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AGE, GEOCHEMISTRY AND ORIGIN OF PERALUMINOUS A-TYPE GRANITOIDS OF THE ABLAH-SHUWAS PLUTON, ABLAH GRABEN, ARABIAN SHIELD

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ABSTRACT

The A-type granitoids of the Ablah-Shuwas pluton, situated in the Ablah graben of the Asir terrane, occur as discontinuous ring complexes, cone sheets and irregular bodies. They intrude into the younger diorite and tonalite rocks of probably 744±22 Ma old. Their emplacement is contemporaneous with the movement (~610 Ma or later) along the Umm Farwah shear zone, which cuts the eastern margin of the rift-related epiclastic and volcanic complex of the Ablah group. The whole rock Rb-Sr isochrons indicate shear zone compatible ages of 617±17 and 605±5 Ma for the syenites and quartz syenites-granites, respectively. The low initial $^{87}Sr/^{86}Sr$ ratios (0.7035-0.7038) in the A-type granitoids indicate either a mantle origin or a Rb-depleted crustal source.

The granitoids show the petrological and geochemical characteristics of a typical A-type granite. They are composed of suites of cogenetic syenites, quartz syenites, and syenogranites with iron- and alkali-rich silicates, high FeO^t/MgO and Ga/Al ratios. They show the marked enrichment of high field strength elements (Zr, Nb, Y and Ga), Zn, and Na_2O+K_2O and depletion in CaO and MgO with a large negative Ba anomaly.

The origin of A-type granitoids is related with the Umm Farwah shear zone that trigger off partial melting in the volatiles and LIL-enriched metasomatized mantle. The rise of this mantle flux through reactivated; deep-seated; heat-laden shearzones/faults caused crustal fusion in the arc-related lower mafic and upper volcano-plutonic crust of intermediate to felsic compositions to produce A-type granitoids.

Key words: A-type granitoids, Ablah-Shuwas pluton, Ablah-graben, Asir terrane, Umm Farwah shear zone, ring complexes, syenites, quartz syenites, syenogranites, metasomatized mantle, crustal fusion.

INTRODUCTION

The Arabian Shield mainly developed and cratonized in the Neoproterozoic (~950-550 Ma) as a results of subduction-related volcano-plutonic arc magmatism and their related sedimentation (~950-715 Ma) followed by arc/backarc and microplate accretion and continental collision (715-640 Ma), filling of intracratonic rifts, and post-accretion magmatism and tectonism (640-550 Ma) (Stoeser, Camp, 1985; Jackson, 1986; Greene 1993).

The Arabian Shield alkali-feldspar granites of the post-accretion magmatism are considered as A-type (anorogenic) granites (Stoeser, 1986). The tectonic environment of the alkali-feldspar granites that emerge late in orogenic cycles is used as a basis of classification (Loiselle, Wones, 1979; Collins et al., 1982; Pitcher, 1982). Stoeser (1986) described that the post-orogenic magmatism of the Arabian A-type granites was continued for about 70 years after accretion. He subdivides the alkali-feldspar granite that constitutes about 7% of all plutonic rocks of the Shield into: biotite and (or) hornblende alkali-feldspar granite; alkali granite; and aluminous granites.

Detailed petrological studies of the plutonic rock associations of the post-accretion stage in the western part of the Arabian Shield (central Hijaz: Jackson et al., 1984; Jackson, 1986; Midyan region: Ramsay et al., 1986) and eastern part (southern Najd province: Dodge, 1979; Kanaan, 1979; Stuckless et al., 1982, 1983; Le Bel, LaVal, 1986; Du Bray, 1986) reveal the domination of at least three types of felsic plutonic rock associations: 1) monzogranite and granodiorite with high Ca and Mg contents; 2) syenogranite and monzogranite with moderate Ca and Mg contents; and 3) alkali-feldspar granite and quartz-alkali-feldspar syenite with very low Ca and Mg contents. The major difference found between eastern and western felsic plutonic rocks was the widespread occurrence of low-Ca, low-Mg, high FeO_t alkali granites in the western part. Jackson et al. (1984) grouped the high Ca granites of the monzogranite association with I-type rocks and the alkali granite and alkali-feldspar granite association with A-type.

The term 'A-type' was defined by Loiselle, Wones (1979) to differentiate 'mildly alkaline' rocks (A-type) from typical calc-alkaline (I-type) rocks with anhydrous character of magmas. The other geochemcial characteristics of the A-type granites, which are discussed by several workers (Loiselle, Wones, 1979; Whalen et al., 1987; King et al., 1997; Pearce et al., 1984; Hermes et al., 1981; Collins et al., 1982) are high ratios of FeO(t)/(FeO(t)+MgO), F/H_2O, and Ga/Al, high contents of Na_2O+K_2O, highly charged cations such as Ga, Zr, Nb, Y, and trivalent rare earth elements (REE^{3+}) and Zn, and lower abundances of Mg, Ca, and Fe-Mg trace elements (Cr, V, Ni,Cu) and Sr with significant Ba and Eu anomalies.

A-type granitoids are typically metaluminous but peralkaline and peraluminous A-types also occur. Whalen et al. (1987) and Bonin (1988) included calc-alkaline and peralkaline rocks in their A-type group, respectively. Brown et al. (1984) included the alkaline to alkali-calcic and peralkaline rocks in their A-type category. Based on distinctive field, chemical and petrographic characteristics, King et al. (1997) strongly opposed the inclusion of peralkaline rocks in the category of A-type granites. A-type granitoids from the southwestern part of the Indian Peninsula are designated as ultrapotassic aluminous A-type granitoids on account of high contents of $K_2O/Na_2O>2$, $K_2O>3$ wt.% (Foley et al., 1987) and Al_2O_3 (14 to 19 wt%).

A-type granitoids are reported from a variety of tectonic settings such as rift environment (e.g., Oslo graben: Sundvoll, 1978; Yemen rift: Capaldi et al., 1987); intra-continental ring complexes (e.g., the anorogenic complex of Evisa, Corsica: Boninet et al., 1978; alkaline complexes of Sudan: Black et al., 1985); hotspots or plume environment (e.g., White Mountain batholith, New Hampshire: Eby et al., 1992; Ras ed Dom ring complex, Sudan: O'Halloran, 1985); and post-collisional or post-orogenic settings (e.g., Gabo and Mumbulla suites of the Lachlan fold belt, Australia: Collins et al., 1982; Topsails complex, Newfoundland: Whalen et al., 1987b; granites of the western Adirondacks, USA: Whitney, 1992; Homrit Waggat complex, Egypt: Hassanen, 1997). Rocks classified as A-type granitoids generally include large group of rocks such as syenite, quartz syenite, granites, rapakivi granites, etc.

In the present investigation, new geochemical and Sr isotopic data are presented for the A-type granitoids of the Ablah-Shuwas pluton, situated in the Ablah graben of the Asir terrane. The results obtained from this investigations are used to determine the nature and probable origin of these A-type granitoids.

TECTONIC AND GOLOGIC SETTING

The Arabian Shield is thought to have formed by accretion of intra-oceanic island arcs, back-arc basin complexes, and allochthonous continental blocks or microplates mainly during Pan-African time (about 680-640 Ma) (Stoeser et al., 2001; Johnson, 2000; Camp, 1984; Stoeser, Camp, 1985). This complex tectonic history formed the Neoproterozoic (about 900- ~570) Arabian Shield crystalline basement, composed of: (1)deformed and metamorphosed volcano-sedimentary assemblages of oceanic plateau, mid-oceanic-ridge, intraoceanic and continental-margin tholeiitic and calc-alkaline volcanic arcs, epicontinental volcano-sedimentary rocks, and back-arc, pull-apart and graben assemblages; (2) vast amount of orogenic plutonic rocks such as gabbro, diorite, quartz diorite, tonalite, trondjeminte and granodiorite; and (3) synorogenic, post-orogenic and anorogenic granites such as tonalite, trondhjemite, granodiorite, gabbro, granite and syenite (Johnson, 2000; Stoeser, 1986).

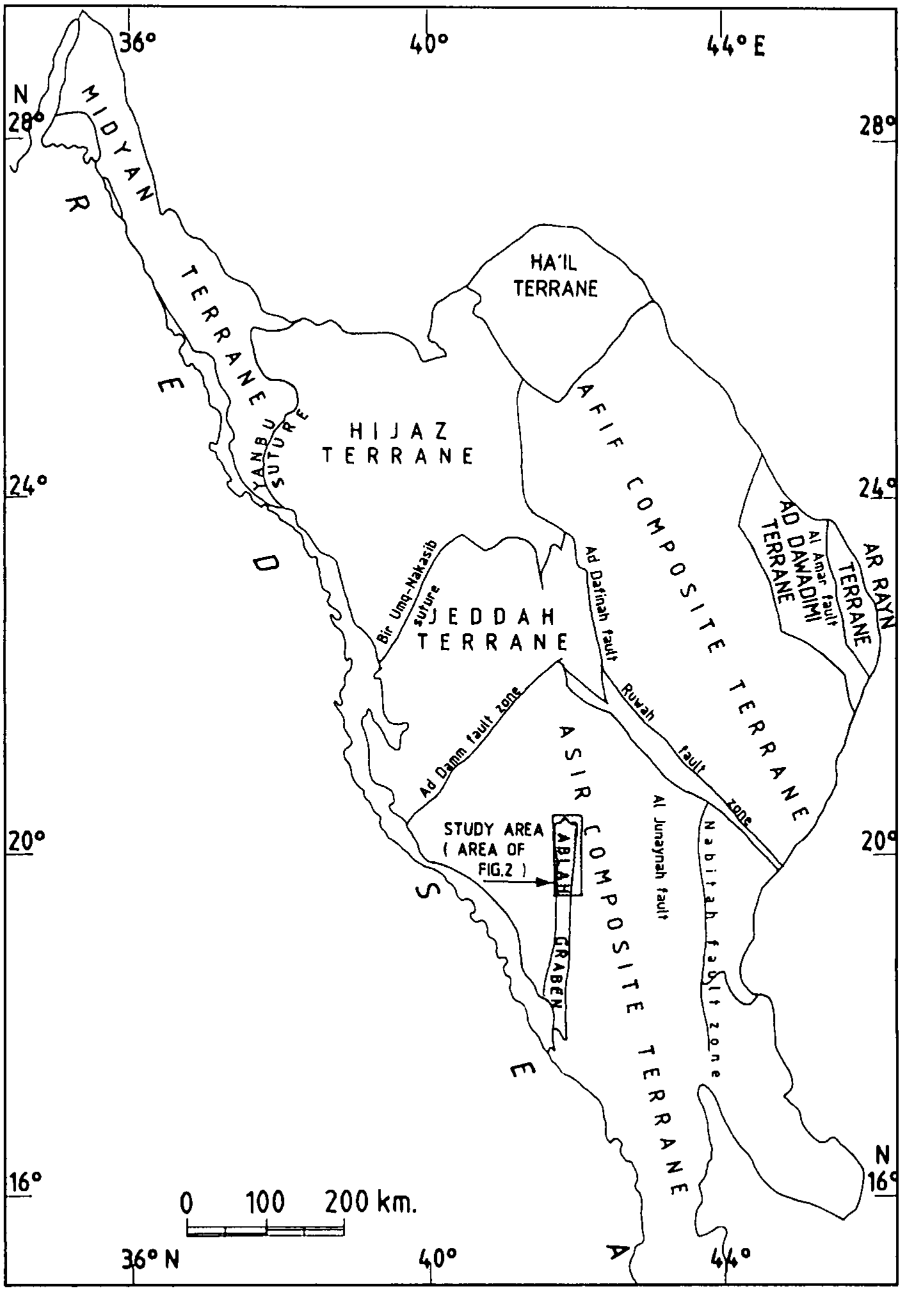

Fig. 1. Tectonic framework of the Arabian Shield showing major terranes, suture zones, location of Ablah graben and the study area (after Stoeser, Camp, 1985; Johnson, 2000).

The latest tectonic model divides the Arabian Shield into eight distinct geological terranes separated mostly by ophiolite-decorated suture zones (Fig. 1). The four ensimatic terranes: Asir composite, Jeddah, Hijaz, and Midyan, occur in the west, whereas the four continental affinity terranes: Afif composite, Ad Dawadimi, Ar Rayn and Hail, crop out in the east.

The A-type granitoids of the Ablah-Shuwas pluton, which are exposed in the Ablah graben are part of the oceanic Asir composite terrane that forms north-trending belts of arc-related meta-volcanosedimentary and orogenic plutonic rocks. Three principle layered arc assemblages in the Ablah-Shuwas area are, from east to west, the Qirsha and Khutna formations and the Ablah group (Fig. 2).

A major submeridian fault marked by serpentinite separates Ablah group from the Khutna formation (Donzeau, Beziat, 1989).

The orogenic younger diorite-tonalite rocks, which are exposed in the Jabal Ibrahim quadrangle (GM-96 C, Sheet 20E; Cater, Johnson, 1987) are represented by at least three groups of plutons, two of them are trending in northeast direction and the third one in the northwest. They intrude at the contact between the Khutnah formation and the Ablah group.

The anorogenic (post–tectonic) A-type granitoids, which occur in three phases as successive rings, cone sheets and irregualr bodies, intrude the northeast trending Ablah-Shuwas diorite-tonalite pluton (Fig. 3). The complex forms an elliptical pluton of about 16 km long and as much as 6 km wide. Greenwood (1975) classified the A-type granitoids into late- to post-tectonic, granodiorite and monzogranite. Fleck et al. (1980) reported a Rb-Sr whole rock age of 636±21 Ma (initial $^{87}Sr/^{86}Sr=0.7035$) for this A-type granitoids. The same rocks, which occur about 3 km southwest of the studied pluton, produced Rb-Sr ages of 617±10 Ma and 630±10 Ma (Brown et al., 1978; Greenwood, 1975).

The Qirsha and Khutnah formations and their related diorite-tonalite intrusive rocks represent an island-arc complex, which is probably developed between 750 and 720 Ma (Cater and Johnson, 1986). They consist of sheared and altered volcanic and volcaniclastic rocks of tholeiitic and calc-alkalic composition (Bokhari, Kramers, 1981). Donzeau, Benziat (1989) assigned the Qirsha and Khutna formations to the Jeddah group (> 800 Ma). The 11-point errochron Rb-Sr age of 721±55 Ma and a Nd-Sm age of 757±256 are reported for metavolcanic rocks of Qirsha (Surgah) formation (Bokhari, Kramers, 1981). A Rb-Sr age of 744±22 Ma is determined (Marzouki et al., 1982) for the younger diorite-tonalite rocks of the Tharad pluton, which occurs northwest of the Ablah-Shuwas pluton.

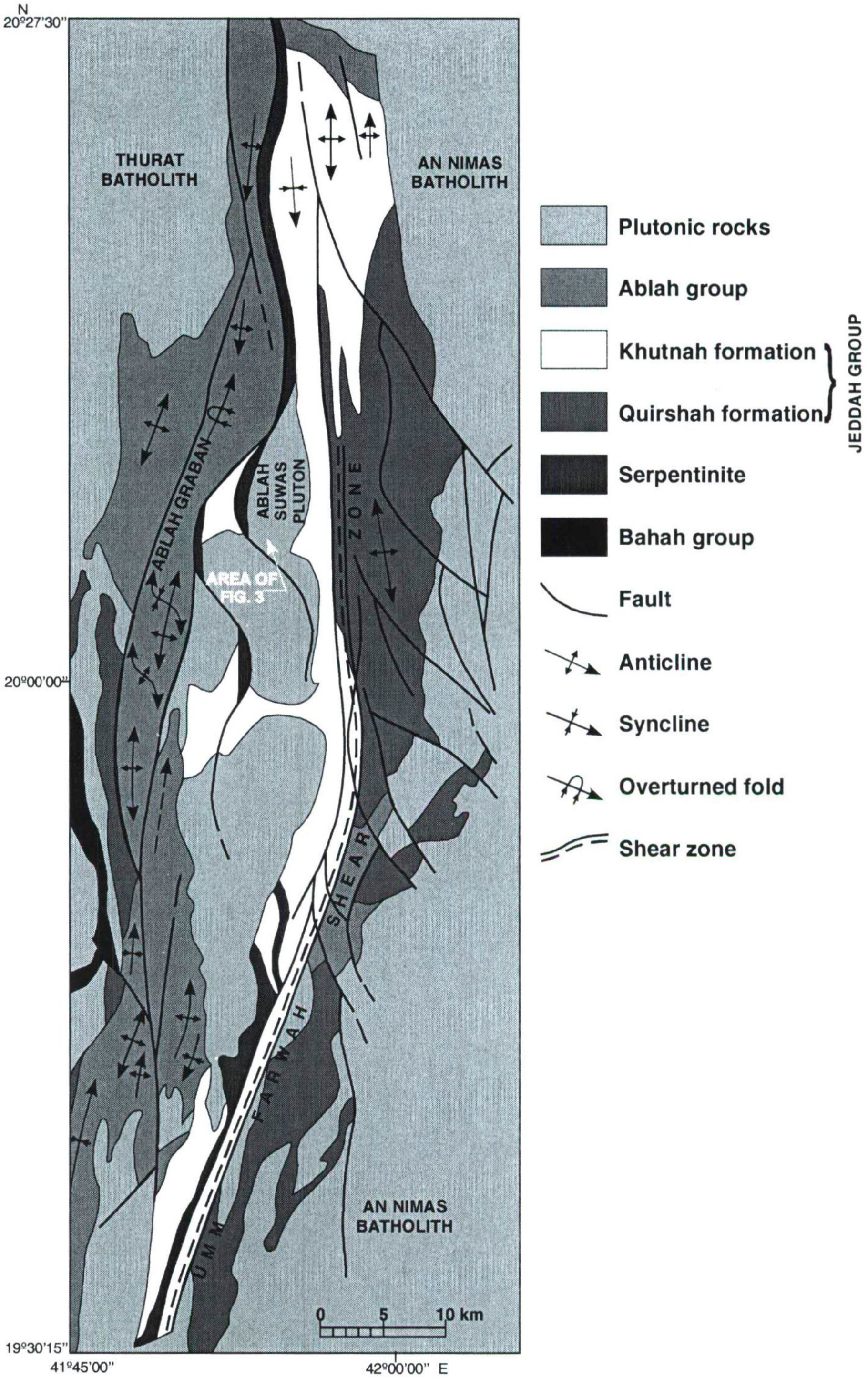

Fig. 2. Simplified geological map of the Ablah-Wadi Shuwas area showing major geologic units and Umm Farwah dextral shear zone (after Donzeau, Beziat, 1989; Johnson, 2000).

The Ablah group consists mainly of epiclastic sedimentary and volcanic complex, deposited unconformably on the adjacent volcanic arc complex. The bimodal volcanism in the Ablah graben indicates a continental-rift or back-arc environment in relation to adjacent Qirsha and Khutnah volcanic arc, which is characterized by mafic to felsic volcanism (Donzeau, Beziat, 1989). The Ablah-belt or Ablah volcanic rift (Greenwood et al., 1982) is about 150 km long, north-south trending graben of extensional tectonic regimes in the Arabian Shield (Fig.1). The rocks of the Ablah group are strongly folded about north-south axes, and are strongly metamorphosed to greenschist and amphibolite facies. They were intruded by 778 and 746 Ma (Cooper et al., 1979) tonalite gneiss in the south, while the volcanic unit of the belt in the north produced an age of 721 Ma (Bokhari, Kramers, 1981).

The volcanic Jerub formation of Ablah group in the north yielded a Pb/Pb zircon depositional age of 641±1 Ma (Johnson, 2000).

PETROGRAPHY

The model abundances of the Shuwas A-type granitoids are given in Table 1. The model quartz-alkali feldspar-plagioclase (QAP) data plotted on the diagram (Fig. 4a) shows syenite, quartz-syenite and syenogranite rock compositions.

Quartz syenite and syenogranite

The quartz syenite is a holocrystalline rock with hypidiomorphic granular texture. It is composed of alkali feldspar (50-55%), plagioclase (10-25%), quartz (9-15%), hornblende (4-7%), and biotite (5-8%), with accessory sphene, apatite, magnetite and iron oxides. Alkali feldspar is represented by subhedral to anhedral orthoclase perthite and microcline perthite. Perthitic intergrowth and carlsbad and cross-hatch twinning is common in alkali feldspar. K-feldspar is slightly altered to clay minerals. Plagioclase feldspar (~14 An%) is mainly subhedral to anhedral in form and is dominated by oligoclase. It is mainly found as intergrowths within the orthoclase and microcline. Quartz is present as subhedral crystals containing inclusions of perthite. The prismatic or rhombic hornblende crystals are euhedral to subhedral in form and are locally altered to chlorite and epidote. It is strongly pleochroic with X=yellowish green and Y=Z= olive green, and shows simple twinning. Biotite occurs as prismatic crystals. It is also strongly pleochroic with X=yellowish brown and Y=Z= dark brown. Sphene occurs as rhombic or granular shape, subhedral to anhedral and light brown in color. Apatite forms euhedral to subhedral grains with prismatic or six-sided shape. It is found as inclusions in biotite, hornblende and even sphene.

The major difference between quartz syenite and syenogranite is the high contents of quartz (15-25%) at the expense of alkali feldspar (45-50%), domination of biotite over hornblende and the presence of muscovite and rutile as additional accessories in the syenogranite.

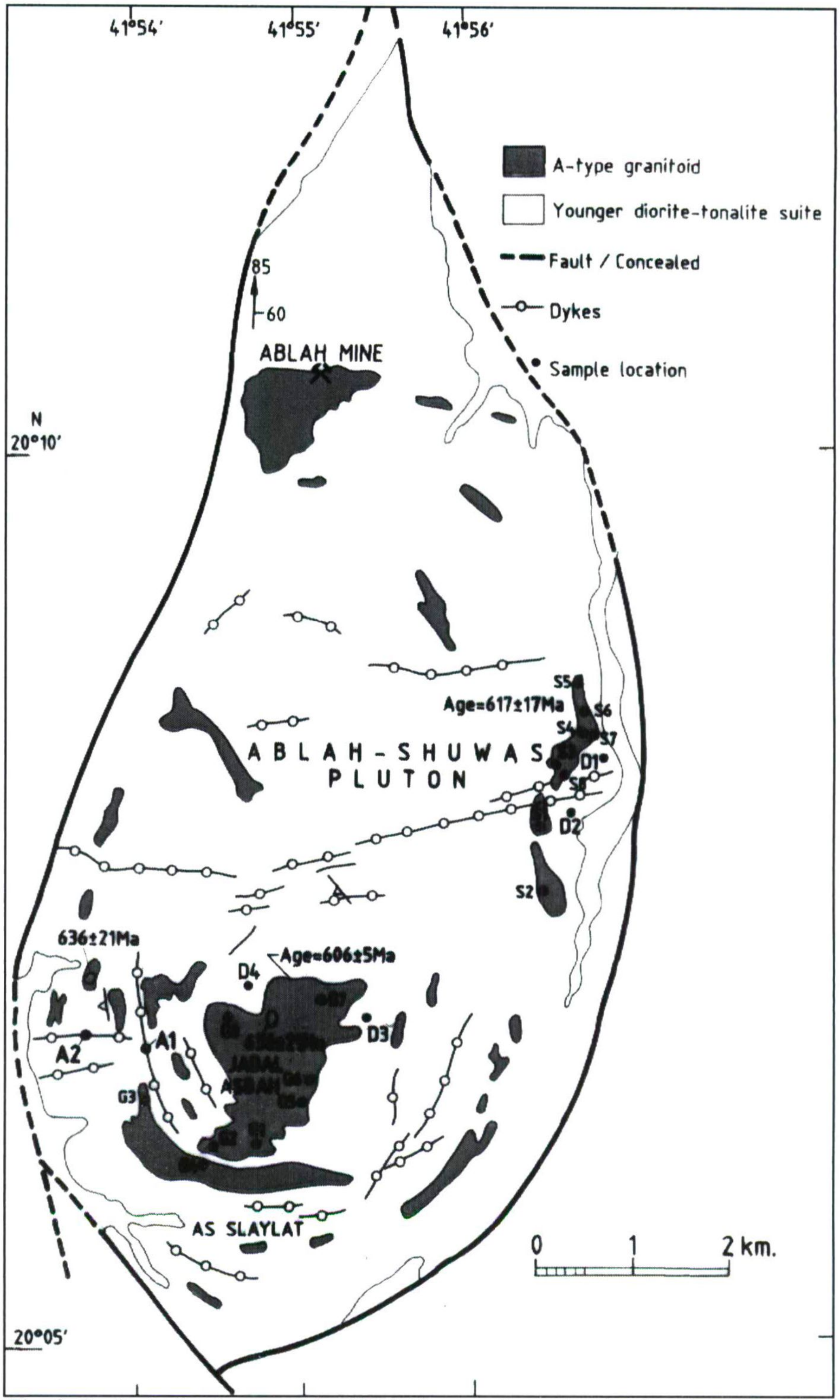

Fig. 3. Geologic sketch map of the Ablah-Shuwas pluton showing location of samples, discontinuous ring dike structure and irregular bodies of A-type granitoids (after Greenwood, 1975).

The syenite

The syenite consists mainly of alkali feldspar (55-69%), plagioclase (15-21%), hornblende (2-8%; average (n=8)=5.9%), biotite (1-10%; average (n=8)=3.75), and quartz (2-5%) with accessory sphene, rutile, apatite, zircon, iron oxides and opaque minerals. The syenites are holocrystalline with hypidomorphic granular texture; dominated by perthitic orthoclase and microcline; sodic plagioclse altered slightly to sericite and twinned on the albite law; and hornblende.

Table 1. Model analyses (volume percent) of A-type granitoids of the Ablah-Shuwas pluton.

Minerals	Syenite								Quartz Syenite					Syenogranite		
	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	G-1	G-4	G-5	G-6	G-7	G-2	G-3	G-8
Orthoclase	30	31	25	30	26	25	30	30	30	20	20	20	20	25	20	30
Microcline	30	30	35	35	40	36	34	39	20	35	30	30	34	20	31	20
Plagioclase	20	19	20	21	19	19	21	15	20	20	20	20	23	25	18	10
Quartz	3	3	5	4	5	5	3	2	15	14	14	10	9	15	22	25
Hornblende	8	2	8	7	5	8	8	7	7	4	6	6	4	3	2	5
Biotite	5	10	2	1	1	5	3	3	4	3	5	8	5	8	5	6
Sphene	2	-	2	1	2	2	2	1	3	3	3	4	2	3	2	3
Apatite	-	-	-	-	-	-	-	-	1	1	1	2	1	1	1	1
Iron oxides	2	5	3	3	2	3	2	2	-	-	-	-	-	-	-	-
Rutile	1	1	1	-	-	-	-	1	-	-	-	-	-	-	-	-
Zircon	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-

GEOCHEMISTRY AND GEOCHRONOLOGY

Analytical methods

Major and trace element and Sr isotopic ratios were determined at the Faculty of Earth Sciences, King Abdulaziz University by XRF on pressed powder pellets. Accuracy is estimated as better than 3% for major elements and 5 to 8% for most of the trace elements. Rb and Sr concentrations for geochronological work were determined by XRF following the method of Pankhurst, O'Nions (1973).

Sr isotopic ratios were determined on a Isomass 54 E mass spectrometer. Standard value obtained during the course of this investigation is: $^{87}Sr/^{86}Sr = 0.710260 \pm 0.00004$ (n=16) for NBS 987 normalized to a $^{87}Sr/^{86}Sr=0.1194$. Isochron/errochron was calculated by the regression analysis of York (1969). Errors are

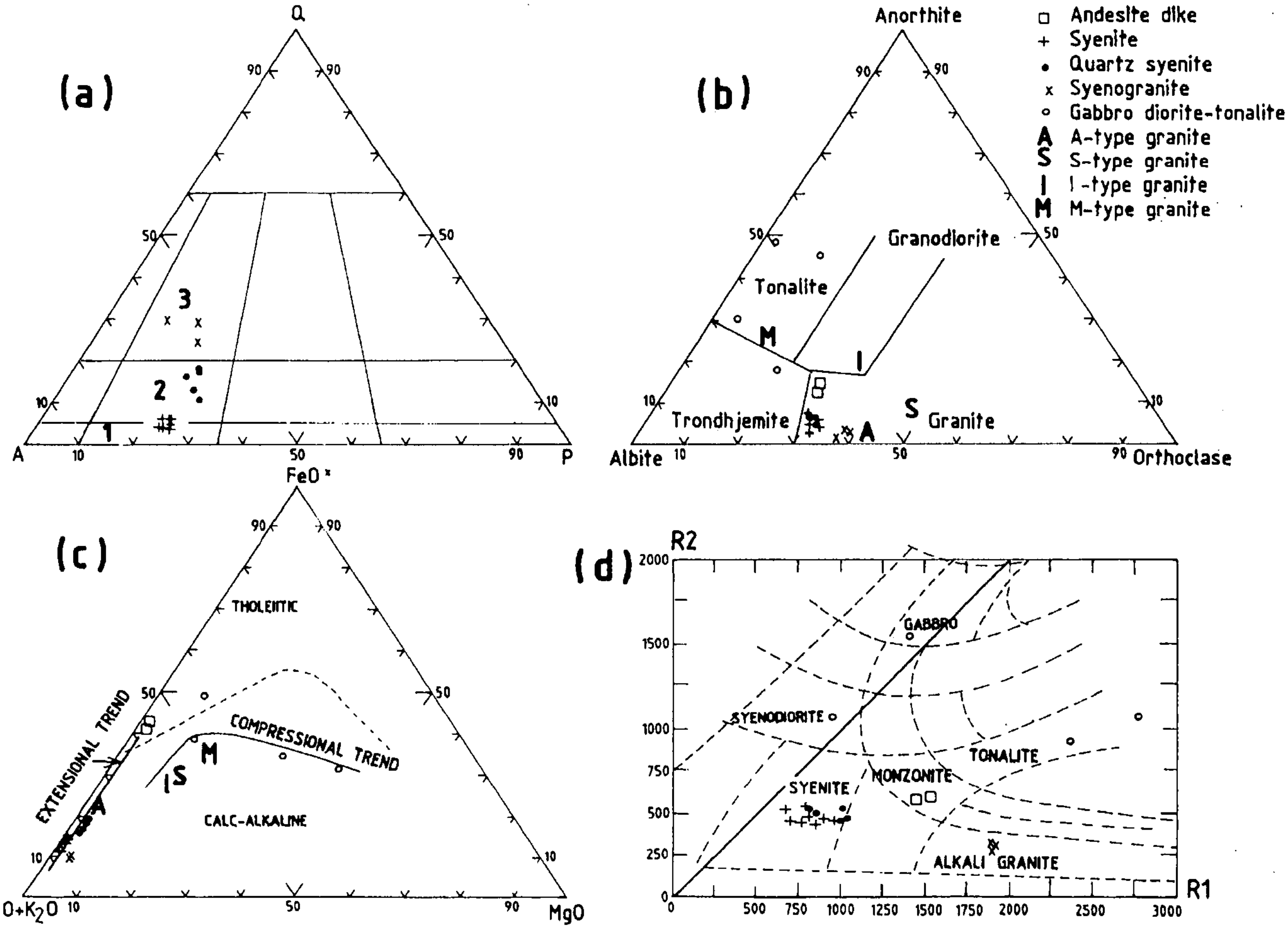

Fig. 4. The plutonic rocks of the Ablah-Shuwas pluton including A-type granitoids are plotted in : **(a)** Modal quartz-alkali feldspar-plagioclase (QAP) ternary diagram (Streckeisen, 1976), fields and petrographic nomenclature are as follows: 1=syenite; 2=quartz syenite; 3=syenogranite; **(b)** Normative An-Ab-Or diagram (Barker, 1979); **(c)** AFM diagram (Irvine, Baragar, 1971) showing trends of extensional and compressional plate boundaries (Petro et al., 1979) and **(d)** R1-R2 multicationic diagram (De La Roche et al., 1980) showing classification of granitoid rocks. The average values of A-, S- and I-type (Lachlan fold belt; Whalen et al., 1987) and M-type (Uasilau-Yau Yau complex, New Britain; Whalen, 1985) are used for comparison purposes.

quoted at the 2-sigma level. The ^{87}Rb decay constant used is $1.42\times10^{-11}\times$ a -1 (Steiger, Jager, 1977). The goodness of fit of the regression line is quoted as the MSWD (Mean Square of Weighted Deviates) of McIntyre et al. (1966), calculated here as the ratio of "chi-squared to degree of freedom" (chi-squared/(N-2). The cut-off point between isochron (MSWD <2.5) and errochron (MSWD >2.5) was made following the methods of Brook et al. (1972).

A total of 22 samples have been analyzed for major and trace elements. Out of these, 16 samples are from the A-type granitoids, 4 from the host orogenic diorite-tonalite complex, and 2 from the trachytic andesite dyke. The results are listed in Table 2. The comparison data of the studied average A-type granitoids with M-, A-, I-, and S-type granites from the Uasilau-Yau Yau complex, New Britain, PNG and the Lachlan fold belt of Australia are given in Table 3.

Geochemistry

All A-type granitoids (syenite, quartz syenite and syenogranite) of the Ablah-Shuwas pluton show restricted range of SiO_2 content from 63.90 to 65.71 wt.% in the syenite and quartz syenite and 71.46 to 72.16 wt.% in the syenogranite. All rock samples fall within the granite field on an An-Ab-Or diagram (Fig. 4b) The host gabbro-diorite-tonalite plots mostly in the tonalite field. The average compositions of the S-, I-, M-, and A-type granitoids plotted on an An-Ab-Or diagram are from data cited in Whalen et al. (1987). The host rocks are plotted as M-type and the Wadi Shwas A-type granitoids are plotted close to the average A-type granites.

The syenites and quartz syenites are characterized by high Na_2O/K_2O values (average 1.37) and Al_2O_3 content (average 18.49 and 17.36, respectively), and can be considered as high Al_2O_3 A-type granitoids. The syenogranites have average $Na2O/K_2O$ and Al_2O_3 values of 1.07 and 15.18, respectively.

On the AFM diagram (Fig. 4c), the A-type granitoids and dyke rocks are plotted very close to AF-side with parallel trend, which is a characteristic feature of the rocks developed in

Table 2. Major (in wt.%) and trace (in ppm) element concentrations for A-type granitoids, host diorite-tonalite and dyke rocks from the Ablah-Shuwas pluton.

Sample No.	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
	Syenites							
SiO_2	63.74	63.93	65.88	64.04	65.82	64.66	64.14	64.53
TiO_2	0.45	0.53	0.31	0.34	0.37	0.38	0.58	0.47
Al_2O_3	18.38	18.53	18.41	18.55	18.68	18.83	18.35	18.15
Fe_2O_3	2.09	2.12	1.62	2.23	1.74	1.82	2.07	1.89
MnO	0.04	0.03	0.03	0.05	0.05	0.03	0.04	0.04
MgO	0.06	0.07	0.06	0.08	0.07	0.07	0.07	0.07
CaO	1.81	0.98	0.67	1.07	0.98	0.96	1.27	0.89
Na_2O	6.60	6.41	6.64	6.53	6.44	6.56	6.56	6.51
K_2O	4.54	4.77	4.80	4.84	4.54	4.81	5.07	5.13
P_2O_5	0.08	0.10	0.06	0.06	0.06	0.06	0.09	0.08
H_2O^+	0.70	0.48	0.12	0.18	0.20	0.09	0.50	0.27
H_2O^-	0.07	0.07	0.07	0.07	0.06	0.08	0.07	0.10
Total	98.56	98.02	98.67	98.04	99.01	98.35	98.81	98.13
	Trace elements (ppm)							
Rb	140	136	132	137	127	138	129	133
Sr	197	70	35	130	57	68	147	61
Y	31	25	38	47	35	18	36	35
Ga	-	26	20	22	-	-	14	32
Zr	329	554	933	1085	876	956	815	943
Nb	12	17	12	12	12	12	20	12
Ba	-	456	194	285	457	-	0	680
Cr	9	7	9	6	6	8	9	9
Ni	6	8	8	8	8	8	8	8
Co	9	8	9	7	9	8	8	8
Sc	3	5	4	4	4	3	4	4
Cu	22	23	17	31	24	23	18	66
Zn	99	74	73	117	75	116	94	122
Mo	1.8	1.2	1.06	1.87	1.87	1.87	1.14	1.36
K/Rb	269	291	302	293	297	289	326	320
Rb/Sr	0.71	1.94	3.77	1.05	2.23	2.03	0.88	2.18
Ga/Al	-	2.65	2.05	2.24	-	-	1.44	3.33
Rb/Ba	-	0.30	0.68	0.48	0.27	-	-	0.20
Y/Nb	2.58	1.47	3.17	3.92	2.92	1.50	1.80	2.92
ZNY	372	596	983	1144	923	986	871	990

(- = not determined)

Table 2. continued

Sample No.	G-1	G-4	G-5	G-6	G-7	G-2	G-3	G-8
	Quartz syenite				Syenogranite			
SiO_2	65.24	64.37	64.80	64.32	65.71	71.66	71.46	72.16
TiO_2	0.54	0.62	0.54	0.55	0.50	0.21	0.21	0.26
Al_2O_3	17.45	17.38	18.06	17.88	16.82	15.24	15.63	14.66
Fe_2O_3	2.31	2.73	2.46	2.48	2.98	1.24	1.30	1.43
MnO	0.06	0.08	0.07	0.06	0.04	0.04	0.04	0.04
MgO	0.42	0.42	0.41	0.42	0.42	0.44	0.46	0.42
CaO	1.17	1.37	1.29	1.37	1.15	0.45	0.52	0.37
Na_2O	6.22	6.22	6.20	6.47	6.14	4.81	4.93	5.18
K_2O	4.40	4.56	4.45	4.47	4.69	4.73	4.71	4.49
P_2O_5	0.06	0.09	0.08	0.08	0.07	0.04	0.04	0.04
H_2O^+	0.34	0.34	0.25	0.30	0.37	0.15	0.34	0.26
H_2O^-	0.08	0.05	0.07	0.07	0.08	0.08	0.04	0.06
Total	98.29	98.23	98.68	98.47	98.97	99.09	99.68	99.37

Table 2. continued

Sample	G-1	G-4	G-5	G-6	G-7	G-2	G-3	G-8
				Trace elements (ppm)				
Rb	127	128	126	144	139	134	139	131
Sr	304	234	364	277	202	159	164	57
Y	35	39	34	36	32	32	34	26
Ga	33	-	26	25	29	16	43	26
Zr	669	683	711	740	606	415	378	317
Nb	22	27	12	25	12	17	19	13
Ba	526	515	144	205	51	508	-	719
Cr	8	8	7	8	7	7	6	6
Ni	8	8	8	8	8	8	8	8
Co	7	5	7	6	7	9	8	8
Sc	4	3	5	4	2	5	3	3
Cu	40	46	37	33	38	15	26	31
Zn	155	201	136	166	107	115	150	129
Mo	1.4	1.3	1.5	1	108	1.3	1.3	1.3
K/Rb	288	296	293	258	280	293	281	285
Rb/Sr	0.42	0.55	0.35	.052	0.69	0.84	0.85	2.30
Ga/Al	3.57	-	2.72	2.64	3.26	1.98	5.20	3.35
Rb/Ba	0.24	0.25	0.88	0.70	2.72	0.26	-	0.18
Y/Nb	1.59	1.44	2.83	1.44	2.67	1.88	1.79	2.0
ZNY	726	749	757	801	650	464	421	356

Table 3. Comparison of average major and trace element concentrations of Ablah-Shuwas A-type granitoids with M-type (1-Uasilau-Yau Yau complex, New Britain; Whalen, 1985) and A-, I-, and S-type granites (2-Lachlan fold belt of Australia; Whalen et al., 1987).

Sample	Average A-type granites (this Study)	(1) Average M-type granites (17)	(2) Average A-type granites (148)	(2) Average I-type granites (991)	(2) Average S-type granites (578)
SiO_2	66.03	67.24	73.81	69.17	70.27
TiO_2	0.43	0.49	0.26	0.43	0.48
Al_2O_3	17.56	15.18	12.40	14.33	14.10
Fe_2O_3	2.03	1.94	1.24	1.04	0.56
FeO	1.42	2.35	1.58	2.29	2.87
MnO	0.05	0.11	0.06	0.07	0.06
MgO	0.25	1.73	0.20	1.42	1.42
CaO	1.02	4.27	0.75	3.20	2.03
Na_2O	6.15	3.97	4.07	3.13	2.41
K_2O	4.69	1.26	4.65	3.40	3.96
P_2O_5	0.07	0.09	0.04	0.11	0.15
			Trace elements (ppm)		
Rb	134	17.5	169	151	217
Sr	158	282	48	247	120
Y	33	22	75	28	32
Ga	20	15	25	16	17
Zr	688	108	528	151	165
Nb	16	1.3	37	11	12
Ba	296	263	352	538	468
Ni	8	2	<1	7	13
Sc	4	15	4	13	12
Cu	31	42	2	9	11
Zn	121	56	120	49	62
K/Rb	290	598	229	187	151
Rb/Sr	0.85	0.06	3.52	0.61	1.81
Ga/Al	0.60	1.87	3.75	2.10	2.28
Rb/Ba	0.45	0.07	0.48	0.28	0.46

extensional plate margins (Petro et al., 1979). The host gabbro-diorite-tonalite rocks show compressional trend, which is nearly perpendicular to the FM-side.

Chemical data of the Ablah-Shuwas pluton plotted in the multi-cationic R1-R2 [4Si - 11(Na+K) - 2(Fe+Ti) - 6Ca + 2Mg + Al] diagram (Fig. 4d; De La Roche et al., 1980) show a broad chemical range of plutonism from mafic to felsic. The host rocks are plotted in the gabbro-syenodiorite-tonalite fields and the A-type rocks in the syenite/quartz syenite and alkali granite fields. The dyke rocks show quartz monzonite composition.

Major and trace element data have been plotted in Harker diagrams (Fig. 5A-B). The Ablah-Shuwas pluton ranges from gabbro to granite (51-72 wt% SiO_2). The host gabbro-diorite-tonalite rocks show scatter on the variation diagram, whereas A-type granitoids show two different restricted ranges of SiO_2 contents: syenite (63.9-65.7) and syenogranite (71.46-72.16). The A-type granitoids are characterized by high contents of Na_2O, K_2O, Al_2O_3, Zr, Nb, Y and Zn compared to host rocks, which are enriched only in the Fe, CaO, Mg and Sr contents. The A-type granitoids do not show any statistically significant correlation between SiO_2 and Na_2O, K_2O, Mg, Al_2O_3, TiO_2, MnO, Zr, Ga, Nb, Y, Zn, Ba and Rb. The Fe and Sr in the syenite and the CaO in the quartz syenite display statistically significant negative correlation with SiO_2 (Fig. 5A-B). In the Harker diagram, the average M-type granites from New Britain (Whalen, 1985) and the I-, S-, and A-type granites from Lachlan fold belt of Australia (Whalen et al., 1987 and unpublished data of B.W.Chappell) are plotted for comparison. The Ablah-Shuwas A-type granitoids are high in Na_2O, Al_2O_3, TiO_2, CaO, Zr and Sr, low in SiO_2, Fe, Y, Nb and almost identical in K_2O, Mg, MnO, Rb, Ga, Ba and Zn compared to average A-type granitoids. They overlap in composition with average I- and S-types granitoids with respect to TiO_2, MnO, Nb, Y, Ba, Sr and Rb and M-type with respect to Sr, Ba and TiO_2.

In the FeO(T)/(FeO(T)+MgO versus SiO_2 plot (Fig. 6) of Maniar and Piccoli (1989), the Ablah-Shuwas A-type granitoids (syenite and quartz

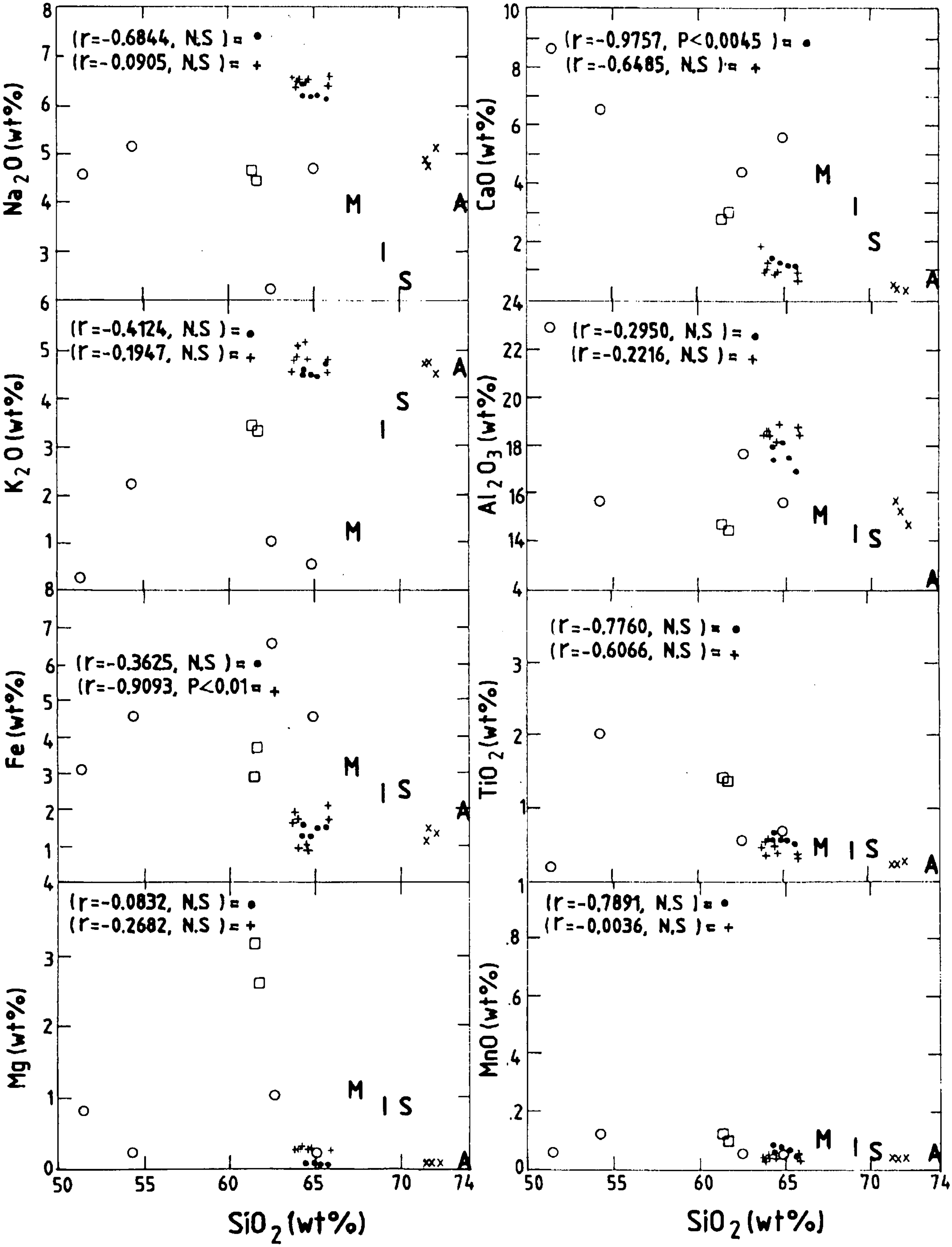

Fig. 5A. Harker variation diagrams for major element compositions. Symbols as in Fig. 4.
(r = Correlation Coefficient, N.S. = Not Significant, p= Level of Significance =< 0.05)

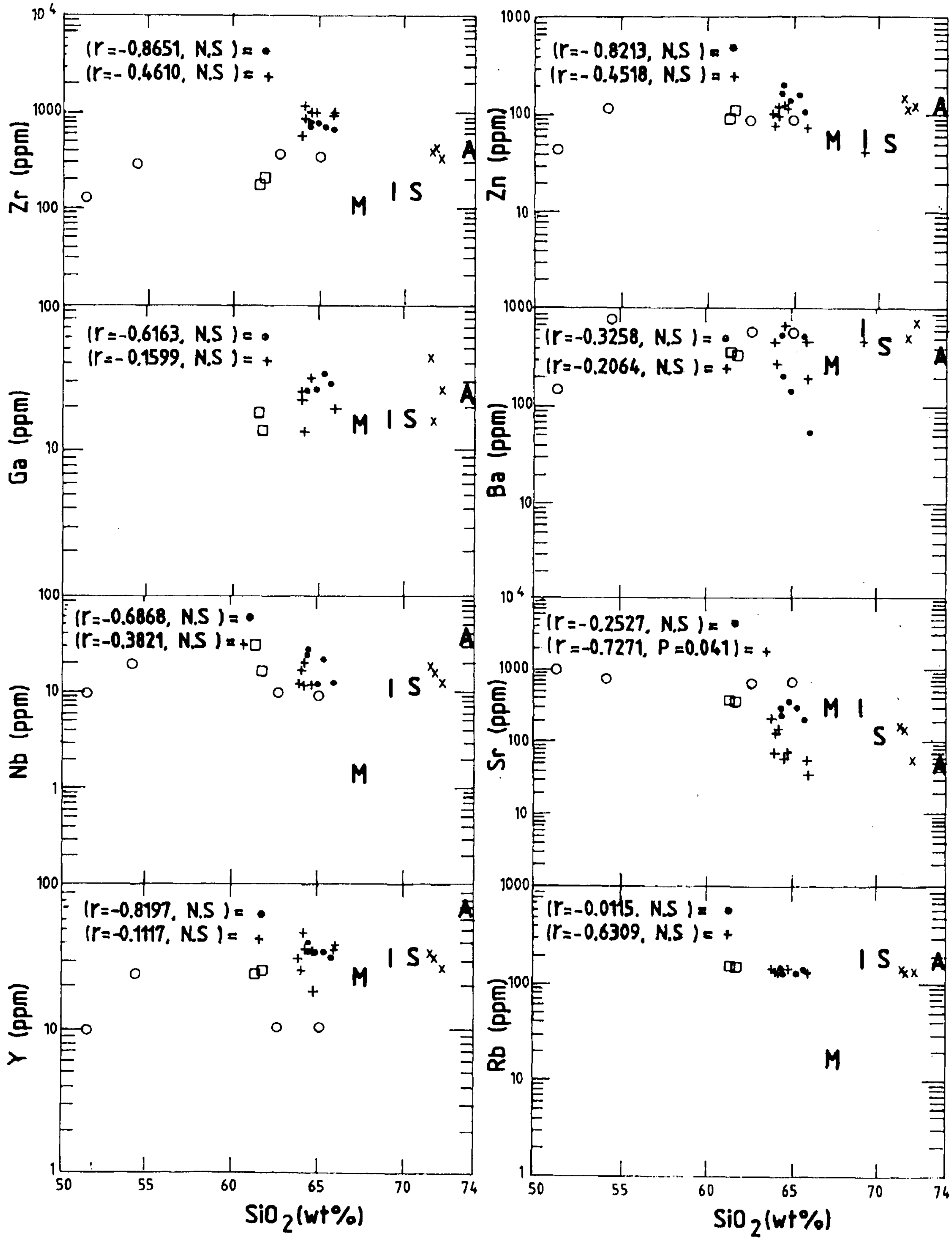

Fig. 5B. Harker variation diagrams for some trace element compositions. Symbols as in Fig. 4.
(r = Correlation Coefficient, N.S. = Not Significant, p= Level of Significance =< 0.05)

syenite) plot in the field of anorogenic rift-related or continental epiorogenic granitoids. The average values of M-, I-, and S-type granitoids (Whalen et al., 1987), are similar in composition to orogenic granitoids, whereas the average A-type granites exhibit anorogenic or rift-related setting.

In a ZNCY (Zr+Nb+Ce+Y) versus FeO*/MgO and (K_2O+Na_2O)/CaO granite discrimination diagrams (Fig. 7A-B; Whalen et al., 1987), the granitoids plot in the field of A-type granites. The average values of orogenic granites (M-, I- and S-types) are clearly discriminated in these diagrams. The Ablah-Shuwas A-type granitoids range from slightly metaluminous to peraluminous and do not show any correlation between the A/CNK (molar Al_2O_3/CaO+Na_2O+K_2O) and ZNCY indices (Fig. 7C). The highest concentration of ZNCY is found in the syenites followed by quartz syenite and syenogranite.

Whalen et al. (1987) found the good discrimination between A-type granites and the M-, I- and S-type by using Ga/Al versus Zr diagram (Fig. 7D). In this diagram, the studied granitoids plot in the A-type field and away from the I- and S-type field boundaries. The peraluminous nature of the granitoids lowered the Ga/Al ratios, so many samples are plotted well over the 10000*Ga/Al boundary of I- and S-type granites.

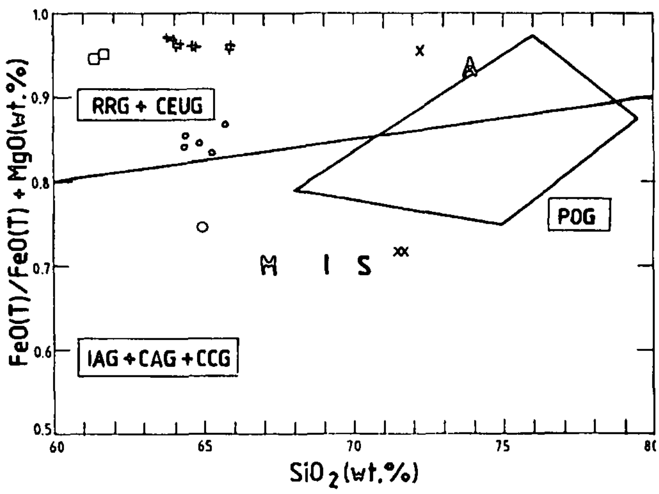

Fig. 6. FeO(T)/(FeO(T)+MgO) versus SiO_2 granitoid tectonic discrimination diagram (Maniar, Piccoli, 1989). RRG=rift-related granitoids; CEUG=continental epirogenic uplift granitoids; IAG=island arc granitoids; CAG=continental arc granitoids and; CCG=continental collision granitoids. Symbols as in Fig. 4.

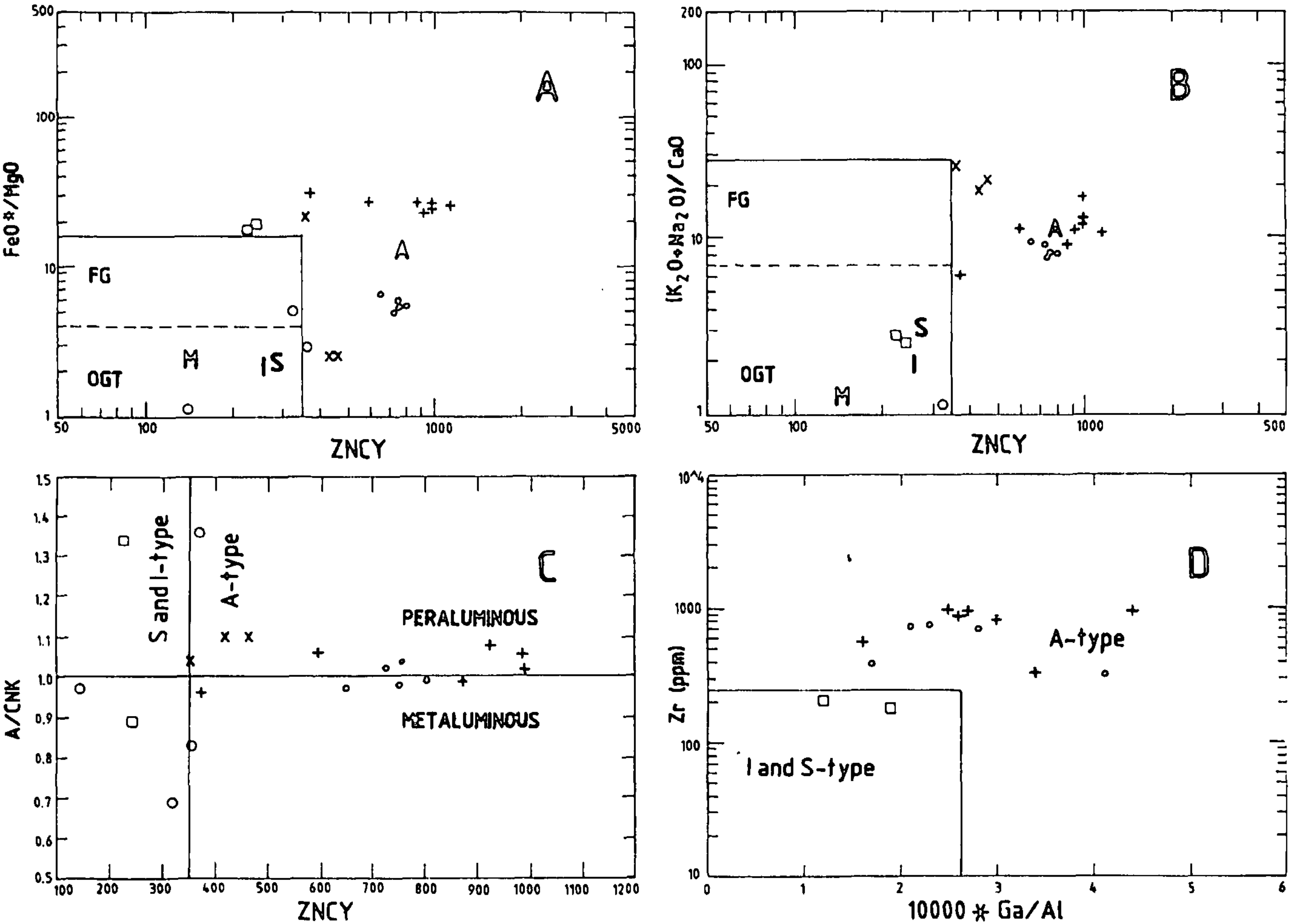

Fig. 7. **(A-C)** ZNCY (Zr+Nb+Ce+Y) versus FeO*/MgO, (K_2O+Na_2O)/CaO (Whalen et al., 1987) and A/CNK (molecular values of Al_2O_3/(CaO+Na_2O+K_2O); Condie 1991) plots showing the A-type characteristics for the syenite, quartz syenite and syenorgranite rocks of the Ablah-Shuwas pluton. **(D)** 10000*Ga/Al versus Zr plot for various phases of the Ablah-Shuwas pluton. Symbols as in Fig. 4.

Eby (1992) divided the A-type granitoids into A_1 and A_2 chemical groups, based on tectonic affiliations (A_1=truly anorogenic rifting; A_2=post-orogenic) and the Y/Nb ratios to differentiate between mantle (Y/Nb <1.2) and crustal (Y/Nb>1.2) origin. The studied A-type granitoids have Y/Nb ratios ranging from 1.4 to 3.92, and they plot clearly in the A_2 granite field in the Rb/Nb-Y/Nb binary and Nb-Y-Ga*3 ternary diagrams (Fig. 8A-B). This affiliation is consistent with the studied A-type granitoids' postcollisional or postorogenic environment and the derivation of the magma largely from arc-derived Pan-African mafic to intermediate continental crust.

In Rb-Y+Nb and Nb-Y granite discrimination diagrams (Fig. 9A-B; Pearce et al., 1984), the studied A-type granitoids show a limited distribution in the field of within plate granites (i.e. A-type granite, Whalen et al., 1987). This reflects the depletion of Y and Na elements compared to A-type granites from the Lachlan fold belt of Australia (Whalen et al., 1987).

All three rock types (syenite, quartz syenite, and syenogranite) of the A-type suite and the host rocks of the Ablah-Shuwas pluton normalized to ocean ridge granite values (ORG; Pearce et al., 1984), are shown in Fig. 10. All three rock type of the A-type suite exhibit almost identical patterns of elements distribution. They are enriched in LIL-elements (K_2O, Rb and Ba) relative to HFS-elements (Nb, Zr, Y). The most characteristic features of the A-type granitoids are a large negative Ba anomaly especially in the quartz syenites, Ba apart, significantly enriched Zr and Sr abundances, and a lesser values of Nb and Y.

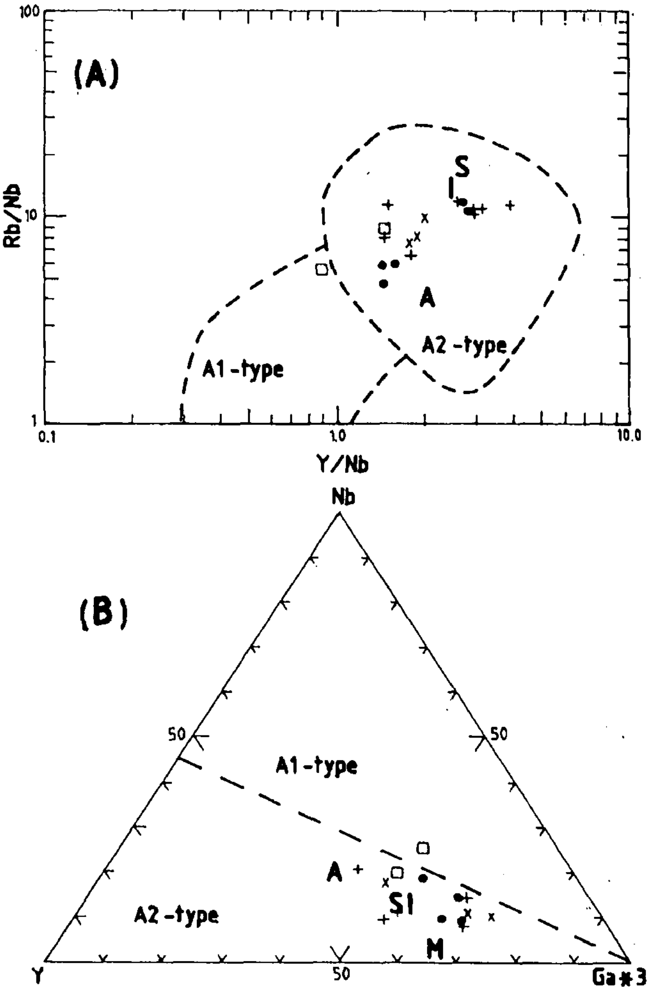

Fig. 8. (**A**) Rb/Nb versus Y/Nb binary and (**B**) Nb-Y-Ga*3 ternary diagrams (Eby, 1992) to distinguish between A_1 and A_2 granitoids. Symbols as in Fig. 4.

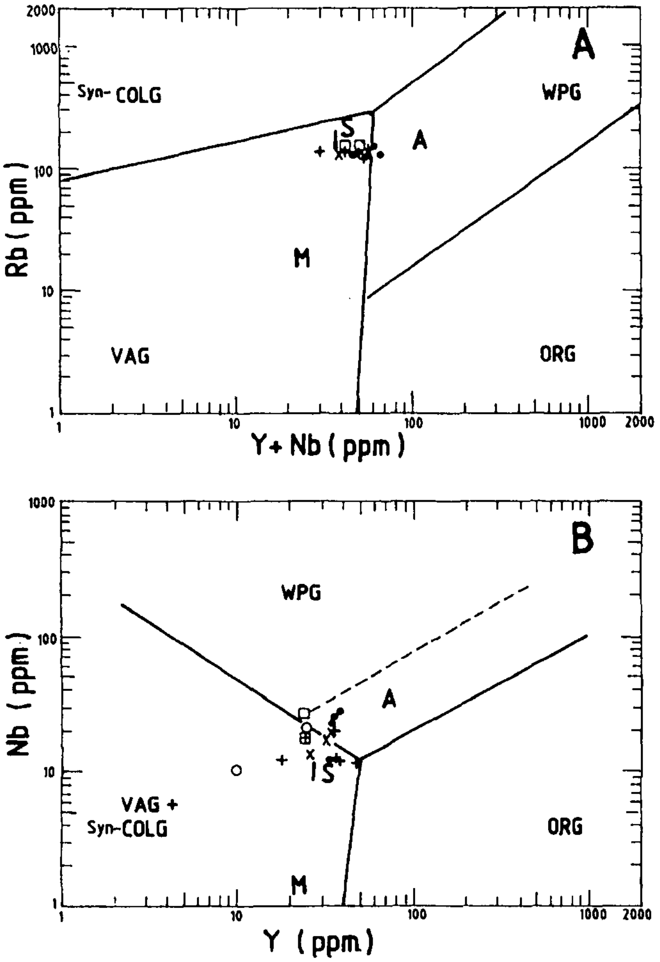

Fig. 9. (**A**) Rb/Nb versus Y/Nb binary and (**B**) Nb-Y-Ga*3 ternary diagrams (Eby, 1992) to distinguish between A_1 and A_2 granitoids. Symbols as in Fig. 4.

The patterns for average A-type granite of Whalen et al. (1987) are compared and shown in Fig. 10A-C. The Wadi Shuwas A-type granitoids exhibit almost identical abundances of K_2O, Rb and Ba, depletion of Nb and Y, and a significant enrichment of Sr and Zr. Compared to average I-, and S-type granite patterns (Fig. 10E; Whalen et al., 1987), the rocks exhibit slighlty higher Nb and Y abundances, high and approximately equal Sr contents and almost overlapping patterns with K_2O, Rb and Ba. The abundances of Ba, Sr and Y closely resemble with M-type granites. The patterns for the host gabbro-syenodiorite-tonalite are shown in Fig. 10D. Most of the patterns (e.g., K_2O, Ba, Zr, Y) resemble with M-type granites with significant enrichment in Nb and Sr.

Rb-Sr isotopic studies

Syenites: Rb-Sr data for the A-type granitoids are given in Table 4. The Rb/Sr isotopic data for six whole-rock samples from A-type syenites that cut the east-central part of the Ablah-Shuwas pluton yield an errochron age of 617±17

Table 4. Rb-Sr data for the A-type granitoids from the Ablah-Shuwas pluton.

Sample No.	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
S-1	140	197	2.0555	0.721052
S-3	132	35	11.1466	0.801880
S-4	137	130	3.0561	0.731370
S-6	138	68	5.9143	0.755850
S-7	129	147	2.5440	0.727146
S-8	133	61	6.3050	0.757808
G-3	139	164	2.46673	0.724920
G-5	126	364	1.0056	0.712130
G-6	144	277	1.5056	0.716650
G-7	139	202	1.9934	0.720611
G-8	131	57	6.7067	0.761270

Ma (MSWD=9.39) and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70380±0.0008 (2σ) (Fig. 11A).

Quartz syenite/syenogranite: whole rock Rb/Sr data for the five samples from A-type quartz syenite/syenogranite that cut the southwestern part of the Ablah-Shuwas pluton define a 606±5 Ma isochron age (MSWD=0.49) with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70350±0.00012 (2σ) (Fig. 11B).

The low initial $^{87}Sr/^{86}Sr$ ratios of 0.7035 and 0.7038 obtained for the A-type granitoids are within the range (0.701-0.706) expected for rocks derived from mantle-like protoliths. The Rb-Sr ages obtained in this study are compatible with post tectonic granitic rocks that intrude the Shuwas pluton. Fleck et al. (1980) reported an Rb-Sr isochron age of 636±21 for the granitic rocks which intrude the Ablah-Shuwas puton. The Rb-Sr ages of 617±10 Ma and 630±10 Ma are also reported for post-tectonic granites, that cut the diorite-tonalite pluton of similar age in the south west of the studied area (Brown et al., 1978; Greenwood, 1975).

DISCUSSION

A-type granitoids of the Arabian Shield have not been given much attention. Stoeser (1986) labeled the post-tectonic alkali-feldspar granites of the Arabian Shield as "A-type granites (anorogenic)". He suggested that vast amount (7% of all plutonic rocks of the Shield) of A-type granites was being generated for about 70 years after accretion of the Shield (~630–560 Ma) as a result of crustal thickening due to continental collision. On the basis of some trace-element and major-oxide composition, Jackson et al. (1984) suggested that the late Precambrian younger (686-517 Ma) granitic associations of the alkali granite and alkali-feldspar granites can be grouped as "A-type granites". The above authors did not discuss about the distinctive chemical, mineralogical and textural characteristic of the A-type granites. They simply used the tectonic definition of A-type granites such as anorogenic, within-plate, post-collision or post-orogenic. King et al. (1997) suggested that A-type granites can be emplaced at any time during a tectonic-magmatic episode. They found the occurrence of coeval I- and A-type granitoids adjacent to each other with similar field relations in the Lachlan fold belt of southeastern Australia. Thus, the tectonic setting is not a good discriminator to classify the A-

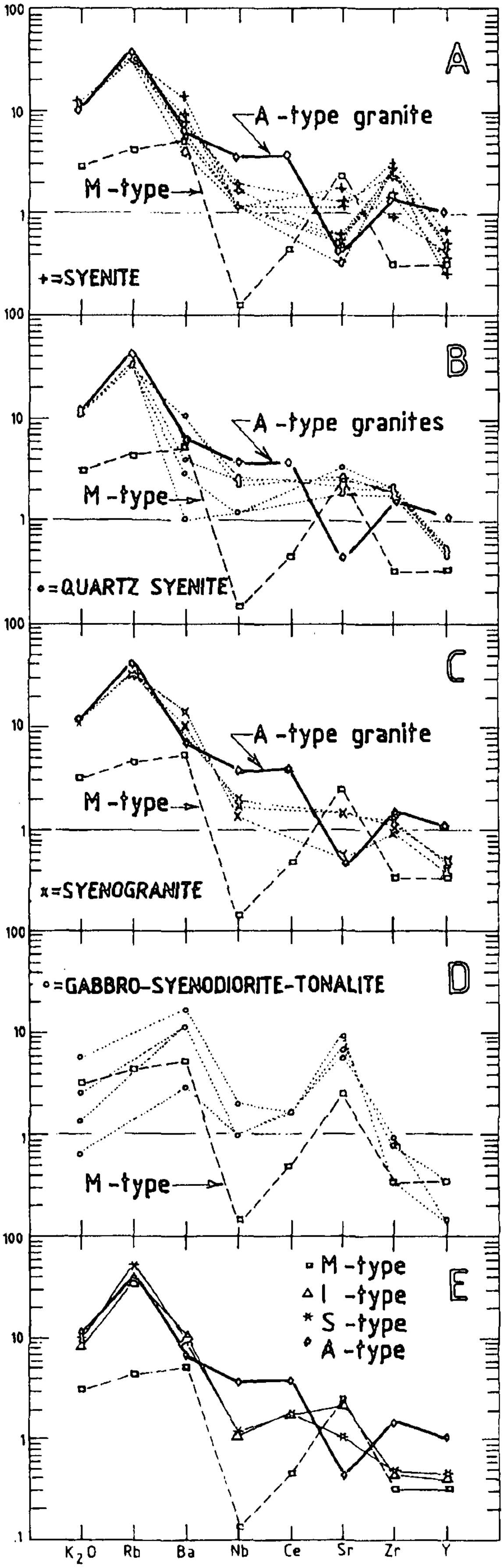

Fig. 10. ORG-normalized multi-element patterns for the Ablah-Shuwas granitoid pluton. Normalization values are from Pearce et al. (1984).

type granites, which occur in a variety of tectonic setting such as extensional, hotspots or plume, plate margins, post-collisional or post-orogenic. Various petrogenetic models have been proposed for the A-type granitoids such as mantle-derived fractionation of mafic (basaltic) magma (e.g., Turner et al., 1992; Loiselle, Wones, 1979), melting of I-type granites or their residual sources and (e.g., Clemens et al., 1986; Whalen et al., 1987; Sylvester, 1989; Anderson 1983), remelting of hybridized lithospheric mantle generated during arc-continent collision (e.g., Whalen et al., 1996). The thickened crustal source (Stoeser, 1986) is not a major mechanism, which generates the A-type granitoids.

The Wadi Shuwas A-type granitoids have distinctive chemical signatures such as high Al_2O_3, Zr, and Sr and low range of SiO_2 (~63-72%) relative to a typical A-type granitoids. The high content of Zr in the A-type granitoids implies their derivation from a significantly high temperature melt (King et al., 1997). The Wadi Shuwas A-type syenites and quartz syenites units are clearly peraluminous (~17-19 wt.%) with high contents of Na_2O (6.0-6.6 wt.%) and Zr (329-1095 ppm) and restricted range of SiO_2 (64-66 wt%), whereas A-type synogranites with high contents of SiO_2 (71-72 wt.%) are weakly peraluminous (14.6-15.6) with low Na_2O (4.8-5.2 wt.%) and Zr (317-415 ppm) contents, probably as a result of fractionation and low temperature melts.

In my opinion, the A-type granitoids should be classified into primitive or A-type$_p$ and evolved or A-type$_e$ granitoids based on their field associations with the primitive or evolved crustal rocks. Crustal rocks, especially felsic rocks play a major role in modifying the chemical signatures of the intrusive rocks. The A-type$_p$ granitoids, such as those of the Wadi Shuwas, are associated with the M-type or primitive crustle rocks, whereas A-type$_e$ are associated with the evolved and highly fractionated I-type crustal rocks. Both varieties of the A-type granitoids are present in the Lachlan fold belt of Australia (Whalen et al., 1987) and elsewhere.

The Wadi Shuwas A-type granitoids are depleted to a lesser extent in Y (33 ppm) and Nb (16 ppm), which is somewhat different from typical A-type granitoids. This type of difference is attributed to the different crustal source composition (Condie, 1991). The low Nb content is a distinctive feature of some continental rift tectonic settings. The low Nb content is reported from the Arbaat volcanic rocks of Sudan (Abdelsalam, Stern, 1993), Shadli rift volcanic of the south Eastern Desert of Egypt (Stern et al., 1991) and within-plate dykes of Sinai (Friz-Toppfer, 1991). The low Nb content in the Wadi Shuwas A-type granitoids and their intrusion into the rift-related Ablah group of rocks may indicate the presence of subduction-related volcanic arc material in the subcontinental lithosphere, which played a major role in inheriting the arc signature, represented by low Nb. The seismic-refraction crustal model of western Saudi Arabia (Mooney et al., 1985; Badri, 1991), divides the horizontal layered structure of the Arabian Shield into four layers. The upper two layers, 5-15 km below the surface, are made up of deformed Precambrian rocks, while the two lower layers, 20-45 km below the surface are mafic in composition, derived entirely from mantle-derived magmas. They are similar to calc-alkaline island arc and low-K tholeiitic basalts (McGuire, Stern, 1993).

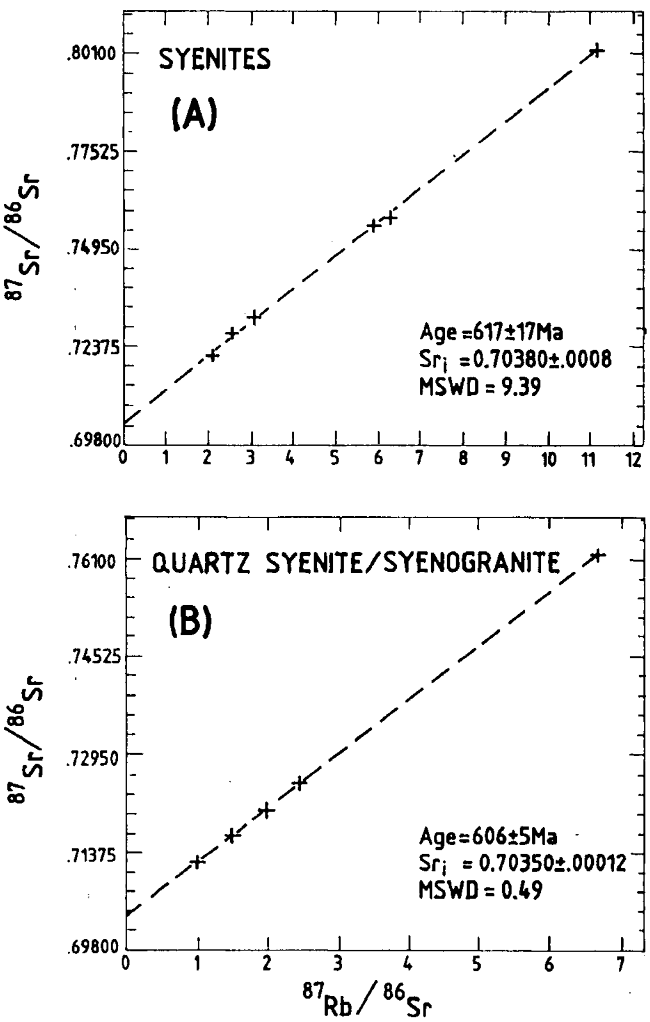

Fig. 11. Rb-Sr isochron plots of A-type (**A**) syenites and (**B**) quartz-syenites and syenogranites rocks of the Ablah-Shuwas pluton.

The 150 km long north-trending Ablah graben of the Asir terrane, situated in the southwest corner of the Arabian Shield, was developed at different times as a result of continuous extensional tectonic activity. The presence of calc-alkaline volcanic rocks at the base of the Ablah group rocks in the south indicate initialization of oceanic rifting in the south. The metamorphosed clastic and carbonate units found in the belt show deep water sedimentation in the south, shallow water marine origin sedimentation towards northward, and deltaic, marginal continental environment in the north (Parker, Smith, 1980). The island arc complex represented by Qirsha and Khutnah formations occurs in the proximity of the continental-deltaic environment. Donzea, Beziat (1989) suggested a rift environment (back-arc) for the Ablah group. The Wadi Baqarah granodiorite gneiss, which intrudes the Ablah group in the south, yielded a U/Pb zircon age of 763±4 Ma. Thus Ablah group must be older than at least 763 Ma (Cooper et al., 1979), whereas in the north Ablah group rocks yielded a Pb/Pb zircon age of 641±1 Ma (Johnson, 2000) and a Rb/Sr age of 721 ±55 Ma (Bokhari, Kramers, 1981). This variability indicates that the Ablah graben was probably developed progressively from south to north. If the age of 641±1 Ma for the Ablah group is accepted, then the younger diorite-tonalite rocks which intrude the Ablah group must be younger than the 641 Ma and cannot be correlated with the 744±22 Ma Tharad pluton (Marzouki et al., 1982), which occurs northwest of the Ablah-Shuwas pluton.

The A-type granitoids, which intrude the Ablah-Shuwas younger diorite-tonalite pluton, are believed to be contemporaneous with the movement (610 Ma or later) on the Umm Farwah strike-slip shear zone, which cuts the eastern margin of the Ablah group. The Ablah group rhyolite, which intrudes the Umm Farwah shear zone, gave an age of 613±7 Ma (SHRIMP-RG analyses on zircons; Johnson et al., 2001). The Rb-Sr ages of 617±17 and 605±5 Ma obtained from this study for the A-type granitoids are almost compatible with the young shearing event. The out cropping of alkaline rocks along zones of lithospheric fractures, deep-seated tectonic zones, shear zones, and transform faults in Africa (Bowden, 1985) and Egypt (Schandelmeier et al., 1987; Schandelmeier, Pudlo, 1990; Mohamed et al., 1999) imply that the reactivation of lithospheric structures played an important role in the generation of alkaline magmatism of mostly A-type granitoids.

The reactivation stage (670-550 Ma) in the Arabian Shield formed the Najd system of transcurrent faults, deposition of volcanic and sedimentary rocks in pull-apart basins or grabens, and intraplate S- and A-type magmatism (Johnson et al., 1987). The origin of the Wadi Shuwas A-type granitoids can be related to the Umm Farwah strike-slip shear zone, that facilitated the partial melting in the volatiles and LIL-enriched matasomatized mantle, which was developed due to long history of 200 to 300 Ma subduction related magmatism (Pearce, 1982). The rise of volatiles and F-rich flux through reactivated weak lithospheric structures caused anhydrous high temperature partial melting in the homogeneous mafic lower crust and early formed intermediate composition host diorite-tonalite rocks to form primitive A-type granitoids. The presence of regional dyke swarms in the study area may indicate the presence of deep-seated faults or zones of lithospheric weakness through which mantle flux rised to the surface.

CONCLUSIONS

All post-orogenic alkali-feldspar or alkali granites of the Arabian Shield do not define a distinctive character of A-type granites as proposed by Stoeser (1986) and Jackson (1986). The classification presented by the authors is too broad. Based on chemical, mineralogical and tectonic criteria, a clear distinction should be made between post-tectonic and anorogenic A-type granitoids.

About 610 Ma old granitoids, which intrude the young arc-related diorite-tonalite rocks of the Ablah-Shuwas pluton show 'A-type', peraluminous to slightly metaluminous character rich in total alkalies and Fe, high field strength elements, Ga and Zn and low in CaO and MgO with a large negative Ba anomaly. The low initial $^{87}Sr/^{86}Sr$ values (0.7035-0.7038) of the granitoids indicate their derivation from mantle-like protoliths.

The A-type granitoids can be classified into primitive (A-type$_p$) and evolved (A-type$_e$) granitoids, based primarily on their field associations with the primitive or evolved crustal rocks in which they intrude.

The low Nb content in the Wadi-Shuwas A-type granitoids reflects the presence of arc-related mafic material in the subcontinental lithosphere.

The studied A-type granitoids are believed to be contemporaneous (610 Ma or later) with the movement on the Umm Farwah strike-slip shear zone that cuts the eastern margin of the Ablah group of rocks.

The origin of the studied granitoids is related with the Umm Farwah shear zone, that trigger off partial melting in the volatiles and LIL-enriched mantle and brought the mantle flux with advect heat into higher level of the crust. The ascent of this mantle flux through the deep-seated shear zone initiated partial melting in the lower mafic and upper crustal rocks of dominantly intermediate to felsic composition to generate A-type granitoids.

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