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POST-OROGENIC PERALKALINE AND CALC-ALKALINE GRANITES AND ASSOCIATED MINERALIZATION OF THE ARABIAN SHIELD, KINGDOM OF SAUDI ARABIA

by

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U. S. GEOLOGICAL SURVEY

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ABSTRACT

Following a long period of island arc-like orogenic activity, post-orogenic granites of Pan-African age (670-550 m.y.) were emplaced throughout the Arabian Shield. Most of these rocks are typical subsolvus calc-alkaline biotite monzogranite. The early Pan-African granites are associated with widespread small tholeiitic gabbro intrusions, many of which are layered. The calc-alkaline granites are not evenly distributed and their area of exposure relative to other rock types increases from southwest to north and northeast. In the northeastern part of the shield, they are associated spatially with rhyolites of similar composition and with molasse derived from granitic terrane.

The occurrence of 45 late alkali granites, most of which are peralkaline, is described and their chemistry discussed. Most of these rocks are medium- to coarse-grained hypersolvus alkali granites, but phenocrystalline and micrographic varieties are also common. The mafic silicate minerals of the alkali granites are arfvedsonite, aegirine, aegirine-augite, riebeckite, and sparse biotite, aenigmatite, and barkevikite. The alkali granites do not occur in the southwestern third of the Arabian Shield nor in the southeastern portion of the adjacent Nubian Shield of Africa. A syenite-shonkinite province located in the southwestern part of the Arabian Shield is identified.

No economic mineral deposits are known to be associated with the Pan-African granites. Numerous mineral occurrences and geochemical anomalies have been found that contain tungsten, molybdenum, tin, beryllium, zirconium, niobium, thorium, uranium, rare earths, and fluorite. The most important of these occurrences are tabulated and their distribution shown.

INTRODUCTION

This report is a result of one of a series of studies by the United States Geological Survey (USGS) made in accordance with a work agreement with the Ministry of Petroleum and

Mineral Resources, Kingdom of Saudi Arabia. Among the projects of the Directorate General of Mineral Resources (DGMR) five-year plan is a study of the petrogenesis and mineral potential of the granitic rocks of the Arabian Shield. The Acid Plutonic Rock Project involves two DGMR geologists and the two authors, members of the USGS Saudi Arabian Mission. Stoeser's primary concern is the petrology of the rocks and Elliott's their economic geology. This paper is our first contribution to the geology of the Arabian Shield granites.

The Arabian Shield is the eastern half of the Arabian-Nubian Shield, which was exposed by early to middle Tertiary uplift and ensuing erosion and split into two segments by the Red Sea rift (Coleman and others, 1977). The Arabian portion of the shield occupies an area of approximately 770,000 km^2 and is composed of approximately 40 percent granitoid plutonic rocks (quartz diorite and tonalite to granite), and most of the remainder is volcanic and sedimentary rocks, many of which have been metamorphosed to the greenschist facies (Brown and Jackson, 1960; Greenwood and Brown, 1973; Greenwood and others, 1976). The rocks of the Arabian Shield appear to be late Proterozoic in age (Fleck and others, 1976 and 1979; Baubron and others, 1976). Their history can be divided into two main periods, an early island arc-like orogenic phase (960-700 m.y. (million years)) succeeded by a post-orogenic period (Pan-African, 670-550 m.y.) during which massive amounts of granite were emplaced throughout most of the shield (Brown and Jackson, 1960; Greenwood and others, 1976; Delfour, 1977). It is the purpose of this paper to describe briefly the general geologic setting, distribution, characteristics, and economic geology of the post-orogenic granites, with emphasis on the peralkaline rocks.

The primary method of plutonic rock classification used is the IUGS system (Streckeisen, 1975). In addition, the following modifying terms for granites are used: alkaline, alkali, peralkaline, and metaluminous. Alkaline (or alkalic) granite is used as a general chemical term for a granite that contains more alkali metals than is considered average for the group of rocks to which it belongs. An alkali granite is one containing soda pyroxene and/or amphibole (Sørensen, 1974). A peralkaline granite is one in which molecular $Al_2O_3 < (Na_2O + K_2O)$ (Carmichael and others, 1974). A metaluminous granite, however, has $Al_2O_3 < (CaO + Na_2O + K_2O)$ but $Al_2O_3 > (Na_2O + K_2O)$ (Carmichael and others, 1974). Common granites are metaluminous. As used in this paper, a shonkinite is a mafic syenite whose essential mineralogy is potassium feldspar plus augite and whose composition is more than half mafic silicates (pyroxene, amphibole, olivine, and biotite).

ANALYTICAL METHODS

Nineteen chemical analyses are presented in this paper of which ten are new and nine are taken from the literature. The ten new analyses were performed by Skyline Labs, Inc. of Wheat Ridge, Colorado, USA. The following were determined by atomic absorption: SiO_2, Al_2O_3, MgO, CaO, Na_2O, K_2O, and Li. TiO_2 and P_2O_5 were determined by colorimetry (TiO_2 using TIRON and P_2O_5 by the vanadate-molybdate procedure). P_2O_5 was below the limit of detection (0.2 percent) for all ten samples and therefore no values for this oxide appear in table 2. Strontium and rubidium were done by flame emission spectroscopy and fluorine by the specific ion electrode method using an ammonium citrate solution after fusion in sodium hydroxide. Total volatiles were detected by loss on ignition (L.O.I.) at 1000°C for two hours.

EVOLUTION OF THE SHIELD

The evolution of the southern shield has been documented by Greenwood and others (1976) and by Fleck and others (1976, 1978, 1979), and the northern part of the shield has been described by Baubron and others (1976) and Delfour (1977). The geologic history of the Arabian Shield can be divided into two main periods. The first and longer period (1165-680 m.y.) is dominantly orogenic and was characterized by calc-alkaline intermediate volcanic and plutonic rocks and associated clastic sediments. The second period (680-550 m.y.), was dominantly non-orogenic and characterized by silicic volcanics, granites, and arkosic molasse deposits. The volcanic, sedimentary, and plutonic rocks of the first period appear to be typical of those found in subduction-related Late Phanerozoic island arcs. Based on this relationship, first realized about 1975-1976, a number of subduction models for the evolution of the Arabian-Nubian Shield were put forth (Greenwood and others, 1976; Bakor and others, 1976; Garson and Shalaby, 1976; Neary and others, 1976; Frisch and Al-Shanti, 1977).

Studies of the southern shield indicate that the oldest known rocks of the Arabian Shield are the Baish metabasalt greenstones and overlying Bahah metagraywackes, which are cut by 900 m.y. plutons and may be as old as 1165 m.y. (Greenwood and others, 1976; Fleck and others, 1979). To the east and intercalated(?) with the Baish-Bahah belt is a broad belt of andesitic and dacitic metavolcanic rocks and lesser amounts of metasedimentary rocks, the Jiddah group, which is about the same age as the Baish-Bahah, or somewhat younger (Greenwood and others, 1976).

The layered rocks of the Baish, Bahah, and Jiddah groups have been intruded by a belt of tonalitic calc-alkaline batholiths that stretches along the western side of the shield from the Yemen border to north of the city of Jiddah. Greenwood and others (1976) report that these rocks were emplaced during two main episodes. Their "first dioritic series" (960 m.y.) had an early phase of gabbro, diorite, and quartz diorite that was followed by more voluminous and more leucocratic biotite-hornblende tonalite (fig. 1). This first episode of tonalitic plutonism was followed by orogeny and a "second episode of tonalitic plutonism" (800-680 m.y.), which included tonalite and trondhjemite. The tonalites of the second series are similar to those of the first series, but appear to be spread over most of the Arabian Shield (Greenwood and others, 1976; Baubron and others, 1976; Schmidt and others, in press). During the later part of the second episode, granodiorite was emplaced largely as syntectonic gneiss domes throughout at least the southern half of the shield (Nebert, 1970; Fleck and others, 1978; Schmidt and others, in press; Cooper and others, in press). In the northern half of the shield during this time massive amounts of intermediate volcanics and associated clastic sediments, the Halaban (Hulayfah) group were deposited (Greenwood and others, 1976; Baubron and others, 1976, Delfour, 1977).

After the end of the long orogenic episode at about 700-680 m.y., plutonism shifted from intermediate composition to acidic such that massive amounts of calc-alkaline monzogranite accompanied by minor gabbroic magma were emplaced throughout the shield (Fleck and others, 1976, 1979; Baubron and others, 1976). These granites were generally emplaced as simple circular or ovoid plutons, although some were ring structured (Dodge, in press, 1979). In the following 80 to 100 million years the shift in magma composition from calc-alkaline to alkaline granite was pervasive. In the northern shield these granitic magmas also appear to be represented by the Murdama and Shammar group rhyolitic intrusives (Delfour, 1977; Schmidt and others, in press). The Murdama group, although containing acidic flows, is dominantly composed of clastic sediments that apparently are a molasse derived from this granitic terrane (Schmidt and others, in press). In the southern shield the Murdama and Shammar are lacking possibly due to a greater depth of erosion.

One outstanding question presently being debated is whether the late Proterozoic rocks of the Arabian Shield are underlain by an older evolved crystalline basement. At present there is no good evidence to support this idea. For the southern shield the lack of older dates, low initial Sr^{87}/Sr^{86} ratios of 0.702 to 0.704 (Fleck and others, 1979), and lack of old granites suggest no contamination by, or partial melting of, an underlying older evolved crust, and thus indicate that no such basement exists. For the northern part of the shield, however, the question of an older basement is more debatable.

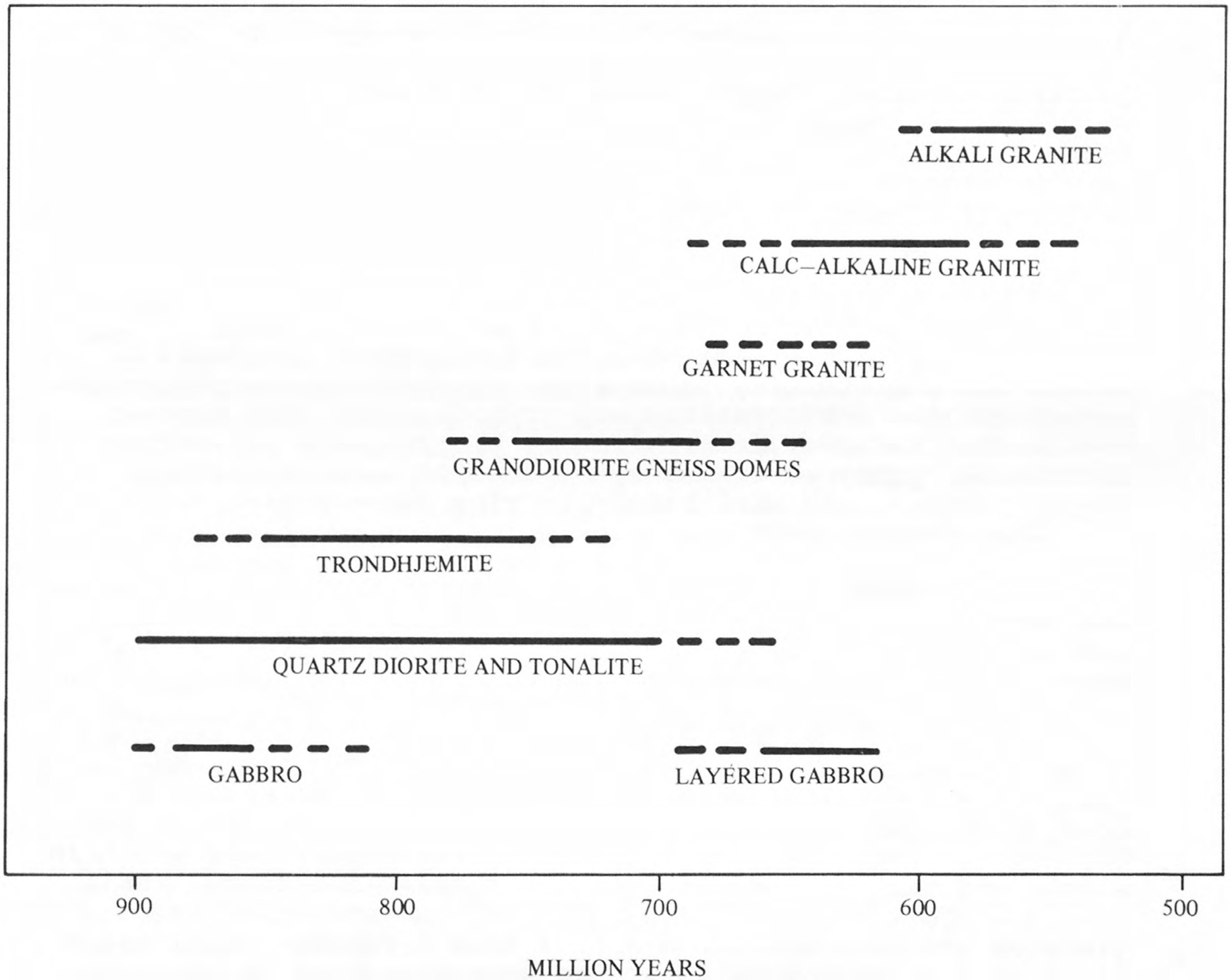

Figure 1. Plutonic rock geochronology of the Arabian Shield. Data from Coleman and others (1972), Baubron and others (1976), Fleck and others (1976 and 1979), and Cooper and others (in press).

Although no dates that would provide direct evidence for an older evolved crust are available, six granites dated by Baubron and others (1976) using the Sr/Rb method have initial Sr^{87}/Sr^{86} ratios in the range 0.704 to 0.7122. The higher of these ratios clearly suggest that evolved crustal material was involved in the formation of these granites. Fundamentally, the question awaits more and definitive isotopic studies.

PETROGRAPHY

The bulk of the calc-alkaline granites of the Arabian Shield are pink to gray, subsolvus, equigranular to porphyritic, medium-grained monzogranites and granodiorites that contain 1-8 percent mafic silicates, mostly biotite with or without hornblende. They occur mainly as oval to somewhat irregularly shaped plutons, and more rarely as ring dikes having calc-alkaline granite or country rock cores (for example, Dodge, in press, 1979). No attempt will be made here to synthesize the considerable data already available on this group of rocks; for further information the reader is referred to Greenwood and Brown, 1973; Nasseef and Gass, 1977; Delfour, 1977; and Kanaan, 1979.

Less common members of the calc-alkaline group are rapakivi granites, alaskites with or without garnet, and 'big-feldspar' porphyroblastic monzogranites. The garnet-bearing alaskites are volumetrically insignificant but appear to be distributed throughout at least the central and southern shield and are reported from Egypt as well (Schurmann, 1966). They are typically medium-grained, have xenomorphic inequigranular texture, and contain less than 5 percent total garnet, biotite, and muscovite. What are interpreted to be potassium-metasomatized monzogranites, containing porphyroblasts as large as 5-10 cm, are concentrated mainly in the southern shield. Insufficient data are presently available on the Arabian rapakivi granites to describe them accurately.

In addition to the calc-alkaline granites, post-orogenic gabbros occur throughout most of the Arabian Shield but are distinctly concentrated in the south-central shield (Coleman and others, 1972). The best criterion for field recognition is the presence of olivine and pyroxene, both of which have been destroyed in the older gabbros through metamorphism. Many of these late gabbros are layered, and the layering appears to be due to repeated infusions of magma rather than to crystal settling (Shanti, 1974; Coleman and others, 1977). The composition of the parental magma of these gabbros appears to have been olivine tholeiitic. Coleman and others (1972, 1977) give K/Ar dates on these gabbros that fall in the range 415-769 m.y., many of them around 630 m.y. In the southern shield, we have found these gabbros in intrusive complexes with the older calc-alkaline granites but never with the younger alkaline granites. In general it seems unlikely that these gabbros could be any younger than about 550 m.y. because neither they nor the granites have been observed to intrude the basal Cambro-Ordovician cover rocks.

The alkali granites of the Arabian Shield are mainly gray, pink, or red, medium- to coarse-grained, hypersolvus alkali granites. In the field, they can often be distinguished by their dark red to almost black weathered surface and their tendency to weather to very large, smooth, rounded blocks. Seen in thin section, they consist of alkali feldspar that has exsolved to a patch perthite, 20-30 percent quartz and 5-15 percent late interstitial sodic mafic silicates, which include aegirine, aegirine-augite, arfvedsonite, and, less commonly, aenigmatite, barkevikite, and acmite. A reddish-brown biotite is also present in some samples. Deep-blue, very pleochroic riebeckite(?) is present in many samples, usually as a secondary amphibole replacing the primary sodic pyroxene or amphibole. Most of the peralkaline granites are more mafic than the calc-alkaline granites. Accessory minerals are magnetite, allanite, zircon, fluorite, and, in several samples, brick-red elpidite ($Na_2ZrSi_6O_{15}.H_2O$). Plagioclase is usually present only as secondary albite, partially replacing the primary alkali feldspar. The alkali feldspar of the red granites is typically turbid and clouded by very fine dark inclusions (hematite?).

In the northeastern part of the shield, the alkali granites are commonly associated with pink to red granophyric granites. These granophyric granites typically consist of 10-50 percent phenocrysts of alkali feldspar and less quartz in a micrographic groundmass. Mafic minerals are usually extensively altered or completely destroyed. The alkali granites and granophyres are generally closely associated with rhyolitic volcanics of the Shammar group, which typically are also porphyritic and have phenocrysts of alkali feldspar and quartz (Delfour, 1977).

DISTRIBUTION

Arabian Shield

On the bais of the distribution of the calc-alkaline and alkali granites, the Arabian Shield is here divided into three regions (fig. 2). From the southwest to northeast these are the Asir, Hijaz-Najd, and Hail-ad Dawadimi regions. The post-orogenic granites as a whole are not homogeneously distributed over the shield. They are least abundant in the Asir region and increase in areal extent to the northeast. Small-scale

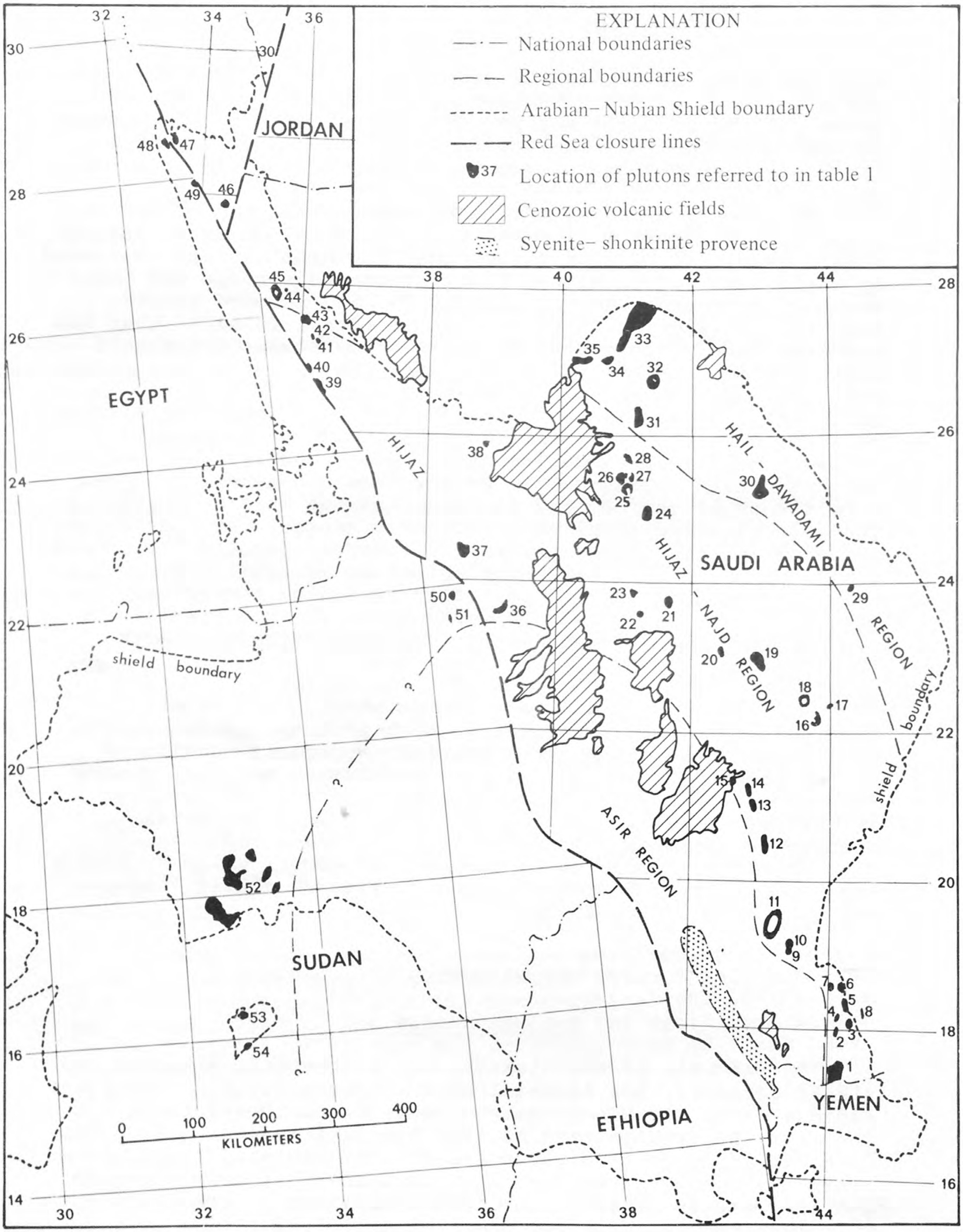

Figure 2. Pre- Red Sea rift palinspastic map of the Arabian- Nubian Shield showing the location and distribution of alkali granite plutons.

maps and LANDSAT imagery covering the northeastern portion of the Arabian Shield reveal that there granites are the dominant rock type.

The Asir and Hijaz-Najd regions are separated by the alkali-granite line, which is defined by the distribution of alkali granites in the Arabian Shield. A literature search combined with the authors' own work produced the location of 45 Saudi Arabian alkali granites. One noticeable aspect of their distribution is that it is not homogeneous and that an alkali-granite line can be drawn through the shield south and west of which no such granites have been reported.

The boundary between the Hijaz-Najd and Hail-ad Dawadimi regions is based on relative amounts of granite. The increase in area of exposed granite from the central shield to the northeast is not gradational but is sharply demarcated. This demarcation is the dividing line between our Hijaz-Najd and Hail-ad Dawadimi regions.

Calc-alkaline granites are least abundant in the Asir region, and in the southwestern Asir they are very sparse. Interestingly, it is here that recent mapping has revealed a linear shonkinite-alkali syenite province (fig. 2). Coleman (1973b) and Ratte (1974) reported a pluton, a plug, and several dikes of shonkinite in the Abha area in the southern part of the Asir region. Further to the northwest is the Lakathah ring complex, which consists of a core of layered mafic and ultramafic rocks and a thick outer ring of alkali syenite (Martin and others, 1979). Greenwood (in press) also reports several small syenite plugs just to the east of the Lakathah complex. Current mapping in the southern end of the Asir region in the Jizan area by G. M. Fairer (personal commun., 1978) has revealed several major plutons and dikes of shonkinite, mafic-rich quartz-poor alkali granite, and related rocks. No detailed petrography or chemical analysis of these rocks is available as yet.

The Hijaz-Najd and Hail-ad Dawadimi regions are distinguised from the Asir region not only by the occurrence of alkali-granites but by the presence of the Shammar and Murdama groups. The Hijaz-Najd region also contains the broad northwest-trending, latest Proterozoic Najd fault zone (Fleck and others, 1976, 1979), which extends throughout most of the region approximately parallel to our regional boundaries. The boundary between the Hijaz-Najd and Hail-Ad Dawadimi regions also appears to coincide with the northern limit of the Najd fault zone.

In our work to date, which has been mainly on granites in the southern and northeastern portions of the shield, we have come to accept as a general rule that the calc-alkaline granites are older and give way temporally to alkaline and peralkaline granites. These later plutons are generally simple ovoid masses that cut all major rock types and that are rarely cut by dikes or directly associated with other igneous rock types. A few are more complex and some are ring complexes (table 1). Two of these complexes, the Jabal al Hassir and Jabal Aja granites, should provide much information on the evolution of the late post-orogenic granites when they are more thoroughly studied.

The Jabal al Hassir ring complex (loc. 11, fig. 2, table 1) is a north-trending, nearly perfect oval with axial dimensions of 17 by 35 km. It consists of an outer ring of coarse, hypersolvus, peralkaline granite (analysis 5, table 2) more than a kilometer thick, and a complex core of medium-grained, leucocratic, biotite monzongranite and granodiorite. Separating the two main units is a partial ring dike of quartz porphyry whose phenocrysts are set in a fine-grained groundmass. Large, angular, xenolithic blocks of unaltered country rock are abundant in both the core and rim granites, and in the southern half of the core unit they are more voluminous than the granitic matrix itself; one block is more than 5 km long. The Al Hassir complex probably represents a subvolcanic caldera complex, in which both calc-alkaline and peralkaline granitic magmas were emplaced. It is presently being studied in detail by Stoeser. The Jabal al Kursh, Jabal Hadeb, and Jabal Dibbagh ring complexes (locs. 18, 22, and 45, table 1) are all similar to the Al Hassir complex in that they all consist of peralkaline granite rims and metaluminous granite cores.

The Jabal Aja granite complex (loc. 33, fig. 2, table 1) is a huge, somewhat dumb-bell shaped pluton about 80 km long. The complex consists of four main units: (1) on the east and north, a thick partial outer ring of coarse, greenish-gray, peralkaline granite (analysis 11, table 2); (2) a complex core of pink to red granophyric granite (analysis 15, table 2); (3) a xenolithic block or intrusion more than 5 km long of a green, probably comenditic (peralkaline) rhyolite and granite porphyry; and (4) a partial cap of red porphyritic rhyolite (analysis 18, table 2). In addition, the core and rim contain large xenolithic blocks, as much as several kilometers in diameter, of country rock and pink (cogenetic?) granophyric granite. On one steep wadi wall 150 m high, the granophyre decreases in grain size upwards and is capped by three flow(?) units of rhyolite. The Jabal Aja complex, then, apparently comprises a subvolcanic caldera complex. It is presently under detailed study by the authors.

Table 1.--*Locality names, reported rock types, and references to Arabian-Nubian alkali granite plutons*

Locality number	Locality name	Rock type	References
1	unnamed	biot.-arf-rieb. gr.	this paper
2	unnamed	biot.-arf. gr.	Greenwood, in press
3	J. Ashirah ring complex	biot.-arf.-rieb. gr.	-do-
4	unnamed	-do-	-do-
5	unnamed	-do-	-do-
6	Wadi Idimah ring complex	-do-	-do-
7	unnamed	biot.-arf. gr.	-do-
8	unnamed	rieb. granophyre	-do-
9	unnamed	aeg.-rieb. gr.	this paper
10	unnamed	biot.-arf. gr.	-do-
11	J. al Hassir ring complex	-do-*	-do-
12	J. Taweel	aen.-rieb.-acmite gr.*	Schmidt, in prep.
13	unnamed	arf.-rieb. gr.	R.C. Greene, personal commun., 1978
14	unnamed	-do-	-do-
15	unnamed	-do-	-do-
16	J. Dahul	bark. gr.	Brosset, 1975
17	J. Salamah	-do-	-do-
18	J. Kursh ring complex	bark, gr.	-do-
19	unnamed	bark.-biot. gr.	Letalenet and Bounny, 1977
20	J. Safway	aeg.-rieb.-biot. gr.	-do-
21	J. Hasla	biot.-aeg. gr.	Conraux, 1969
22	J. Hadeb ring complex	aeg.-rieb. gr.	Conraux, 1969, Radain, 1978
23	J. Sayid	-do-	-do-
24	J. Bidayah	aeg. gr.*	Delfour, 1977
25	J. Tuwalah	aeg.-rieb. gr.*	-do-
26	Ar Raqab	aeg.-arf. gr.	-do-
27	An Namar	rieb. gr.*	-do-
28	J. Awja	-do-	-do-
29	unnamed	arf.(?) gr.	Bois and Shanti, 1971
30	J. Aban al Ahmar	arf. gr.	Aguttes, 1971

Table 1.--*Locality names, reported rock types, and references to Arabian-Nubian alkali granite plutons* (continued)

Locality number	Locality name	Rock type	References
31	J. al Qunnawat	aeg.-arf. gr.	this paper
32	J. ar Rumman	-do-	-do-
33	J. Aja	aeg.-arf.-aen. gr.*	this paper
34	J. al Raud	aeg.-arf. gr.	-do-
35	Bidat Nathil	biot.-aeg., arf., rieb. gr.	-do-
36	J. Subh	rieb. gr.	V. Skiba, personal commun., 1978
37	J. Radwah	aeg. gr.	Petot, 1976
38	J. Lyaynat al Badan	rieb. gr.	Hadley, 1974
39	unnamed	soda-amphibole gr.	J. Kemp, personal commun., 1978
40	unnamed	-do-	-do-
41	unnamed	-do-	-do-
42	unnamed	-do-	-do-
43	unnamed ring dike	rieb. microgranite	-do-
44	al Ghurayyah	rieb.-albite gr.	Lalande, 1977
45	J. Dibbagh	aeg.-arf. gr.*	Harris, 1978
46	unnamed	rieb. gr.	Schurmann, 1966
47	Gebel Merzeqa	-do-	-do-
48	Gebel Gharib	-do-	-do-
49	Ras Zeit	-do-	-do-
50	J. Shendib	granophyric hastingsite gr.	Neary and others, 1976
51	Karam Arit	granophyric rieb. gr.	-do-
52	Bayuda Desert complex	aeg.-arf.-rieb. gr.	Almond and others, 1977
53	Sabaloka complex	soda-amphibole microgr.	Almond, 1977
54	Sileitat es Sufr	rieb. gr.	Vail, 1976

The following abbreviations are used: J.-Jabal, aeg.-aegirine or aegirine augite, aen.-aenigmatite, arf.-arfvedsonite, bark.-barkevikite, biot.-biotite, gr.-granite, microgr.-microgranite, rieb.-riebeckite. An asterisk (*) after a rock name indicates that an analysis for that rock is presented in table 2.

Two basic interpretations of the distribution of granite for the Arabian Shield are (1) that the shield is more deeply eroded in the south so that previously existing high crustal-level granites and effusives still present in the north have been removed, or (2) that post-orogenic granites were more voluminous in the northeastern shield. The distribution of rhyolites of the Shammar group strongly suggests that depth of erosion is greater to the south. These rocks are voluminous to the northeast and in a number of places even cap granitic complexes, such as at Jabal Aja, indicating about a kilometer or less of erosion. To the south, the volume of Shammar volcanic rocks gradually decreases and in the southern third of the shield they are absent altogether, even though the same types of granites occur there. Furthermore, whereas in the northeastern area, contacts of granites often dip outward, in the south they are very steep and typically dip inwards and thus suggest a greater depth of erosion.

Even assuming the above interpretation is correct, no great depth of erosion of the post-orogenic (Pan-African) crust in the south is apparent. It seems unlikely that the present level of exposure of the Al Hassir represents a depth of erosion of more than several kilometers. Coleman and others (1977) have estimated a depth of erosion of about 1.2 km for the Jabal Shayi gabbro, which lies about 70 km southwest of Jabal al Hassir. Dodge (in press, 1979) has estimated approximately 3 km of erosion on the calc-alkaline Uyaijah ring structure in the east central shield.

In the Asir region relief on the Red Sea escarpment is more than 2 km, so that exposures near sea level may indicate a minimum depth of erosion of at least 3 to 5 km in the crust. Even given this depth of erosion, the granite exposed in the Asir region is insufficient to suggest that it is an eroded high portion of the crust containing as much granite as that observed in the north. Thus the distribution pattern of granites in the Arabian Shield probably reflects emplacement of a greater volume of Pan-African granite in the north and northeastern than in the southern shield. In addition most of the layered rocks in this region have been metamorphosed only to the greenschist facies, which suggests that significant amounts of granite did not pass through them.

Nubian Shield

We have extended the alkali granite line into the Nubian part of the Arabian-Nubian Shield (fig. 2). We found no reports of peralkaline granites east of this line either in

Table 2.--*Major and minor element analyses for*

ANALYSIS NO.	1	2	3	4	5	6	7	8	9
SAMPLE NO.	112765	112361	112326	79G-JCB91 2/	112522	83248A 3/	86E-LC442 2/	86A-LC443 2/	78H-JCB123 2/
LATITUDE	19°24.8'	18°54.4'	19°12.2'	25°44'20"	19°37.2'	20°46.8'	25°07'55"	25°26'15"	25°31'40"
LONGITUDE	43°20.6'	43°43.4'	43°11.4'	41°34'40"	43°05.2'	42°55.9'	41°09'40"	41°04'05"	40°58'10"
LOCALITY	NE ¼ Duthur as Salam quad.	Jabal Lahu	Jabal Duthur as Salam	Jabal ar Rahadah	Jabal al Hassir, rim	Jabal Taweel	Jabal Bidayah	Jabal Tuwalah	Jabal Tuwalah
ROCK TYPE	late biotite syenogranite	late biotite monzogranite	leuco. biotite monzogranite	biotite monzogranite	aenig. biotite arfved. peralk. granite	aenigmatite acmite peralk. granite	aegirine alkali granite	aegirine alkali granite	riebeckite alkali granite
<u>Major</u>									
SiO_2	67.6	74.0	75.0	77.00	75.1	74.26	73.60	76.10	75.20
TiO_2	0.48	0.25	0.31	0.10	0.41	0.42	0.43	0.19	.19
Al_2O_3	14.5	13.0	11.9	11.75	11.1	11.20	12.40	10.80	11.20
Fe_2O_3	1.1	0.39	1.0	1.03	0 94	5.28	1.55	2.15	1.40
FeO	2.6	0.64	0.52	0.15	2.0	4/	0.90	1.10	1.15
MnO	----	----	----	0.03	----	0.02	0.10	0.03	0.04
MgO	0.19	0.22	0.18	0.05	0.14	0.10	0.40	0.15	0.10
CaO	1.3	1.1	0.63	0.52	0.74	0.65	0.85	0.45	0.42
Na_2O	5.0	4.3	4.2	4.10	4.0	4.80	4.80	4.40	4.60
K_2O	5.9	4.7	4.4	4.66	4.8	5.15	4.30	4.30	4.24
P_2O_5	----	----	----	0.01	----	----	0.06	0.05	0.02
CO_2	----	----	----	0.04	----	----	0.11	0.05	0.08
SO_3	----	----	----	0.03	----	----	----	----	0.01
F	0.057	0.086	0.057	----	0.092	----	----	----	----
H_2O^+	----	----	----	0.36	----	----	0.30	0.25	0.34
H_2O^-	----	----	----	0.00	----	----	0.15	0.20	0.03
L.O.I. 1/	0.34	0.41	0.44	----	0.21	----	----	----	----
TOTAL	99.07	99.10	98.64	99.83	99.53	101.88	99.95	100.22	99.02
<u>Minor</u>									
Rb	144	346	182	189 5/	118	----	104 6/	179 7/	----
Sr	42	162	51	20 5/	51	----	54 6/	12 7/	----
Li	20	10	40	----	20	----	----	----	----
<u>CIPW Norms</u>									
Q	13.44	29.18	32.82	34.52	32.29	27.29	27.35	33.75	32.58
C									
OR	35.19	28.03	26.36	27.58	28.50	29.87	25.46	25.41	25.30
AB	42.13	36.72	36.03	34.55	30.52	28.40	39.92	31.61	34.34
AN		2.31	0.63						
TH				0.05					0.02
AC	0.51				3.08	5.40	0.68	3.38	2.69
NS						1.24		0.41	0.43
WO	2.53	1.06	0.87	0.95	1.26	1.32	1.31	0.66	0.67
EN	0.48	0.55	0.45	0.13	0.35	0.24	1.00	0.37	0.25
FS	2.60	0.50	0.83	0.94	2.79	5.45	1.83	3.56	2.78
MT	1.71	0.54	0.81	0.61			0.94		
IL	0.92	0.48	0.60	0.19	0.78	0.78	0.82	0.36	0.36
AP				0.02			0.14	0.12	0.05
FR	0.12	0.19	0.13		0.19				
CC				0.09			0.25	0.11	0.18
TOTAL	99.63	99.56	99.53	99.63	99.76	99.99	99.70	99.74	99.65
SALIC	90.76	96.24	95.84	96.70	91.31	85.56	92.73	90.77	92.24
FEMIC	8.87	3.32	3.69	2.93	8.45	14.43	6.97	8.97	7.41
AGPAITIC RATIO	1.01	0.94	0.98	1.00	1.06	1.20	1.01	1.10	1.09

1/ loss on ignition (L.O.I.) values equal originally reported L.O.I. values minus the fluorine values above

2/ from Delfour, 1977

3/ from Schmidt, in prep.

4/ all Fe reported as Fe_2O_3

5/ average of 9 samples from Baubron and others, 1976

10 79E-JD3924 2/ 25°35'20" 41°04'20" an Namar riebeckite alkali granite	11 112991 27°20.8' 41°26.1' Jabal Aja rim granite aenigmatite, aegirine arfved. peralk. granite	12 124017 27°54'55" 35°44'38" J. Dibbagh rim granite aeg. arfved. peralk. granite	13 78G-JD3985 2/ 25°43'00" 40°33'20" 2 km SE of Suhur granophyric rhyolite	14 78D-JD3955 2/ 25°48'45" 40°49'25" 6 km SW of Bir al Biday granophyre	15 112981 27°20.9' 41°24.6' Jabal Aja core granite medium-grained biot. alkali granite	16 112914 25°48.4' 41°54.4' Nuqrah quad. Shammar plagioclase porphyritic rhyolite	17 79E-JD3919 2/ 25°39'40" 41°07'10" Jabal al Malhah Shammar porphyritic alkali rhyolite	18 112975 27°22.0' 41°22.3' Jabal Aja cap rhyolite alkali-feld. quartz porphyritic rhyolite	19 128032 27°09.9' 42°14.5' Jabal Selma cap rhyolite feldspar porphyritic rhyolite
73.40	77.2	76.4	66.80	68.60	78.9	71.4	72.20	77.4	77.0
0.25	.42	0.31	0.68	0.45	0.27	0.54	0.26	0.29	0.25
11.30	9.4	11.0	13.80	15.05	10.6	13.4	13.35	10.4	11.7
1.75	2.4	1.6	2.75	1.35	1.3	1.8	1.60	1.2	0.72
1.75	1.4	1.2	2.45	1.85	0.39	0.60	1.00	0.26	0.39
0.09			0.11	0.06		----	0.07	----	----
0.35	0.027	0.032	0.90	0.90	0.080	0.39	0.50	0.051	0.13
0.80	0.35	0.27	2.40	1.30	0.36	1.0	1.00	0.38	0.55
4.50	4.4	4.2	4.15	4.50	3.6	5.5	4.35	3.5	3.8
4.85	4.5	4.6	3.95	4.10	4.5	3.6	4.90	4.4	5.0
0.03	----	----	0.19	0.14	----	----	0 05	----	----
----	----	----	----	----	----	----	----	----	----
0.10	----	----	0.075	0.055	----	----	0.03	----	----
----	0.17	0.12	----	----	0.21	0.11	----	0.18	0.12
0.45	----	----	1.55	1.20	----	----	0.80	----	----
0.10	----	----	0.10	0.05	----	----	0.00	----	----
----	<0.1	<0.1	----	----	0.39	0.59	----	0.42	0.48
99.72	100.27	99.73	99.91	99.61	100.60	98.93	100.11	98.48	100.14
----	200	155	----	----	264	118	----	391	255
----	34	34	----	----	34	114	----	34	42
----	90	60	----	----	30	20	----	20	30
28.31	38.83	34.51	20.99	22.38	39.97	23.58	25.06	40.33	34.84
				1.26					
28.77	26.51	27.24	23.39	24.34	26.43	21.50	28.92	26.40	29.51
31.24	23.22	31.04	34.66	37.85	29.29	47.04	36.57	29.45	32.11
			7.65	5.56		1.26	2.53		0.10
0.18			0.14	0.11			0.05		
3.66	3.95	2.93			0.87			0.55	
0.51	2.19	0.29							
1.58	0.21	0.19	1.27		0.10	1.23	0.88	0.24	0.73
0.87	0.07	0.08	2.25	2.25	0.20	0.98	1.24	0.13	0.32
3.88	3.76	2.78	3.66	2.19	1.28	1.24	1.97	0.96	0.56
			2.72	1.68	0.44	1.26	1.36	0.50	0.58
0.48	0.80	0.59	1.29	0.86	0.51	1.04	0.49	0.56	0.47
0.07			0.45	0.33			0.12		
	0.35	0.25			0.43	0.23		0.38	0.25
99.55	99.89	99.90	98.47	98.81	99.52	99.36	99.19	99.50	99.47
88.50	88.56	92.79	86.83	91.50	95.69	93.38	93.13	96.18	96.56
11.05	11.33	7.11	11.64	7.31	3.83	5.98	6.06	3.32	2.91
1.12	1.29	1.09	0.81	0.79	1.02	0.97	0.93	1.01	1.00

6/ average of 13 samples from Baubron and others, 1976

7/ average of 11 samples from Baubron and others, 1976 southeastern Sudan or in Ethiopia. Although our search of literature on the Nubian shield was limited, it is clear that a late Proterozoic (Pan-African) peralkaline granite province extends over much of the Arabian-Nubian shield and is possibly the largest such province in the world.

Several differences between the Arabian and Nubian shield segments became apparent from our literature search. The first relates to the distribution of syenites in the two areas. In Sudan, many of the post-orogenic granites are closely associated with minor gabbroic and over- and undersaturated syenitic rocks, and more than half of the ring complexes, including those of the coastal region north of Port Sudan, contain syenite (Vail, 1976; Neary and others, 1976). Except in the syenite-shonkinite province of the Asir regions, syenites are rare in the Arabian Shield, including the coastal area north of Jiddah, which would match the area north of Port Sudan. A second difference is that many intrusions of Paleozoic and Mesozoic age are reported from Sudan and Egypt, and even Tertiary granitic intrusions have been recognized in Egypt (Vail, 1976; Neary and others, 1976; El Ramly and others, 1969a, 1969b). Radiometric age determinations have not revealed, so far, any such young rocks in the Arabian Shield although only a few determinations have been made for rocks in the Hijaz region. Intrusions cutting the basal Cambrian and Ordovician sedimentary rocks east of the Red Sea are known from only two localities, the Ar Raha dacites just north of Harrat ar Raha (Villemur and others, in press) and quartz porphyry dikes of about 560 m.y. in Jordan (Lenz and others, 1972).

AGE

The original definition by Kennedy (1964) of the Pan-African Thermo-Tectonic Episode was applied to events of about 500 m.y. age in central Africa. Since then, common usage has expanded the Pan-African episode to cover the approximate range 500-650 m.y. Using the potassium-argon dating method, Fleck and others (1976) show that the Arabian Shield was subjected to a major thermal event between 560 and 610 m.y. and to a minor one between 510 and 540 m.y. Dates for these thermal events are close to that assigned to the Pan-African by Kennedy. The net result of the thermal episodes was that the potassium-argon systematics were disturbed throughout the Arabian Shield, thus rendering the method of little use in dating the older rocks.

Considerable rubidium/strontium dating has now been done, and a clear picture of the emplacement dates of the post-tectonic metaluminous calc-alkaline granites has emerged.

For granites of the southern shield, Fleck and others (1979) have obtained ages mainly in the range 600-650 m.y. Zircon age determinations on post-tectonic granites and gabbros of the southernmost shield indicate that they were emplaced around 660-670 m.y. (Cooper and others, in press; Stacey and Stoeser, work in progress). For metaluminous granites of the north-central and eastern shield, Baubron and others (1976) have determined somewhat younger rubidium/strontium ages, in the range 552-638 m.y., and Nasseef and Gass (1977) report 525 m.y. and 592 m.y. respectively for two metaluminous granites from the At Taif area east of Mecca. It remains to be seen whether the apparent progressive decrease northward in the ages of the post-tectonic granites is real or is merely an artifact of the data.

Baubron and others (1976) give two rubidium/strontium age determinations for peralkaline granites: Jabal Bidayeh, 571 ± 8 m.y. (initial $^{87}Sr/^{86}Sr$ = 0.7055 ± 0.0006) and Jabal at Tuwalah, 600 ± 24 m.y. (initial $^{87}Sr/^{86}Sr$ = 0.7041 ± 0.0006) (locs. 24 and 25, fig. 2; analyses 7-9, table 2). Given these data plus the field relationships of the late alkaline and peralkaline granites that indicate that they are the last major plutonic phase of the Arabian Shield, we tentatively assume that these granites were largely emplaced during the period 550-620 m.y. If this assumption is correct, then emplacement of the peralkaline granites and the major Pan-African thermal event found by Fleck and others (1976) were broadly contemporaneous.

CHEMISTRY

Table 2 presents a number of new analyses as well as selected analyses from the literature for Arabian Shield granites and rhyolites. Most of these analyses are of alkaline-granitic rocks of the shield. Chemically a rock is defined as peralkaline if the agpaitic ratio (molecular $(Na_2O + K_2O)/Al_2O_3$) is greater than one (Carmichael and others, 1974). For the Arabian rocks a maximum ratio of 1.29 was found (table 2). The ratio is sensitive to errors in the analysis, and the presence of soda-mafic silicates such as aegirine or arfvedsonite in the rock generally confirms their peralkalinity. Rocks with ratios slightly greater than one in table 2 should not be taken as necessarily peralkaline unless the presence of such minerals is indicated in the table.

The calc-alkaline granites of the Arabian Shield appear to be the end products of 300 million years of calc-alkaline evolution (Fleck and others, 1979). Figure 3 is a standard AMF triangular diagram that illustrates that the plutonic and volcanic rocks of the west and central parts of the shield

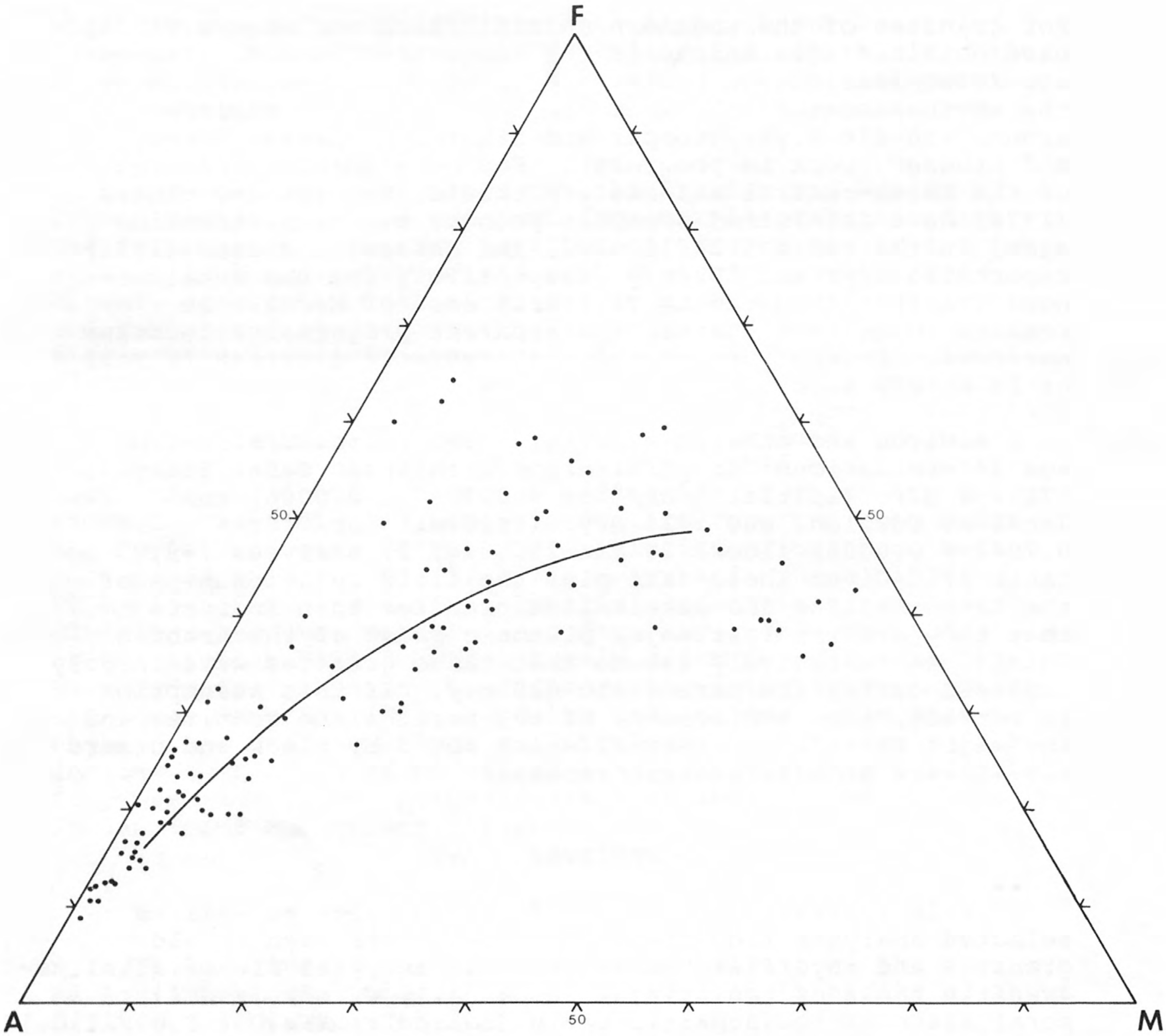

Figure 3. AMF triangular diagram for plutonic and volcanic rocks of the Arabian Shield. A = $Na_2O + K_2O$, M = MgO, and F = $FeO + Fe_2O_3$. Data from R.J. Fleck (unpublished data), F.C.W. Dodge (unpublished data), Nasseef and Gass (1977), Delfour (1977), and Kanaan (1979). The curve is the average trend line for the Sierra Nevada batholith (Carmichael and others, 1974).

have a typical calc-alkaline trend (Carmichael and others, 1974). Several new analyses of alkalic metaluminous granites are given in table 2 (anal. 1-4). For detailed descriptions of the chemistry of the calc-alkaline granites the reader is referred to Delfour (1977), Nasseef and Gass (1977), Kanaan (1979), and Dodge (1979). Various plots using available major element analyses show that a continuum appears to exist between the calc-alkaline and peralkaline granites (figs. 4, 5). In the field, it is usually possible to distinguish the two classes of granites by means of a total count scintillometer (Geometrics C_1R-101A, 43.1 cm^3 NaI crystal) because the calc-alkaline granites typically produce 60 to 150 counts per second, whereas the peralkaline granites typically produce 150 to 350 counts per second.

The peralkaline granites of the Arabian Shield are typical of such granites elsewhere and are very similar to the classic suite of the Jos Plateau of Nigeria (Jacobsen and others, 1958). The Arabian peralkaline granites have total alkali contents similar to those of the calc-alkaline granites, but are relatively low in alumina (thus leading to the peralkalinity) as well as in magnesia and strontium and are enriched in iron (table 2, figs. 4, 5).

As noted earlier, many of the alkaline and peralkaline granites are closely associated with rhyolites of the Shammar group. Based on their chemistry, the rhyolites do not appear, however, to be effusive equivalents of the peralkaline granites because, although some of them are alkaline, they generally are not peralkaline and appear to be transitional in composition between the calc-alkaline and peralkaline granites (table 2, fig. 5). Nevertheless, because of the possibility of post-eruptive changes in the composition of the rhyolites, particularly loss of alkalis, which generally occurs for oversaturated peralkaline volcanics during crystallization or glass hydration (Noble, 1968; Macdonald and Bailey, 1973), a firm conclusion on the relationship of the Shammar rhyolites to the late post-tectonic granites must await more field and analytical data. The close spatial relationship of the peralkaline granites, pink and red granophyres, and Shammar rhyolites, however, strongly suggests a genetic link.

One characteristic of many of the late post-tectonic granites is their red, often brick-red, color. Taylor (1978) finds that this color is typical of many granites from Precambrian terranes, and that such rocks also show a strong enrichment in O^{18}. Taylor also has observed that these granites typically contain feldspars rendered turbid by hematitic dust; primary mafic minerals altered to uralitic amphibole, chlorite, Fe-Ti oxides, and epidote; and local

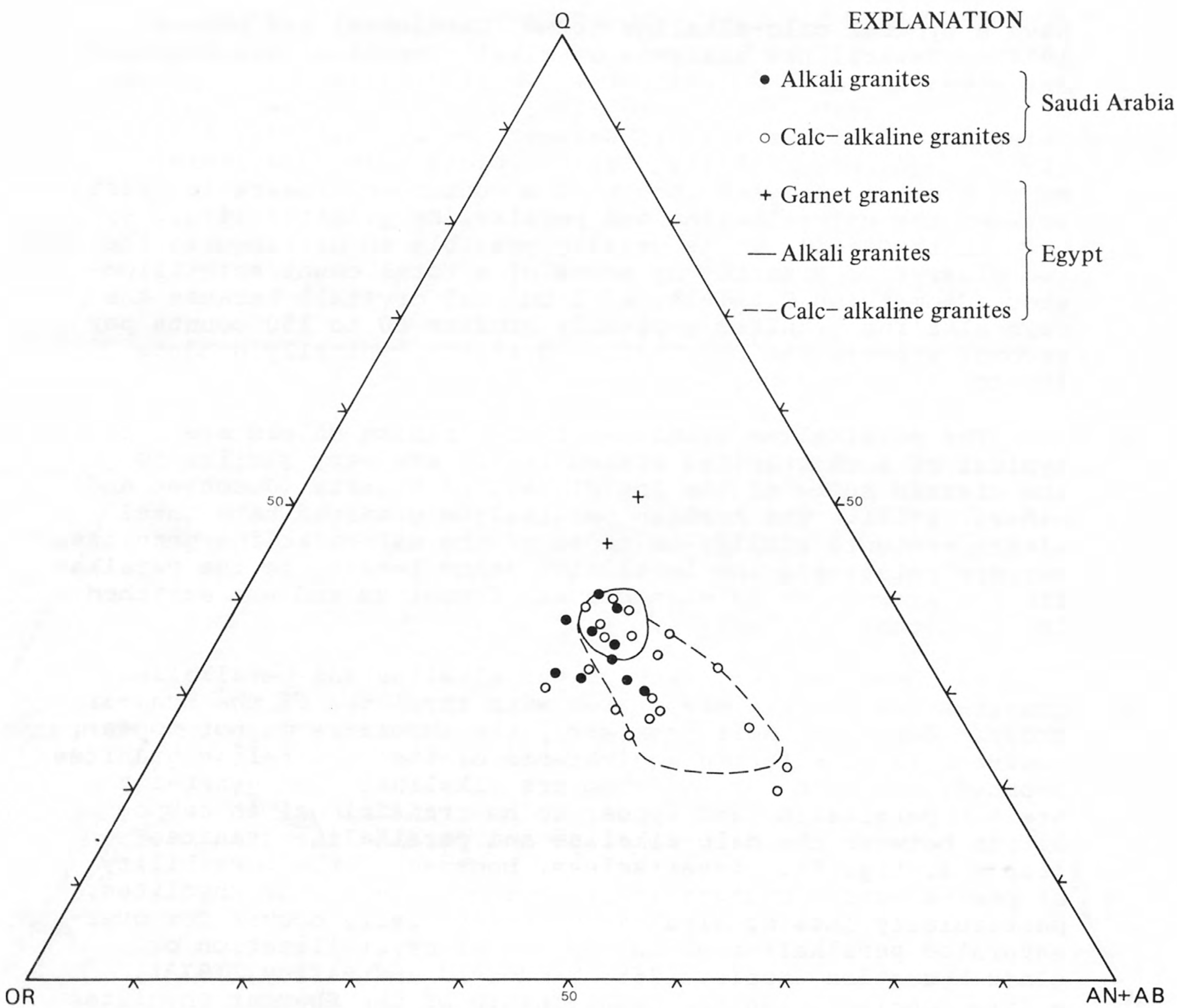

Figure 4. Normative quartz (Q)–orthoclase (OR)–plagioclase (AN+AB) triangular diagram for Saudi Arabian and Egyptian granites (Schurmann, 1966). Diagram includes data from Delfour (1977), Greenwood and Brown (1973), and Schmidt and others (in press).

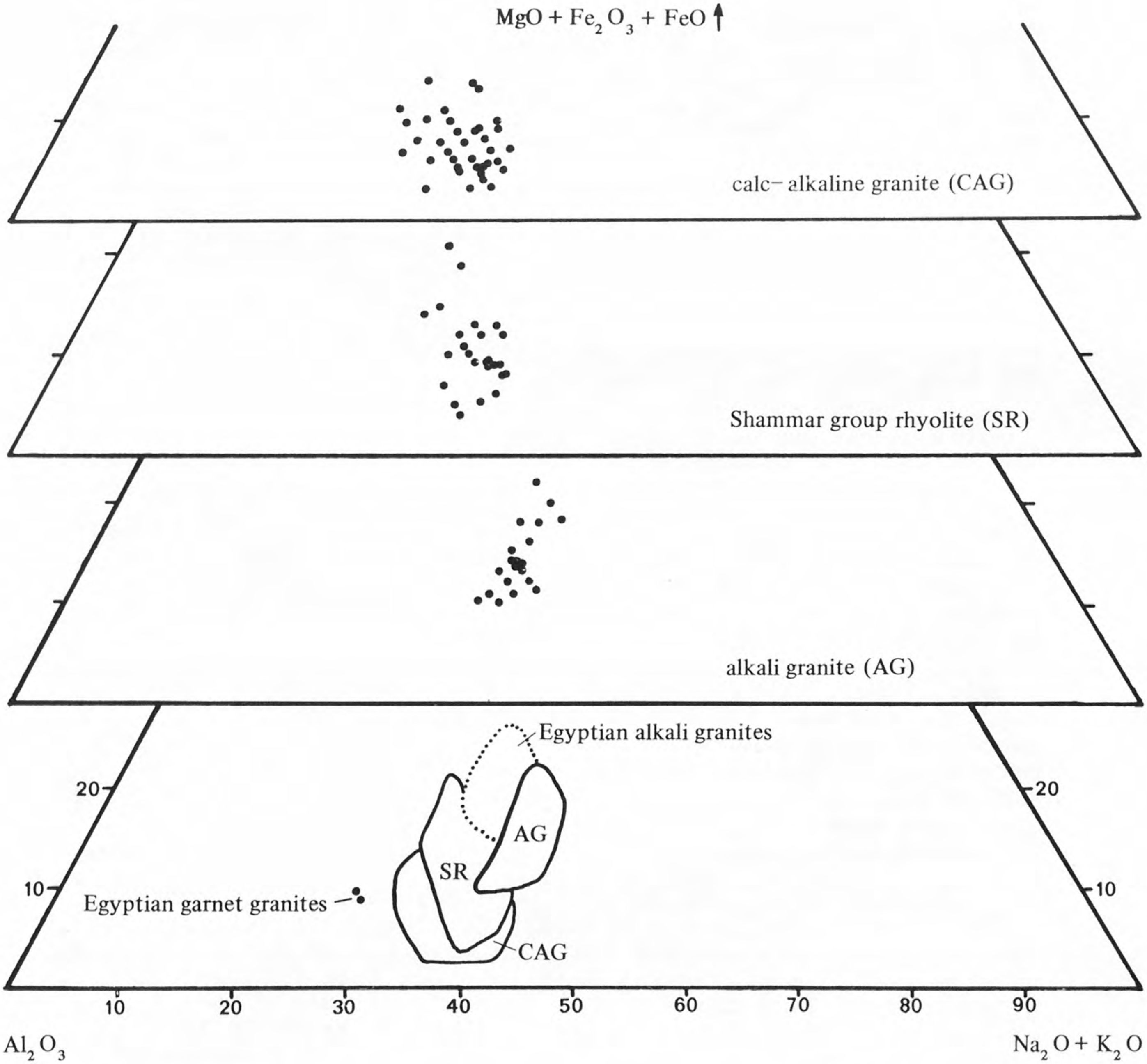

Figure 5. Total alkali–alumina–total iron oxide magnesia ternary diagrams (weight percent) for Arabian granites and rhyolites. The four fields shown in the lower diagram are for calc-alkaline granites (CAG) of the Arabian Shield, Shammar rhyolite (SR), Saudi Arabian alkali granites (AG), and Egyptian alkali granites (after Schurmann, 1966); also plotted are two Egyptian garnet granites. Arabian data from R.J. Fleck (unpublished), Greenwood and Brown (1973), Nassef and Gass (1977), Delfour (1977), and Kanaan (1979).

miarolitic cavities. These features are also characteristic of the late alkali granites of Arabia, particularly the granophyric granites. Taylor (1978) also notes that alteration of the rubidium-strontium systematics of the red granites make these rocks difficult or impossible to date by the rubidium/strontium method. Radiometric work in the Arabian Shield by Fleck (personal commun., 1979) indicates that the Arabian red granites have been similarly affected. Taylor attributed these changes to a low-temperature hydrothermal alteration event of long duration involving meteoric water. Radain (1978) similarly interprets peralkaline granites of the Jabal Sayid area of Saudi Arabia that have very high O^{18} contents (locs. 22, 23, fig. 2). Clearly, the interpretation of chemical data for such rocks will be difficult.

PETROGENESIS

The origin of oversaturated peralkaline magmas is not understood. The study of oversaturated peralkaline rocks has focused on the glassy phases of peralkaline effusive rocks--the comendites and pantellerites--in order to minimize the problems related to composition changes caused by hydration or crystallization such as loss of sodium and gain or loss of silica, potassium, halogens, and alkaline rare earths (Noble, 1968). These two rock types compositionally grade into one another; the comendites are mildly peralkaline (agpaitic ratio 1.00-1.25) whereas the pantellerites are very peralkaline (agpaitic ratio >1.25)(Bowden, 1974; Macdonald and Bailey, 1973). According to the data presented on table 2 then, the Arabian peralkaline granitic rocks are comenditic in composition.

Theories of origin for the peralkaline effusive rocks differ from those for the plutonic peralkaline granites. Many authors apparently believe that the peralkaline effusive rocks are the products of crystal fractionation that followed the general trend from transitional or mildly alkaline basalt through trachyte and oversaturated alkaline trachyte to comendite or pantellerite, although addition of alkalies by volatile transfer at a late stage may also play a role (Noble, 1968; Noble and others, 1969; Bowden, 1974). These rock types are sometimes found together in volcanic sequences for which a genetic relationship seems likely (Dickinson and Gibson, 1972; Berberi and others, 1975).

For the peralkaline granites a wide range of theories of genesis have been presented, most of which involve partial melting of the crust. These are: (a) metaluminous granitic melts fractionate to leave a peralkaline residual magma (Wright, 1969); (b) basaltic and metaluminous granitic melts form in the mantle and lower crust and upon rising into the upper crust generate peralkaline partial melts (Bowden and Turner, 1974); (c) basaltic melts rise into the crust and through interaction with palingenetic melts generated in the crust form peralkaline granitic melts; and (d) peralkaline melts are the primitive melts of the lower crust, and as they rise are converted by reaction and contamination with sialic crustal material to normal metaluminous granitic melts (Bailey and Schairer, 1966). These ideas are mainly suggestions as none is supported by detailed modeling. In any case, the facts that the Arabian peralkaline granites appear late, after most of the calc-alkaline metaluminous granites, and are closely associated only with these granites, are highly suggestive that the two are related and that the metaluminous granites have an antecedent role. Genesis of the peralkaline granites by partial melting of the calc-alkaline plutonic rocks seems possible. In contrast, the Sudanese peralkaline granites appear to be closely associated with gabbro and syenite, an association that suggests an origin similar to that proposed for the comendites and pantellerites. It will be interesting to see if further work in the Arabian-Nubian Shield substantiates the apparent difference in associations of the peralkaline granites in the two shield halves. Many of the ideas above can be tested by determining the initial $^{87}Sr/^{86}Sr$ ratios of carefully selected suites of these rocks.

The correlation of peralkaline magmas with both oceanic and continental anorogenic tensional environments is one of their outstanding characteristics and has been widely recognized (Bailey and Schairer, 1966; Wright, 1969; Bowden, 1974). The general nature of the occurrence of peralkaline granites in the Arabian Shield and their appearance before and during the period of Najd faulting, which was in part tensional, seems consistent. Models relating this period to a time of nearby continental collision have been proposed by Fleck and others, 1979, and Schmidt and others, in press.

MINERALIZATION ASSOCIATED WITH THE YOUNGER GRANITES

Despite the abundance and widespread distribution of granites in the Arabian Shield, very few mineral deposits have been discovered thus far that show evidence of a common origin with the granitic rocks. Some quartz veins bearing precious and/or base metals, which were exploited in ancient times, may have a genetic relationship to younger granites in some areas but in most cases this relationship is difficult to establish. Many fluorite occurrences, some of which have ancient workings, are commonly associated with younger granites (Kemp, 1977).

Even though few deposits are associated with the younger granites in the Arabian Shield, numerous occurrences and geochemical anomalies of tungsten, molybdenum, tin, niobium, beryllium, zirconium, thorium, uranium, rare earths, and fluorite show a close spatial relationship with these granites. Table 3 is a compilation from all available sources, published and unpublished, of these mineral occurrences and areas of geochemical anomalies. Figure 6 shows that these occurrences and anomalies are widely but irregularly distributed throughout the shield. They appear to be concentrated in the northeastern shield, north of lat 24° and east of long 40°, and in the east-central part of the shield, between lats 20° and 24° and east of long of 42°. The distribution shown in figure 6 may reflect in part the difference in the scope of geologic investigation in various parts of the shield. However, most of these occurrences were found during reconnaissance geologic and geochemical surveys, and practically all of the shield has been covered by these surveys; therefore, figure 6 is believed to reflect fairly accurately the distribution of mineralization associated with granitic rocks. Occurrences and anomalies are concentrated where granitic rocks are abundant relative to dioritic rocks; in the northeast and central parts of the shield, the ratio of granite to diorite is about 1:2, whereas in the southwest part of shield, in which mineral occurrences of these types are few, the ratio is about 1:7 (Mineral Resources Activities, 1976).

Although no deposits are known to have significant past production or reserves of present commercial value, at least three areas where deposits are associated spatially with granites have been investigated in sufficient detail to allow these deposits to be classified as resources. These are the Ablah Hill fluorite deposit, the Uyaijah-Thaaban area, and the Ghurayyah radioactive granite (locs. 45, 31, and 1, table 3 and fig. 6).

The Ablah Hill fluorite deposit in the southern part of the shield is a pipe in a breccia zone that is probably related to an unexposed granite intrusion. The deposit was worked in ancient times, probably to extract high-grade pockets of metallic ores dispersed through the fluorite. About 20,000 tonnes of fluorite possibly remain in the pipe to a depth of 50 m (Kemp, 1977).

In the east-central part of the shield, occurrences of molybdenum and tungsten are associated with the Uyaijah ring structure. The location and nature of these occurrences were first indicated by reconnaissance geochemical sampling of sediments, which revealed strong anomalies for tungsten and molybdenum and weaker anomalies for tin and other elements (Whitlow, 1968). Later work by Theobald and Allcott (1975) outlined two areas of about 40 km^2 each in the Uyaijah ring

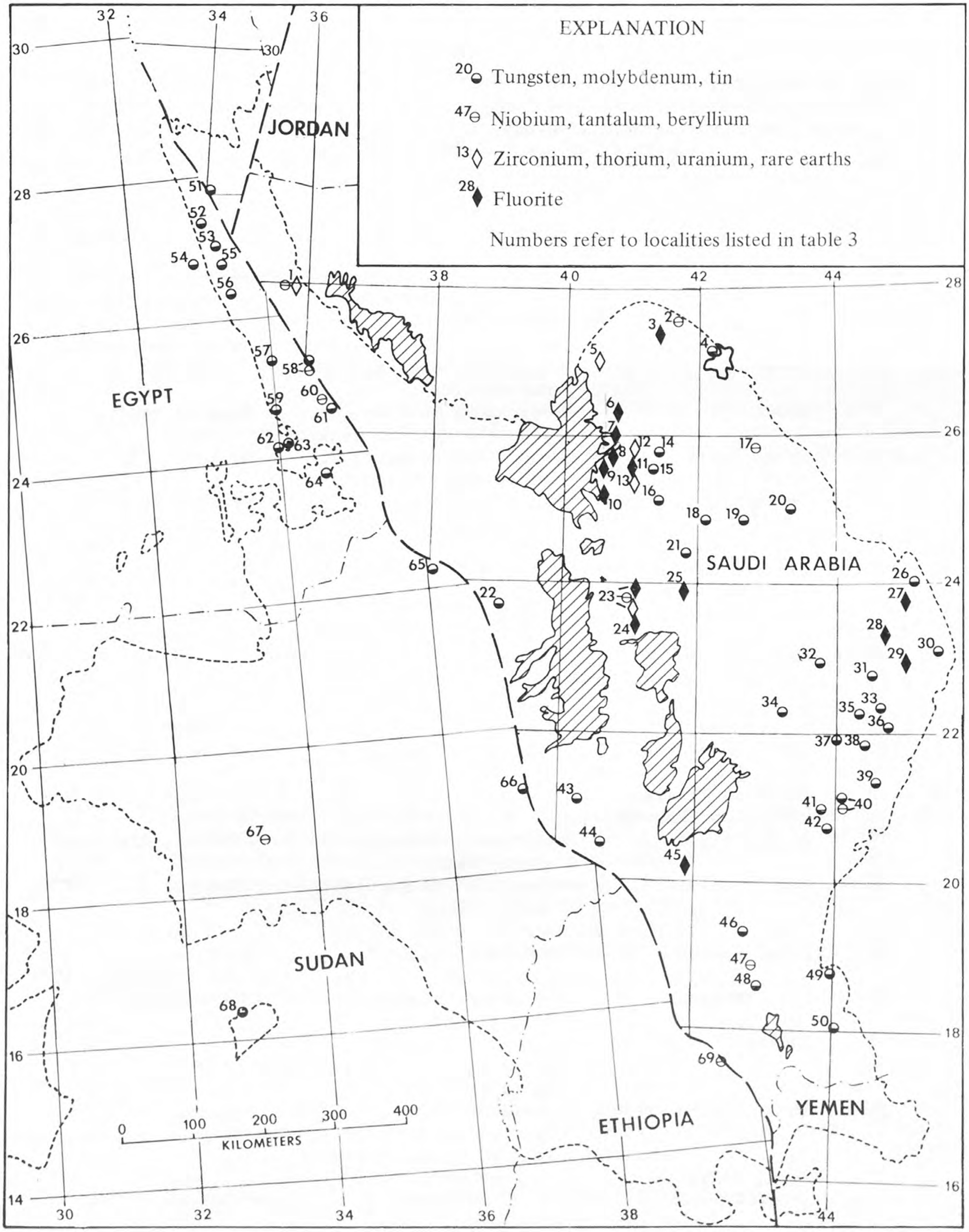

Figure 6. Mineral occurrences and geochemical anomalies associated with young granitic plutons in the Arabian–Nubian Shield.

Table 3.--*Names, descriptions, and references for mineral occurrences and geochemical anomalies associated with young granitic plutons in the Arabian-Nubian Shield*
[locations shown on figure 6]

Locality number	Locality name	Description	References
1	Al Ghurayyah	Prospect; granite with Zr, Nb-Ta, U	Lalande, 1977; Shepherd, 1966
2	Ha'il area	Occurrence; Nb, Th, rare earth elements in veins and granite	Matzko and Naqvi, 1978
3	Jabal Aja	Occurrence; quartz-fluorite vein in granite	Present study
4	Jabal Selma	Geochemical anomaly; W, Mo in wadi sediments	Mytton, 1970
5	Baydā'Nathīl area	Occurrence; elpidite (Na-Zr-silicate) in granite	Present study
6	Zarghat-Hanakiyah-Nuqrah area	Occurrence; fluorite	Kemp, 1977
7	-do-	-do-	-do-
8	-do-	-do-	-do-
9	-do-	-do-	-do-
10	-do-	-do-	-do-
11	-do-	-do-	-do-
12	Jabal Awja	Occurrence; Th-bearing zircon in pegmatites	Delfour, 1977
13	Jabal at Tuwalah-Jabal ar Rabuth	-do-	-do-
14	Al Hayitiyah	Occurrence; scheelite in quartz vein	MODS no. 539, 540[1/]
15	Wadi Shaela	Occurrence; scheelite in veins	MODS no. 562, 566
16	Jabal Subhah	Occurrence; scheelite in veins	MODS no. 219; Le Chapelain, 1971
17	Wadi Maraghān	Geochemical anomaly; Be in wadi sediment	Mytton, 1970
18	El Koom	Occurrence; wolframite and scheelite in quartz veins in granodiorite	Ankary, 1965
19	Jabal Sha'bā	Geochemical anomaly; W in heavy mineral concentrates of wadi sediment	Mytton, 1970
20	Jabal Minya	-do-	-do-

Table 3.--*Names, descriptions, and references for mineral occurrences and geochemical anomalies associated with young granitic plutons in the Arabian-Nubian Shield* [locations shown on figure 6] (continued)

Locality number	Locality name	Description	References
21	Wadi al Furdukhiyah	Occurrence; scheelite in heavy mineral concentrates of wadi sediment	MODS no. 389, 390; Duhamel, 1971
22	Jabal Subh area	Occurrence; scheelite in heavy mineral concentrates of wadi sediment	Goldsmith, 1971
23	Jabal Sayid	Occurrence; Nb, U, fluorite, rare earth elements in granite	Aguttes and Duhamel, 1971; Shepherd, 1965
24	Jabal Hadb Daheen	Occurrence; fluorite-bearing quartz vein	Kemp, 1977
25	Jabal al Jayasir	Occurrence; fluorite with limestone, rhyolite, and granite	-do-
26	Southern Jabal Khuff quadrangle	Occurrences; cassiterite in quartz veins and scheelite in marble near granite	Eijkelboom and others, 1971
27	Hajlan	Occurrence; fluorite with quartz in rhyolite	Kemp, 1977
28	Sabhah	Occurrence; fluorite in granite	-do-
29	Jabal Hawshat ibn Huwayl	Occurrence; fluorite-bearing veins in granite	-do-
30	Southwestern Ayn Qunay quadrangle	Occurrence and geochemical anomaly; scheelite in quartz vein in granite; W in heavy mineral concentrate of wadi sediment	Overstreet and others, 1972
31	Uyaijah ring structure	Occurrence; scheelite in contact metamorphic zone and molybdenite in quartz veins in granite	Dodge, 1973; Dodge and Helaby, 1974
32	Jabal Kirsh	Occurrence; disseminated molybdenite in granite	Letalenet and others, 1972
33	Jabal Ahmera	Occurrence; molybdenite in pegmatite in microgranite	Leca, 1970
34	Ad Duwayh	Geochemical anomaly; W in heavy mineral concentrate from mined area	Whitlow, 1971

Table 3.--*Names, descriptions, and references for mineral occurrences and geochemical anomalies associated with young granitic plutons in the Arabian-Nubian Shield* [locations shown on figure 6] (continued)

Locality number	Locality name	Description	References
35	Jabal ash Shumrah	Geochemical anomaly; W in heavy mineral concentrate	-do-
36	Jabal Sāhah	Geochemical anomaly; W and Sn in wadi sediment and heavy mineral concentrates associated with granite	-do-
37	South of Athīrayn	Occurrence; molybdenite in quartz pegmatite and granite	-do-
38	West of Jabal ash Shawnah	Geochemical anomaly; W and Mo in heavy mineral concentrates	-do-
39	Jabal Khida	Geochemical anomaly; W, Sn, and Mo in heavy mineral concentrates assoicated with granite	-do-
40	Southeast of Jabal Tarban	Geochemical anomaly; Sn, W, and Mo in wadi sediment and heavy mineral concentrates; occurrence; beryl in pegmatite dike	-do-
41	Dahlat Shahāb	Geochemical anomaly; W in sample from mine waste	Whitlow, 1971
42	West of Bi'r Zā'in	Occurrence; scheelite in contact metamorphic zone	D. L. Schmidt, personal commun., 1978
43	At Tā'if area	Geochemical anomaly and occurrence; W in heavy mineral concentrates and scheelite in heavy mineral concentrates and small veins	Goldsmith and Kouther, 1972; Kouther, 1966
44	Jabal Afaf area	Geochemical anomaly and occurrence; W and scheelite in heavy mineral concentrates of wadi sediments	Goldsmith, 1971
45	Ablah Hill	Deposit; fluorite-bearing pipe associated with granite	Allcott, 1970; Kemp, 1977
46	Khadrah quadrangle	Occurrence; scheelite in heavy mineral concentrates of wadi sediment; associated with granite	Mytton and Ankary, 1966

Table 3.--*Names, descriptions, and references for mineral occurrences and geochemical anomalies associated with young granitic plutons in the Arabian-Nubian Shield* [locations shown on figure 6] (continued)

Locality number	Locality name	Description	References
47	Bi'r Karath	Occurrence; beryl-bearing pegmatite in granite	Coleman, 1973a
48	Wadi as Salile area	Occurrence and geochemical anomaly; scheelite and W in heavy mineral concentrates and in contact metamorphic zone of granite	Abuannaja, 1970
49	Jabal al Mutbig	Occurrence; scheelite in shear zone	MODS no. 671; Van Daalhoff, 1974
50	Area near Jabal Ghern	Occurrence and geochemical anomaly; Sn and Nb in granite and wadi sediment cassiterite in heavy mineral concentrates of sediment	Greenwood, in prep.; present study
51	Wadi Dib	Occurrence; W-Sn deposit	Said, 1962
52	Abu Marwa	-do-	-do-
53	Um Disi, Gattar	-do-	-do-
54	Abu Hammad	Occurrence; wolframite in quartz veins in granite	El Ramly and others, 1970
55	Abu Kharif, El Dob	-do-	-do-
56	Maghrabiya	-do-	-do-
57	Umm Bissila	-do-	-do-
58	Abu Dabbab, Nuweibi, Igla	Prospects; columbite-tantalite, cassiterite and wolframite with fluorite, topaz and mica in quartz veins and greisenized zones of granite	-do-
59	El Mueilha	Prospect; cassiterite and wolframite in quartz veins near granite	-do-
60	Nugrus, Zabara, Sikait	Occurrence; beryl deposit	Said, 1962
61	Um Harba	Occurrence; Sn-W deposit	-do-
62	Um Selim	-do-	-do-
63	Homr Akarem	Prospect; stockwork of molybdenite-bearing quartz veins in granite	Shalaby, 1974

Table 3.--*Names, descriptions, and references for mineral occurrences and geochemical anomalies associated with young granitic plutons in the Arabian-Nubian Shield* [locations shown on figure 6] (continued)

Locality number	Locality name	Description	References
64	Zargat Naam	Occurrence; wolframite in quartz veins in granite	El Ramly and others, 1970
65	Gash Amer	-do-	-do-
66	Khor Arbent	Occurrence; W	Whiteman, 1971
67	Rahaba	Occurrence; beryl in pegmatites	Vail, 1971
68	Sabaloka	Occurrence; cassiterite and wolframite in quartz stockwork near contact of microgranite	Whiteman, 1971
69	Shilicki	Occurrence; beryl in pegmatite	Jelenc, 1966

1/ MODS is the Mineral Occurrence Documentation System used in Saudi Arabia for the recording of all mineralized outcrops, ore bodies, and districts (Delfour, 1974).

structure in which heavy mineral concentrates of surficial debris contained anomalous amounts of tungsten, molybdenum, and bismuth. More detailed geologic and geochemical investigations were made in both of these areas, the Buhairan-Abu Khurg area (Dodge, 1973) and the Uyaijah-Thaaban area (Dodge and Helaby, 1975).

The Uyaijah ring structure consists of an older batholith of granodiorite that is intruded by a small stock and a ring dike of calc-alkaline granite and also cut by numerous late epithermal quartz veins. In the Buhairan-Abu Khurg area, the geochemical anomalies, principally of tungsten, are believed to have resulted from the weathering of small amounts of powellite and scheelite in high-termperature, quartz-rich veinlets and in pods in contact metamorphic rocks. No valuable mineral deposits were found or are thought to be present. The Uyaijah-Thaaban area contains many molybdenite-bearing quartz veins as much as 2 m wide and several hundred meters long. The granite adjacent to the veins is altered and locally contains anomalous amounts of molybdenum. The highest molybdenum values occur in two zones in an area 3 km long by 1 km wide; each zone contains a weighted average of 88 ppm of molybdenum, far below the grade of ore from presently mined molybdenum deposits such as the Henderson mine in Colorado, U.S.A. The Henderson ore body has reserves of 303 million tons at an average grade of 0.49 percent MoS_2 based on a 0.2 percent MoS_2 cut off (Wallace and others, 1978).

Undoubtedly the most important mineral deposit found thus far in association with the younger granitic rocks is the Ghurayyah radioactive granite in the northwestern part of the Arabian Shield. The deposit consists of a small stock of riebeckite-aegirine alkali granite about 900 m in diameter that has resources of zirconium, niobium-tantalum, uranium and other metals contained in irregularly distributed accessory minerals, including zircon, columbite-tantalite, uraninite, monazite, and others (Lalande, 1977). The granite is leucocratic and porphyritic and consists commonly of euhedral phenocrysts of alkali-feldspar and quartz in a fine- to medium-grained groundmass. Grain-size is variable from fine to coarse and the percentage of groundmass is variable from nil to 40. Semi-quantitative analyses indicate highly anomalous contents of niobium, tantalum, cerium, lanthanum, uranium, thorium, yttrium, zirconium, tin, fluorine, and zinc. Some samples also contain anomalous amounts of titanium, chromium, cobalt, molybdenum, tungsten, lead, strontium, and lithium. Quantitative analyses of drill core indicate that the niobium/tantalum ratio is approximately 10; niobium ranges from 2780 to 3040 ppm and tantalum from 230 to 300 ppm.

Possible reserves on the order of 411 million tonnes, containing 0.75 percent zirconium, 0.25 percent niobium-tantalum, 0.0115 percent uranium, 0.105 percent yttrium, 0.25 percent rare earths, and 0.02 percent tin, have been outlined. The economic potential of this deposit is being assessed.

In general minerals and metals associated with the younger granites may be separated into two suites: one mainly of niobium, zirconium, thorium, and fluorite that has a close spatial relationship with alkaline to peralkaline granites, and another of tungsten, molybdenum, and tin that is associated mainly with calc-alkaline granites or granodiorites. Examples of the first suite include the Ghurayyah radioactive granite and the Zarghat-Hanakiyah-Nuqrah area (locs. 1, 6-13, fig. 6), where occurrences of fluorite and zirconium-thorium are associated with alkali amphibole/pyroxene-bearing granites. Examples of the second suite are El Koom (loc. 18, fig. 6), where wolframite-bearing quartz veins occur in a granodiorite stock; the Uyaijah ring structure, where scheelite and molybdenite are associated with an intrusive complex consisting of calc-alkaline granite and granodiorite; the Ta'if area (loc. 43, fig. 6), where scheelite occurrences and tungsten anomalies apparently are related to a large calc-alkaline granitic complex; and the Wadi as Salile area (loc. 48, fig. 6) where scheelite is associated with a calc-alkaline granite.

Certain areas of the Arabian Shield may be more favorable than others for the occurrence of mineral deposits associated with the younger granites. Criteria for evaluating different areas of the shield are: 1) the distribution of occurrences and anomalies of minerals of interest as shown in figure 6; 2) the distribution and abundance of younger granites including both calc-alkaline as well as alkaline to peralkaline types; 3) the occurrence of favorable host rocks and/or structures; and 4) the level of emplacement of the younger granites represented by the present level of erosion. For evaluation, the shield is arbitrarily divided into five areas as follows: a) northwestern--north of lat 24° and west of long 40°; b) northeastern--north of lat 24° and east of long 40°; c) west-central--between lats 20° and 24° and west of long 42°; d) east-central--between lats 20° and 24° and east of long 42°; and e) southern--south of lat 20°.

Northwestern shield: Reconnaissance geologic and geochemical studies in this area, thus far, have resulted in the discovery of only one deposit, the Ghurrayyah radioactive granite. Younger granites of both alkaline-peralkaline and calc-alkaline types are present and are very abundant in the northern part of this area. Further exploration of these granites would seem warranted because the eastern desert of Egypt, which is adjacent to this area in the palinspastic map of the Arabian-Nubian Shield shown in figure 6, has numerous occurrences of tungsten, molybdenum, tin, and other metals associated with younger granites.

Northeastern shield: This area has numerous occurrences and anomalies associated with younger granites, but no economic deposits have been discovered. Favorable factors include the great abundance of younger granites of both alkaline-peralkaline and calc-alkaline types, exposures of the upper parts of many granite bodies as indicated by the presence of cogenetic(?) volcanic rocks, and the presence of abundant favorable sedimentary host rocks, some of which are carbonates. The area is one of the most favorable of the shield for the occurrence of mineral deposits in association with the younger granites, and the authors are currently carrying out reconnaissance mapping and geochemical sampling of these granites.

West-central shield: Occurrences and anomalies are few in this area and include scheelite occurrences associated with calc-alkaline(?) granites and niobium-fluorite-uranium occurrences associated with alkaline-peralkaline granites. In general, older rocks and a deeper crustal level of the Arabian Shield are exposed in this area, and younger granites are less common than in other parts of the shield. Furthermore, the area of exposure of Precambrian rocks is limited because of an extensive cover of younger basalts, alluvium, and sedimentary rocks. The area appears to have a low potential for the discovery of mineral deposits associated with younger granites.

East-central shield: This area has many occurrences and anomalies especially of tungsten and molybdenum and, to a lesser extent, of tin. The area has many features in common with the northeastern shield, including a great abundance of younger granites, exposures of upper levels of granite intrusions, and younger sedimentary sequences that have favorable host rocks. However, calc-alkaline granites predominate over alkaline-peralkaline types, whereas in the northeastern area alkaline-peralkaline granites are apparently more abundant. The potential for the discovery of mineral deposits associated with the younger granites seems to be at least as high for this area as in the northeastern shield.

Southern shield: Occurrences and anomalies associated with younger granites in this area are relatively few, although this is perhaps the most thoroughly studied area of the shield. In general, older rocks and deeper crustal levels are exposed in this area, and younger granites are abundant only in the central and eastern parts. Because the potential for granite-related deposits is generally low and the area has been studied adequately, further exploration of the younger granites would likely be unproductive.

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