

Petrogenesis of Bir Madi Gabbro-Diorite and Tonalite-Granodiorite Intrusions in Southeastern Desert, Egypt: Implications for Tectono-Magmatic Processes at the Neoproterozoic Shield

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Abstract. The Neoproterozoic rocks of the Bir Madi area, south eastern desert, comprise a Metagabbro-Diorite Complex (GDC) and a Tonalite-Granodiorite Suite (TGrS). The GDC has a weak tonalitic to strong calc-alkaline character and is made up of olivine gabbro, hornblende gabbro, diorite and monzodiorite. The olivine gabbro is characterized by abundance of augite and labradorite with pseudomorphic serpentine. The hornblende gabbro is mainly composed of hornblende, labradorite, andesine and minor amounts of quartz with or without augite. The diorite consists essentially of andesine, hornblende, biotite and quartz. The GDC is compositionally broad, with a wide range of SiO_2 (46-57 %) and pronounced enrichment in the LILE (Ba and Sr) relative to the HFSE (Nb, Y and Zr). The GDC rocks exhibit petrological and geochemical characteristics of arc-related mafic magmas, derived possibly from partial melting of a mantle wedge above an early Pan-African subduction zone of the Neoproterozoic Shield. The tonalite and granodiorite have a calc-alkaline affinity and show the geochemical signatures of I-type granitoids. The TGrS contains amphibolite enclaves and foliated gabbroic xenoliths. Based on the field evidence and geochemical data, the GDC and TGrS are not related to a single magma type through fractional crystallization. The presence of microgranular amphibolite enclaves in the tonalitic rocks suggest against their generation by partial melting of a mantle-derived basaltic source. The tonalitic magma originated from partial melting of an amphibolitic lower crust by anatexis process at a volcanic arc regime during construction of the Arabian-Nubian Shield. Fractional crystallization of K-feldspar and biotite gave more developed granodiorite variety from the tonalitic magma. The gabbroic xenoliths are similar in the chemical composition to the investigated metagabbros. They are incompletely digested segments from the adjacent metagabbro rocks incorporated into the granitic magma through an assimilation process.

Introduction

The Neoproterozoic rocks of the eastern desert, Sinai, northern Sudan and western Saudi Arabia are collectively termed the Arabian-Nubian Shield (ANS) (Gass, 1981). The ANS is considered as one of the best examples of crustal growth through terrain accretion of intra-oceanic mantle-derived magmas, initial island arcs and micro-continents during the 950-550 Ma Pan-African event (Vail, 1983). It thus, represents juvenile arc development by subduction-related accretion in an oceanic environment (Stern, 1994). The occurrence of ophiolitic sutures and their association with voluminous calc-alkaline rocks have led most investigators to agree that the shield regions evolved by juxtaposition of a series of island arcs with later development of continental magmatic arcs (Abdel-Rahman and Martin, 1987). The Pan-African crustal components of the eastern desert consist mainly of gneisses, ophiolitic serpentinites and metagabbros with tholeiitic metabasalts, metasediments, island arc metavolcanics and metagabbro-diorite, older granitoids, Dokhan volcanics, Hammamat sediments, younger gabbros and younger granitoids (El-Gaby et al., 1988).

The Neoproterozoic gabbroic rocks of Egypt have been subdivided in various ways (Basta and Takla, 1974; Takla et al., 1981; Ghoneim et al., 1992; El-Sheshtawi et al., 1995;

Basta, 1998; Khalil, 2005). These rocks are essentially classified as older and younger gabbros (Takla et al., 1981). The older gabbros are regionally metamorphosed and are considered as a member of ophiolitic sequence (i.e. ophiolitic metagabbro: El-Sharkawi and El-Bayoumi, 1979) or island arc assemblage. The syntectonic gabbro-diorite intrusives have a calc-alkaline affinity and are interpreted to be belonging to island arc association (El-Gaby et al., 1990). The emplacement of the gabbro-diorite plutonisms occurred at around 987-830 Ma (Hashad, 1980; Abdel-Rahman and Doig, 1987). Thus, they represent the earliest phase of crustal growth in the Nubian Shield of Egypt (Abdel-Rahman, 1990). The younger gabbros occur as small, fresh, unmetamorphosed intrusions comprising nfdite, norite-gabbro, olivine gabbro and troctolite varieties (Basta and Takla, 1974). These gabbros mainly represent the late tholeiitic/calc-alkaline, post-tectonic mafic magmatism of the Pan-African event, which was emplaced before the younger granitoids (Hassan and Hashad, 1990).

Granitoid rocks constitute a major component of the basement outcrop in Egypt (40%), which in general are classified into two main distinct groups: older and younger granitoids (Akaad and Noweir, 1980). According to Harris et al. (1984) and Stern and Hedge, (1985), the older granitoids comprise syn-tectonic calc-alkaline tonalite-

granodiorite intrusions and rarely granites formed 850-614 Ma. These are also known as subduction-related granites (Hussein et al., 1982) or granitoid rocks of island arc stage (Ragab, 1987). The parent magmas of the older granitoids may be originated by partial melting of mantle wedge with little or no crustal contamination (Hussein et al., 1982) or by anatexis process of amphibolitic lower crust (Furnes et al., 1996; Moghazi, 1999) in subduction zones. The younger granitoids cover a wide compositional spectrum, ranging from quartz monzonite to alkali granites (Greenberg, 1981) and have a limited time span of 610-550 Ma (Stern and Hedge, 1985).

This work introduces field, petrographical and geochemical investigations for metagabbro-diorite and tonalite-granodiorite intrusive rocks at Bir Madi area in the southern part of Egypt (Fig. 1). The main aim is to integrate the field evidences and geochemical data to discuss plausible petrogenetic processes associated with such mafic and silicic magmatisms at Arabian-Nubian Shield.

Geological Setting

The Bir Madi area lies in southeastern desert located between longitudes $35^{\circ}00' - 35^{\circ}12' E$ and latitudes $22^{\circ}45' - 23^{\circ}00' N$ (Fig. 1). Despite easy access to the region, west of Shalatein through a desert road, the Wadi Madi area

has received little attention and only few geological studies were conducted (Ashmawy, 1987; Aly et al., 1997; El-Amawy et al., 2000). The Neoproterozoic rocks in the study area consist mainly of serpentinites, metavolcanics, GDC, older granitoids (tonalite-granodiorite), younger gabbros and younger granitoids (Fig. 1). The serpentinites are fine-grained, massive and light green to deep brown in colour. They are particularly foliated and altered to talc-carbonates. The metavolcanic rocks are mainly composed of basalts, meta-andesites, meta-dacites and meta-rhyolites. These are fine-grained, green to grayish green and reddish brown in colour and sometimes, exhibit porphyritic and amygdaloidal textures.

The metagabbro-diorite rocks occupy the eastern and western flanks of Wadi Atluk, with a nearly moderate relief, which have an obvious intrusive contact against serpentinites and metavolcanics. The metagabbro-diorite masses are heterogeneous, medium to coarse grained and dark to pale green in colour. These are usually massive with pronounced foliations along their outer parts. The foliations are generally striking NW and dipping at gentle and moderate angles towards NE.

The metagabbroic rocks contain mafic enclaves (up to 20 cm in size), which have blackish green colour and show

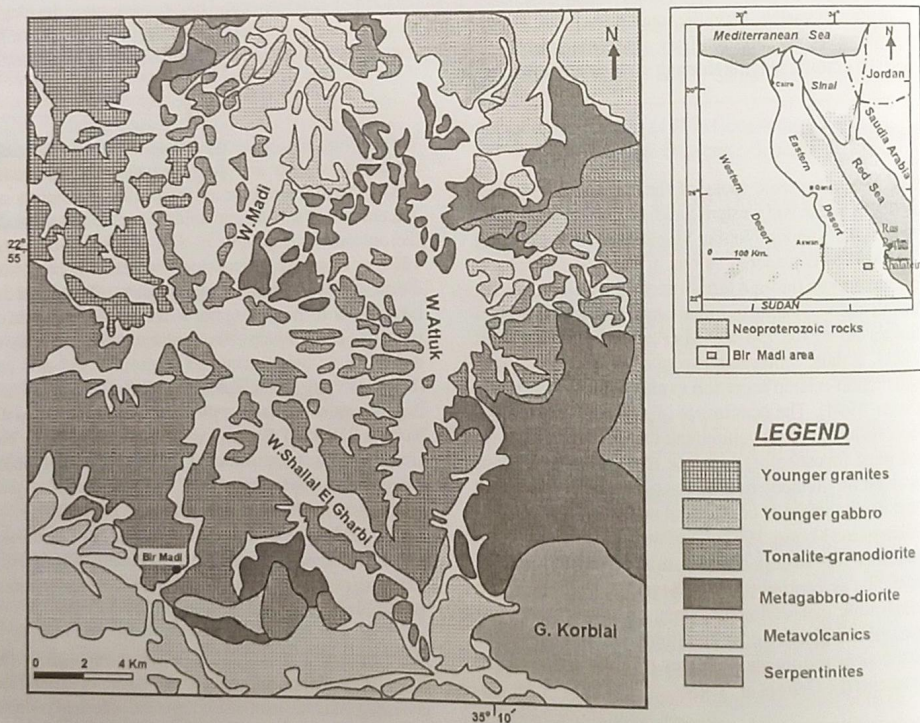


Fig. 1. Geologic map of the Bir Madi area, South Eastern Desert of Egypt.

irregular outlines. The enclaves are fine-grained (ca. 0.5 mm) and possess larger proportions of hornblende compared with their hosts. The tonalite-granodiorite rocks mainly occur around Bir Madi and along Wadi Shallal El Gharbi. These are equigranular, coarse to medium-grained with pale gray to pinkish gray colour and show an intrusive contact with the neighboring metagabbro-diorite, as indicated by presence of some tonalitic patches in rims of the gabbroic rocks. The tonalite-granodiorite rocks are massive except those found near shear and fault zones, where a gneissose texture is observed. The foliation of the gneissose rocks strike mainly in NNW and dip outward at a moderate angle. In places, the massive tonalite-granodiorite contains foliated metagabbro and amphibolite xenoliths, which retain variable shapes inside the non-foliated older granitoids, as recognized by El-Amawy et al. (2000) in the Wadi Madi area. The metagabbro xenoliths are medium-grained with hazy rims partly digested by the tonalite and granodiorite varieties.

The amphibolitic enclaves are fine-grained, ovoid to ellipsoidal in shape and lack any significant reaction with the hosting tonalite. The younger gabbros occur as a large circular mass in the northeastern part of the studied area, intruding the metamorphosed rocks and the tonalite-granodiorite. The contact between the gabbros and metavolcanics is sharp and distinct. The younger granitoids have limited distribution in the study area, which are massive, medium to coarse grained and pink in color commonly cut across by a series of mafic and felsic dykes.

Materials and Methods

The petrographic study of fifty samples belonging to Metagabbro-Diorite Complex (GDC), Tonalite-Granodiorite Suite (TGrS), encountered enclaves and xenoliths was carried out. Based on microscopic study, selected samples from the GDC, TGrS and gabbroic xenoliths were chemically analyzed. Major oxides were measured by wet chemical analysis, whereas trace elements were determined by X-ray fluorescence technique. Calibration was done with the international reference samples, some of which were also run as unknown. Loss on ignition was calculated by heating about 3 grams of the rock powder in a porcelain crucible at about 1000°C for 4 hours, until constant weight was attained (Table 1).

Petrography

Metagabbro-Diorite Complex (GDC): Microscopically, the Bir Madi GDC consists of four main rock varieties: olivine gabbro, hornblende gabbro, diorite and monzodiorite. The olivine gabbro is characterized by abundance of clinopyroxene (augite) and plagioclase with pseudomorphic serpentine. The hornblende gabbro is mainly composed of hornblende, plagioclase and minor amount of quartz with or without clinopyroxene. Secondary minerals are actinolite, chlorite, epidote, zoisite and sericite. Plagioclase feldspar occurs as subhedral prismatic crystals (6 mm) ranging from labradorite to andesine.

It is occasionally altered to sericite, epidote and zoisite. Augite is partly replaced by chlorite. Hornblende is present as medium grained anhedral twinned crystals (upto 4 mm), which contain minute inclusions of plagioclase, apatite and magnetite. In the hornblende gabbro, quartz occurs as anhedral interstitial grains of about 2 mm in diameter. Sphene forms shapeless grains between different mineral phases.

The diorite consists predominantly of andesine, hornblende, biotite and quartz with minor amounts of K-feldspar. Andesine forms subhedral crystals, which are partly altered to sericite. Hornblende is nearly equal in amount to biotite, which occurs as dark brown flakes with pronounced pleochroism. Quartz crystals are medium-grained, anhedral and slightly deformed. K-feldspar is less abundant and occurs as anhedral interstitial grains. Mineralogically, the monzodiorite is similar to the diorite, but it is richer in K-feldspar and quartz. The fine-grained mafic enclaves of the metagabbroic rocks have relatively large proportion of hornblende, actinolite, pyroxene opaques and low proportion of plagioclase relative to the metagabbros. Hornblende is present as subhedral laths (up to 0.3 mm in length). Augite is present as fine-grained prisms enclosed in poikiloblastic grains of iron oxides. Plagioclase feldspar occurs as subhedral to anhedral prismatic crystals (An_{70-80}). It sometimes, has calcic resorbed cores and twinned according to Carlsbad law.

Tonalite-Granodiorite Suite (TGrS): The TGrS of Bir Madi area consists essentially of plagioclase feldspar, hornblende and biotite with subordinate amounts of quartz. Plagioclase (An_{5-50}) is the most abundant mineral constituent. It usually forms euhedral to subhedral prismatic crystals (up to 8 mm). The crystals are often complexly zoned and twinned according to Carlsbad law. Hornblende is present as subhedral prisms and laths. Biotite occurs as flakes (3 mm) enclosing minute inclusions of opaque minerals forming poikilitic texture. It sometimes, occurs as fine-grained clusters. Quartz forms anhedral grains (up to 5 mm) between the plagioclase crystals.

The granodiorite is made up of plagioclase feldspar, quartz, K-feldspar, biotite and hornblende. Plagioclase (An_{25-35}) is generally fresh, but altered crystals are occasionally observed. Quartz occurs as large subhedral crystals (5 mm), which commonly exhibit wavy extinction. K-feldspar is represented by orthoclase and occasional microcline. Orthoclase is present as large tabular crystals (up to 8 mm across) or as small grains. Biotite is the dominant mafic mineral in the granodiorite variety. It occurs as separate flakes (up to 2 mm) or irregular aggregates. Apatite, sphene, zircon and iron oxides are accessories. Secondary minerals are actinolite, sericite, epidote and chlorite. The mineralogical constituents of the gabbroic xenoliths in the tonalite and granodiorite resemble to the studied metagabbros. The amphibolite enclaves are fine-grained and consist of hornblende and plagioclase (An_{30-45}) as essential components. Actinolite, chlorite,

Table 1. Chemical analyses of the metagabbro-diorite and tonalite-granodiorite rocks at the Bir Madi area

Metagabbro-diorite complex			Older granitoids and their associated gabbroic xenoliths		
Rock type	Gabbro	Diorite	Tonalite	Granodiorite	Gabbroic xenoliths
Sample No.	G1-G6	D1-D6	1-6	7-12	X1 X2 X3
Major oxides (wt. %)					
SiO ₂	49.69	55.18	67.24833	69.37	48.84
TiO ₂	0.68	0.47833	0.3666	0.388	0.253
Al ₂ O ₃	17.4	16.868	15.4667	14.975	17.21
Fe ₂ O ₃	7.84	8.191667	3.66	2.355	8.256
MnO	0.1	0.155	0.033	0.0466	0.18
MgO	6.96	4.1	1.6466	1.893	7.86
CaO	11.76	8.056	4.46166	2.893	12.163
Na ₂ O	2.45	3.0666	4.043	3.896	2.77
K ₂ O	0.70	0.7933	1.323	2.456	0.683
P ₂ O ₅	0.21	0.17	0.09	0.088	0.783
L.O.I.	1.17	1.715	1.455	1.563	1.243
Total	98.96	98.885	99.80	99.965	100.316
Trace elements					
Ba	233.66	211.16	726	472.66	271.66
Ce	30.666	19.5	68.33	60.5	32.66
Co	41.1667	27.833	5.66	5.5	56
Cr	234.833	122.833	38.333	24	246.66
Cu	45.333	101.66	3.66	11.166	37.666
La	9.166	11.666	27.833	36.166	11
Nb	3.333	3.66	9.5	10.5	03
Nd	7.833	10.166	13.666	14.5	14.66
Ni	83	36	14.666	08	69.33
Pb	40.333	37.833	13.666	15.83	33.66
Rb	19.5	14.166	59	90.5	53.33
Sr	356.5	256.5	464.1667	283.83	262.33
V	262.166	217	30	32.333	197
Y	26.666	20.333	11	23.556.166	23.666
Zn	101.5	84.666	44.333	56.166	74.333
Zr	48.833	40.833	70.5	167.1667	45.333
Total	1544.47	1215.809	1531.984	1288.818	1432.288
Geochemical ratios					
K ₂ O/Na ₂ O	0.2933	0.2666	0.338	0.645	0.293
A/CNK	0.665	0.851	0.958	1.0466	0.16
Rb/Sr	0.055	0.055	0.1266	0.4216	0.0766
Zr/Y	1.68	2.02	7.048	7.54	1.9866
K/Rh	435.83	690.833	271.667	329.833	163.666
Mgr	46.5	30	27.1667	39.5	45
Total	485.0233	724.0256	307.3043	378.9862	211.1822

sericite and epidote are secondary minerals. Accessories are quartz, biotite, sphene and iron oxides.

Geochemistry

Trace Elements: Based on the geochemical classification of De La Roche et al. (1980), the GDC samples are classified as olivine gabbro, gabbro, diorite and

monzodiorite (Fig. 2). These rocks have SiO₂ content ranging from 46 to 57wt% and a low K₂O/Na₂O (<0.4) ratio with a wide spectrum in MgO and CaO (Table 1). The GDC shows variable contents of Cr, Ni, V, Ba and (Table 1). The concentration of Nb is considerably less than those of Y and Zr (Table 1). Major and trace elements show well-defined trends with increasing SiO₂, demonstrated by decrease in CaO, Sr, Y and increase in Na

(Fig. 3). Most of the GDC samples appear to be Fe-poor relative to MgO and are thus classified as tholeiitic to calc-alkaline (Fig. 4). The tholeiitic geochemical affinity for the early-crystallized gabbroic variety may be attrib-

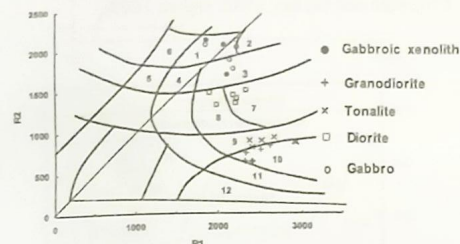


Fig. 2. R_1 , R_2 Discrimination diagram for chemical classification of the examined rocks. (1) olivine gabbro (2) gabbro norite (3) gabbro (4) monzogabbro (5) syeno-gabbro (6) alkali gabbro (7) diorite (8) monzodiorite (9) tonalite (10) granodiorite (11) granite and (12) alkali granite.

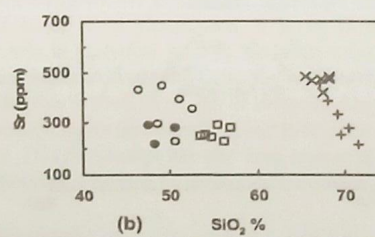
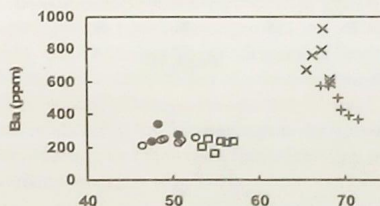
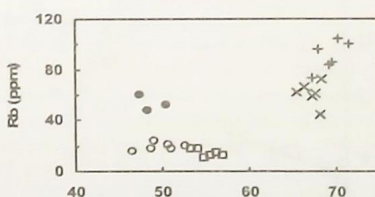
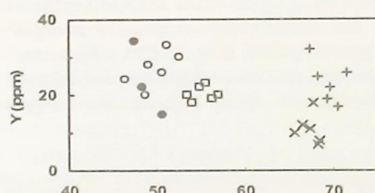
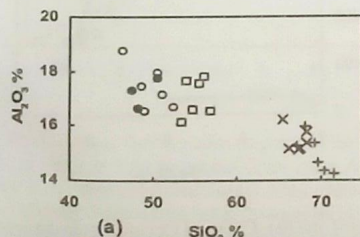
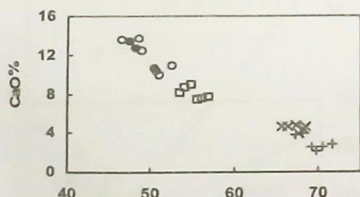
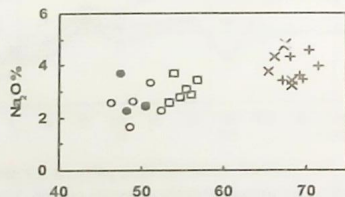
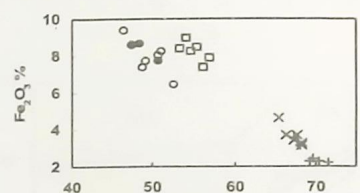


Fig. 3. Harker variation diagrams for CDG and TGrS rocks. SiO_2 vs. some selected (a) major oxides and (b) trace elements. Symbols as in Fig. 2.

ted to fractionation of olivine and clinopyroxene before emplacement, which enriches the residual melt in Fe relative to Mg and produces a Fe-enriched tholeiitic affinity on the AFM diagram. The dioritic samples are characterized by $\text{Al}_2\text{O}_3/\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O}$ (A/CNK) molar ratio less than one with a metaluminous character (Fig. 5). In the primitive mantle-normalized spider diagram, the investigated gabbroic and dioritic rocks show high contents of the large ion lithophile elements (Rb, Ba, Sr and K) relative to Zr, Y and Ti (Fig. 6). The strong negative Nb anomaly in the GDC is a characteristic feature of mantle derived arc magmas (Pearce, 1983; Holm, 1985) due to highly immobile character of this element during partial melting processes (Mc Culloch and Gamble, 1991).

For the TGrS, the major oxides like Al_2O_3 , CaO and Fe_2O_3 show negative correlation with SiO_2 but K_2O increases with increasing SiO_2 (Fig. 3). The suite forms roughly curvilinear arrays with relatively smooth Ba and Zr variations in the Harker diagram. The SiO_2 is positively correlated with Rb, Y and Zr and negatively correlated

with Sr and Ba (Fig. 3). The TGrS rocks define a considerable calc-alkaline magmatic trend on the AFM diagram (Fig. 4). On the A/CNK versus SiO_2 diagram, the TGrS is mostly metaluminous with only two granodiorite samples of slightly peraluminous character (Fig. 5). The normalized multi-element patterns of the TGrS are characterized by a pronounced enrichment in the K_2O , Ba, Rb, La, Ce and Nd as well as marked depletion in Nb contents (Fig. 6). The significant depletion in Nb and the enrichment in LILE is a striking feature indicative of subduction-related processes (Pearce, 1983). There is a compositional gap between the GDC and TGrS, which appears in their SiO_2 contents from 57 to 65% (Table 1). Moreover, the chemical variation trends of K_2O , Sr, Ba, Rb, Y and Zr of the GDC samples are not on the same trend as the TGrS on the Harker plots (Fig. 3). In this regard, the relationship between Fe_2O_3 versus CaO and Cr is used to demonstrate the contrast in chemical composition of the GDC and TGrS (Fig. 7 a, b). Such variation in the geochemical behaviour may suggest that the GDC and TGrS rocks are not related to a single magma type through fractional crystallization process. The gabbroic xenoliths of the TGrS fall in the olivine gabbro and resemble the investigated metagabbroic rock types of the GDC (Fig. 2). This is also confirmed by the average primitive mantle-normalized trace element abundances, which indicate that the gabbroic

xenoliths of TGrS have more or less remarkable similarity to the studied metagabbroic rocks of the area (Fig. 6). The noticeable high Rb contents in the gabbroic xenoliths in Figure 6 reflect the rapid exchange of alkalis between xenoliths and the more silicic melt (Johnston and Wyllie, 1988; Baker, 1990).

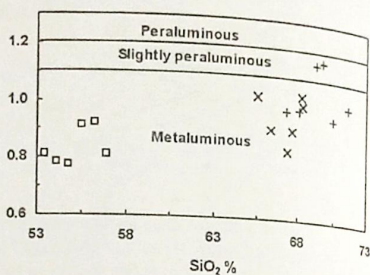


Fig. 5. SiO_2 versus A/CNK plot for the investigated rocks (after Chappell and White, 1974). Symbols as in Fig. 2.

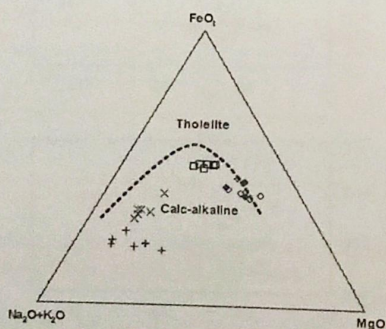
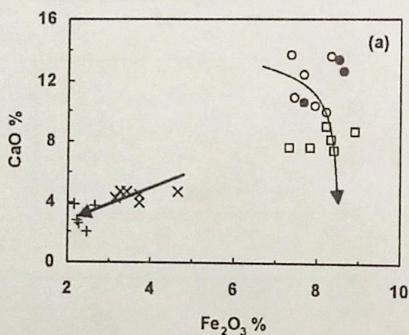


Fig. 4. AFM diagram (after Irvine and Baragar, 1971) showing the magma type of the examined rock suites. Symbols as in Fig. 2.

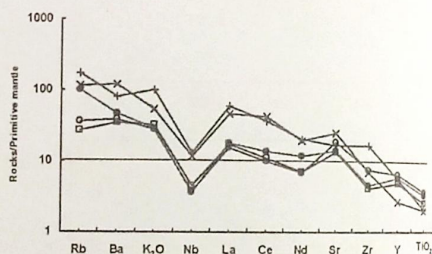


Fig. 6. Normalized multi-element patterns for the GDC and TGrS rocks using primitive mantle values. Symbols as in Fig. 2.

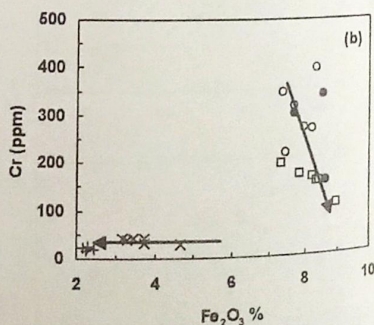


Fig. 7 (a) and (b). CaO and Cr contents in the gabbro-diorite and tonalite-granodiorite suites plotted against Fe_2O_3 to show the difference in their compositional trends. Symbols as in Fig. 2.

Genetic Environment

Discrimination diagrams used in deciding the tectonic environment of mafic plutonic rocks are commonly based on well known volcanic suites. The binary relationship $Zr-Zr/Y$ is considered to be an effective discriminator between Island Arc Basalts (IAB) generated at subducted convergent boundaries, Mid-Ocean Ridge Basalts (MORB), divergent oceanic plates and Within Plate Basalts (WPB), erupted in rifting continental setting (Pearce and Norry, 1979). The GDC samples mainly plot in the IAB field (Fig. 8 a). Further, these samples were plotted on the TiO_2 versus FeO/MgO diagram of Glassely (1974), where they fall exclusively in the island arc field (Fig. 8 b). The GDC rocks are of tholeiitic to calc-alkaline character and have a significant wide range in K/Rb ratio (Table 1) suggesting that these rocks represent a gabbroid magma emplaced into a thick immature island arc crust ($K/Rb > 300$), Jelinek and Dudek (1993).

Many workers have tried to achieve a genetic classification of granitoid rocks based on petrological and geochemical parameters, where the granitoid rocks are classified into I, S, A, and M-types (White, 1979; White and Chappell, 1983; Whalen et al., 1987). I-type granites are generated in cordilleran subduction and post-orogenic uplift regimes. S-type granites are formed as a result of continental collision (Pitcher, 1983). On the K_2O-Na_2O diagram, the TGrS rocks have a Na_2O/K_2O ratio > 1 and are equivalent to I-type granites (Fig. 8 c). However, the calc-alkaline affinity and metaluminous character, absence to low normative corundum (< 1) and relatively low Rb/Sr ratios (Table 1), suggest that this suite represents I-type granitoids of White and Chappell (1983). Moreover, several schemes have been proposed for the nomenclature of granitoids on the basis of their tectonic environment (Pitcher, 1983; Brown et al., 1984; Maniar and Piccoli, 1989; Rogers and Greenberg, 1990; Pearce, 1996). With respect to tectonic environment, granitoid rocks have been classified into ocean ridge granites, volcanic arc granites, syn-orogenic granites and within-plate granites. The Rb versus $(Nb + Y)$ diagram of Pearce et al. (1984) is based mainly on one of a fluid-mobile element (Rb) against two fluid-immobile elements, Nb and Y. Based on this relationship the TGrS occupies the volcanic arc sector reflecting that they were formed through subduction-related processes (Fig. 8 d).

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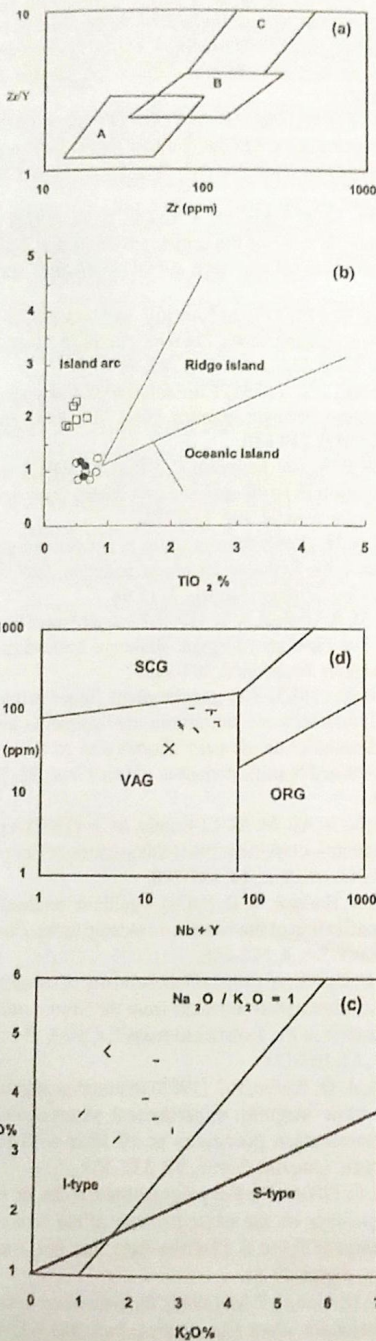


Fig. 8 a-d. Tectonic discrimination diagrams of the various rocks, (a) Zr versus Zr/Y for the gabbro-diorite rocks; A: island arc basalts, B: mid-ocean ridge basalts and C: within-plate basalts, (b) TiO_2-FeO/MgO relationships, (c) K_2O versus Na_2O plot for the tonalite-granodiorite samples. Dashed line separates I- and S-type granites and (d) $Y+Nb$ versus Rb diagram. VAG-Volcanic Arc Granites; SCG-Syn-Collision Granites; ORG-Ocean Ridge Granites; WPG-Within-Plate Granites. Symbols as in Fig. 2.

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