples decrease away from silica, whereas Mg-values for Jabal at Tirf samples decrease towards silica. The separation of the data from the three areas suggests fractionation at different levels within the lithosphere (shown in parentheses). For comparison, low-K Azores basalts (ocean island, 20 km crust) are shown. Liquidus relationships are from the experimental work of Stolper (1980) and Walker and others (1979).

pressure of CO_2 may have been high, which in turn would shift the invariant point toward more nephelinitic compositions. As indicated by the arrows connecting bottom flows with top flows in each volcanic field shown on figure 22, the lavas appear to fractionate away from the silica saturation plane, and the most nepheline-normative compositions appear to be highly fractionated rocks rather than the minimum melts of a lherzolite mantle. Thus, in this system the natural rocks appear to be following a fractional crystallization trend rather than a trend due to migration of the invariant point as a function of pressure.

By utilizing the Walker projection method, major element analyses have been transformed into the diopside-plagioclase-silica-olivine system. Nepheline in this system lies in the minus-silica field and is not shown explicitly. This projection system expands the nepheline field of figure 22. Walker and others (1979) and Stolper (1980) have defined the approximate positions of the cotectic boundaries for tholeiitic systems. The most primitive basal picritic compositions of the harrats lie close to the olivine-clinopyroxene-enstatite point at 20 kb. With increasing fractionation presumably at pressures greater than 10kb, the lavas become more silica undersaturated. In contrast, the Jabal at Tirf diabase dikes move toward the silica corner with increasing fractionation similar to the trend followed by oceanic tholeiites. The fractionation trend of the Jabal at Tirf diabase dikes is consistent with low-pressure fractionation that probably occurred in magma chambers, now preserved as the layered gabbro bodies.

The fractionation trends in the harrats also have some internal structure, but these indicate a different history. Comparing the peridotite nodule-bearing Al Birk lavas with the nodule-free lavas of Harrat Khaybar shows that the fractionation trends are crudely parallel and separable. In the topology of figure 23, the Khaybar lavas appear to fractionate at lower pressure (<40km) than the Al Birk lavas. In order to check the sensitivity of the fractionation trends to changes in pressure, analyses of the Azores low-potassium series were plotted on the same diagram. The Azores alkali olivine basalts are indeed separable from the Saudi Arabian rocks. The Azores lavas that erupted through 20 km-thick oceanic crust appear to have fractionated at lower pressures than the Saudi Arabian lavas. The fanning of the fractionation or cotectic trends appears consistent with the extrapolation of the cotectics of Walker and others (1979) and Stolper (1980).

If we assume that analyzed basalts from Saudi Arabia are representative of primary or derivitive magmas, then the position on these diagrams (fig. 22 and fig. 23) should provide some clue as to the nature of the primary magma. Nearly all of the samples are nepheline-normative and therefore plot within the nepheline field. The most primitive basalts containing more than nine percent MgO plot on or near the critical plane, and those basalts that evolve to hawaiite move away from the critical plane and become more undersaturated in silica. As hypersthene is not present in any of the alkali basalts, it can be safely assumed that the magmas followed the undersaturated course of crystallization in the olivine-nepheline-diopside-plagioclase volume of the tetrahedron.

Both pseudoliquidus diagrams support the concept that the basalts probably originated at pressures greater than 20 kb and that in the harrats much of the magma fractionation took place at high pressure (>10kb). A deep seismic refraction profile in southern Saudi Arabia (Healey and others, 1979/1983) has shown that the Arabian continental crust is about 40 km thick. Thus, a comparison of Harrat Khaybar, Harrat al Birk, and the Azores (fig. 23) suggests that much of the fractionation of the harrat basalt has occurred under upper mantle-lower crustal conditions. The generation of the basalt at pressures in excess of 20 kb would indicate depths of more than 60 km (within the upper mantle). However, to provide the proper geotherm to initiate melting (19kb, 1250°C) as estimated by Ghent and others (1980), a marked increase in the normal Shield geotherms (at depths of 60 to 70 km, temperatures of 600° to 700° occur) would be required. The nodule geotherm that can be inferred from the data of Ghent and others (1980) is similar to that inferred by Baldridge (1979) for the Rio Grande rift. The nodule geotherm for the Rio Grande rift appears to be too low to explain the rift heat-flow data (Baldridge, 1979). In addition, because the nodule geotherm (Ghent and others, 1980) appears too low (by 200°C; see Stolper, 1980) to generate Saudi Arabian parental picrites, the depth of magma generation is uncertain. Thermal structure of the Arabian Plate is critical to this issue and deserves much more attention from geophysicists. The perturbations in heat flow of the mantle under the Arabian Plate are due to the establishment of a spreading center along the Red Sea axis and heat from this event would raise the temperature several hundred kilometers from the new ridge system.

The intermediate and silicic volcanic rocks associated with the large volume of basalt provide special insight into the evolution of the harrats. The volume of these rocks is extremely small, and where the full sequence of eruptions can be observed, these intermediate and silicic melts were produced in the late phases of eruptive cycles. They are important because they may indicate the presence of magma at shallow depths and therefore may indicate geothermal potential. These intermediate and silicic rocks (56-64 and greater than 69 percent SiO_2), when plotted on a standard Harker diagram (fig. 17), are separated from the basalt series and from each other by large compositional gaps. The phonolite and trachyte suite is separated from the basalt series by gaps in both SiO_2 (53-56 percent) and alkalies (7.5-10 percent), whereas the group of comendites area a distinct suite of rocks containing silica in excess of 69 percent and less total alkalies (less than 11 percent). A partial cause of the origin of the silicic suites may be fractionation of plagioclase and ferromagnesium minerals. Many of the hawaiites related to these silicic centers contain plagioclase megacrysts that may have fractionated from a basaltic magma. As shown earlier on the pseudoliquidus diagrams (figs. 22 and 23), the primitive basalt liquids tend to fractionate at high pressure toward a more nepheline normative magma, whereas at low pressure the lavas, depending upon their composition, may fractionate towards silica oversaturation. Baker and others (1973) have suggested that magma of phonolite-comendite association can be explained by the $NaAlSiO_4$-$KAlSiO_4$-SiO_2 system. Intermediate rocks that plot in the undersaturated field below the albite-orthoclase join could have been produced by fractionation of alkali feldspar, and fractionation of anorthoclae may result in the comendites. However, it has not been demonstrated whether low pressure fractionation of the harrat lavas can produce the comendites because the silica oversaturated lavas may be separated from the silica undersaturated rocks by a thermal divide (see fig. 5, Baker and others, 1973). The comendites may be the result of melting of the granitic crust by the basalt as it accummulated during the final stages of volcanism.

Theoretically the Tihamat 'Asir complex and the continental dikes could be derived from a tholeiitic magma similar to the tholeiites in the axial trough of the Red Sea and from a picritic magma similar to the parental magmas of the harrats. However, differentiation at low pressure has taken place during the formation of the complex and dikes. Field relationships indicate that the layered gabbros of the Tihamat 'Asir complex were emplaced at shallow depth (Coleman and others, 1977). The extensional system that developed during the initial Red Sea opening allowed intimate contact between the basaltic magma and the older Precambrian crust. Under these conditions, it is likely that silicic magma formed by melting of the preexisting crust (Hildreth, 1981) and that the magma was emplaced as dikes and granophyric sills. The distinct bimodal nature of the volcanic rock combined with a ratio of basalt to silicic rock of 3 to 1 strongly favors subcrustal melting of continental rock rather than fractionation of primary basalt magma to produce rhyolitic compositions.

In summary, it is reasonable to suggest that the entire suite of Cenozoic volcanic rocks were directly formed as a result of the Arabian Plate separating from Africa. During the early stages of lithospheric thinning, mantle convection broke the Arabian Plate and provided conduits for the early picritic eruptions. Magma that erupted through the continental lithosphere was predominantly silica-saturated to undersaturated picrite, whereas fractionated tholeiite flowed in the attenuated rift zones. Continued crustal thinning and dike invasion into the older continental crust caused the generation of silicic magma. Dikes, sills, and flows compose the early constructional material of the Red Sea crust. Farther inland, picrite parent magma evolved mainly by high pressure fractionation to alkali olivine basalt and hawaiite and, to a much lesser degree, to trachyte, phonolite, and comendite. The eruption of the undersaturated lava was so rapid that there was little or no melting of the thick Precambrian crust. The comendite of Jabal Abyad may represent a small portion of crustal melting; however, the origin of the comendite is unresolved. The larger volume of trachyte and phonolite may be the product of shallow or possibly deep-level fractionation of hawaiite magma.

This present eruptive cycle continues to the present time, and, as the Arabian Plate moves away from the African Plate, it is inevitable that volcanic activity will take place.

VOLCANIC HAZARDS

According to historical records eruptions have taken place in Saudi Arabia within the last 400 years; thus, it would be prudent to review the available information in detail to determine possible potential volcanic hazards. The possibility of future eruptions exists and scientific methods can be employed to forecast the location and time of these eruptions. Even though past eruptions in Saudi Arabia have not been of the explosive type, huge areas have been covered by lava flows. In some of these areas valuable agricultural land was undoubtedly lost because the lava tends to flow along soil-filled valleys (for example, Harrat Rahat).

The World Organization of Volcano Observatories has established a strategy that could be used for countries like Saudi Arabia where volcanic activity has occurred during historical times (Anonymous, 1981). Their recommendations are:

1. A country with a large number of active volcanoes should set priorities according to the hazard in each area.

2. Some major volcanic areas should be equipped with advanced observation systems based on continuously operating seismic recording stations.

3. Regional seismic monitoring could provide information needed to mobilize national or international observers who would monitor specific areas for short periods.

4. The efforts of geophysical institutions should be coordinated between countries to facilitate the economical observation of geophysical phenomena over large areas. Rapid transmission of information would permit appropriate action.

5. The history of active volcanoes within national areas (onshore and offshore) should be studied and events calculated on a statistical basis.

From our preliminary studies we recommend detailed study of the following areas of historical eruption. These are listed in a priority sequence (data from Simkin and others, 1981; see fig. 16).

1. Harrat Lunayyir - historic eruption 1000? A.D.

2. Harrat Ithnayn - historic eruption 1800? A.D.

3. Harrat Rahat near Al Madinah - Chada flow 1256 A.D.

4. Harrat Khaybar - historic eruption 650? A.D.

5. Harrat ar Rahah - historic eruption 500-650? A.D.

6. Jabal Yar near Abu Arish - historic eruption 1810? A.D.

We recommend a temporary seismic network of three stations (short-period vertical seismometers linked by radiotelemetry and recording) in these six areas for periods of as long as 6 months. This project should also include a modest trilateration (geodometer) network and a few levelling lines to permit the establishment of benchmarks and initial baseline measurements.

Historical records should be studied in detail to ascertain at least the historic eruptive pattern. Detailed geologic mapping and petrologic studies should be concentrated near Holocene flows to improve the knowledge of prehistoric activity.

Employment of Saudi Arabian graduate geology students to do the geologic and geophysical studies would provide a cadre of nationals capable of pursuing a volcano hazards program.

GROUND-WATER POTENTIAL

A systematic study should be made of the harrats of Saudi Arabia in order to establish their potential for ground water. Some early works have been successful, but there still remains a need for considerable evaluation. Many of the harrats occupy former drainage systems and act as barriers along these systems. The best example is the area between Harrat Rahat, Harrat al Kishb, and Harrat Hadan where north-flowing streams have been effectively dammed and the interior basin of Sahl Rakbah has formed. Considerable ground water may be present where former wadis are now covered by basalt flows. Geologic studies designed to delineate these drainages under the harrats that surround Sahl Rakbah should be followed by a modest drilling program.

Buried flows of the east dipping Harrat Hadan may act as barriers to ground-water flow. Shallow drilling on the eastern flanks of the harrat where these flows are covered by recent alluvium may provide a source of ground water.

The western flanks of Harrat Rahat should be studied to ascertain the presence of aquifers beneath the lava flows.

Numerous craters within the more recent eruptive centers (for example, Harrat Kishb, Jabal Abyad, Harrat Hutaymah and Harrat ash Shamah) may act as reservoirs of substantial ground water. Geophysical studies of the larger craters to establish the presence and level of the water table should preceed drilling.

Surface-water runoff from some volcanic fields represents a possible source of water. The probability is particularly high for Harrat Rahat where enormous areas receive substantial seasonal rainfall. A systematic series of small dams on the west side of the harrat in steep-walled canyons would provide show recharge to the west-flowing wadis and storage for irrigation water to be used on the coastal plain between Yanbu and Jiddah.

Future studies of the ground-water potential of the Cenozoic volcanic fields should concentrate on the discovery of aquifiers, first by geologic and geophysical studies and later by drilling.

GEOTHERMAL POTENTIAL

A resource assessment of the geothermal potential in Saudi Arabia should be an estimate of the amount, kind, and cost of thermal energy that can be extracted from the crust. Muffler and Guffanti (1979) have categorized the various possible sources of geothermal energy: (a) regional conductive environments, (b) igneous-related geothermal systems, (c) hydrothermal convection systems, and (d) geopressured-geothermal systems.

The volcanic rocks of Saudi Arabia may have important igneous-related geothermal systems; however, it is necessary to establish the proper criteria to pinpoint those areas that may have potential. Shallow silicic-magma chambers are generally thought to be the best sites for igneous-related geothermal systems and that any system older than 20 Ma can be considered extinct (Smith and Shaw, 1979).

The factors used to establish the geothermal potential of a shallow silicic-magma chamber are the age and volume of the last eruption with which the potential thermal energy in the system can be calculated. Hydrothermal cooling of igneous systems is an important aspect that needs to be evaluated because extremely efficient hydrothermal cooling could deplete the heat source in approximately 360,000 years (Smith and Shaw, 1979).

From our preliminary data it would appear that Jabal Abyad in Harrat Khaybar is probably the best target as a possible geothermal system related to igneous geothermal systems. All other areas of historic eruptions should be evaluated for the presence of shallow magma chambers. Older fields that contain dissected silicic centers should be studied in order to determine whether hydrothermal systems were operating. Harrat ar Rahah is a prime target because more than a kilometer of vertical section is exposed in the retreating escarpment under the harrat. Studies of the underlying sandstone (similar to that underlying Harrat Khaybar) could serve as an analog area to Harrat Khaybar.

The hydrothermal convective systems that are of most interest in Saudi Arabia are beneath the coastal plain of the Red Sea where the regonal heat flow is considerably above average. Exploratory oil-well drilling along the Red Sea shoreline has encountered extremely high heat flow at moderate depths and there is hot spring activity at Jabal at Tirf and in the Al Lith area. Thus there may be significant convective reservoir systems having temperatures above 90°C at depths of less than 3 km. Estimates need to be made on the amount of thermal energy available within a specified volume of rock and water in areas of promise.

Techniques evolved by the U.S. Geological Survey (Muffler and Guffanti, 1979) are available to make realistic estimates of geothermal energy in Saudi Arabia; the areas of highest potential are the silicic volcanic centers and the coastal plain.

SUMMARY AND RECOMMENDATIONS

This study of the Cenozoic volcanic rocks of Saudi Arabia has provided new insight regarding their evolution. The distribution of the individual volcanic fields reveals more than just a single structural control for localizing the eruptions. It is clear, however, that the localization is related in space and time to the evolution of the Red Sea. The oldest lavas appear to have been produced during crustal thinning or extension that was initiated during the late Oligocene epoch. The presence of fossiliferous marine sediment as well as terrestrial fanglomerate deposits beneath the basal flows has led us to the conclusion that a basin-range type of topography existed in the northern part of Saudi Arabia prior to the main volcanic eruptions. These structures may have connected with the Mediterranean basin and produced gulfs as far south as Jiddah. In the southern part of the Red Sea area, the early lithospheric thinning formed a single large northwest-trending basin that accummulated siliceous, lacustrine sediment and bimodal pyroclastic and subaqueous volcanic rock. The presence of mammalian fossils (Madden, C. T., and others, 1983) indicates that this basin was similar to those that are present today in eastern Africa. The dikes and conical layered gabbro bodies within the southern part of the Red Sea basin were mainly quartz-normative, tholeiitic magma derived by fractionation from mafic tholeiitic magma. The abundance of rhyolite dikes and sills within the Tihamat 'Asir complex and the absence of rock of intermediate composition indicate that the rhyolite was derived by melting of subcrustal continental rock by the ascending tholeiitic magma that formed the layered gabbro bodies and basaltic dike swarms.

The basaltic rocks of the harrats seem to follow general and repetitive eruptive trends, and a crude stratigraphic sequence appears to apply to most of the harrats from Yemen to Jordan. The basal rock is commonly picritic to ankaramitic basalt overlain by alkali olivine basalts that locally contain peridotite nodules. Diktytaxitic basalt that contains cotectic mineral assemblages overlies this more primitive rock. The final stage of eruptive history is generally represented by mugearite containing plagioclase. Minor but important bodies of silicic rock are associated with this sequence of eruption. The trachyte, phonolite, and comendite are believed to be differentiation products of hawaiite in high-level magma chambers, or they may be partly mobilized and melted Precambrian crust.

Petrologic relationships in the early mafic lava indicate that it may have formed by partial melting at temperatures and pressures suggestive of a depth greater than 60 km beneath the Arabian Plate. Melting at depths near 60 km is too shallow for normal subcontinental geothermal gradients and movement away from Africa has enhanced the heat flow under Arabia that caused the production of these lavas.

Volcanic eruptions began in the late Oligocene epoch, dikes were emplaced parallel to the present Red Sea in a discontinuous swarm from Yemen to the Sinai peninsula, and layered gabbro bodies and sheeted sills formed in local magmatic centers. This phase was completed by early Miocene time when left-lateral motion commenced along the Dead Sea Rift and the Arabian Plate rotated slightly counterclockwise away from the African Plate. Later volcanic eruptions were localized along northerly trends. Continuous sea-floor spreading was established in the axial trough of the Red Sea in early Pliocene time and continues to the present. Historical records show that eruptions have taken place in Saudi Arabia since the end of the Bronze age and as late as 1810 A.D. at Jabal Yar near Abu Arish.

The Cenozoic volcanic rocks of Saudi Arabia merit further attention both on scientific and on economic grounds. In particular, volcanic hazards, ground water resources, and geothermal resources have not been adequately evaluated. Because there is no systematic record of recent volcanic activity, a review of the evidence (including a search of Arabic historical records) should be made and a volcanic hazards program should be developed.

Because silicic volcanic centers in many instances have significant geothermal potential, young silicic volcanic centers in Saudi Arabia should be studied to determine their potential as sources of geothermal energy. Stable-isotope studies are expected to define the petrologic history of silicic magmas and the extent of meteoric-water involvement in magma generation. In addition, studies of older dissected volcanic fields such as Harrat ar Rahah might serve as analogs to the younger, more active fields such as Harrat Khaybar and Harrat Rahat. Perhaps more promising are the coastal areas where the continental crust has been thinned and extended. In these areas, particularly to the south, thermal waters are known to exist. Heat flow measurements along the coastal plain and on the harrats would be useful in locating potential geothermal areas. The harrats are capable of storing vast amounts of ground-water, some having been tapped since ancient time. However, the impact of modern pumping techniques on the discharge of these ground-water systems has not been evaluated. Continued geologic mapping and studies of ground water potential are necessary to define and develop these water resources. Thus a program of long term monitoring of the hydrologic system should be implemented in order to manage this most valuable resource.

DATA STORAGE

No entries or updates have been made to the Mineral Occurrence Documentation System (MODS) data bank. Chemical analyses have been stored in base data file USGS-DF-02-6.

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