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MAJOR AND TRACE ELEMENTS IN SOME GRANITIC ROCKS SOUTHEASTERN AT-TAIF AREA, SAUDI ARABIA — THEIR IMPLICATIONS TO MAGMA GENESIS AND TECTONIC SETTING

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ABSTRACT

The Pan-African granites southeast At-Taif area represent the last episode in the Hijaz tectonic cycle. Granites are the youngest and most abundant rock unit in the studied area. Diorite and metamorphic rocks are mainly enclosed within these granites.

Major element studies have revealed the calc-alkaline nature of the examined granites and diorite. The trend of differentiation of these rocks is similar to that recognized in many worldwide studies of calc-alkaline rocks.

Chemical data suggest that the granitic rocks were evolved in a compressional environment by partial melting of the lower crust. The intermediate rocks might have been derived by interaction of melts derived from the oceanic crust and mantle with the rising magmas.

INTRODUCTION

The crystalline rocks of the Arabian Shield occupy a trapezoidal area that extend northwestward and southwestward into two elongated segments along the eastern margin of the Red Sea *(Fig. 1)*. Granitoids (quartzdiorite, tonalite to granite) form about 40% of the basement exposures (STOESER and ELLIOTT, 1979). The granitic plutons are emplaced into eruptive volcanics and volcano-clastics of similar composition. Numerous mafic-ultramafic bodies occupy narrow, discontinuous N. W.—S. E. zones. All rocks reliably dated ($\sim$1,100 to $\sim$500 m.y.) appear to be late Proterozoic in age (FLECK *et al.*, 1976, 1979; BAUBRON *et al.*, 1976). GREENWOOD *et al.*, (1976) coined the term "Hijaz Tectonic Cycle" to cover the 600 m.y. during which the late Proterozoic events have led to the formation of the southern part of the Arabian Shield. GASS (1979) considered the estimated age of the non-cratonic basement of the Arabian Shield to fall within the extended (1100—450 m.y.) Pan-African time scale.

The present paper deals with some granitic rocks, located 27 km southeast At-Taif in the southern Hijaz quadrangle of the Arabian Shield. The studied granitic rocks belong to the Younger Granites of BROWN *et al.*, (1962), and to the last episode (third) of the Hijaz tectonic cycle of GREENWOOD *et al.*, *(1976)* according to NASSEEF and GASS (1976). It is the purpose of this paper to describe in brief the general geologic setting and petrography of the granitic rocks southeast At-Taif area with emphasis on magma genesis and tectonic setting.

Worthy of remark, the granitic rocks northeast At-Taif city (north the studied area) were studied in detail by NASSEEF (1971) and NASSEEF and GASS (1977). Field, geochemical and petrographic studies carried out by these authors suggest that the granitic rocks of At-Taif area were emplaced in an island arc environment.

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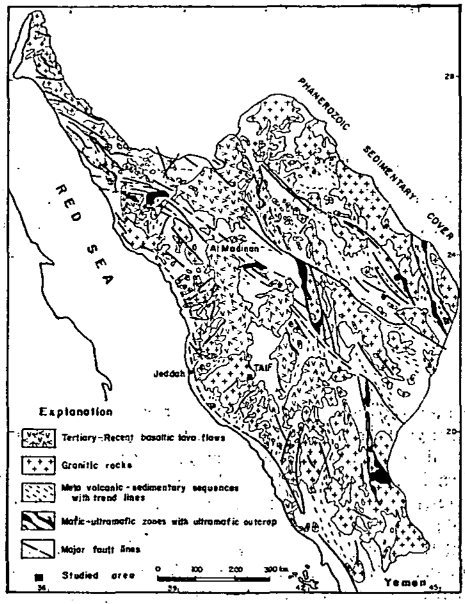

Fig. 1. Major rock types and structure of Arabian Shield and location of the studied area. Based on tectonic map of Arabian peninsula, compiled by BROWN (1970) and simplified by NASSEF and GASS (1977)

GEOLOGIC SETTING

Buff and grey granites are the youngest and most dominant plutonic rocks in the studied area. Local variation in colour of these two types and the difference between them appear to be due to varying in abundance of biotite and K-feldspar. Dykes of leucocratic granite are distinguished as the youngest rock unit in the studied area cutting all the older rock units.

Diorite is older than granites, being mainly enclosed within the granitic rocks. Metamorphic rocks represent the oldest rock unit in At-Taif area, and similar to diorite, they are mainly enclosed within the exposed granites. The metamorphic rocks consist mainly of hornblende-biotite schist, quartz-feldspathic schist and marble. Locally, the hornblende-biotite schist show evidence of assimilation by the granitic magma, while contacts of the quartz-feldspathic schists with the granites are sharp.

The investigated area is dissected by few minor faults, without any clear indication of apparent movement. These faults trend mainly in N—S and E. NE—W. SW directions, where they mainly control the courses of wadis (e.g. Wadi El-Shagrah, W. Hamem).

PETROGRAPHY

Granites are medium to coarse-grained, and grey to buff in colour with hypidiomorphic granular texture. Uncommonly, granites show porphyritic and gneissose textures. K-feldspars, plagioclase, quartz, and biotite are the essential minerals.

Sphene, zircon, and apatite are accessories. K-feldspars are usually present as orthoclase and microcline with abundant perthite intergrowths. Quartz and plagioclase are observed as inclusions in the K-feldspars. Plagioclase (An_{13}—An_{22}) forms subhedral to anhedral crystals, which are uncommonly zoned. Core and rim structure is observed in altered plagioclase. Quartz occurs as interstitial anhedral grains. Graphic quartz-potash feldspar intergrowths are common in these rocks. Biotite is the only mafic mineral and is observed in the examined granites with X=straw yellow, Y=Z= dark brown.

Leucocratic granite is medium-grained and pink in colour, with hypidiomorphic granular texture. Quartz, K-feldspars and plagioclase (An_{12}—An_{18}) are the essential minerals, while mafic minerals are minor constituents. Muscovite, apatite and zircon are accessories.

Diorite is fine- to medium-grained, dark to light grey in colour, and displays a hypidiomorphic texture. Plagioclase (An_{26}—An_{32}) si the most dominant feldspar and forms euhedral to subhedral tabular crystals with pronounced zoning. Plagioclase is accompanied by irregular interstitial quartz and small amounts of orthoclase. Biotite occurs as brown to greenish brown flakes and is mainly associated with hornblende. Sphene, opaque oxides and zircon are accessories.

CHEMISTRY AND MAGMA GENESIS

Eleven samples representing grey, buff, and leucocratic granites and diorite were selected for chemical and spectrographic analyses. The results of analyses for both major and trace elements and the CIPW norms of the examined rocks are given in Tables 1 and 2.

The chemical analyses of the examined rocks are plotted on O'CONNOR's (1965) variation diagram to classify the examined rocks according to their normative contents. All the plots of granites fall within the field of granite or lie along the border line separating the granite and trondhjemite fields. Diorite falls within the granodiorite field. For simplicity, the term "granitic rocks" is here used to cover all these rock types *(Fig. 2)*.

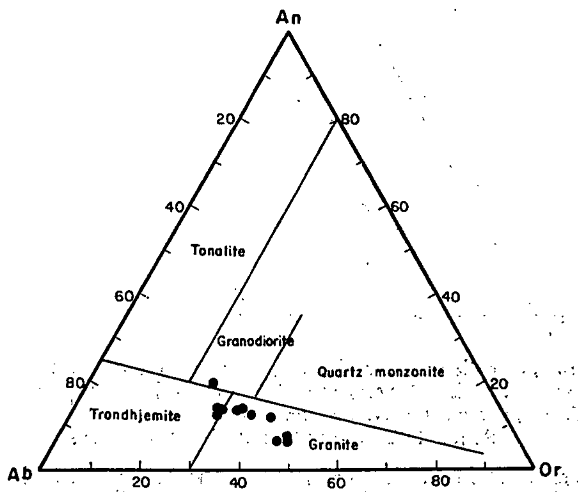

Fig. 2. Chemical classification of At-Taif granitic rocks using their normative feldspar ratios. Field boundaries are those of O'CONNOR (1965)

Fig. 3-A is a standard AFM triangular diagram which illustrates that the investigated rocks show a typical calc-alkaline trend (CARMICHAEL *et al.*, 1974). The plots of At-Taif granitic rocks also follow the average trend of the plutonic and volcanic rocks of the Arabian Shield (STOESER and ELLIOTT, 1979). *Fig. 3-B* and *Fig. 4* reveal again the calc-alkaline nature of the granitic rocks, where they plot in the fields defined by STOESER and ELLIOTT (1979) for the calc-alkaline granites of the Arabian Shield. The diorite plot falls outside the Arabian field since this field represents the calc-alkaline granites.

The chemical analyses of At-Taif plutonic rocks are plotted on a variation diagram against the differentiation index of THORNTON and TUTTLE (1960) in *Fig. 5*. It may be noted that the trend of differentiation is similar to that recognized in

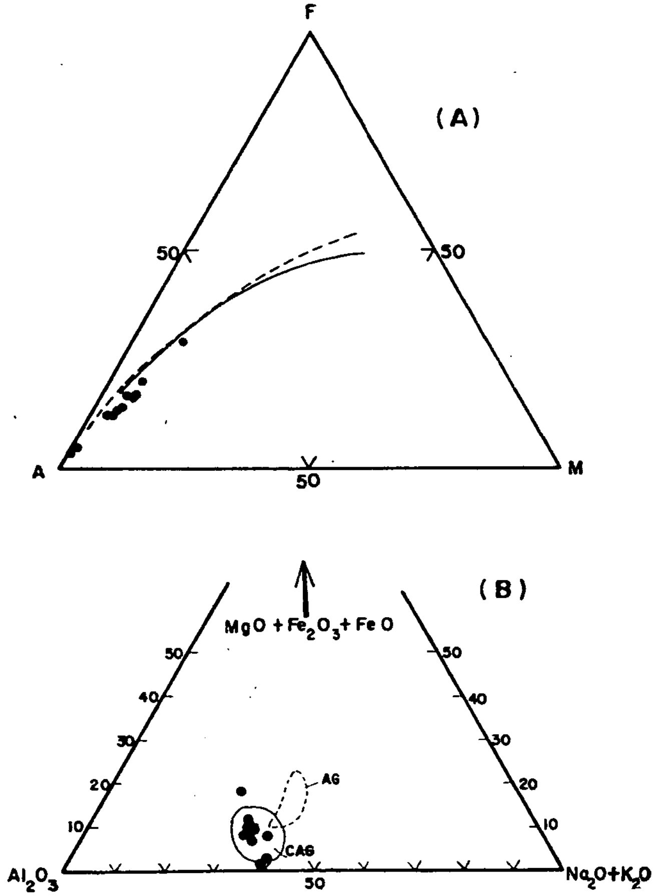

Fig. 3. A. AFM triangular diagram for At-Taif granitic rocks. A: Na_2O+K_2O, M: MgO and F: $FeO+Fe_2O_3$. The solid curve is the average trend line for the Sierra Nevada batholith (CARMICHAEL *et al.*, 1974). The dashed curve is the average trend line for the plutonic and volcanic rocks of the Arabian Shield (STOESER and ELLIOTT, 1979).

B. Total alkali-alumina-total iron oxide+magnesia ternary diagram (wt. %) for At-Taif granitic rocks. The two fields shown are for calc-alkaline granites (CAG) and alkali granites (AG) of the Arabian Shield (after STOESER and ELLIOTT, 1979)

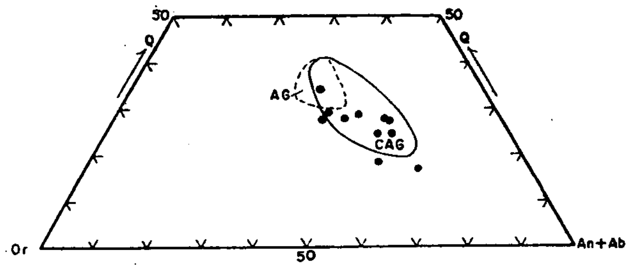

Fig. 4. Normative quartz-orthoclase-plagioclase (An+Ab) triangular diagram for the investigated granitic rocks. Diagram includes the fields designated by STOESER and ELLIOTT (1979) for calc-alkali (CAG) and alkali (AG) granites from Saudi Arabia

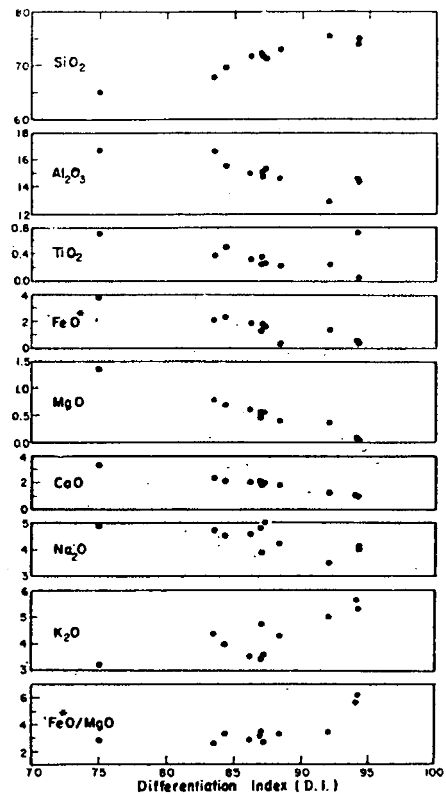

Fig. 5. Variation diagram of the major element (wt. %).

many worldwide studies of calc-alkaline rocks (NOCKOLDS and ALLEN, 1953; ALBUQUERQUE, 1971). SiO_2, K_2O and FeO* (total iron)/MgO show a steady increase toward the more differentiated types, while Al_2O_3, TiO_2, FeO*, MgO and CaO decrease in the same direction, which is the normal trend. Na_2O shows some scatter. The Na_2O content ranges from 3.51 to 4.99. Within this narrow range, it appears

TABLE 1

Chemical analyses and CIPW norms of At-Taif granitic rocks

%	1*	2	3	4	5	6	7	8	9	10	11
SiO_2	64.77	68.04	71.40	72.24	72.78	71.61	71.47	69.62	73.99	75.18	74.64
TiO_2	0.70	0.37	0.26	0.23	0.21	0.32	0.34	0.50	0.07	0.24	0.03
Al_2O_3	16.74	16.60	15.27	15.04	14.58	14.86	14.79	15.53	14.45	12.94	14.44
Fe_2O_3	1.50	0.81	0.68	0.56	0.63	0.94	0.91	1.05	0.38	0.63	0.21
FeO	2.49	1.32	0.87	0.84	0.68	0.90	0.98	1.34	0.16	0.74	0.12
MnO	0.06	0.03	0.02	0.01	0.02	0.03	0.05	0.03	0.0	0.02	0.0
MgO	1.37	0.78	0.55	0.44	0.38	0.60	0.53	0.70	0.09	0.38	0.05
CaO	3.32	2.29	1.88	2.03	1.81	1.96	1.76	2.09	0.99	1.06	0.96
Na_2O	4.87	4.74	4.99	4.75	4.17	4.59	3.87	4.51	3.98	3.51	4.05
K_2O	3.19	4.38	3.59	3.42	4.26	3.50	4.69	3.95	5.64	4.99	5.26
P_2O_5	0.32	0.13	0.10	0.09	0.07	0.12	0.11	0.16	0.02	0.08	0.02
H_2O	0.67	0.52	0.39	0.35	0.42	0.57	0.51	0.52	0.21	0.22	0.20
Total	100.00	100.01	100.00	100.00	100.01	100.00	100.01	100.00	99.98	99.99	99.98
FeO*/MgO	2.80	2.63	2.69	3.05	3.28	2.91	3.39	3.26	5.58	3.44	6.18
CIPW Norms											
Q	14.96	17.48	23.80	26.47	27.81	26.60	26.52	22.85	27.08	32.86	28.90
Or	18.85	25.88	21.21	20.21	25.17	20.68	27.71	23.34	33.32	29.48	31.08
Ab	41.19	40.09	42.20	40.17	35.27	38.82	32.73	38.14	33.66	29.69	34.25
An	14.38	10.51	8.67	9.48	8.49	8.94	8.01	9.32	4.78	4.74	4.63
C	0.01	0.21	0.00	0.05	0.0	0.25	0.41	0.42	0.05	0.03	0.39
En	3.41	1.94	1.37	1.10	0.94	1.49	1.32	1.74	0.22	0.95	0.12
Fs	2.29	1.20	0.64	0.72	0.42	0.40	0.58	0.82	0.0	0.48	0.0
Mt	2.17	1.17	0.99	0.81	0.91	1.36	1.32	1.52	0.31	0.91	0.30
Hm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.16	0.0	0.0
Il	1.33	0.70	0.49	0.44	0.40	0.61	0.65	0.95	0.13	0.46	0.06
Ap	0.76	0.31	0.24	0.21	0.17	0.28	0.26	0.38	0.05	0.19	0.05
D.I.	75.00	83.45	87.21	86.85	88.25	86.10	86.96	84.33	94.06	92.02	94.23

* Sample 1: Diorite, Samples 2—7: Grey granite, 8—10: Buff granite, 11: Leucocratic granite.

TABLE 2

Trace element contents (ppm) and element ratios of At-Taif granitic rocks

	1*	2	3	4	5	6	7	8	9	10	11
Rb	88.4	114.1	86.0	78.0	105.1	87.7	147.0	92.7	102.6	80.8	119.2
Sr	882.8	726.2	770.2	585.4	394.6	511.6	389.2	563.8	329.8	438.6	232.3
Zr	201.2	213.2	119.3	152.9	120.6	156.8	149.5	210.5	77.7	168.0	79.5
Nb	9.9	7.0	3.2	4.9	5.8	6.8	17.7	10.9	2.8	11.9	2.0
Y	14.3	6.8	3.0	2.7	2.8	7.2	23.7	7.9	2.3	16.6	3.5
Zn	67.3	55.7	39.6	34.4	35.0	47.2	47.2	59.8	11.3	33.2	7.4
$\frac{Sr \times 10^3}{Ca}$	3.7	4.4	5.8	4.0	3.1	3.7	3.1	3.8	4.7	5.8	3.4
K/Rb	300	319	347	364	337	332	265	354	456	512	367

* Numbers refer to Table 1.

that the content of Na_2O does not vary systematically with differentiation (BATEMAN and DODGE, 1970, p. 414).

The trace elements and trace element ratios are also plotted against the differentiation index *(Fig. 6)*. Zr and Sr show a progressive decrease toward the highly differentiated granites, while K/Rb ratio increases in the same direction. The Rb, Y contents and Sr/Ca ratio are approximately constant throughout the examined rocks. However, Y shows a slight increase toward the diorite.

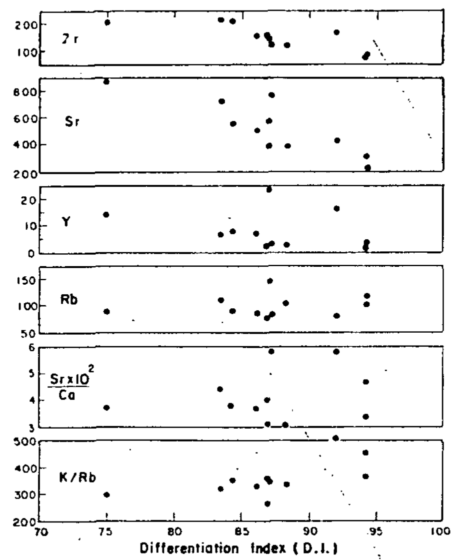

Fig. 6. Variation diagram of some trace elements and element ratios (ppm).

The normative albite, orthoclase and quartz proportions of At-Taif granitic rocks are plotted on the ternary diagram Ab-Or-Q, the residua diagram of TUTTLE and BOWEN (1958). The plots *(Fig. 7-A)* show a tight pattern that elongates toward the Ab corner. It is clear that all the analyses fall within or near the centre of the diagram. According to TUTTLE and BOWEN (*op. cit.*, p. 79) "the concentration of the analyses near the centre of the diagram is readily explained if a magmatic history is involved in the origin of most granites". Consequently, At-Taif granitic rocks are considered to possess a magmatic history. In addition, the concentration of most plots near the minimum of 1 kb pressure, suggested that the examined rock were formed at or near this particular pressure. The same points shown in *Fig. 7-A* are plotted on a figure showing the isobaric fractionation curves at 1000 bars water-vapour pressure *(Fig. 7-B)*, in order to reveal their fractionation behaviour. It is clear that most plots lie along the fractionation curves, suggesting their formation by fractional crystalization from a single magma (TUTTLE and BOWEN, 1958). This conclusion has been previously achieved from *Fig. 5* and *Fig. 6*.

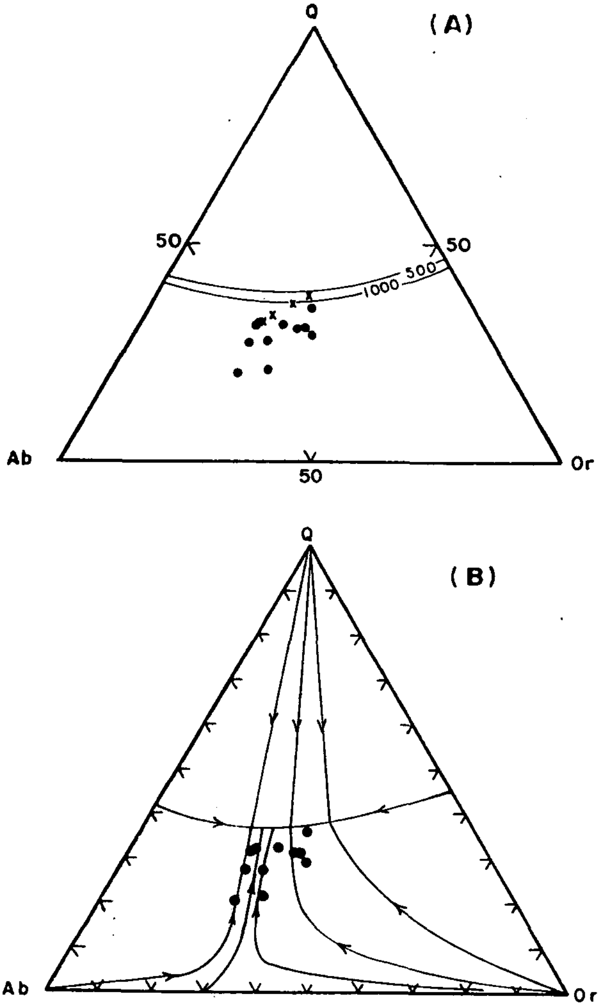

Fig. 7. A. Orthoclase-quartz-albite "residua diagram" (TUTTLE and BOWEN, 1958) for At-Taif granitic rocks. The projections of the boundary between quartz and feldspar fields at 500 and 1000 kg/cm^2 of water-vapour pressure, and the isobaric temperature minima for these pressures and for 2 and 3 kilobar pressures are also shown as crosses

B. The same plots shown in *Fig. 7-A* are plotted in relation to isobaric fractionation curves for 1000 bars water-vapour pressure (TUTTLE and BOWEN, 1958).

TECTONIC ENVIRONMENT

In the light of plate tectonic theory, it is generally accepted that the bulk of calc-alkaline granitic rocks lie above subduction zones. In the present study, two lines of evidence are used to predict the tectonic environment of the studied granitic rocks, *i)* the major elements content, and *ii)* the Nb, Zr and Ti concentrations of these rocks.

According to PETRO *et al.* (1979), it is assumed that on the AFM diagram, the variation trends of granites evolved in compressional environment (subduction zones) tend to be nearly perpendicular to the FM side for the entire trend. *Fig. 3-A* shows that the examined rocks follow the average trend of the plutonic and volcanic rocks of the Arabian Shield, which tends to be nearly perpendicular to the FM side. In addition, Table 1 shows that nearly all the analysed samples contain normative corundum (i.e. peraluminous rocks). The higher frequencies of peraluminous rocks are characteristic of compressional environment, while peralkaline rocks are characteristic of extensional environment (PETRO *et al.*, 1979).

Considering minor and trace elements, PEARCE and GALE (1977) have demonstrated that there are substantial geochemical variations between volcanic arc magmas and within-plate magmas. Igneous rocks of all SiO_2 values that evolved above subduction zones have Nb contents below 15 ppm, whereas for granitic rocks (60—75% SiO_2) Nb ranges from 50 to 500 ppm. According to GASS (1979, p. 12), the Nb content in 100 Sudan-Arabian granitic rocks are below 40 ppm and in over 80% the Nb content is below 15 ppm. All the investigated samples have Nb content below 15 ppm, except for sample 7 where the Nb content is 17.5 ppm. *Fig. 8* shows PEARCE and GALE's (1977) plot of Nb-SiO_2 for magmatic rocks of known tectonic setting. All the analysed samples plot in the field of volcanic arc magmas. The majority of plots fall in the field defined by PEARCE and GALE *(op. cit.)* for rocks derived from crustal melts by metamorphism of sediments.

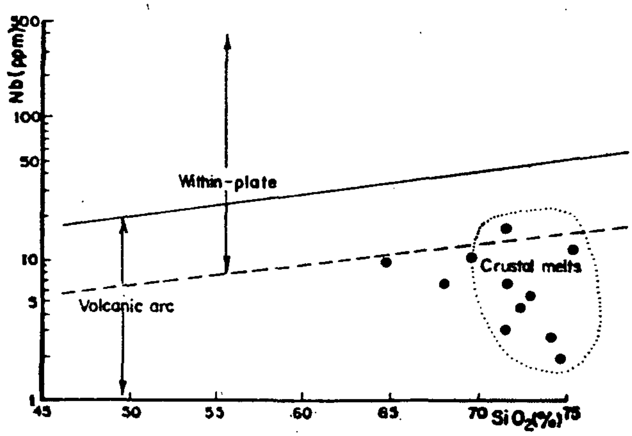

Fig. 8. Nb-SiO_2 diagram of the analysed granitic rocks. The dashed diagonal line gives lower limit for within-plate magma type, the solid diagonal line gives upper limit for volcanic arc magma type. Estimate of Nb-SiO_2 range of crustal melts derived from sediments metamorphosed up to and including amphibolite facies superimposed on diagram (PEARCE and GALE, 1977).

PEARCE (1980) regarded the immobile elements Ti and Zr as the most realistic geochemical discriminator between arc and within-plate magmatic products. All the studied rocks plot in the arc field *(Fig. 9)*.

To sum up, it is argued that the Pan-African granitic rocks of At-Taif area were evolved in a compressional environment by partial melting of the lower crust. The rising magmas may mix with melts derived from the subducted oceanic crust and mantle wedge to account for the origin of intermediate rocks (PETRO *et al.*, 1979).

Worthy of remark, the Rb/Sr ratio of At-Taif granitic rocks indicates a crustal thickness more that 30 km *(Fig. 10)*. The estimated thickness is in accordance with that reported by KNOPOFF and FOUNDA (1975) for the Pan-African crust.

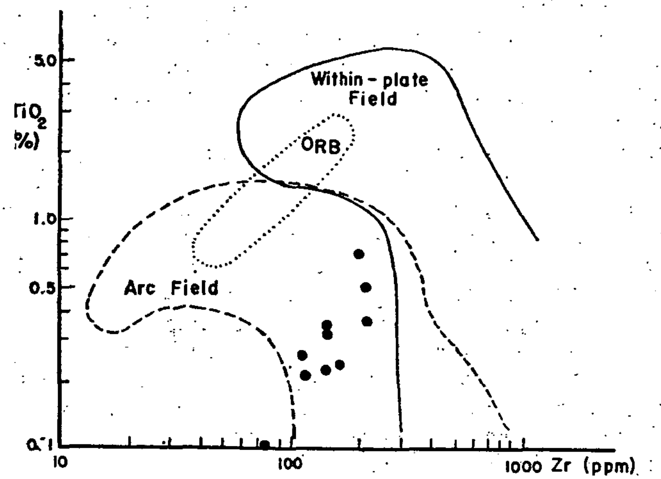

Fig. 9. TiO_2-Zr plots for At-Taif granitic rocks. Compositional fields for present-day volcanic rocks from island arc, ocean ridge basalts (ORB) and within-plate settings are after PEARCE (1980).

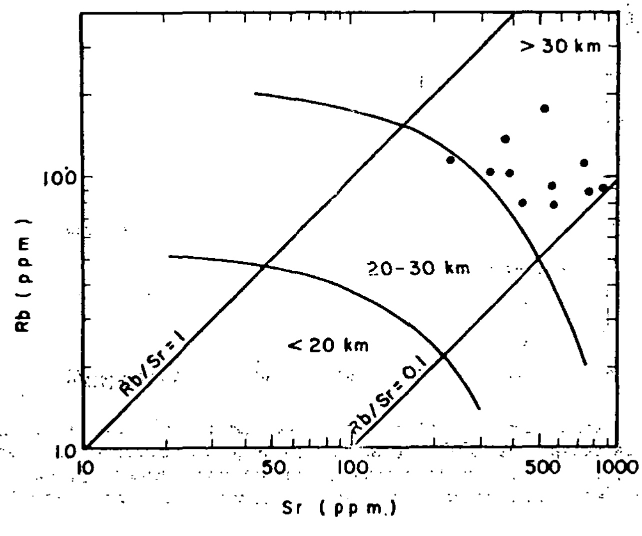

Fig. 10. Rb-Sr diagram showing distribution of At-Taif granitic rocks. Numbers in kilometers refer to crustal thickness as inferred from the Rb-Sr crustal thickness index (CONDIE, 1973).

The suggested tectonic environment for At-Taif granitic rocks is in harmony with previous studies on the Arabian-Nubian Shield (e.g. AL SHANTI and MITCHELL, 1976; BAKOR *et al.*, 1976; GARSON and SHALABY, 1976; NASSEEF and GASS, 1977; GASS, 1979) that led to the conclusion that the crystalline basement of Arabia and northeast Africa is the product of cratonization of island arc over a period of 600 m.y. According to NASSEEF and GASS (1977), At-Taif granitic rocks represent the final phases in the episodic cratonization process.

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