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GEOLOGY AND GEOCHEMISTRY OF THE GRANODIORITE ROCKS OF THE AL-OTAYBI AREA, AL-QUWAYIYAH QUADRANGL, SAUDI ARABIA

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ABSTRACT

The Al-Otaybi area is located in the Al-Quwayiyah Quadrangle at the easternmost central part of the Precambrian Arabian Shield, Saudi Arabia. This area consists of post-tectonic per-aluminous sub-alkaline granodiorite pluton that sharply cuts the Halaban group. Quartz veins, simple pegmatite and dykes of different ages and composition cut these bodies in various directions. This granodioritic pluton belongs to the I-type granite that has immiscible heterogeneous magma. The geology, geodynamic, petrology, petrochemistry and mineralogy of 35 collected samples confirm that the Al-Otaybi area has been affected by the ensimatic island-arc sequence of the Al Amar-(Marjan-Ar Rayn)-Idsas fault (A.M.R.I. Suture).

INTRODUCTION

The Al-Otaybi area is located 20 km west of the Al-Quwayiyah city at the easternmost central edge of the Arabian Shield, Saudi Arabia (Fig. 1). Bramkamp and Ramirez (1958) and Nebert (1970) studied the geology of the Al-Quwayiyah Quadrangle and produced preliminary maps of scale 1:500000 and 1:100000 respectively. The focus of this paper is to deal with the reconnaissance studies of the geology, geochemistry and the origin of the granodioritic rocks of the Al-Otaybi area (44° 58' – 45° 07'E and 23° 58' – 24° 06'N) and to identify the suites of the granitoid rocks of the Jabal Al-Otaybi, Aba Al-Rahi, Jafara, Meheariga, Mizil, Nasaq, Uthainan Shamal and Saqit (Fig. 1).

The area of study comprises of the Precambrian Halaban group and the kinematic and post-kinematic intrusions. The Halaban group consists

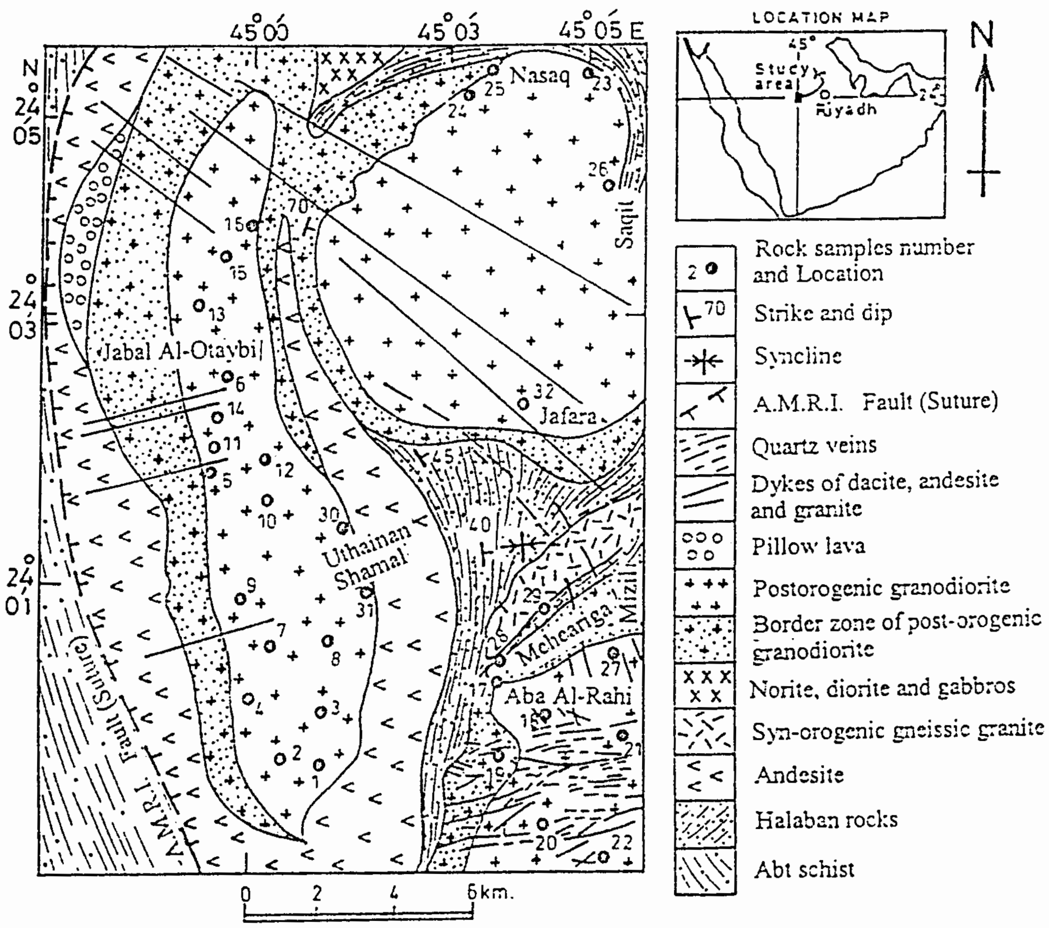

Fig. 1: Geologic and location maps of the Al-Otaybi area. The figure illustrates the location of the collected samples. (Modified after Nebert, 1970).

metamorphic sequence consists of ortho- and para-schists and gneisses with assorted mineralogical and geochemical compositions. The mineralogy constituents of these units reveal that the Halaban gneisses and schists belong to the amphibolite facies (Sindi, 2005). Syn-tectonic Precambrian gabbros, granitoid pluton and small undeformed gabbroic and dioritic rocks of different ages and composition intruded the host rocks with no original igneous layering (Nebert, 1970). The predominant volcanic rock type is andesite that occurs to the south east of the Jabal Al-Otaybi pluton.

The post-tectonic coarse to medium massive grained, pinkish to light grey, heterogeneous Jabal Al-Otaybi and Al-Quwayiyah granodioritic pluton contains variable sizes of basic xenoliths with sharp contacts. This pluton is contaminated, at its boarder zones, 50-200 m width, with the adjacent basic and the syn-tectonic rocks. Simple pegmatite, quartz veins, granitic, andesite and dolerite dykes cut these post-tectonic pluton and the consequence group in several directions. These dykes have assorted composition and occur with different shapes extend > 6 km with variable width from few centimetres to six meters. The ratio of their width to length is about 1:1000. Younger post-tectonic fresh sheets of granodiorite, monzogranite, granite, plagiogranite, aplite, simple pegmatite, andesite and dolerite dykes cut, with E-W bearing and steeply dipping, the Halaban metamorphic sequence and the granite pluton. These dykes were affected by two forces, which are the buoyancy forces that affect the vertical motion and the excess pressure at source that drive the dykes in various directions. The former forces are larger than the latter. The second force remains constant as long as the volume of the dykes remains small compared with the volume of the source magma.

Basaltic pillow lava occurs in a strip of 2000 m long and 100 m wide between the andesite and the Al-Quwaiyiyah granodiorite bodies to the east and the eastern side of the Al Amar-(Marjan-Ar Rayn)-Idsas fault (A.M.R.I. Suture) line to the west (Fig. 1). These pillow lavas are elongated in shape with long axis 10-150 cm and average radius of 45 cm though spherical ones occur. They are tholeiitic spilitic/komatiitic in composition and are amphibolitized indicating high degree of metamorphism.

METHODS OF STUDY

Selected samples were collected from the Al-Otaybi area for petrography, mineralogical and geochemical studies. The term "granitoid" is used for the studied samples to encompass all types of granites, granodiorites, quartz-monzonites and tonolites of the Al-Otaybi area. Data for these granitoid rocks were separated into four groups which are:

1- Modal and petrographical analyses were done using the classical techniques of Kerr (1977) in which Swift counter was used to determine the percentages of the existing minerals. The result is produced in Table 1. Trace quantity of minerals (0.005-0.5 %) include calcite, muscovite, chlorite, apatite, epidote, zircon and sphene were add together and tabulated under the name Accessories (Table 1). The nomenclature of the selected rocks follows the recommendations of the IUGS (Streckeisen, 1976; and Le Bas and Streckeisen, 1991).
2- Major oxides and trace elements for the collected 35 samples were analysed using the wet chemistry, AA spectrophotometer (Perkin Elmer 5000) and the XRF following the methods described by Sindi (1981). Some of the major oxides were analysed using fused pellets while others were analysed using powder pellets. The analytical precision (relative standard deviation) is ≤1% for the SiO_2, 1-2% for most of the other major elements and 5-10% for the trace elements. The result is presented in Table 2 alongside their averages.
3- CIPW norms have been calculated and produced in Table 2.
4- The REE were analysed (Table 3) by the ICP following the methods of Jeffery and Hutchison (1981) at the laboratories of the University of London (Queen Mary College and King's College). The analytical precision (relative standard deviation) is 3-4%.

PETROLOGY

The post-kinematic norites, diorites, gabbros and the Jabal Al-Otaybi granodioritic pluton intruded the metamorphic Halaban group that consists of basic and acidic schists and gneisses, metasedimentary, metavolcanics and metagabbroic complexes (Nebert, 1970 and Sindi, 2004). The basic metamorphic rocks compose of chloritized hornblende, phenocrysts of K-feldspars ($Or_{80-60}Ab_{25-15}An_{10-5}$), olivine ($Fo_{80-90}$), altered clinopyroxene ($En_{50}Wo_{37}Fs_{12}$), ilmenite, magnetite and elongated Cr-spinel plus irregular normal zoned andesine (An_{35-45}).

The post-tectonic heterogeneous granodiorite is coarse to medium grained at the centre of the pluton changing gradually to fine grained tonalite at the boarders of the pluton. The Colour Index of the main pluton is 3-15 with light grey to light pinkish colour. These rocks have granitic texture with slightly weak gneissose structure at the centre to porphyritic texture and stronger foliation at the edges of the pluton. This post-tectonic

Table 1: Petrographical modal analyses(wt.%) of the collected Granodioritic samples from the Al-Otaybi area, Al-Quwayiyah Region, Arabian Shield, Saudi Arabia

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Quartz	37	38	37	35	40	35	40	31	37	30	38	35	36	38	35	34
Orthoclase	15	14	15	21	14	16	16	11	9	9	5	14	14	19	13	17
Oligoclase	33	36	35	36	38	35	37	45	45	46	40	38	38	28	37	36
Perthite	3	5	4	4	3	2	3	5	3	8	7	2	3	5	5	5
Hornblende	2	1	1							3	1	3		2	2	2
Biotite	2	1	2	2	2	1	2	2	1	1	2	2	2	3	2	2
Opaque	6	4	4	2	2	8	2	5	4	2	4	5	5	1	4	1
Accessories*	2	1	2		1	3		1	1	1	3	1	2	4	2	3

Continue Table 1: Petrographical modal analyses(wt.%) of the collected Granodioritic samples from the Al-Otaybi area, Al-Quwayiyah Region, Arabian Shield, Saudi Arabia

	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Quartz	34	32	36	38	30	36	34	35	40	34	36	29	30	35	31	34
Orthoclase	15	12	10	13	10	11	11	10	10	16	12	14	15	8	10	13
Oligoclase	37	38	37	35	42	40	38	40	39	40	40	40	40	39	40	39
Perthite	6	4	5	6	3	7	4	5	4	2	7	7	9	4	5	8
Hornblende		4	3		4	1	5	1		1	1	2	1	4	5	1
Biotite	3	2	2	2	5	2	2	2	2	2	1	3	2	3	2	2
Opaque	5	6	6	4	5	1	5	6	4	2	1	3	1	6	6	2
Accessories*		2	1	2	1	2	1	1	1	3	2	2	2	1	1	1

* Accessories include Apatite + Calcite + Corundom + Sericite + Muscovite + Sphene and Zircon

Petrographical Discription

Rock No.	Rock Name	Location
1-12.	Pink Granodiorite	Jabal Al-Otaybi
13	Grey Granodiorite	Jabal Al-Otaybi
14	Pink Granodiorite	Jabal Al-Otaybi
15	Pink Granodiorite	Jabal Al-Otaybi
16	Pink Granodiorite	Jabal Al-Otaybi near Mizil
17-20	Pink Granodiorite	Aba Al-Rahi
21-22	Grey Granodiorite	Aba Al-Rahi
23	Pink Granodiorite	Nasaq
24-25	Grey Granodiorite	Nasaq
26	Pink Granodiorite	Saqit
27	Pink Granodiorite	Mehearigah
28-29	Grey Granodiorite	Mehearigah
30-31	Grey Granodiorite	Uthainan Shammam
32	Grey Granodiorite	Jafara Dyke's area

granodioritic body shows cataclastic metamorphism to the area under investigation. The borders of these granodioritic rocks are contaminated with the adjacent basic Halaban and the syn-tectonic rocks to make an aureole zone of 50-200 m width. The average rock density is 2.37 gm/cm^3, which is slightly lower than the average normal granitic rocks due to the secondary quartz in the studied samples. This granodioritic body is divided into three subgroups according to the mineralogy, texture, structure and contamination that indicate a heterogeneous origin for these rocks though they will be treated in this paper as one unit. Such subgroups are:

a) Post-tectonic cataclastic granodiorite (Al-Quwayiyah and Jabal Al-Otaybi);
b) granitic rocks with syn-tectonic xenoliths and
c) the contaminated and tonalite boarder and edges.

These rocks consist of 29-40% quartz, 5-21% anhedral to subhedral K-feldspars ($Or_{90-70}Ab_{7-20}An_{1-10}$), 2-10% micro- to crypto-perthitic intergrowths, 25-46% subhedral to euhedral plagioclase (An_{10-20}), 1-5% subhedral to anhedral green to brown isolated biotite flakes with light to dark brown pleochroism, 1-5% subhedral brown hornblende laths, 1-8% opaque and 1% muscovite, sericite and other interstitial and accessory minerals such as apatite, calcite, chlorite, epidote and zircon (Table 1). Irregular quartz grains with suture margins, undulatory extinction and mortar structure occur in these studied samples. Some large quartz grains are fractured. These fractures are filled with sericite and secondary quartz. These secondary quartz are also present as interstitial and interlocking grains with the feldspars. The plagioclase ranges from albite to oligoclase. The turbid plagioclase have yellowish stain colour and are altered to sericite reflecting the hydrothermal alteration. These plagioclase crystals are elongated parallel to the plane of the shearing though some crystals show albite twining while some crystals show normal weak zoning (An_{5-25}). Graphic texture is present in these rocks due to the intergrowths of the quartz with the feldspars. Anhedral fine-grained quartz occurs with feldspars to form a myrmekitic texture, which may represent a final quench or late-stage vapour saturation of the residual magma and/or deuteric origin. Orthoclase intergrowths with plagioclase causing the vein, string and braided macro- and micro-perthitic textures. These feldspars occur as poikilitic grains and have normal carlsbad and pericline twinning indicating post-crystallisation re-equilibration though the majority is kaolinitized. K-feldspar laths show kink and deformation bands at the boarders of the pluton. The presence of the irregular quartz

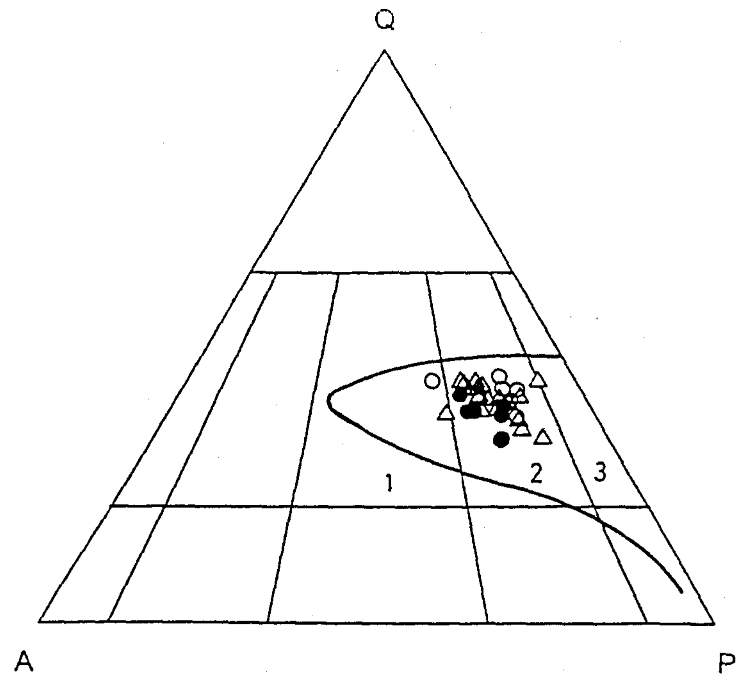

Fig. 2: QAP diagram showing the classification of the studied igneous samples of the Jabal Al-Otaybi area based on the fields of Streckeisen (1976) with the continental arc granitoids (CAG) field of Maniar and Piccoli (1989). 1- Monzogranite 2-Granodiorite 3-Tonalite

Symbols (and abbreviations) of the samples in all figures are:

Δ = Post-tectonic Al-Otaybi Granodiorite samples;

● = Granodioritic rocks with syntectonic xenoliths;

o = The contaminated granodioritic rocks.

grains with suture margins, undulatory extinction and mortar structure plus bending feldspar and biotite flakes are due to the strains and late cataclastic tectonism.

Of the mafic minerals, biotite flakes is common, altered to chlorite and are crushed and oriented to the plane of shearing, in which they occur along zones of fluid alteration defined by fractures and sericite. Clusters discrete biotite plus green and brown intergrowth biotite flakes occur. Muscovite occurs along the margins of these biotites. The hornblende laths have inclusions of quartz, magnetite and sphene. The accessory minerals were formed during the subsolidus alteration. The modes of these granitoid rocks are presented on the Alkali feldspar-Quartz-plagioclase (AQP) diagram (Fig. 2) in which they fall in the granodioritic field according to the classification and nomenclature of Streckeisen (1976). These samples fit within the continental arc granitoids (CAG) field as indicated by Maniar and Piccoli (1989).

The post-tectonic fine-grained doleritic to andesitic dykes is composed of calcic-plagioclase (An_{35-40}), hornblende, diopside, olivine, opaque and traces of mica and iron sulfides in decreasing abundance. The pyroxene is replaced by green amphibole. The albitization and alteration to chlorite, kaolinite, sericite and the uralitization of pyroxene occur in these sheets. The monzogranite dykes are red to grey in colour. The K-feldspar crystals in the pegmatites have general composition of $Or_{60}Ab_{30}An_{10}$. The presence of this pegmatite indicates high temperature and comparatively anhydrous magma to these rocks.

GEOCHEMISTRY

The mineralogy and geochemistry of this post-tectonic coarse-grained, heterogeneous, unfoliated, granodioritic Al-Otaybi pluton show changes in composition from the centre to the borders of the pluton because of the contamination with the Halaban and the syn-tectonic rocks. These boarders are higher in some compatible elements (e.g. Ti, Mn, Mg, Ni and Sr) and more depleted in Al_2O_3, CaO, Na_2O, K_2O and Nb than the centre of this pluton.

The SiO_2 is 67.83-75.55 wt %, with an average of 71.74 wt % (Table 2) indicating high silica content that put these rocks with the Si-saturated group. Some samples (e.g. 14, 19, 24, 25, 28, 30 and 31) are low in the SiO_2, Na_2O, alkalinity ratio and Felsic Index (F.I.) and high in the Solidification Index (S.I.), density, An%, mafic and calcic elements which is due to the contamination with the adjacent basic rocks. Other samples (e.g. 5, 6, 7 and 11) are high in SiO_2 and F.I. and low in CaO which is due

Table 2:Geochemical analyses of the Granodiorite from the Al- Otaybi area, Al-Quwayiyah Region, Saudi Arabia

Table 2-A:Geochemical analyses of the major oxides (wt.%) of the *Granodioritic samples from the Al-Otaybi area*

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	16	17
SiO2	71.85	74.53	72.61	74.81	74.55	67.83	75.55	72.16	73.65	72.99	75.45	72.65	72.21	68.41	73.07	72.41
TiO2	0.31	0.25	0.27	0.23	0.25	0.28	0.19	0.35	0.27	0.35	0.28	0.34	0.28	0.28	0.16	0.31
Al2O3	12.78	11.97	12.85	12.61	11.93	13.63	12.03	13.82	12.58	13.01	12.34	12.83	13.11	12.55	14.88	13.44
FeO	1.36	0.77	0.63	0.99	0.86	2.13	0.98	0.78	0.96	0.89	0.68	0.63	1.05	0.09	0.04	1.35
Fe2O3	2.99	1.97	2.98	0.58	1.88	4.01	1.31	2.87	2.99	1.28	1.99	3.39	2.96	2.94	1.33	2.89
MnO	0.13	0.07	0.09	0.05	0.11	0.05	0.05	0.08	0.09	0.11	0.06	0.09	0.09	0.15	0.05	0.17
MgO	1.08	0.63	0.89	0.21	0.77	0.77	0.49	0.77	0.43	0.58	0.51	1.22	0.95	1.08	0.45	1.12
CaO	3.28	2.41	2.61	1.93	1.32	1.57	1.61	2.04	1.22	2.91	0.85	3.03	2.85	6.23	1.97	2.21
Na2O	3.42	3.42	3.51	3.75	3.73	2.89	3.59	5.41	4.84	5.63	6.04	3.68	3.51	1.01	4.39	3.86
K2O	1.95	2.33	2.19	3.13	2.42	2.67	2.65	1.13	1.51	0.15	0.11	2.43	2.21	2.86	2.39	2.53
H2O+	0.32	0.95	0.98	1.11	1.61	2.55	1.11	0.29	1.01	1.12	1.51	0.11	0.36	2.15	0.36	0.21
H2O-	0.03	0.12	0.09	0.02	0.02	0.11	0.03	0.05	0.07	0.06	0.05	0.02	0.11	0.19	0.08	0.05
P2O5	0.08	0.04	0.05	0.02	0.04	0.06	0.03	0.08	0.05	0.05	0.04	0.06	0.11	0.23	0.08	0.06
CO2	0.01	0.01	0.01	0.02	0.02	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.01	1.58	0.14	0.01
Others	0.2	0.16	0.16	0.12	0.11	0.27	0.16	0.15	0.19	0.1	0.07	0.2	0.18	0.24	0.27	0.17
Total	99.79	99.63	99.92	99.58	99.62	98.87	99.79	99.99	99.87	99.24	99.99	100.7	99.99	99.99	99.66	100.8
D.I.	76.89	82.63	79.55	88.49	85.56	77.62	86.23	83.48	83.43	87.84	89.26	79.99	78.84	69.72	85.17	81.55

Table 2-B: Geochemical analyses of the Trace Elements (ppm) of the Al-Otaybi area

Ba	411	480	463	589	441	526	556	586	630	172	63	495	449	1795	1415	574
Ce	49	41	40	64	41	47	50	37	35	38	28	37	47	26	48	41
Cl	169	200	275	73	87	41	93	112	60	49	71	186	175	35	32	188
Co	9	6	8	3	5	11	5	6	5	5	4	8	8	10	5	8
Cr	32	24	24	14	26	26	12	32	18	16	10	56	26	68	38	24
Cu	59	17	26	9	9	26	42	26	26	9	17	42	158	289	29	42
La	25	20	20	31	18	15	24	13	15	19	13	19	23	19	21	19
Li	9	10	18	9	9	4	9	11	4	7	5	9	10	4	11	11
Mo	8	5	12	1	1	8	7	9	4	2	1	24	9	12	11	10
Nb	1	5	3	7	6	1	5	7	4	3	5	1	3	2	4	9
Ni	20	15	14	10	9	14	10	15	12	10	12	27	15	14	13	14
Pb	1	1	1	1	1	1	1	1	1	1	1	1	1	3	4	1
Rb	55	57	65	92	55	77	63	20	29	18	18	51	59	76	84	57
S	786	715	274	78	54	1514	560	491	642	346	244	713	815	224	141	296
Sc	14	9	11	6	9	14	8	13	11	12	10	14	12	9	3	14
Sr	157	114	147	44	114	144	88	149	83	49	61	142	140	54	429	158
V	69	33	51	8	32	75	23	21	12	9	8	71	58	13	19	65
Y	33	36	30	60	41	15	47	48	39	39	36	31	33	40	10	41
Zn	58	37	49	21	50	33	38	34	62	121	55	63	51	85	36	98
Zr	130	80	80	140	80	90	56	175	200	170	160	85	80	220	150	90

Table 2-C: Calculated C.I.P.W. Norms (wt.%) of the analysed samples of the Al- Otaybi area

qz	36.54	39.98	36.74	35.32	40.18	37.45	40.24	30.86	36.57	30.28	37.56	34.09	35.85	42.48	33.89	33.29
c			0.08		0.87	3.11	0.4	0.17	0.86		0.83		0.02		2.22	0.46
zir	0.03	0.02	0.02	0.03	0.02	0.02	0.01	0.04	0.04	0.03	0.03	0.02	0.02	0.04	0.03	0.02
ort	11.55	13.79	12.97	20.77	14.32	16.38	15.69	6.69	8.94	0.89	0.67	14.38	13.08	16.93	14.16	14.97
ab	28.94	28.94	29.7	31.71	31.52	25.44	30.38	45.74	40.96	54.38	51.11	31.14	29.7	7.87	37.14	32.52
an	13.84	10.52	12.74	7.61	6.32	7.24	7.99	9.67	5.95	6.79	3.96	11.4	13.53	20.8	9.08	10.72
hi	0.01	0.01		0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.03	0.03	0.01		0.03
di	1.65	0.99		0.94						3.37		2.55		2.36		
wo										0.38						
hy	3.01	1.16	2.92	1.1	1.96	3.25	1.72	2.56	2.09		1.27	2.67	3.42	0.84	1.12	4.07
ml	2.62	2.01	2.02	0.84	2.42	2.58	1.9	2.08	2.48	1.86	1.84	1.58	2.57	1.29	0.61	2.62
crm	0.01	0.01	0.01		0.01	0.01		0.01				0.01	0.01	0.01	0.01	0.01
hm	0.5	0.78	1.01		0.12	1.09		0.89	0.36		0.51	0.96	0.59	0.49	0.67	0.21
il	0.59	0.47	0.51	0.44	0.47	0.53	0.36	0.66	0.51	0.66	0.53	0.66	0.31	0.31	0.17	0.59
ru															0.07	
H.Ap	0.19	0.09	0.12	0.05	0.09	0.14	0.07	0.19	0.12	0.12	0.09	0.14	0.25	1.46	0.19	0.14
py	0.15	0.12	0.03	0.01	0.01	0.03	0.04	0.02	0.01	0.01	0.02	0.02	0.11	0.04	0.03	0.05
c.c.	0.01	0.02	0.02	0.02	0.03	0.06	0.02	0.02	0.02	0.02	0.02	0.02	0.02	5.06	0.16	0.02
spod	0.01	0.02	0.04	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.02
T.H2O	0.35	1.07	1.07	1.13	1.63	2.66	1.14	0.34	1.08	1.18	1.56	0.13	0.47	2.34	0.44	0.26

Continue Table 2: Geochemical analyses of the Al- Otaybi area, Arabian Shield, Saudi Arabia

Continue Table 2-A:Geochemical analyses of the major oxides(wt.%) of the Granodiorite from the Al-Otaybi area

Sample	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Average
SiO2	73.68	67.96	72.85	70.75	70.85	72.95	67.95	69.51	72.21	72.75	67.95	70.95	68.88	67.91	71.85	71.73
TiO2	0.28	0.38	0.29	0.31	0.41	0.29	0.39	0.37	0.18	0.18	0.39	0.21	0.38	0.48	0.22	0.3
Al2O3	11.88	12.96	13.41	12.41	12.68	12.55	13.31	12.81	14.87	13.25	15.05	15.17	12.89	12.96	14.54	13.13
FeO	0.59	2.32	0.11	0.68	1.52	0.68	1.26	1.47	0.31	0.04	0.51	0.05	0.51	0.98	0.09	0.82
Fe2O3	3.05	2.93	3.54	3.47	3.35	3.12	4.41	3.99	1.84	1.48	2.99	2.11	4.74	4.98	2.18	2.79
MnO	0.09	0.12	0.08	0.11	0.14	0.09	0.12	0.09	0.07	0.03	0.09	0.05	0.09	0.13	0.06	0.09
MgO	1.05	2.15	0.96	0.96	0.96	0.89	1.48	1.39	0.49	0.24	1.39	0.63	1.96	1.58	0.61	0.93
CaO	2.09	4.07	2.91	3.79	3.13	3.29	4.68	4.39	2.25	2.44	4.24	3.09	4.98	4.47	2.84	2.93
Na2O	3.67	3.49	3.86	3.78	4.12	3.35	3.41	3.15	3.88	3.99	4.51	4.61	3.12	3.98	4.11	3.86
K2O	2.18	1.63	1.74	1.77	1.12	1.61	1.32	1.33	2.63	2.08	1.66	1.91	0.78	0.88	1.78	1.84
H2O+	1.11	1.75	0.15	1.37	1.01	0.49	1.09	0.91	0.61	2.65	0.38	0.51	1.42	1.18	0.89	1.01
H2O-	0.01	0.03	0.03	0.09	0.16	0.03	0.16	0.18	0.11	0.06	0.02	0.03	0.12	0.18	0.32	0.08
P2O5	0.04	0.05	0.05	0.07	0.11	0.08	0.09	0.08	0.07	0.06	0.12	0.08	0.07	0.15	0.07	0.07
CO2	0.02	0.07	0.01	0.01	0.11	0.21	0.08	0.14	0.02	0.15	0.01	0.11	0.01	0.01	0.01	0.09
Others	0.26	0.22	0.13	0.27	0.18	0.28	0.21	0.18	0.33	0.32	0.18	0.48	0.18	0.2	0.15	0.2
Total	100	100.1	100.1	99.84	99.85	99.91	99.96	99.99	99.87	99.72	99.49	99.99	100.1	100.1	99.72	99.87
D.I.	81.98	69.25	79.07	76.2	76.67	77.4	68.87	70.26	82.42	82.43	74.99	79.88	66.23	69.8	79.54	79.07

Continue Table 2-B: Geochemical analyses of the Trace Elements (ppm) of the Al-Otaybi area

Ba	883	808	400	435	290	863	360	854	1722	1810	673	627	367	288	559	664
Ce	38	30	43	53	24	36	31	35	49	23	38	38	28	33	27	39
Cl	345	190	240	947	422	392	387	632	62	20	42	100	871	290	73	221
Co	7	11	8	9	8	8	12	11	5	5	8	6	10	11	6	7
Cr	36	52	44	44	30	16	48	42	30	38	54	48	66	59	48	36
Cu	28	38	17	53	78	87	57	70	17	17	20	10	24	29	15	45
La	17	12	20	23	8	17	13	15	20	10	15	16	15	18	9	17
Li	12	12	5	5	9	9	12	7	9	4	15	12	5	6	6	9
Mo	7	37	8	43	29	18	35	37	35	30	29	35	39	38	35	19
Nb	6	1	5	4	3	3	5	2	1	5	3	2	3	2	2	4
Ni	9	19	15	13	12	9	16	16	13	13	22	15	20	19	15	15
Pb	4	4	1	4	4	4	4	3	3	4	4	4	3	2	4	2
Rb	56	34	46	53	43	48	40	29	94	52	55	26	24	21	57	50
S	709	554	131	709	573	703	705	77	503	606	73	2736	256	765	147	553
Sc	13	21	14	15	17	13	20	20	3	3	5	4	16	26	4	12
Sr	155	178	132	144	129	155	200	171	400	227	507	740	200	226	364	194
V	51	110	52	60	54	54	119	110	19	22	52	28	99	83	27	49
Y	30	35	50	39	33	35	35	40	10	8	12	9	25	35	8	32
Zn	38	45	36	46	57	39	59	32	26	18	46	33	38	41	33	48
Zr	70	149	52	70	50	280	50	55	80	50	71	143	41	85	41	106

Continue Table 2-C: Calculated C.I.P.W. Norms (wt.%) of the analysed samples of the Al- Otaybi area

qz	37.95	33.76	35.96	33.63	35.51	39.33	31.42	34.89	34.15	36.27	25.21	29.76	34.66	30.24	34.31	35.11
c			0.01						1.76	0.65	0.51	0.58			0.8	0.43
zir	0.01	0.03	0.01	0.01	0.01	0.06	0.01	0.01	0.02	0.01	0.01	0.03	0.01	0.02	0.01	0.02
ort	12.97	9.63	10.3	10.48	6.64	9.53	7.82	7.87	15.58	12.38	9.83	11.29	4.64	5.21	10.54	11
ab	31.06	26.62	32.66	31.99	34.86	28.35	28.86	26.66	32.83	33.76	39.82	39.01	26.4	33.68	34.78	32.86
an	9.67	19.37	14.21	12.05	12.96	14.64	17.26	17.17	11.19	11.71	16.49	14.81	19.22	15.03	13.85	12.19
hi	0.03	0.03	0.02	0.08	0.03	0.03	0.03	0.05	0.01		0.01	0.01	0.03	0.02	0.01	0.02
di	0.48	0.4		5.25	1.33	0.6	4.26	3.13			1.49		4.15	5.06		1.23
wo																0.01
hy	3.09	4.88	3.03	0.97	3.31	2.75	3.88	4.05	1.22	0.6	3.11	1.55	4.59	3.79	1.52	2.44
mt	1.85	2.51	1.23	2.01	2.64	1.99	2.89	3.32	0.78		1.55	0.66	1.73	2.09	0.92	1.85
crm	0.01	0.01	0.01	0.01	0.01		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
hm	1.08		1.72	1.26	0.31	1.09	1.15	0.62	1.15	1.48	0.51	1.11	2.12	2.04	1.54	0.82
il	0.53	0.72	0.46	0.59	0.78	0.55	0.75	0.7	0.34	0.07	0.74	0.4	0.72	1.19	0.32	0.54
ru			0.04							0.1					0.01	0.01
H.Ap	0.09	0.12	0.12	0.16	0.25	0.19	0.21	0.19	0.16	0.14	0.28	0.19	0.16	0.35	0.16	0.2
py	0.02	0.05	0.02	0.05	0.07	0.08	0.05	0.05	0.02	0.02	0.01	0.01	0.02	0.03	0.02	0.04
c.c.	0.02	0.08	0.02	0.01	0.12	0.24	0.09	0.18	0.02	0.12	0.01	0.06	0.01	0.01	0.01	0.21
spod	0.03	0.03	0.01	0.01	0.02	0.02	0.03	0.02	0.02	0.01	0.03	0.03	0.01	0.01	0.01	0.02
T.H2O	1.12	1.78	0.18	1.46	1.17	0.52	1.25	1.09	0.72	2.71	0.4	0.54	1.54	1.36	1.21	1.09

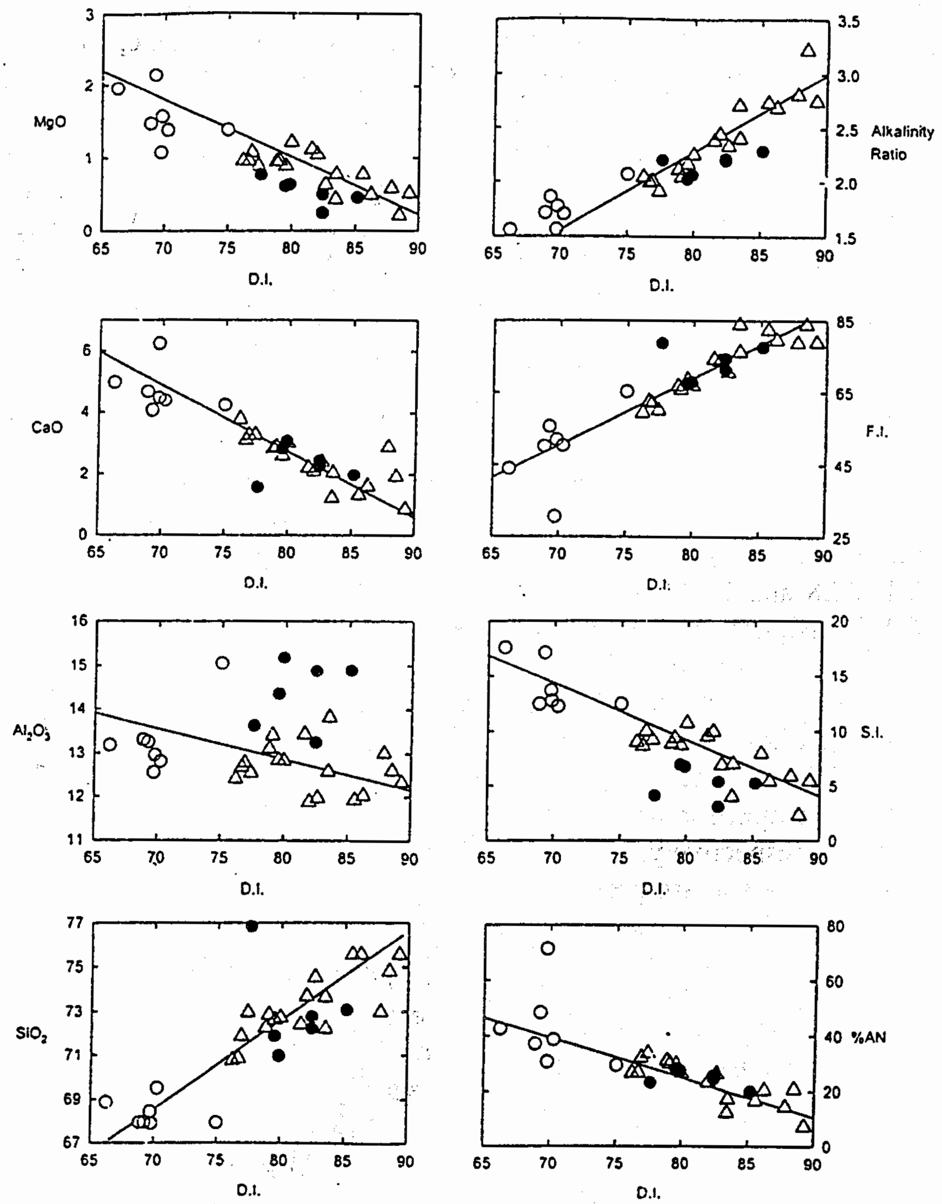

Fig. 3: D.I. vs. (a) SiO_2, (b) Al_2O_3, (c) CaO, (d) MgO, (e) % AN, (f) S.I., (g) F.I., (h) alkalinity ratio.

to the assimilation and the injection of the secondary quartz. SiO_2 and the Differentiation Index (D.I.) of Thornton and Tuttle (1960) vary sympathetically with Al_2O_3, Na_2O, K_2O, Rb and F.I. and antipathetically in linear manner with the S.I., TiO_2, CaO, MgO, P_2O_5, Fe, Co, Cr, Mo, Ni, Sc, V, Eu and Er with some spread in values (Table2 and 3). Some of these variations are local and were a result of the contamination and partial assimilation with the Halaban sequences. Al_2O_3 is 11.88-15.17 wt. % with an average of 13.15 wt %. Shand's index (1947) puts these rocks in the per-aluminous field (Maniar and Piccoli, 1989), in which the average of the molar ratio of the $Al_2O_3/(CaO+ Na_2O+K_2O)$ is >1.0. The average FeO/Fe_2O_3 ratio is 0.34 indicating high degree of oxidation and weathering. K_2O is a mobile constituent and it is possible to be low with alteration and in the highly tectonic environment that can be identified by the absence/or low value of the alkali feldspar. Several features of the major oxides, e.g. the low amount of the total alkalis and alumina, put these samples in the subalkaline sector that is identified by Nockolds (1954), Wright (1969) and Le Bas and Streckeisen (1991). The average ratios of the Na_2O/CaO, Na_2O/K_2O, MgO/T.FeO and MgO/MnO are 1.32, 2.1, 0.28 and 10.33 respectively. These ratios fit with the figures of the CAG assigned by Maniar and Piccoli (1989). The pillow lavas are tholeiitic spilitic/komatiitic in composition and are amphibolitized indicating high degree of metamorphism. They have high Mg, Cr, Ni and Ca/Al and low in the K_2O and the normalized LREE (Sindi, 2005).

Selected trace elements are illustrated in Table 2. Cr is low and is directly proportion with Ni. K_2O and Rb are directly proportion with CaO and Sr, respectively. Ba and Sr have averages of 664 and 194 ppm respectively and are present in the amphibole, apatite, feldspars and mica. Nb, Sc, V, Y and Zr are low reflecting the low contents of some accessory minerals (e.g. Zirconium). Samples 6, 16, 26 to 29 and 32 are low in Y. The variation of the ferroalloy elements, Ba, Be, Sr and Zn indicates the latter hydrothermal alteration to the ferromagnesian minerals of this pluton. The Rb/Sr varies antipathetically with D.I. and selected ratios (e.g. Ca/Sr, K/Rb and Ti/Zr). Sr, Ca, and Zr increase with the amount of the feldspars and mica. The central Al-Otaybi pluton has higher La and Ce concentrations than the rest of the pluton.

The C.I.P.W. norms show that the normative diopside reflects the modal hornblende while the hypersthene reflects the amount of the mica. The magnetite, ilmenite, zirconium and apatite reflect the concentration of the iron oxides, TiO_2, Zr and P_2O_5 respectively (Table 2).

Table 3-A: Geochemical analyses of the non -normalized REE (ppb) of the Granodiorite rocks from the Al -Otaybi area, Arabian Shield, Saudi Arabia

Sample No.	1	3	8	14	16	18	19	21	22	23	24	25	26	27	28	29	30	31	32	Average
La	18	15.9	7.9	8.15	7.78	13.1	9.86	18	6.93	10.5	10.5	9.83	15.5	6.95	10.4	12.8	9.87	11.1	7.53	11.08
Ce	25.8	34.9	24.9	16.7	16.7	24.8	25.3	41	18.1	23.8	26.2	25.8	37.5	17.9	29.3	32.7	21.1	25.1	17	25.49
Pr	3.66	4.46	4.18	2.87	2.19	4.33	3.15	5.83	3.12	3.54	3.72	3.25	4.18	1.83	4.4	4.36	3.12	4.12	2.61	3.63
Nd	17.8	16.3	18.3	12.7	8.51	16	12.3	21.3	12.8	13.4	14.1	13	14	7.29	16.9	16	11.2	15.7	7.95	13.97
-																				
Sm	4.09	3.36	4.83	3.26	1.44	3.43	2.99	5.06	3.64	3.23	3.6	3.18	2.03	1.03	3.23	2.72	2.76	4.28	1.46	3.14
Eu	0.72	0.49	0.95	0.75	0.26	0.47	0.49	0.64	0.56	0.51	0.61	0.59	0.46	0.27	0.77	0.43	0.56	1.03	0.39	0.58
Gd	4.14	3.1	5.17	3.17	0.32	3.94	2.74	4.76	3.75	2.68	3.47	3.15	0.98	0.9	2.58	1.97	2.58	4.35	0.98	2.88
Tb																				
Dy	5.06	3.72	6.4	4.59	1.91	4.23	4.18	5.98	4.73	4.26	4.5	4.36	1.96	0.97	1.99	1.89	3.27	5.06	1.93	3.74
Ho	1.12	0.83	1.4	1.08	0.24	0.86	0.95	1.33	1.03	1.01	1.01	0.96	0.38	0.14	0.4	0.28	0.73	1.09	0.32	0.8
Y	27.3	26	41.5	28.5	6.56	28	27.9	38.8	32.4	28.3	31.5	30.5	6.5	4.35	10.3	7.27	22.4	31.1	7.38	22.97
Er	3.8	2.94	4.65	3.11	0.98	2.8	2.91	4.76	3.75	3.01	3.69	3.03	0.99	1.55	1.93	2.09	2.78	3.69	2.33	2.88
Tm																				
Yb	3.89	3.01	4.78	2.56	0.97	3.19	3.17	4.72	3.51	3.17	3.46	3.42	0.96	0.95	1.95	0.98	2.37	3.12	1.71	2.73
Lu	0.64	0.51	0.77	0.32	0.11	0.51	0.53	0.78	0.58	0.52	0.58	0.59	0.11	0.07	0.17	0.12	0.41	0.52	0.14	0.42

Table 3-B: Geochemical analyses of the normalized REE (ppb) of the Al-Otaybi area

La	73.7	65	32.3	33.3	31.8	53.7	40.3	73.4	27.9	42.8	43.1	40.2	63.4	28.4	42.5	52.2	40.3	45.3	30.8	45.28
Ce	40.4	54.7	39.1	26.2	26.1	54.6	39.7	64.3	28.4	37.2	41	40.5	58.8	28	46	51.2	33	39.3	26.6	40.79
Pr	38	46.2	43.4	29.8	22.7	4.96	32.7	60.5	32.4	35.9	38.6	33.7	43.4	19	45.7	45.3	32.4	42.8	27.1	35.5
Nd	37.5	34.4	38.6	26.9	18	33.7	26	45	27	28.3	29.7	27.5	29.5	15.4	35.7	33.8	23.6	33.1	16.8	29.48
Sm	26.6	21.8	31.4	21.2	9.37	22.3	19.4	32.9	23.7	21	23.4	20.7	13.2	6.67	21	17.7	17.9	27.8	9.49	20.38
Eu	12.4	8.45	16.4	13	4.45	8.17	8.52	11.1	9.58	8.86	10.5	10.2	8.01	4.62	13.2	7.47	9.68	17.7	6.65	9.95
Gd	20.3	15.2	25.3	15.5	1.56	19.3	13.4	23.3	18.3	13.1	17	15.4	4.77	4.38	12.6	9.66	12.6	21.3	4.81	14.1
Tb																				
Dy	19.9	14.6	25.2	18.1	7.52	16.6	16.4	23.5	18.6	16.8	17.7	17.2	7.71	3.81	7.82	7.44	12.9	19.9	7.61	14.7
Ho	19.7	14.6	24.8	19	4.29	15.3	16.8	23.5	18.1	17.8	17.9	16.9	6.69	2.49	7.12	4.98	12.9	19.3	5.57	14.08
Y	17.4	16.6	26.4	18.2	4.18	17.8	17.8	24.7	20.6	18	20	19.5	4.14	2.77	6.54	4.63	14.2	19.8	4.7	14.63
Er	22.9	17.7	28	18.7	5.92	16.9	17.5	28.7	22.6	18.2	22.2	18.3	5.95	9.33	11.6	12.6	16.8	22.3	14	17.37
Tm																				
Yb	23.6	18.2	29	15.5	5.86	19.3	19.2	28.6	21.3	19.2	21	20.7	5.84	5.78	11.8	5.92	14.3	18.9	10.4	16.54
Lu	25.2	20.1	30.4	12.6	4.34	20.1	20.7	30.6	22.9	20.3	22.9	23.2	4.14	2.72	6.6	4.84	16.1	20.6	5.6	16.52

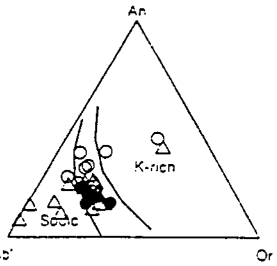

Fig. 6: The Ab-An-Or digram shows that the Al-Otaybi rocks are Na-K rich.

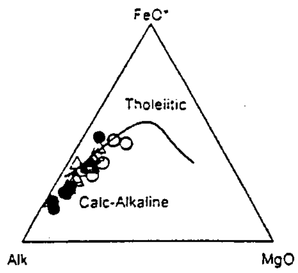

Fig. 5: The AFM digram shows subalkaline magmatic source.

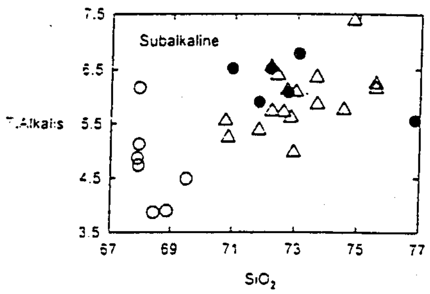

Fig. 4: SiO_2 vs. total alkalis (TAS) diagram shows that the Al-Otaybi rocks fall in the sub-alkaline category indicated by Nockolds (1954) and Wright (1969).

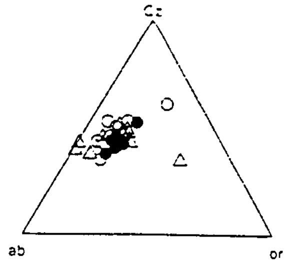

Fig. 9: The normative qz–ab-or-H_2O diagram for the studied samples with the experimental data of Tuttle and Bowen (1958) show that these samples fall in the cotectics of 0.5-5 k-bar P_{H_2O} as most of the studied samples fall near the minimum ternary P_{H_2O} of 5 k-bar.

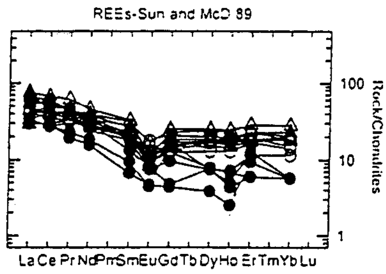

Fig. 8: REE reflecting one magmatic source following different magmatic pulses and/or the assimilation with the country rocks and the meta-somatism according to the pattern of Sun and McDonough (1989).

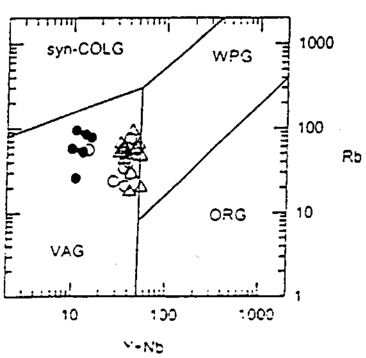

Fig. 7: Y+Nb vs. Rb put the Al-Otaybi samples in the VAG field defined by Pearce et al. (1984

Selected 13 samples were analysed for the REEs (Table 3). They are depleted in Eu and Ho. Sm/Nd is 0.4334-0.8779 with an average of 0.066 indicating a magmatic source for the Al-Otaybi pluton. The LREE/HREE ratio is low suggesting a slow diffusion rate of the REE at low temperature end of the crustal melting.

The oligoclase (An_{10-20}) and K-feldspars ($Or_{90-70}Ab_{7-20}An_{1-10}$) have high percentage of Al and K indicating the presence of the sericitization, saussuritization and kaolinitization as hydrothermal alteration, decomposition of the feldspars plus the intergrowth with the K-feldspars. They are heterogeneous with normal Carlsbad twinning. Crypto-perthitic inter-growth is the main factor of the schiller effects in these samples. Most of these K-rich planes are parallel to the *y*-axis of the crystals (Sindi, 2005). The biotite have high amount of Mg indicating assimilation process with the basic country rocks. The Fe/(Fe+Mg), Mg/Fe and Al/ Si ratios of these biotite flakes indicate that Fe replaces Mg; and Al replaces Si during the process of the metamorphism to form the formula of these biotites, which is $(K,Na)_2(Mg,Fe)_6\ Al_4Si_6O_{20}\ (OH)_4$ (Sindi, 2005). Some ferroalloy elements substitute Fe readily in the crystal lattice of the amphiboles and magnetite. The Mg/(Mg+Fe) ratio shows that amphibole was introduced to this acidic melt through the assimilation process of the impure dolomitic limestone rocks. Fe/Ti in the magnetite reflects that Ti, Mn and Mg are low in these opaque.

DISCUSSION

The chemical analysis of the rocks in the Al-Otaybi area is low in TiO_2, Fe_2O_3, K_2O, Ba, Nb, Sr, V, Y and Zr and high in SiO_2, Al_2O_3, MnO, Na_2O, Fe, Ba, Cr, Mo, Ni, Rb, Sr, Zn and Zr. Applying the classification of Yoder and Tilly (1962), these rocks fit with the normative analyses of the mildly alkaline series. It indicates a discontinuous spread of silica for the Jafara, Saqit and Uthainan Shamal outcrops. The D.I. versus selected elements shows discrepancy between the contaminated and the uncontaminated groups of these rocks which can be clearly recognized in the diagrams of the D.I. versus SiO_2, Al_2O_3, CaO, MgO, alkalinity ratio, F.I and S.I. (Fig. 3). The studied rocks fall in the sub-alkaline category indicated by the SiO_2 versus total alkalis (TAS) diagram (Fig. 4) according to Nockolds (1954) and Wright (1969). These samples are per-aluminous subalkaline with meso- to epi-zonal stage of emplacement according to Shand's index diagram that is identified by Maniar and Piccoli (1989). The saturation of the initial alkalis melt with volatiles is from the mineral association of the studied samples. The AFM digram (Fig. 5) shows subalkaline magmatic source to these samples. The Ab-An-Or digram shows that these rocks are Na-K rich (Fig. 6). Y+Nb versus Rb (Fig. 7) put these samples in the VAG field defined by Pearce et al. (1984).

The magma generation for this granitoid pluton is complicated to be discussed on the basis of the magma dynamics and the nature of the surrounding crust. The REE can be taken in account to determine the origin of the magma due to their less effect with the weathering, alteration and metamorphism. So, representative REE data were studied following the pattern of Sun and McDonough (1989) and plotted on the chondritic-normalized diagram (Fig. 8). They reflect one magmatic source for this pluton though magmatic pulses and/or assimilation with the country rocks and metasomatism occur regardless the weathering of the area.

These post-tectonic Al-Quwayiyah rocks are differentiated and derived from a parent saturated sub-alkaline granodiorite immiscibility magma that belongs to the I-type granite with meso- to epi-zonal emplacement according to the definition of Chappell and White (1992). The rise of this magma near the surface indicates low water content and rapid rates of rise to prevent cooling and solidification at depth. The immiscible field expands with increasing the volatiles and the f_o. High temperatures and P_{H2O} may have developed during mobilization to produce a granite minimum melt (Winkler, 1976). Luth et al. (1964) concluded that at H_2O saturation, the system qz-ab-or-H_2O (Fig. 9) changed from minimum to eutectic melting at pressures >3.6 k-bar while with changing the P_{H2O} and the invasion of Fe and K would lower the temperatures and increasing the partial P_{H2O} to allow the biotite and amphibole to crystallize. Comparing the normative qz–ab-or-H_2O with the experimental data of Tuttle and Bowen (1958), it shows that these samples fall in the cotectics of 0.5-5 k-bar P_{H2O} (Fig. 9). Most of the studied samples fall near the minimum ternary P_{H2O} of 5 k-bar. As the present samples reach water saturation, and according to the mineralogy and chemistry of these rocks, plus their depletion with the volatile materials (eg. Cl, CO_2, F, S); the P_{H20} is equal to the P_{Total} which is equivalent to 5 k-bars. Elkins and Grove (1990) indicate that the thermometer of the two-feldspar liquid (Or in plagioclase and An in K-feldspar) calibration in granites could be in the range of 650-800°C±50°C. The crystallization of the studied samples may begin with the association of the plagioclase and K-feldspars at about 750°-850°C with assumed pressure of 5 k-bars according to the T-P model of Yoder and Tilly (1962, P. 451-452), Carmichael et al. (1977); Keppler (1989) and Ebadi and Johannes (1991).

The Al-Quwayiyah Quadrangle is part of immature and mature island-arc that is developed on ophiolite and metamorphic complexes terrane, which is represented on the subducted A.M.R.I. Suture (Sindi, 1996, 2004 and 2005). The absence of any seismic activity in this area may suggest that the dipping of the subducted plate is not deep enough to generate volcanic activity. This complex has magma immiscibility with gravitationally controlled influence, differentiation and uniform density plus mixing with the meta-sedimentary rocks.

CONCLUSION

The Al-Quwaiyiah Quadrangle consists of several syn-tectonic and post-tectonic plutons differ in age, metamorphic grade, deformation style and lithofacies in addition to the presence of the phreatomagmatic activity in the region. These post-tectonic Al-Quwayiyah granodiorite rocks intrude the Halaban group. The texture, structure and mineralogy of this granitic group show weathering and low temperature hydrothermal alteration. Also, they show cataclastic metamorphism to the area under investigation. The boarders of the Al-Otaybi pluton has contaminated border zones of 50-200 m width with the adjacent basic rocks, which are enriched in Ti, Mg, Ca, Fe, Ba, Sr and Zr and depleted in Si, Nb, Rb and Y. The central part of this post-tectonic granitic pluton is low in TiO_2, Fe_2O_3, K_2O, Ba, Sr, V and Zr and high in SiO_2, MnO, Cr, Ni and Zn. Na-Ca metasomatism and hydrothermal alterations have affected these rocks. The studied rocks fit with the continental arc granitoids.

Dykes of different ages and compositions have intruded the area in various directions. In the light of these petrography, mineralogy and chemical data, it is possible to attribute the origin of the studied granitic samples to the I-type origin with the presence of the immiscible heterogeneous single sub-alkaline Si-saturated magma that is affected by fractional crystallisation and magma mixing. This area falls on the A.M.R.I. Suture subduction zone.

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جيولوجية وجيوكيميائية صخور الجرانودايورايت في منطقة العتيبي، مربع القويعية، المملكة العربية السعودية

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الملخص

تقــع مــنطقة العتيبــي في مربع القويعية عند طرف الجزء الشرقي من الدرع العربي. تتكون هذه المنطقة من بلوتون جرانودايورايتي فوق ألوميني تحت قلوي ظهر في فترة ما بعد العملــيات التكتونــية الــتابعة لفترة ما قبل الكمبري بالمملكة العربية السعودية. قطعت هده الصخور بشكل حاد صخور أخرى متحولة لمتكون حلبان ومجموعات من الصخور البركانية المــتحولة، ثــم 'قطعــت هده الصخور الجرانودايورايتية في إتجاهات عديدة بعروق المرو وبجماتايــتات بســيطة وقواطــع ذات تراكيــب وأعمــار متبايــنة. ينتمــي هدا البلوتون الجرانودايورايتــي إلــى نوع الجرانيت ذا الأصل الناري لماجما سيليكاتية مشبعة تحت قلوية وغــير متجانســة. 'جمعــت عينات من منطقة الدراسة وأجريت عليها دراسات جيولوجية وجيوديناميكــية وجيوكيميائية حيث تبين أن منطقة الدراسة هي جزء من معقد افيوليتي يمثل طــرفا من جزر قوسية تكونت في منطقة اندساس {الأمار-(مرقان-الرين)-إدساس} وتعتبر منطقة العتيبي جزءا من خط هذا الاندساس الذي أثر على أقصى شرق الدرع العربي.