JKAU: Earth Sci., **vol. 10,** pp. 17-43 (1419 A.H. / 1998 A.D.)

Geochemistry and Tectonic Evolution of the Orogenic Granitoids Associated with the Andean-Type Siham Arc, Central Arabian Shield

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Received: 10th Sept., 1997 Accepted: 8th March, 1998

ABSTRACT. The syntectonic granitoids and the Al Bara batholith trondhjemite-granite suite exposed in the Afif quadrangle, Saudi Arabia, are the major plutonic components of the Andean-type Siham arc, developed during the period from about 750 to 700 Ma along the western margin of the Afif terrane. These plutonic rocks have a wide range of lithologies, from diorite to leucogranite. They are characterized by multiple periods of plutonism and rejuvenation during Pan-African orogeny (c. 900-550 Ma).

The syntectonic granitoids and the Al Bara batholith rocks are calc-alkaline, I-type and metaluminous to marginally peraluminous. They are enriched in Rb, Ba, K, La, Ce and Sr relative to Nb, Zr and Ti, suggesting their emplacement along an active continental margin. The Al Bara batholith rocks, with the largest variations in lithology, texture and incompatible elements' patterns, indicate the greater effects of Pan-African rejuvenation.

The post-tectonic Dariyah batholith granites were intruded at 585 ± 8 Ma in the late Proterozoic (650-615 Ma) Murdama group, a back-arc basin filled up with clastic sedimentary rocks with minor limestone and volcanic rocks. The batholith ranges in composition from co-magmatic granodiorite to syenogranite. Biotite granite is the abundant rock type. All lithologies of the batholith are in part porphyritic with lack of chilled contacts. The porphyritic varieties are modeled as mixtures of phenocrysts (presumably restite) and minimum melts. The higher levels of Rb, Na, La, Ce and Sm, the marked depletion of Ba, Sr, and Ti and the strong Eu negative anomaly are all indicative of in-situ fractionation of the Dariyah rocks after intrusion into higher levels of the crust.

Introduction

Many tectonostratigraphic terranes (*i.e.* domains which are characterized by internal homogeneity and continuity of stratigraphy, tectonic style and history; Coney *et al.* 1980) have been identified in the Arabian Shield by various workers (Greenwood *et al.* 1982, Delfour 1983, Stoeser and Camp 1985, Johnson *et al.* 1987, Pallister *et al.* 1988). Stoeser and Camp (1985) divided the Arabian shield into five principle terranes of oceanic-(Asir, Hijaz, Midyan) and continental -(Afif, Ar Rayn) affinities separated by four major ophiolite-decorated suture zones (Bir Umq, Yanbu, Nabitah, Al Amar) (Fig. 1).

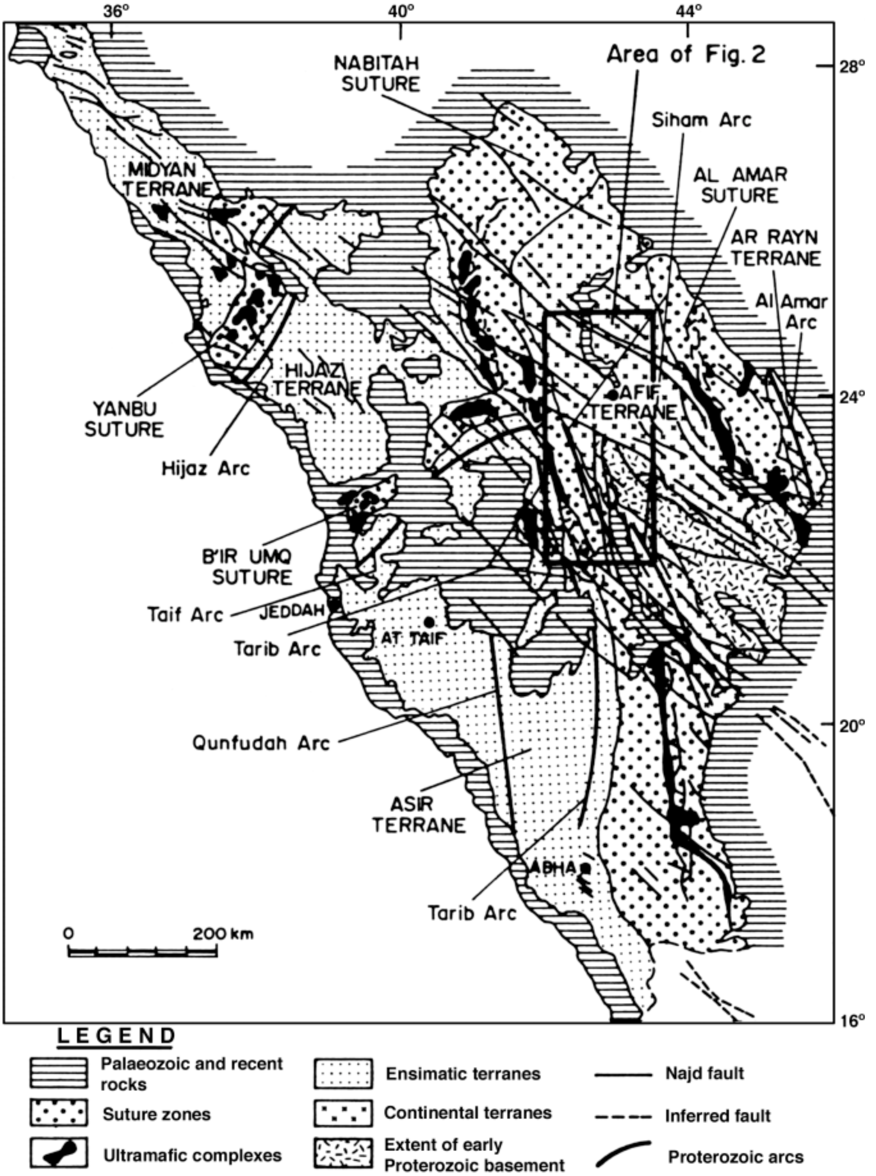


FIG. 1. Tectonic sketch map of the Arabian Shield showing terranes, Proterozoic Arcs, and suture zones (from Stoeser and Camp 1985, Agar 1992).

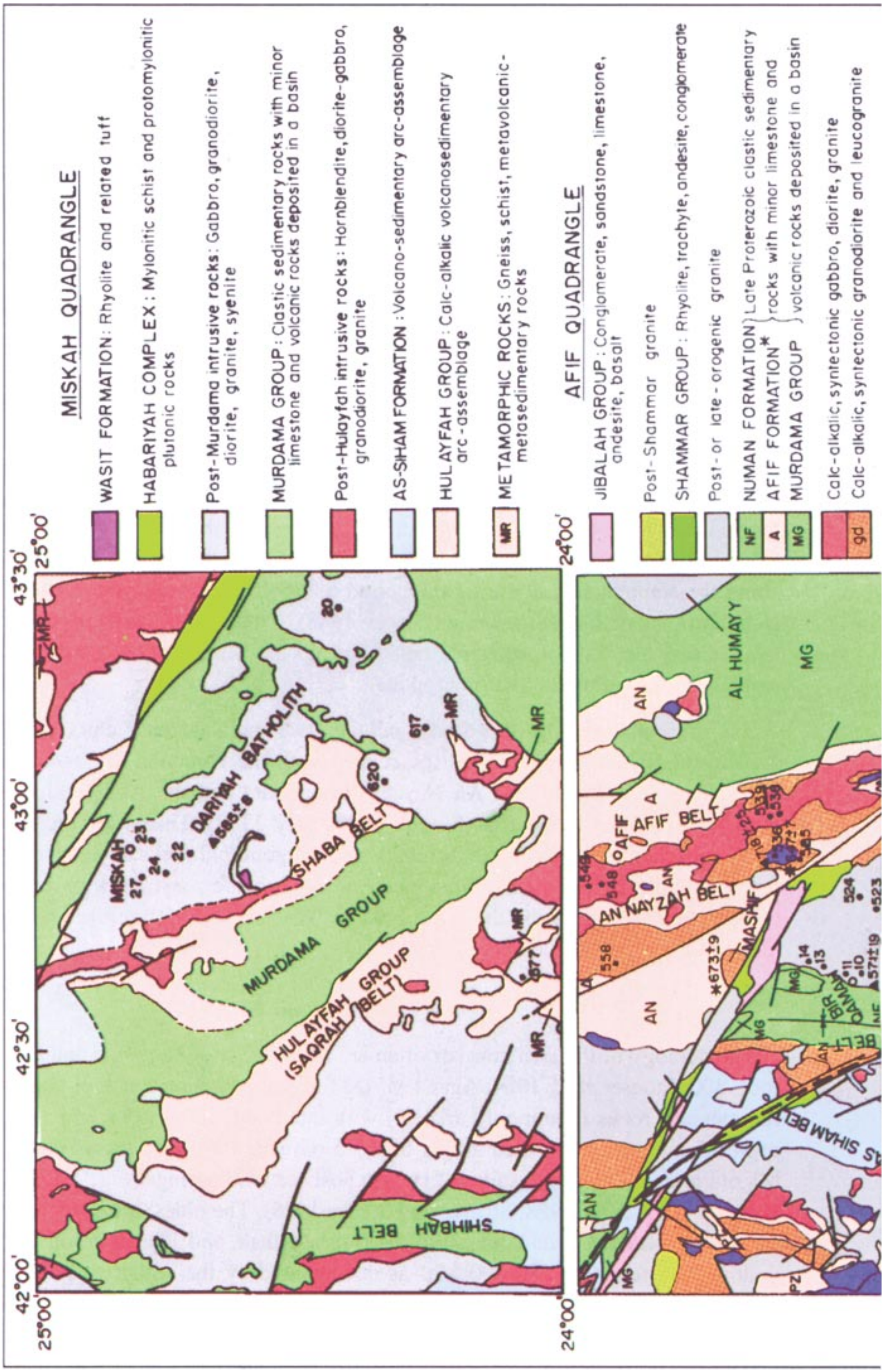
A clear model of tectonic evolution of the Arabian shield is still an enigma. The modelers are encountering difficulties by later mostly regional workers who present the conflicting views on the tectonic evolution of the area based on their findings. The discovery of many arc terranes, oceanic basins, plateau segments in the Asir and Afif terranes and the existence of continental basement in the Afif terrane (Greenwood *et al.* 1982, Camp 1984, Stoeser *et al.* 1984, Reischmann *et al.* 1984, Kroner 1985, Stacey *et al.* 1980, Stacey and Stoeser 1983, Stacey and Hedge 1984, Agar 1985, Stacey and Agar 1985) led Stoeser and Stacey (1988) to rename Asir and Afif terranes as composite terranes. They referred to the Al Amar suture zone as Ad Dawadimi terrane.

A 1200 km long north striking Nabitah suture (Fig. 1) is located on the ancient convergent and collision plate boundary. The west-dipping subduction of oceanic crust from the western margin of the Afif terrane beneath the accreted Hijaz-Asir microplate generated the Hulayfah arc assemblage prior to 680 Ma (Stoeser *et al.* 1984). Agar (1985) discovered the 750-700 old Siham arc in the Zalm region, developed as a result of east-dipping subduction of oceanic crust beneath western continental margin of the Afif terrane. The collision between the western Hijaz-Asir and eastern Afif terranes formed the Nabitah suture with ophiotic assemblage at about 690-683 Ma (Stoeser and Stacey 1988). Crustal deformation, remobilization and synorogenic granitoid plutonism along the Nabitah suture, during the period 680-640 Ma, formed the 100-200 km wide Nabitah orogenic belt (Stoeser and Stacey 1988). Crustal uplift and erosion of the highlands along the Nabitah orogenic belt filled up the Murdama basin with clastic sedimentary rocks within the Afif microplate.

The area convered by this study includes two main tectonic units of the Arabian shield: the Nabitah orogenic belt associated with the Hulayfah arc assemblage or its equivalents (*e.g.* Siham and An Nayzah formations) and the Afif continental terrane with younger Murdama basin (Stoeser and Stacey 1988). This study presents and discusses geochemical data on the different types of granitoid rocks developed in these different tectonic environments. The objective is to provide constraints on the source rock composition and to discuss the effects of Pan-African (900-550) rejuvenation on the evolution of these granitoids.

Geology and Tectonic Setting

The geology of the area consists of an arc assemblage of Hulayfah and Siham groups (680-800; Stoeser *et al.* 1984, Agar 1985), a fore-arc Murdama basin of abundant clastic sedimentary rocks (commonly arkosic) with interbedded limestone and volcanic rocks of Murdama group deposited during 650-615 (Greene 1993) and the associated 700-510 Ma old granitoid plutonic suites of syn- to post-tectonic settings (Fig. 2; Letalenet 1979, Pellaton 1985, Agar 1988, Stoeser and Stacey 1988). The oldest arc terranes (950 to 800 Ma) of the Arabian shield consist of the Baish, Bahah, and Jeddah groups (> 800), and younger arc terranes (680-800 Ma) as documented by the Ablah and Hulayfah (Halaban/Siham equivalent) groups (Greenwood *et al.* 1982, Delfour 1979a, Fleck *et al.* 1980).


MISKAH QUADRANGLE
WASIT FORMATION: Rhyolite and related tuff
HABARIYAH COMPLEX: Mylonitic schist and protomylonitic plutonic rocks
Post-Murdama intrusive rocks: Gabbro, granodiorite, diorite, granite, syenite
MURDAMA GROUP: Clastic sedimentary rocks with minor limestone and volcanic rocks deposited in a basin
Post-Hulayfah intrusive rocks: Hornblendite, diorite-gabbro, granodiorite, granite
AS-SIHAM FORMATION: Volcano-sedimentary arc-assemblage
HULAYFAH GROUP: Calc-alkalic volcanosedimentary arc-assemblage
METAMORPHIC ROCKS: Gneiss, schist, metavolcanic-metasedimentary rocks
MR
AFIF QUADRANGLE
JIBALAH GROUP: Conglomerate, sandstone, limestone, andesite, basalt
Post-Shammar granite
SHAMMAR GROUP: Rhyolite, trachyte, andesite, conglomerate
Post- or late-orogenic granite
NUMAN FORMATION } Late Proterozoic clastic sedimentary
AFIF FORMATION* } rocks with minor limestone and
MURDAMA GROUP } volcanic rocks deposited in a basin
NF
A
MG
Calc-alkalic, syntectonic gabbro, diorite, granite
Calc-alkalic, syntectonic granodiorite and leucogranite
gd
42°00'
42°30'
43°00'
43°30'
25°00'
24°00'
MISKAH
DARIYAH BATHOLITH
SHABA BELT
MURDAMA GROUP
HULAYFAH GROUP (SAQRAH BELT)
SHIHBAH BELT
AFIF BELT
AN NAYZAH BELT
AL HUMAYY
AS SIHAM BELT
MASHIF
AFIF
BIR DAWADMI
AN

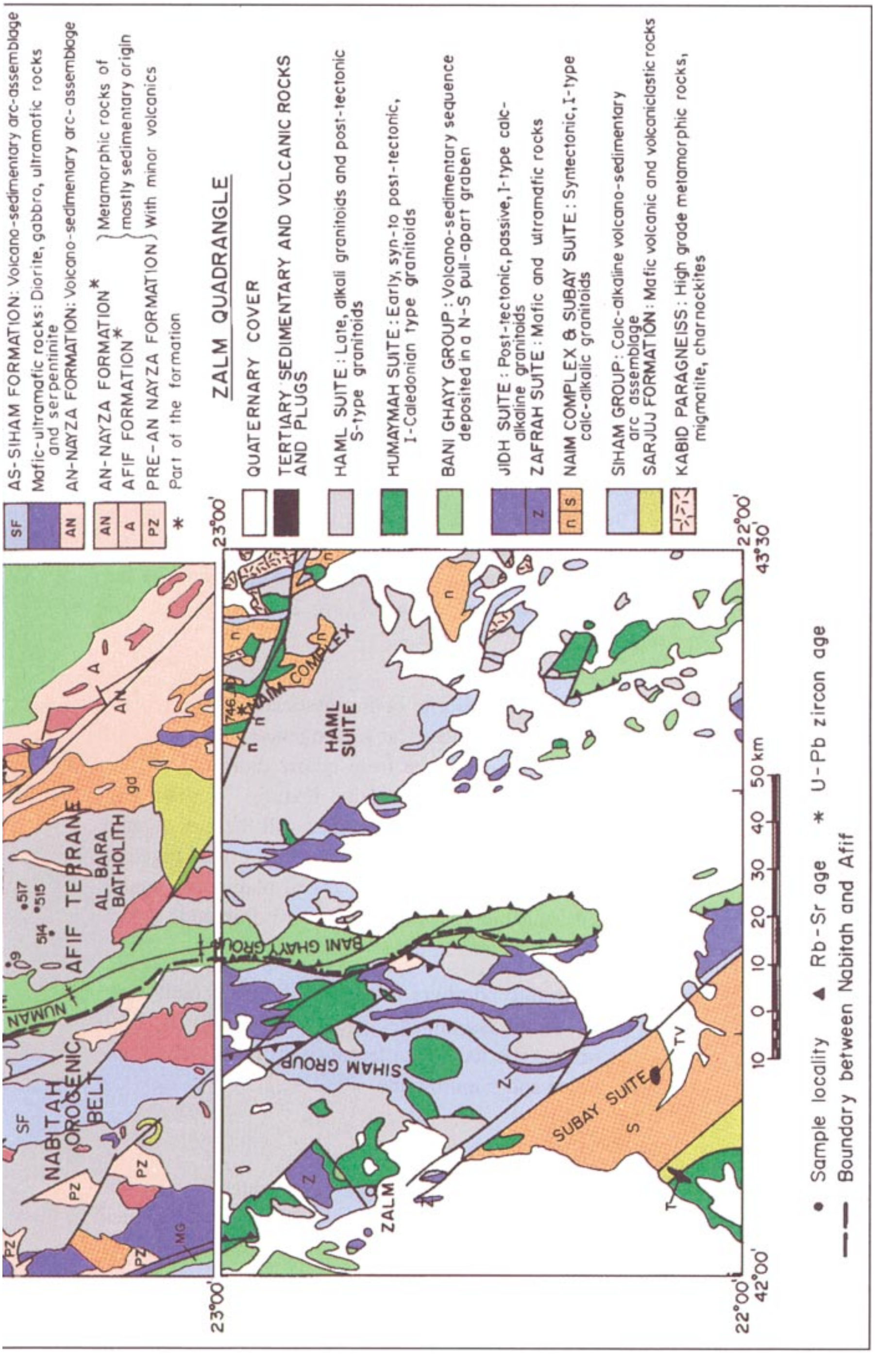


FIG. 2. Simplified and modified geological map of the Zalm (Agar 1988), Afif (Letalenet 1979) and Miskah (Pellaton 1985) quadrangles.

The Hulayfah group covers large areas in the eastern and northern parts of the Arabian shield and consists of mostly andesitic, dacitic and rhyolitic flows, breccias and pyroclastic rocks (Delfour 1977). Latalenet (1979) divided the Hulayfah group in the Afif quadrangle into five formations (pre-An Nayzah, An Nayzah, Numan, As Siham, Afif) grouped into three units (I to III) besides intrusive diorite, gabbro, ultramafic rocks and serpentinite. While, Pellaton (1985) divided the Hulayfah group in the Miskah quadrangle into unassigned metamorphic rocks (mostly gneiss and schist) and four formations (Shihbah, Madin, Utra and Shabah). In the Zalm quadrangle the Hulayfah equivalent group is referred to as Siham group (Agar 1988). The continuation of this group into the Afif quandrangle is mapped as As Siham formation.

Several types of plutonic rocks intrude the Hulayfah and its equivalent groups, which are folded and metamorphosed in the greenschist and amphibolite facies. The fault-bound syntectonic granitoids (diorite, tonalite-trondhjemite, granodiorite) occur as elongate bodies with schistose or migmatitic texture in the Afif composite terrane. Whereas, the so-called post-tectonic Al Bara granite batholith (Al Bara) of diorite to leucogranite composition, situated close to the Nabitah orogenic belt is possibly rejuvenated older granites (Latalenet 1979). The Hulayfah group rocks are unconformably overlain by Murdama group, a late orogenic molasse sedimentation. The Murdama group is intruded by large post-tectonic differentiated batholiths of gabbro to alkali granite in the Miskah (Dariyah complex) and Afif (Al Humayy) quadrangles (Fig. 2).

Syntectonic Granitoids

The syntectonic granitoids are elongated granodiorite bodies associated with the Hulayfah arc complex and are mainly bound by faults. The heterogeneous character of these bodies is shown by the wide compositional range from quartz diorite to granite and by the oriented, schistose, gneissic and almost migmatitic textures. Xenoliths of country rocks (Hulayfah arc) are commonly found in these bodies. All these elongated bodies, regardless of their compositions, have been metamorphosed and folded together with the Hulayfah arc assemblage. The granodiorite contains zoned plagioclase and a small amount of microcline, myrmekite and biotite with ± garnet ± hornblende and ± muscovite. The amphibole is altered to chlorite and epidote.

Small post-tectonic plutons of leucogranite porphyry located in the Najd fault zone also intrude the metamorphosed Hulayfah arc assemblage. They occur mainly as muscovite granite, pegmatite and aplite veins. The leucogranite consists of microcline, albite, myrmekite, biotite, muscovite, garnet and ± tourmaline.

Post-Tectonic Granites

Post-Murdama group intrusive rocks in the study area are represented by the so-called Al Bara and the Dariyah batholiths, located in the Afif and Miskah quadrangles respectively. On the basis of similar petrographic signatures, both batholiths were mapped as post-Murdama intrusives (Letalenet 1979). Although no contact between the Al Bara granites and the Murdama group was observed.

Al Bara Batholith

The Al Bara batholith rocks range in composition from diorite to trondhjemite. Latalenet (1979) suggested that the granites of the Al Bara batholith might represent older granites rejuvenated during the Murdama epoch. The biotite granite of the batholith contains both white and pink K-feldspar, hornblende and biotite; sodic plagioclase is slightly higher than K-feldspar. Xenoliths of amphibole- or biotite-rich metamorphic rocks are common. Fleck and Hadley (1982) analyzed the whole rock samples of myremekitic, muscovite-bearing biotite granite from the Al Bara batholith (south of Bir Qamah) and obtained a Rb/Sr age of 571 ± 19 Ma with an initial ratio of 0.7036 ± 0.005. On the basis of textural and mineralogical characteristics, Fleck and Hadley (1982) suggested that the unit sampled may be a shallowly emplaced post-tectonic intrusion rather than a body of batholithic proportion.

The poorly defined trondhjemitic bodies of the batholith grade imperceptibly into more potassic tonalite or granodiorite. The trondhjemite is composed of subhedral, sporadically altered sodic plagioclase, with subordinate quartz, K-feldspar and biotite. Biotite is partly altered and secondary muscovite replaces plagioclase and chloritized mafic clots. Magnetite and apatite occur as accessory.

Dariyah Batholith

The Dariyah batholith or complex (Pellaton 1985) is about 125 km long and has a maximum width of more than 50 km in the south. It is a northwest trending synogranite batholith with minor granodiorite. It intrudes the Murdama basin, a synclinorium composed of detrital sedimentary rocks with volcanic and pyroclastic rocks of Murdama group.

The granitic complex consists mainly of biotite granite and leucogranite and covers the entire southern part of the batholith and the northern Dariyah region. The granitic rocks vary in texture as well as in composition. The rocks are fine- to coarse-grained, equigranular, and slightly porphyritic. The phorphyritic variety is characterized by centimeter-size crystals of pink K-feldspar, white oligoclase, globular quartz and biotite in fine dispersed lamellae or in patches. Fine- to medium-grained and equigranular variety of biotite granite cuts the coarse-grained variety. In thin section, granitic rocks show a partly leucocratic monzogranitic composition. Quartz and potassic feldspar occur in twinned perthitic crystals; whereas plagioclase (oligoclase) in zoned crystals. Zircon and apatite are principal minor minerals.

Quartz syenite and syenogranite are exposed mainly in the Miskah region. The quartz syenite cuts the biotite granite but does not show any chilled margins on the contact, which suggests that these rocks belong to the same magmatic cycle as the biotite granite. Pinkish red, fine-to medium-grained quartz syenite contains abundant euhedral alkali feldspar crystals and globular quartz.

The medium-grained and equigranular granodiorite is poorly exposed at Dariyah village. It is characterized by relatively high abundance of biotite and amphibole. Contact relations with other units of the complex are sharp. The biotite granite and the quartz syenite cut it, but no chilled margins appear between the units.

Geochemistry

Twenty-five samples were analyzed for major oxides, trace elements and REE. All analyses were carried out by inductively coupled plasma-source mass-spectrometry, at the Royal Holloway Bedford New College, University of London. Accuracy is estimated as ± 2% for major oxides and 5 to 10% for trace elements. Major- and trace-element contents of the analyzed samples are given in Table 1.

TABLE 1. Major and trace element data for representative samples of the Afif syntectonic granitoids and Al Bara and Dariyah batholiths.

Sample	Syntectonic granitoids							
	NA525	NA536	NA538	NA539	NA548	NA549	NA558	NA577
SiO_2	70.80	70.70	61.87	62.87	70.60	70.70	68.20	71.05
TiO_2	0.32	0.13	0.63	0.61	0.40	0.39	0.28	0.34
Al_2O_3	15.58	15.39	16.93	16.53	13.90	13.95	14.88	14.52
$Fe_2O_3^a$	2.94	1.68	6.21	6.06	3.68	3.49	2.75	2.98
MnO	0.06	0.04	0.11	0.11	0.07	0.08	0.07	0.06
MgO	0.70	0.32	2.73	2.55	0.57	0.55	0.78	0.93
CaO	3.45	2.53	5.87	5.08	1.98	1.95	3.98	2.56
Na_2O	4.60	4.62	3.60	3.56	4.77	4.69	3.95	3.49
K_2O	1.15	3.33	1.04	1.94	2.98	3.15	3.11	3.72
P_2O_5	0.11	0.04	0.15	0.14	0.08	0.08	1.00	0.10
Total	99.71	98.78	99.14	99.45	99.03	99.03	99.00	99.75
Rb	26	92	31	60	94	104	109	148
Ba	402	895	299	653	623	652	816	692
Sr	510	315	378	391	156	154	389	281
Li	17	16	18	10	9	23	19	9
Nb	5	3	4	4	9	7	6	9
Zr	123	69	93	91	215	211	116	118
Y	8	7	20	20	42	42	12	25
Cr	15	6	22	15	21	7	12	12
Ni	8	5	19	22	8	7	9	14
Co	6	4	17	17	6	5	6	8
Sc	4	1	16	15	7	7	4	6
V	25	9	108	108	24	24	24	40
Cu	4	4	11	8	5	5	5	8
Zn	60	16	66	64	42	48	47	37
La	30.00	27.60	21.00	19.00	31.00	27.49	25.00	42.00
Ce	53.00	48.36	30.00	27.00	58.00	57.53	38.00	61.00
Pr	n.d.	3.72	n.d.	n.d.	n.d.	6.86	n.d.	n.d.
Nd	22.00	10.70	18.00	18.00	23.00	26.50	14.00	22.00
Sm	3.80	1.32	3.20	2.90	5.00	5.78	2.60	3.90
Eu	0.80	0.59	1.00	0.90	0.90	1.23	0.60	0.70
Gd	n.d.	1.07	n.d.	n.d.	n.d.	6.13	n.d.	n.d.
Dy	1.90	1.00	2.20	2.00	5.70	6.80	2.10	2.50
Ho	n.d.	0.19	n.d.	n.d.	n.d.	1.29	n.d.	n.d.
Er	n.d.	0.76	n.d.	n.d.	n.d.	4.13	n.d.	n.d.
Yb	0.50	0.91	1.50	1.60	3.90	4.32	1.10	n.d.
Lu	n.d	0.71	n.d.	n.d	n.d	0.67	n.d.	n.d.

[a] = All Fe calculated as Fe2O3; n.d. = No determined.

TABLE 1. Contd.

Sample	Al Bara batholith trondhjemite-granite suite									
	NA9	NA10	NA11	NA13	NA14	NA514	NA515	NA517	NA523	NA524
SiO_2	69.49	73.09	70.09	65.30	76.37	68.80	68.90	69.48	68.90	74.00
TiO_2	0.41	0.27	0.31	0.66	0.12	0.23	0.23	0.39	0.41	0.17
Al_2O_3	15.22	13.51	17.84	15.16	12.33	16.71	16.50	16.71	14.83	13.25
$Fe_2O_3^a$	3.50	3.86	1.97	4.77	1.69	2.20	2.20	2.32	3.20	3.50
MnO	0.07	0.11	0.03	0.07	0.04	0.04	0.04	0.04	0.05	0.09
MgO	0.77	0.33	0.58	1.90	0.15	0.85	0.85	0.79	1.00	0.58
CaO	2.07	2.14	1.88	3.78	0.71	2.89	2.90	3.27	2.39	3.14
Na_2O	4.49	4.54	4.62	3.98	3.52	5.45	5.40	5.40	4.09	3.64
K_2O	3.43	1.87	3.84	3.22	4.62	1.80	1.65	1.55	4.10	0.60
P_2O_5	0.11	0.06	0.09	0.16	0.02	0.09	0.08	0.12	0.10	0.06
Total	99.56	99.78	101.25	99.00	99.57	99.06	98.75	100.07	99.07	99.30
Rb	77	49	101	123	287	30	29	25	136	16
Ba	1060	673	1345	532	130	722	630	572	698	299
Sr	259	240	694	392	36	639	600	695	380	176
Li	16	8	17	17	13	21	19	14	20	11
Nb	4	6	2	5	20	2	2	2	7	4
Zr	170	113	127	195	141	85	87	77	142	157
Y	17	37	5	23	29	7	6	7	15	21
Cr	7	17	134	29	9	10	14	6	26	1
Ni	9	8	6	5	4	5	5	12	14	4
Co	6	5	5	3	2	5	5	7	8	7
Sc	6	14	3	2	2	3	3	3	4	11
V	26	11	27	8	4	19	19	33	42	30
Cu	768	6	21	4	4	4	23	7	6	4
Zn	226	70	50	43	34	48	47	49	41	50
La	45.00	31.00	29.00	23.00	49.00	11.70	12.00	16.00	22.10	11.00
Ce	79.00	52.00	50.00	43.00	99.00	24.35	20.00	24.00	46.79	23.40
Pr	n.d.	n.d.	n.d.	n.d.	n.d.	2.86	n.d.	n.d.	5.45	2.64
Nd	27.00	22.00	18.00	19.00	33.00	11.60	10.00	14.00	20.20	11.20
Sm	5.00	5.00	3.00	4.00	7.00	2.08	1.60	1.40	3.62	2.53
Eu	1.00	1.00	1.00	0.70	n.d.	0.62	0.50	0.60	0.71	0.63
Gd	1.00	n.d.	n.d.	n.d.	n.d.	1.83	n.d.	n.d.	3.08	2.93
Dy	1.90	4.00	1.00	3.80	3.00	1.28	1.50	0.40	2.67	3.53
Ho	n.d.	n.d.	n.d.	n.d.	n.d.	0.23	n.d.	n.d.	0.50	0.66
Er	n.d.	n.d.	n.d.	n.d.	n.d.	0.65	n.d.	n.d.	1.51	2.15
Yb	1.00	4.00	n.d.	2.0	4.00	0.55	0.40	0.40	1.51	2.23
Lu	n.d.	n.d.	n.d.	n.d.	n.d.	0.10	n.d.	n.d.	0.25	0.36

[a] = All Fe calculated as Fe_2O_3; n.d. = Not determined.

TABLE 1. Contd.

Sample	Dariyah batholith granites						
	NA20	NA22	NA23	NA24	NA27	N617	NA620
SiO_2	73.83	74.84	75.05	67.14	74.85	67.30	71.28
TiO_2	0.18	0.16	0.14	0.49	0.12	0.48	0.24
Al_2O_3	14.16	13.79	13.55	17.02	13.91	15.80	15.35
$Fe_2O_3^a$	1.42	1.87	1.48	2.62	1.19	3.50	2.68
MnO	0.06	0.04	0.04	0.06	0.04	0.08	0.07
MgO	0.38	0.20	0.15	0.42	0.14	1.04	0.63
CaO	1.21	0.95	0.72	0.95	0.76	2.47	2.05
Na_2O	4.05	3.77	3.79	5.49	3.72	4.67	4.26
K_2O	4.31	5.04	5.02	6.41	5.32	4.07	3.49
P_2O_5	0.05	0.04	0.03	0.07	0.03	0.13	0.09
Total	99.65	100.70	99.97	100.67	100.08	99.54	100.14
Rb	171	324	335	105	306	128	105
Ba	541	349	187	440	276	867	649
Sr	295	108	62	97	75	360	268
Li	46	59	49	10	35	35	10
Nb	8	24	30	15	16	8	6
Zr	87	138	157	510	73	219	128
Y	8	32	32	32	21	25	14
Cr	9	7	5	7	7	17	6
Ni	7	6	4	5	6	12	6
Co	4	3	3	5	3	7	6
Sc	3	3	2	6	2	7	3
V	16	14	7	18	7	42	21
Cu	6	5	5	7	4	6	7
Zn	39	45	42	50	34	43	51
La	22.30	28.30	19.90	103.00	13.90	33.00	35.00
Ce	41.45	61.34	45.69	222.06	33.10	58.00	55.00
Pr	4.16	6.72	5.41	24.11	3.81	n.d.	n.d.
Nd	14.20	25.60	21.10	29.10	15.00	23.00	19.00
Sm	2.28	5.40	4.97	15.84	3.50	4.50	2.70
Eu	0.36	0.44	0.28	1.16	0.33	0.80	0.50
Gd	1.68	4.57	4.96	10.43	3.31	n.d.	n.d.
Dy	1.37	4.63	5.89	7.06	3.73	3.80	1.20
Ho	0.25	0.85	1.10	1.14	0.70	n.d.	n.d.
Er	0.73	2.65	3.47	2.59	2.26	n.d.	n.d.
Yb	0.81	3.32	3.59	2.13	2.78	2.10	1.10
Lu	0.31	0.56	0.54	0.13	0.43	n.d.	n.d.

[a] = All Fe calculated as Fe_2O_3; n.d. = Not determined.

The Afif syntectonic granitoids have a SiO_2 range of 61.87-71.05 wt %; whereas the post-tectonic granite suites of the Al Bara and Dariyah batholiths have a range of 65.3-76.37 wt. %. The granitoids show a wide compositional range from tonalite to granite in the Barker's (1979) ternary diagram of normative feldspar composition (Fig. 3A). In this diagram, syntectonic granitoid samples scatter equally between the tonalite-granodiorite and trondhjemite fields, the Al Bara samples plot mostly as trondhjemite-granite while all the Dariyah samples plot in the granite field. The syntectonic granitoids are transitional from metaluminous to peraluminous (Fig. 3B) with the molecular ratio $Al_2O_3/(CaO+N_2O+K_2O)$ in the 0.87-1.03 range. The Al Bara trondhjemite-granite and the Dariyah granite suites are marginally peraluminous to metaluminous with A/CNK ratio of 0.95-1.06 except sample NA-11 of the Al Bara batholith, which has a ratio of 1.18. On the basis of molar ratios (A/CNK) of less than 1.1, all analyzed rocks (except sample NA-11) can be classified into the I-type granitoids (Chappell and White, 1974). On the AFM diagram (Fig. 3C) the analyzed rocks show a well-defined trend in the calc-alkaline field.

Major-element oxides plotted on Harker-type variation diagrams (Fig. 4) show a large scatter that reflects heterogeneous textural and mineralogical segregation in the analyzed suites. However, taken as a group, the analyzed samples show a rough linear trend of decreasing MgO, TiO_2, Fe_2O_3, Al_2O_3, CaO, and P_2O_5 with increasing SiO_2. The variation trend of Na_2O and K_2O show no correlation with SiO_2.

The Afif syntectonic granitoids and the granite-trondhjemite suite of the Al Bara batholith fall together in the field of orogenic granites in the $(K_2O+Na_2O)/CaO$ versus (Zr+Nb+Ce+Y) diagram (Fig. 5A) of Whalen *et al.* (1987). The post-tectonic Dariyah batholith granites plot mostly as fractionated felsic granites, with two samples falling close to the average values of felsic I-type granites and one sample towards A-type granitoids (*i.e.* formed in anorogenic setting).

On the Nb-Y and Rb-(Y+Nb) tectonic discrimination diagrams (Fg. 5B, C), the Afif syntectonic granitoids and the Al Bara batholith rocks plot (except one sample) in the field of volcanic arc granites of Pearce *et al.* (1984), whereas, the post-tectonic Dariyah batholith rocks plot both in the fields of volcanic arc and within-plate granites. The very low Nb contents in the Al Bara batholith rocks (2-7 ppm, except a granite sample with $SiO_2 > 76\%$ has 20 ppm) and Afif syntectonic granitoids (3-9 ppm) suggest their formation above subduction zone (Pearce and Gale 1977). In contrast, most Dariyah batholith rocks with high Nb contents (> 15 ppm) indicate that the melt was most probably derived from a mantle source in a within plate tectonic setting (Pearce and Cann 1973, Pearce *et al.* 1984).

The Afif syntectonic granitoids have a wide range of Rb (26-148 ppm) and Sr (154-510 ppm) concentrations, and Rb/Sr ratios (0.05-0.68). The trondhjemite-granite suite of the Al Bara batholith is almost similar to Afif syntectonic granitoids in Rb (16-136 ppm) and Sr (176-695) contents, and Rb/Sr ratios (0.04-0.36) except sample NA-14 which has anomalous contents of Rb (287 ppm) and Sr (27 ppm) and Rb/Sr ratio (7.97), perhaps due to higher biotite content. Most of the samples from both the suites have

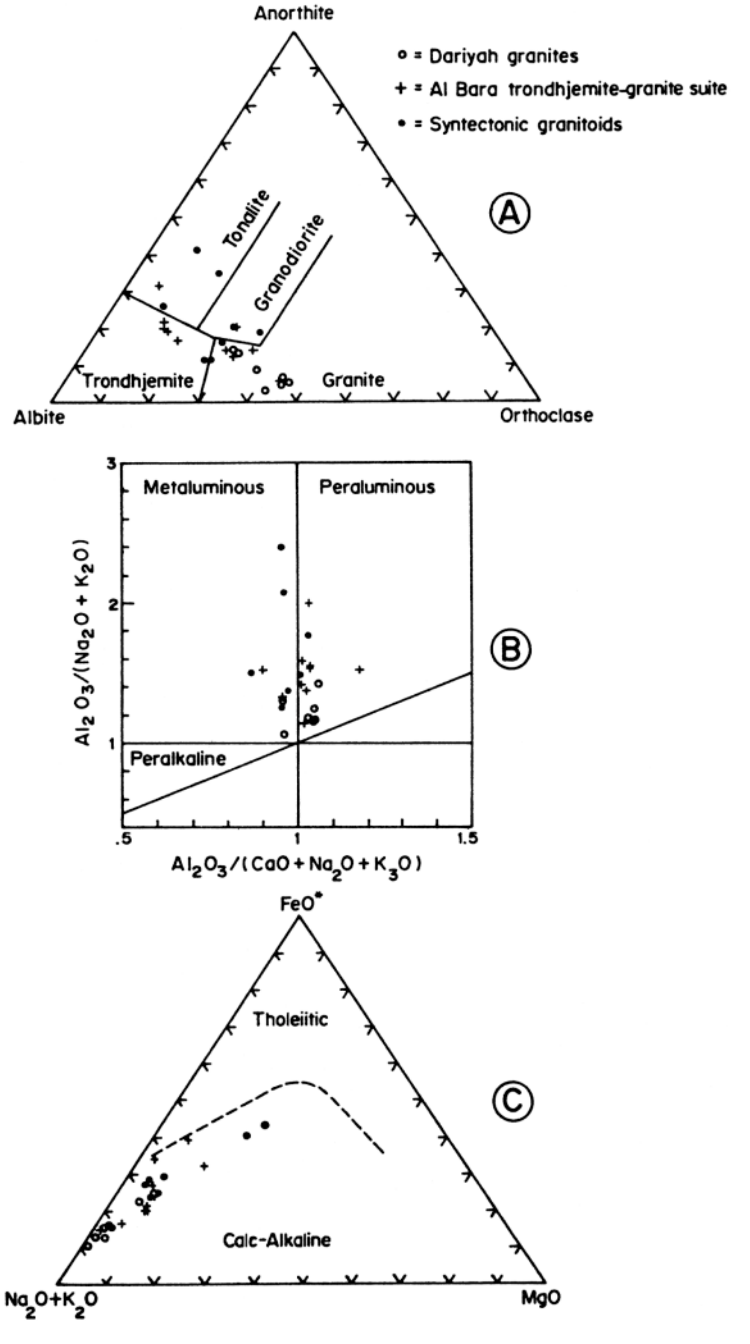


FIG. 3(A-C). **(A)** Normative An-Ab-Or diagram (after Barker 1979). **(B)** Plot of the molecular ratio of A/NK versus A/CNK (A = Al_2O_3, N = Na_2O, K = K_2O, C = CaO). **(C)** AFM diagram showing calc-alkaline trend for all granite groups.

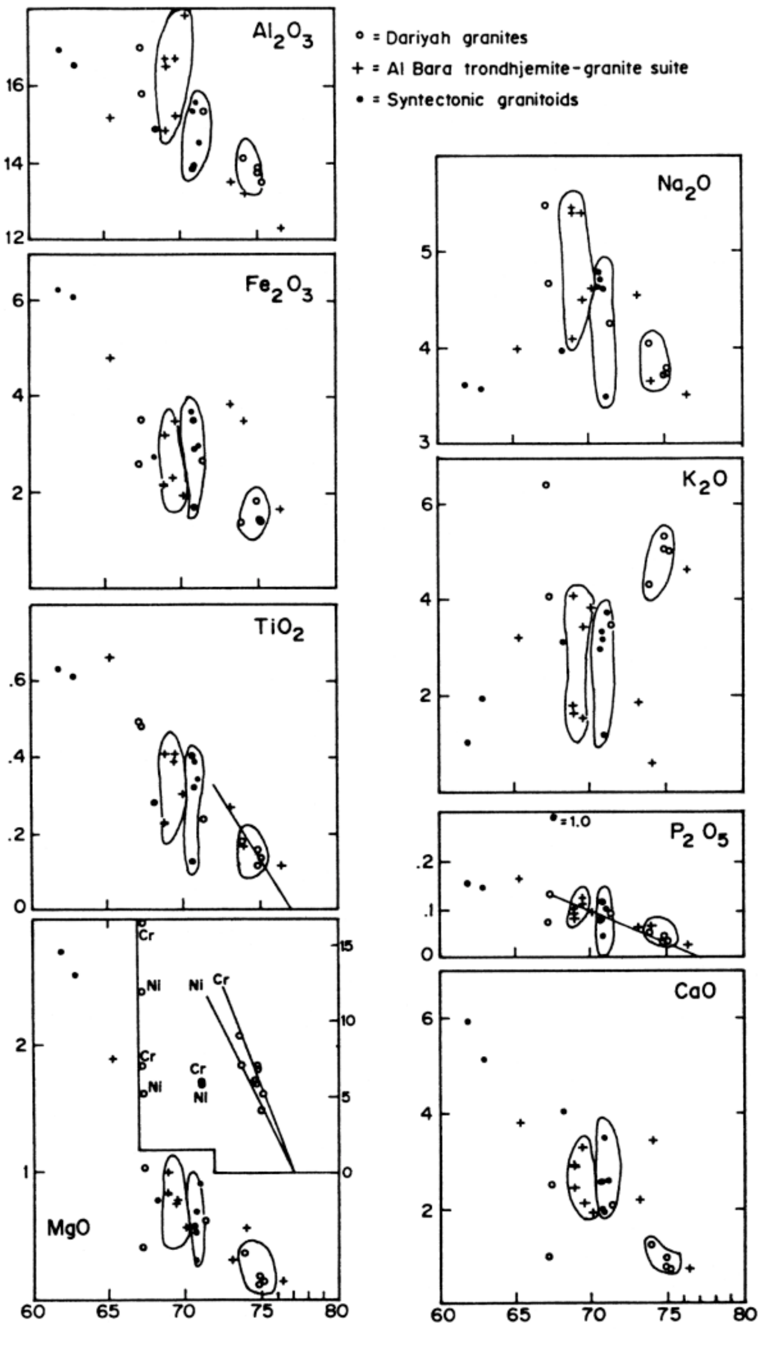


FIG. 4. Harker diagrams for the major elements. Regression lines for Dariyah batholith granites, shown for TiO_2, MgO, P_2O_5, Ni, Cr, were extrapolated to the SiO_2 content (~ 77%) at which contents of these elements reach to zero values.

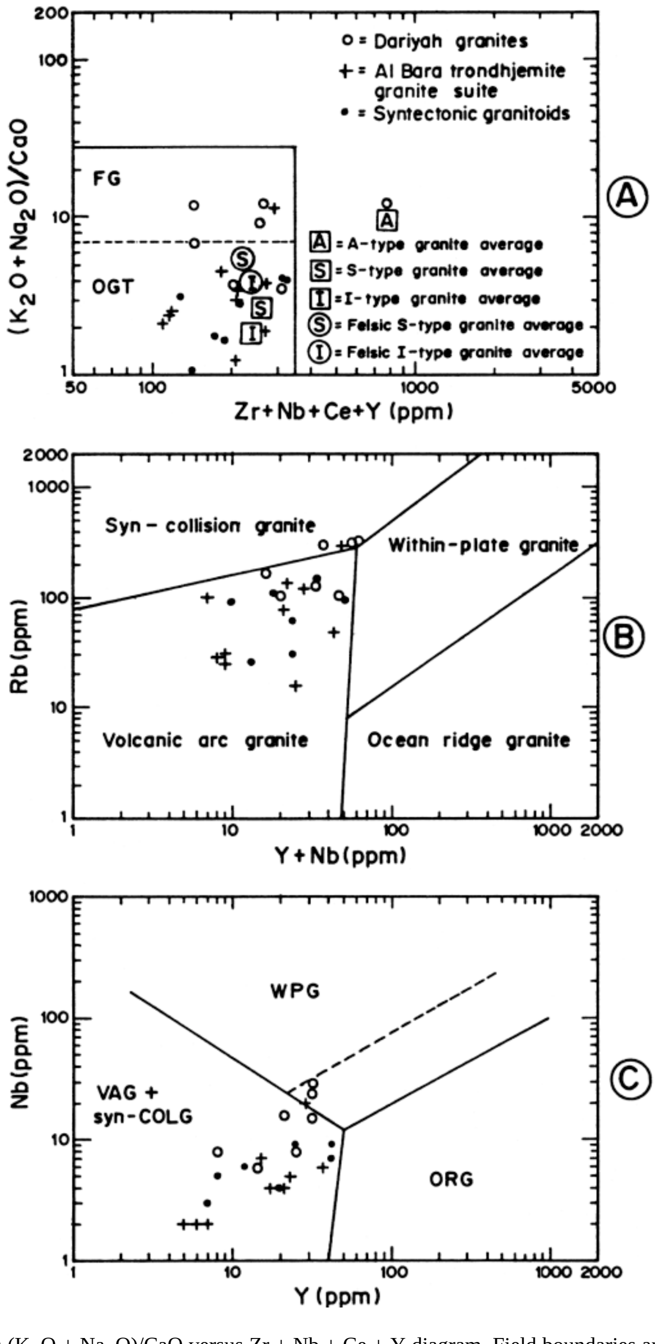
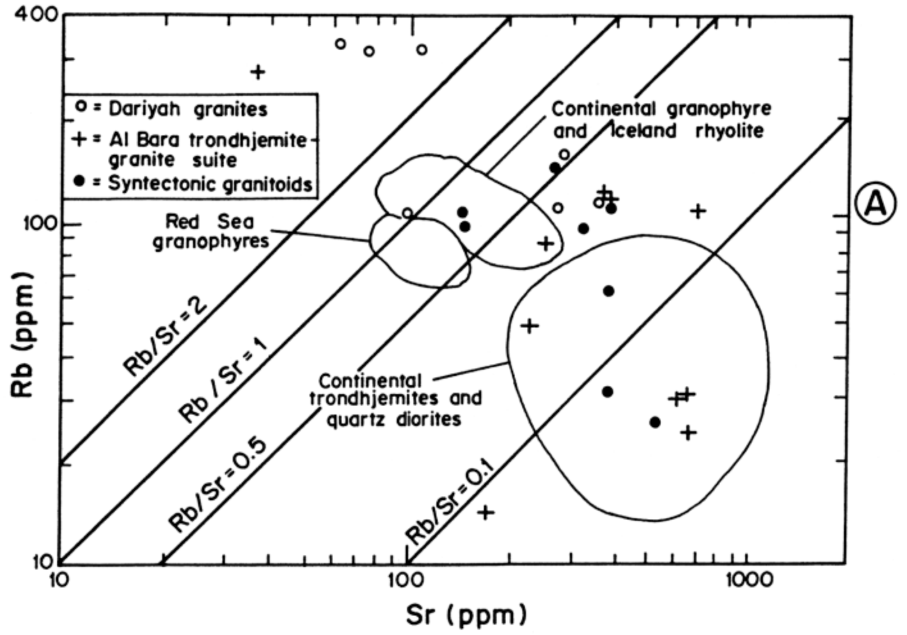


FIG. 5(A-C). **(A)** (K_2O + Na_2O)/CaO versus Zr + Nb + Ce + Y diagram. Field boundaries and average granite compositions from Whalen *et al.* (1987). **(B,C)** Discrimination diagrams after Pearce *et al.* (1984) showing fields of various tectonic settings for granitic rocks and position of the studied granites.

low Rb and high Sr contents than those of evolved average granite with 170-220 ppm Rb (Heier and Billings 1970); or 150 ppm Rb (Taylor 1965) and 285 ppm Sr (Taylor 1965) or 147 ppm Sr (Faure 1978). Both suites, with a range of Rb/Sr ratios (0.04-7.97), indicate a mixed mantle-crust origin for their magmas. In contrast, relatively high Rb (105-335) and low Sr (62-360) contents and high Rb/Sr ratios (0.39-5.40) characterize the post-tectonic Dariyah granites. This Rb/Sr range suggests a continental crustal environment. A bulk mantle-crust Rb/Sr ratio of 0.030 and a continental crust Rb/Sr range of 0.15-0.35 are well documented in the literature (Gast 1960, 1968, Faure and Hurley 1963, Hart and Tilton 1966, Shaw *et al.* 1967, Hurley 1968, Armstrong 1968, Faure and Powell 1972, Shaw 1975, Jahn and Nyquist 1976). On the Rb-Sr variation diagram (Fig. 6A) most Afif syntectonic granitoids and the Al Bara trondhjemite-granite suite plot within or close to the boundary of continental trondhjemite and quartz diorite. The Dariyah batholith granites with high Rb contents plot near the continental granophyre field as well as in the no field defined area of the diagram.

On the K/Rb diagram (Fig. 6B), almost all Afif syntectonic granitoids and the Dariyah granites fall in the range of mature continental crust (100-300; Heier and Adams 1964), with one sample of each falling outside this range. However, within this range there is a tendency for Rb enrichment in the Dariyah granites indicating an evolved stage of differentiation. In contrast, most Al Bara trondhjemite-granite rocks with a K/Rb range of 312-516 indicate a less fractionated magma and an early stage of intrusion. A K/Rb ratio of 300-400 is suggested for the primitive mantle rocks (Sun 1982). The high K/Rb ratio refutes the derivation of this batholith by a normal fractional crystallization from a granitic or S-type crustal protoliths. The low Rb content in the Al Bara batholith rocks clearly indicates scarcity of Rb in the environment.

Multi-element diagrams of incompatible element abundances normalized to primordial mantle values (Wood 1979) are shown in Fig. 7. All three groups of rocks display patterns of significantly negative Nb-Ti anomalies. The Nb depletion (< 15 ppm) is typical of all island arc volcanics as well as rocks from other destructive plate margins like, continental margin (Hofman 1988, Thompson *et al.* 1984). The granitoids formed above subduction zones have a typical Nb value of < 15 ppm (Pearce and Gale 1977). The magmas formed in within-plate tectonic setting are characterized by high Nb (> 15 ppm) contents (Pearce and Cann 1973). Only three samples of Dariyah batholith granites have Nb contents of 16-30 ppm. Deeper troughs at Sr and Ti express fractionation in these rocks. The Afif syntectonic granitoids and trondhjemite-granite suite of the Al Bara batholith show an enrichment of Rb, Ba, K, La, Ce and Sr relative to Nb, Zr, and Ti, suggesting their derivation from mantle source contaminated by a subduction zone component (Hawkesworth 1982). The higher levels of Rb, K, Nb, La, Ce and Sm in the Dariyah granite suite compared to Afif syntectonic granitoids and the Al Bara trondhjemite-granite suite indicate the greater involvement of continental crustal components. The concentration of Sr, K, Rb rule out an origin from intraoceanic arc systems (Pearce 1982). The Al Bara trondhjemite-granite suite shows a large variation in the incompatible element patterns, reflecting a partial rejuvenation of this batholith, most probably during the emplacement of Dariyah batholith granites.



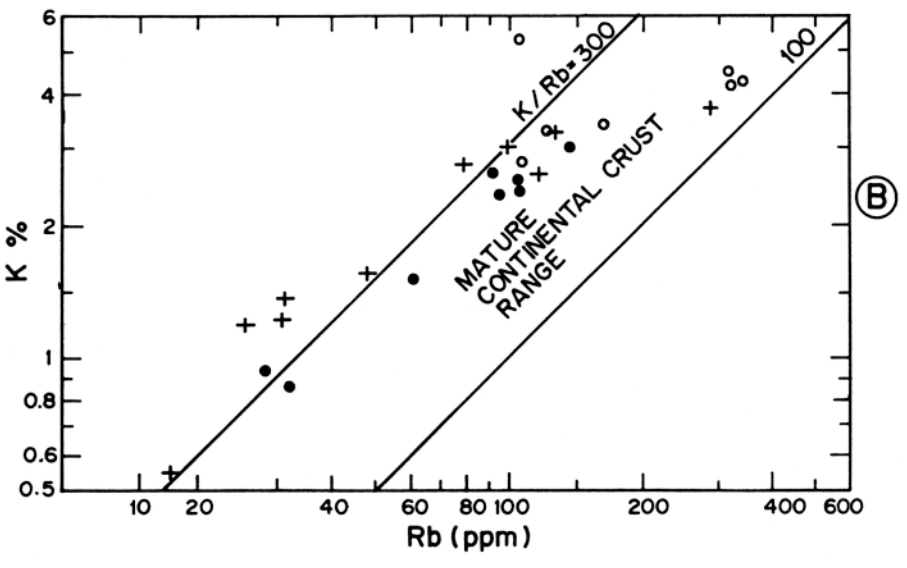


FIG. 6(A-B). **(A)** Rb/Sr discrimination diagram for granitoid rocks (after Coleman and Peterman 1975). **(B)** K/Rb plot showing the mature nature of the continental crust in the study area.

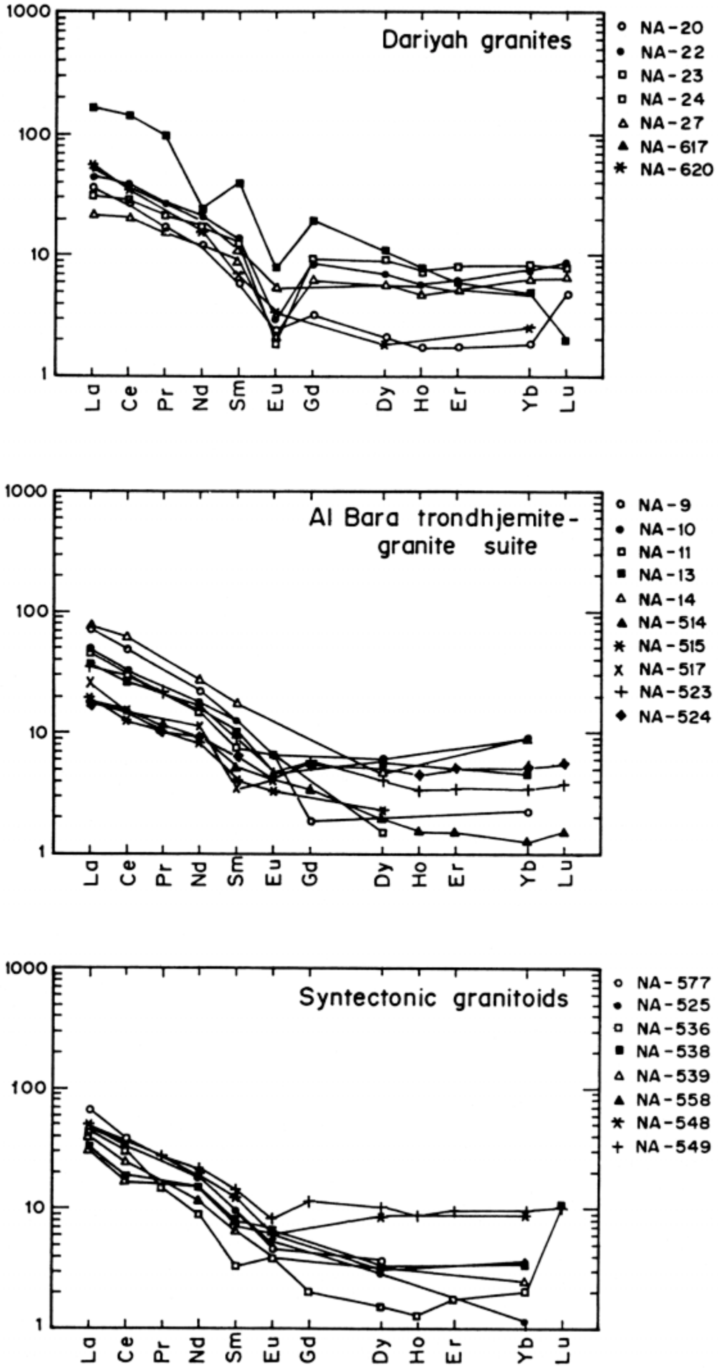


FIG. 7. Multi-element diagram of incompatible element abundances, showing the chemical patterns (normalized to primordial mantle values; Wood *et al.* 1979) of the syn- to post-tectonic granites.

Primitive mantle normalized REE plots of the three granitoid suites are given in Fig. 8. All the patterns show enrichment in light REE (La-Nd) with respect of fractionated flat heavy REE (Gd-Lu) patterns. The Afif syntectonic granitoids and the Dariyah granites have almost similar fractionated REE patterns with La/Yb_n = 3.51-22.32 except one sample from each group with highly deviated La/Yb_n ratios of 42.1 and 34.14 respectively. The Dariyah granites have significantly higher average REE contents (156 ppm) than the Al Bara trondhjemite-granite suite (107 ppm) and the Afif syntectonic granitoids (106-ppm). The Dariyah granites show pronounced negative Eu anomalies [$(Eu)_n/Eu^*$ = 0.04-0.12 (5 samples)], compared to shallow negative anomalies of the Al Bara trondhjemite-granite suite [$(Eu)_n/Eu^*$ = 0.15-0.23 (4 samples)] and the Afif syntectonic granitoids [$(Eu)_n/Eu^*$ = 0.15-0.35 (2 samples)].

Discussion

The Afif syntectonic granitoids (680-640 Ma, Stoeser and Stacey 1988), occurring within or in the vicinity of the Nabitah orogenic belt, are commonly referred to as collision-related granitoids formed as a result of collision between the accreted western oceanic terrane (Asir-Hijaz) and the continental Afif terrane. The discovery of 750-700 Ma old Andean type Siham arc (Agar 1985) along the western margin of the southern part of the Afif terrane led many workers (Agar 1988, Agar *et al.* 1992) to reinvestigate the tectonic relationships and to interpret the tectonic and geologic history of the area. The origin of pre-Nabitah syn-orogenic magmatic rocks was problematical until the discovery of Siham arc. Agar *et al.* (1992) interpreted the pre-Nabitah gneisses as syntectonic granitoid intrusives formed during the formation of an Andean-type Siham arc continental margin. The studied syn-tectonic granitoids with hybrid nature, gneissic/ foliated texture and the contact relationships with the An-Nayzah formation in the Afif quadrangle and the Siham arc metasedimentary rocks in the Zalm quadrangle (Agar 1988) are consistent with synorogenic plutonic rocks that generate in a compressional orogenic environment (Stoeser *et al.* 1984). The Naim complex syntectonic granodiorite gneiss which intrudes the metamorphosed facies of the An Nayzah formation in the Afif quadrangle and Kabid-Tays basement complex (polydeformed high grade metamorphic rocks, migmatites, charnokites) and the Siham group metasedimentary rocks in the Zalm quadrangle is dated at 746 ± 10 Ma by the model 2 (*i.e.* lower intercept forced through 15 ± 15 Ma) U-Pb zircon method (Agar *et al.* 1992). Similar type of granodiorite gneiss of Gathar complex which intrudes the highly deformed and metamorphosed Hulayfah group rocks (equivalent to Siham group) in the Wadi Ar Rika quadrangle (Delfour 1980) to the east of Zalm quadrangle is dated at 750 ± 7 Ma (model 2 U-Pb zircon age; Agar *et al.* 1992). The syntectonic gneissic horblende-biotite granodiorite exposed around sample locality 536 (this study) yielded a whole rock Rb-Sr isochron age of 718 ± 25 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7038 ± 0.0003 (Fleck and Hadley 1982). This widespread occurrence of pre-Nabitah synorogenic granitoids in the vicinity of the Siham arc indicate that the synorogenic granitoid rocks were the major components of the Siham arc prior to Nabitah orogeny.

Latalenet (1979) considered the Al Bara batholith rocks as older granites rejuvenated during the Murdama period (650-615 Ma). Agar *et al.* (1992) extended the limits of the

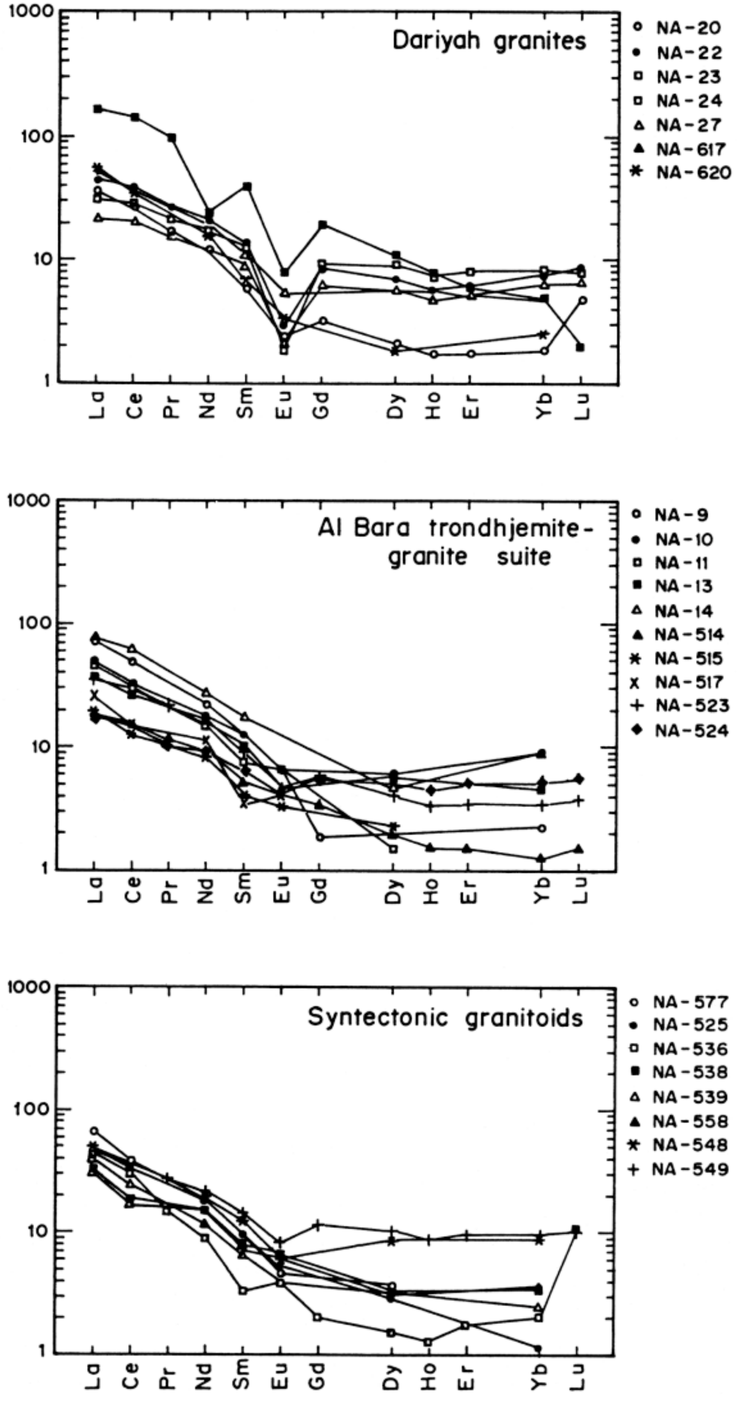


FIG. 8. Primitive mantle normalized REE patterns of the different granite groups.

1800-800 Ma old Kabid-Tays basement complex from the Jabal Khida to near Afif and included the Al Bara batholith in the basement complex. Stoeser and Stacey (1988) found extremely elevated continental-Pb signatures in the feldspars of 673 ± 9 Ma biotite granodiorite ($^{207}Pb/^{204}Pb$ = 15.621, $^{208}Pb/^{204}Pb$ = 37.832) and 647 ± 7 Ma cataclastic biotite-horblende tonalite ($^{207}Pb/^{204}Pb$ = 15.719, $^{208}Pb/^{204}Pb$ = 39.125) exposed in the north-central part of the Afif quadrangle. Their zircon U-Pb data of granodiorite and tonalite show scattering on the concordia due to assimilation of older zircons from the basement rocks during emplacement. Agar *et al.* (1992) concluded that the Najd faulting (620 Ma, Stacey and Agar 1985) fragmented some parts of the basement rocks and transported them at least 100 km to the northwest. A long period of granitoid activity extending from about 746 ± 5 Ma to 570 Ma in the Al Bara batholith rocks is reflected by the inclusions of unassimilated earlier intrusions of diorite, granodiorite, and syntectonic heterogenous-granite suite which itself contains small inclusions of gabbro, diorite and amphibole gneiss. This plutonism is virtually coeval with the formation of Siham arc (750-700 Ma), Nabitah orogenic belt (680-640 Ma) and the post-orogenic activity (610-570 Ma).

The origin of the Al Bara batholith is somewhat problematic. There may be two interpretations for its rocks formation: (1) they represent part of the basement rocks deformed and remobilized during the formation of Nabitah orogenic belt (680-640 Ma) and the Najd orogeny (647-552 Ma), or (2) they were generated by continental margin magmatism associated with east-directed subduction of oceanic crust beneath the Afif basement rocks. The possibility of a continental margin magmatism is supported by the continental trondhjemites (> 15% Al_2O_3), enrichment of LILE and relative depletion of Nb in the Al Bara batholith rocks. These features are consistent with active subduction zones of the Cenozoic environments. The elevated $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios in the fault-bound plutons of granodiorite and tonalite exposed just north of the Al Bara batholith and the presence of Siham arc assemblage to the west of the batholith support the interpretation that the Al Bara batholith was part of the basement of the Siham arc. No U-Pb isotope data are available for this batholith. The 571 ± 19 Ma age of Fleck and Hadley (1982) for the youngest post-tectonic intrusive biotite granite of the Al Bara batholith can not be a representative for the entire batholith. The plutonic record of this batholith extends from about 746 to 570 Ma. In our view, older basement rocks were fragmented and detached from the main mass during early stages of development of the Andean-type Siham arc and deep-seated within the oceanic crust along the western margin of the Afif terrane. Later on, east-directed subduction of the oceanic crust beneath the western margin of the Afif terrane generated the Al Bara batholith rocks and assimilated and pierced the basement rocks on either side of it. A long period of tectonic activity such as deformation, collision, uplifting, crustal thickening, mobilization and plutonism complicated the tectonic and geologic history of the area. A detailed geological study backed up by U-Pb zircon ages is needed to interpret the presence and the extent of involvement of the basement rocks in the formation of the Al Bara batholith.

Large calc-alkaline massifs in the Afif (Letalenet 1979) and Miskah (Pellaton 1985) quadrangles with a dominant lithology of granites and granodiorites are mapped as Post-Murdama age. Although among them there are many granitoid bodies which range in composition from gabbro to leucogranite and have a long history of evolution (*e.g.* The Al Bara batholith of this study). In the case of Dariyah batholith, the dominant lithology is restricted to biotite granite and syenogranite. Stuckless and Futa (1987) collected samples from the full length of the batholith and obtained a whole-rock Rb-Sr isochron age of 585 ± 8 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7037 ± 0.0003. This age is consistent with an intracratonic post-orogenic activity in the northern half of the Arabian Shield during 600-560 Ma (Baubron *et al.* 1976, Calvez *et al.* 1983, Stacey *et al.* 1984, Stuckless *et al.* 1984, Aleinikoff and Stoeser 1988).

The origin of several stocks and batholiths of biotite granite, which intrude the Murdama group, is problematic due to their emplacement in the back-arc basin (Greene 1933). Delfour (1979b, 1980) described the Murdama rocks to have been deposited on a basement of felsic plutonic rocks. Ikeda (1978) found a close relationship between the compositions of Japanese granites and the nature of their country rocks. According to him granodiorite and granite occur where the country rocks are acid igneous or sedimentary, whereas quartz diorite and tonalite occur where the surrounding rocks have a dominant lithology of basic igneous rocks. Dariyah batholith rocks are consistent with Ikeda's model of interaction between country rocks and the compositions of granitic rocks. Dariyah batholith rocks have a progression of composition from biotite-hornblende granodiorite to biotite granite, quartz syenite and eventually syenogranite. The absence of chilled margins among these granite facies reflects that these rocks belong to the same magmatic cycle. On the basis of geological, chemical and tectonic studies, a mixed origin of crustal sedimentary (Cs) and crustal igneous (Ci) (Didier *et al.* 1982) is suggested for the batholith. Low degree of partial melting of felsic crust can produce large batholiths of anatectic leucogranites (Batchelor and Bowden 1985). The mobilization of the felsic melt in the crust and its emplacement at a higher level is reflected by the presence of quartz syenite and syenogranite in the Dariyah batholith. In our view the chemical characteristics of the Dariyah batholiths are also controlled in part by restite-melt mixing model of Chappel and White (1974) and White and Chappel (1977). Compositions of such granitoids define straight lines on element-element diagrams (Meen and Eggler 1989). On the Harker plots (Fig. 4) most of the samples of D ariyah batholith show zero intercepts of MgO, TiO_2, P_2O_5, Cr and Ni at similar extrapolated SiO_2 contents (~ 77%). The liquids derived from most crustal sources such as basalts (Helz 1976) or pelites (Kilinc 1972, Green 1976) show similar compositions of SiO2 (~ 76%) and essentially zero contents of MgO, TiO_2, P_2O_5, Cr and Ni. Melt compositions in the Dariyah granites are dominated by > 90% of minimum melting components (quartz, orthoclase, albite). Thus, the porphyritic granite varieties of the batholith are probably mixtures of phenocrysts (presumably restite) such as plagioclase, amphibole, biotite and hornblende and minimum melts derive from the mafic-intermediate parental melts and the crustal source, respectively.

Conclusions

The elongated bodies of syntectonic granitoids exposed in the Afif quadrangle and which have previously been considered to represent synorogenic plutonic rocks of the

Nabitah orogeny are, actually, of Pre-Nabitah age (< 680 Ma) and were probably generated during the formation of the Andean-type Siham arc (750-700 Ma).

The Al Bara granite batholith has a long history of plutonism that extends from about 750-570 Ma. However, a substantial part of the batholith formed during the formation of Siham arc. Field evidence and age data suggest that these rocks were rejuvenated many times during Pan-African orogeny (c. 900-550 Ma).

The chemistry of the syntectonic granitoids and the Al Bara batholith trondhjemite-granite suite suggest their emplacement along an active continental margin (*i.e.*, Siham arc).

The more silicic Dariyah batholith which intrudes the 650-615 Ma old Murdama basin is mostly biotite granite but has considerable quantities of granodiorite, quartz syenite and syenogranite. All rocks of the batholith are co-magmatic and are in part porphyritic. Chemical and mineralogical variations in the batholith are partly modeled as mixtures of minimum melts and phenocrysts (probably restite). The limited in-situ fractional crystallization of the magma after intrusion into higher levels of the crust is evident by deeper troughs at Ba, Sr and Ti (spider diagram) and by strong negative Eu anomaly.

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جيوكيمياء والتطور التكتوني للجرانيتات التجبلية المصاحبة لقوس سهام من النوع الانديانى وسط الدرع العربي

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المستخلص . تُعد المحقونات الجرانيتية المتزامنة مع التجبل ومجموعة باثوليت البارا (ترونجوميت - جرانيت) التي تظهر في مربع عفيف من المملكة العربية السعودية المكونات الجوفية الرئيسية لقوس سهام من النوع الانديانى والذي نشأ خلال الفترة من ٧٥٠ إلى ٧٠٠ مليون سنة على طول الحافة الغربية لإقليم عفيف .

تتميز الصخور الجوفية بتنوع صخري يتراوح تركيبة من الديوريت وحتى صخور الجرانيت الفاتحة كما تتميز بفترات متعددة من النشاط الجوفي والتجدد خلال زمن تجبل الحمى الافريقية (٩٠٠-٥٥٠ مليون سنة) .

تعتبر التداخلات الجرانيتية المتزامنة مع التجبل وصخور باثوليت البارا صخور كلس قوية من أصل ناري (نوع I) ذات تركيب انتقالي من ميتا الومنية إلى فائقة الالمونية وهي غنية بعناصر Rb, Ba, K, La, Ce, Sr نسبة إلى عناصر Nb, Zr, Ti مما يدل على تموضع على طول حافة قارية نشطة .

إن باثوليت البارا بتغيراته الواسعة الصخرية النسيجية وفي أنماط العناصر غير المتوافقة يدل على التأثير الكبير لتجبل الحمى الافريقي .

باثوليت ضرية اللاحق لتكتونية تداخل قبل ٥٨٥ مليون في مجموعة مردمة التي تكونت في حوض خلف قوسي يتكون من صخور فتاتية رسوبية وكميات قليلة من الحجر الجيري والصخور البركانية وذلك في الحقب البروتوزوي المتأخر (٦١٥-٦٥٠ مليون سنة) .

ويتراوح تركيب باثوليت ضرية من جرانوديوريت إلى سيانو جرانيت لكن صخور البيوتيت - جرانيت هي الأكثر شيوعاً .

معظم صخور الباثوليت له نسيج بوفيري ولا تُظهر أي حواف متجمدة وقد صيغت الأنواع البورفيزية على أنها خليط مكون من بلورات ظاهرة وكبيرة يمكن افتراض أنها متبقيات (RESTITE) وكميات ضئيلة من السوائل .

إن النسب العالية من عناصر Rb, Na, La, Sm والنقص الواضح في عناصر Ba, Sr, Ti والشـذوذ السلبي القـوي لعنصـر Eu دليل على تمايز مـوضـعي لصخور ضرية بعد التداخل في مستويات عالية من القشرة .