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# Major-element geochemistry of Proterozoic Prince's Town granitoid from the southern Ashanti volcanic belt, Ghana

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The Paleoproterozoic metavolcanic rocks of the southern Ashanti greenstone belt of Ghana are intruded by three major suites of granitoids, locally called Prince's Town, Dixcove and Ketan plutons. The Prince's Town pluton is the largest intrusive body in the Axim area, and tends to separate the Axim volcanic branch from the Cape Three Points branch. The pluton consists of granitic to dioritic rocks, which are generally massive but occasionally display alignment of ferromagnesian minerals. The rocks contain mainly plagioclase, K-feldspar, quartz, amphibole, biotite and opaques. The feldspars are mostly sericitized and saussuritized, and alteration of amphibole and biotite to epidote and chlorite is common. Accessory minerals include apatite, sphene and zircon. The geochemical data indicate that the rocks are tonalitic to granodioritic in composition, metaluminous (ASI < 1) and have I-type characteristics. The granitoids have the $SiO_2$ content of 63-70%; total iron, as $Fe_2O_3$ of 3.10-5.80%; ($Na_2O+K_2O$) content of 5.01-6.96% and $Na_2O/K_2O$ ratios from 1.34 to 2.70; and are characterized by Mg# ranging from 53 to 48. The Fe* (= $FeO_{tot}/(FeO_{tot}+MgO)$) and modified alkali-lime index (MALI) of the rocks indicate that the Prince's Town pluton is dominantly magnesian and calcic in nature. Higher values in molar $CaO/(MgO+FeO_{tot})$ coupled with low molar $Al_2O_3/(MgO+FeO_{tot})$ may suggest their derivation from partial melting of metabasaltic to metatonalitic source, with a possible contribution from metagreywacke, but preclude any contribution from metapelitic sources. The Birimian metavolcanic rocks are the likely source material candidate for the rocks. CIPW norm calculations yielded a crystallization temperature of ~ 650-685°C and a pressure of 4-7kb for the rocks, suggesting a lower crustal source. The Prince's Town plutonic rocks also show characteristics of plutons emplaced in a volcanic arc tectonic setting environment. This observation is largely consistent with previous studies conducted on granitoids from other parts of the southern Ashanti greenstone belt c and the belt-type granitoids of Ghana as a whole.

**Keywords:** Geochemistry, tectonic setting, granitoids, Birimian, Ghana

## I. Introduction

The Paleoproterozoic Birimian Supergroup, which forms a major part of the West African craton, is generally made up of greenstone belts – granitoids – basin association. The Birimian terrain is believed to have been accreted onto the Archean continental crust around 2.1 Ga (Abouchami et al., 1990; Boher et al., 1992; Taylor et al., 1992; Hirdes et al., 1996) during the Eburnean orogeny (Liégeois et al., 1991). The lithostratigraphic features, context of crustal accretion and overall tectonic regime of the Birimian formations are contentious and various interpretations have been advanced.

The Birimian terrain of Ghana is characterized by narrow sedimentary basins and linear volcanic belts, and both the basins and the belts are intruded by extensive granitoids of Proterozoic age (Fig. 1). The metavolcanic rocks consist mainly of tholeiitic basalts (basaltic lava flows, mafic dolerites, gabbros, etc) and minor calc-alkaline rocks (andesites, dacites, rhyolites, pyroclastites). The sedimentary basins are composed mainly of dacitic volcaniclastics, wackes and argillites. These Birimian rocks are associated with and overlain by the clastic Tarkwaian formation, derived from them (Junner, 1940; Kesse, 1985; Leube et al., 1990; Davis et al., 1994). The Proterozoic granitoids can be grouped into four main types namely Winneba, Cape Coast, Dixcove and Bongo granitoids (Junner, 1940; Kesse, 1985); the latter three have termed "basin", "belt" and "K-rich" granitoids by Leube et al. (1990). The Cape Coast- and Winneba-type granitoids are emplaced within the Birimian sedimentary basins, while the

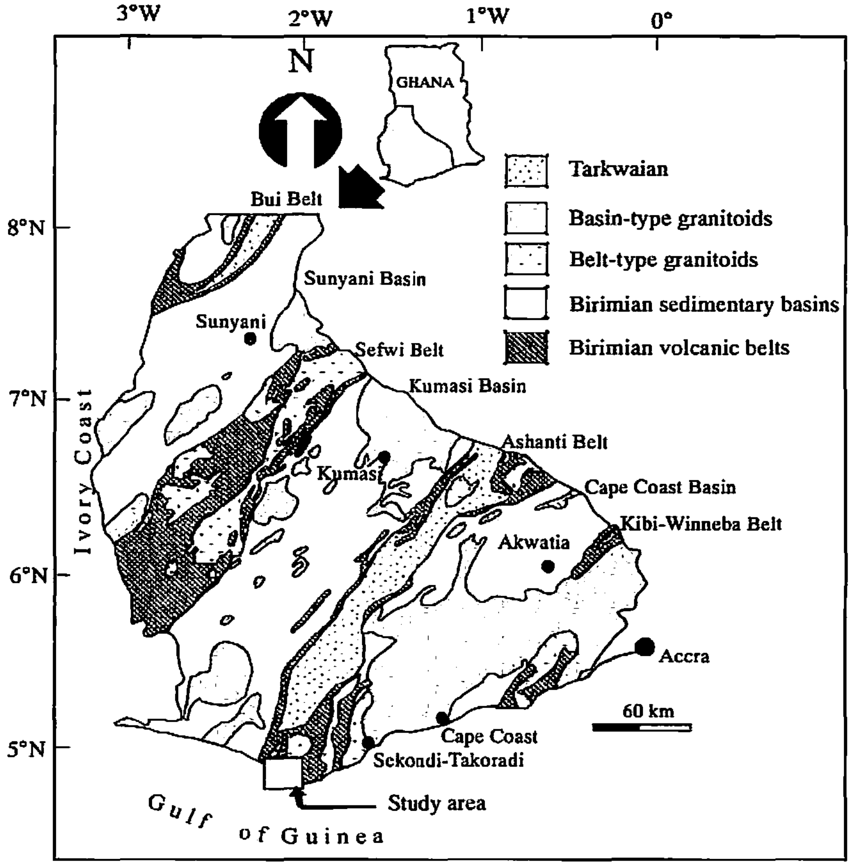

Fig. 1. Simplified geological map of Ghana showing the study area.

Dixcove- and Bongo-type granitoids intrude the volcanic belts. Rb-Sr and Pb/Pb isotopic data on the Winneba-, Dixcove-, and Cape Coast-type granitiods indicate Eburnean age (~2.2 to ~2.0 Ga; Taylor et al., 1992; Hirdes et al., 1992). However, Sm-Nd isotopic data on the data Winneba-type granitoids yielded ~2.6 Ga, indicating a significant magmatic contribution from the Archean continental crust (Taylor et al., 1992). The Bongo-type granitoids, however, are late- to post-Eburnean with Rb-Sr date of 2086 Ma (Leube et al., 1990; Taylor et al., 1992). These plutons range from foliated to massive, and concordant to discordant types, which from field relations are mostly syn- to post-tectonic in emplacement. The granitoids also display different geochemical characteristics, with the belt-type and the basin-type granitoids showing I-type and S-type characteristics, respectively (Leube et al., 1990).

Recent studies conducted on granitoids from the Konongo area, the northeastern part of the Ashanti volcanic belt (Kutu, unpublished) have revealed that some of the belt-type granitoids show S-type characteristics, which might have a different tectonic setting or origin from the others. Whether this is a local occurrence or widespread in the Ashanti volcanic belt is worth investigating. In this paper, we report on the preliminary geochemical results obtained for the Prince's Town pluton, which is one of the three main granitoids suites exposed in the southern Ashanti belt. The objective of this paper is to increase our knowledge of the nature of the plutonic rocks exposed in the Ashanti belt, and to contribute to the geochemical database of the Proterozoic granitoid of Ghana. The geochemical data will also be used in an attempt to discuss the tectonic setting of the rocks.

## II. Geological setting

The Axim area lies within the southern Ashanti volcanic belt (Fig.2), which follows the general geological disposition of the Ashanti volcanic belt. Like most of the Paleoproterozoic Birmian volcanic belts of Ghana, the Ashanti belt comprises NE-SW trending

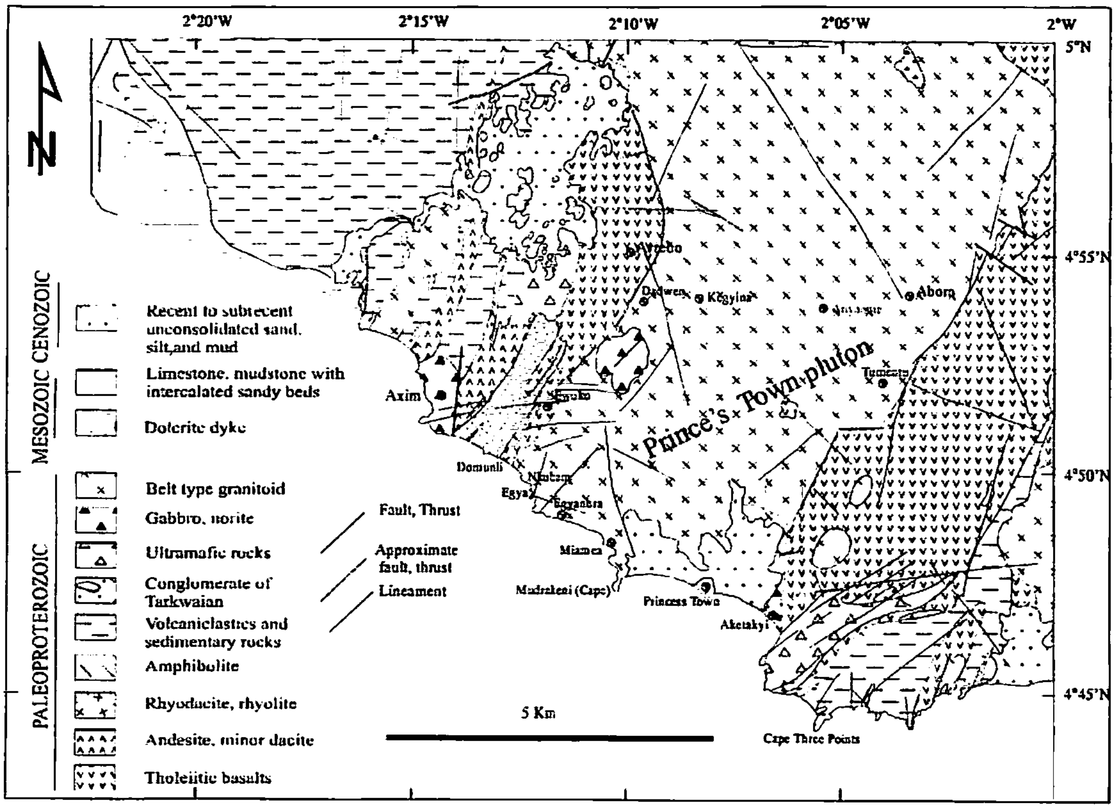

Fig. 2. Geological map of southern Ashanti volcanic belt showing the Prince's Town pluton in between the Axim volcanic branch (left) and the Cape Three Points volcanic branch (right) (Modified after Loh and Hirdes, 1996).

volcanics, and the granitoid formations. The Ashanti belt is, however, characterized by a high proportion of volcaniclastic rocks and sparsely developed lava flows (Loh and Hirdes, 1996). The Birimian rocks of the Ashanti belt are overlain by the Paleoproterozoic clastic sedimentary rocks (i.e., Tarkwaian), and both formations were subjected to a single progressive deformation event, which involved compression along a southeast-northwest directed axis (Eisenlohr and Hirdes, 1992; Blenkinsop et al., 1994). The geological structure of the Ashanti belt is that of a synform (Eisenlohr, 1989), whereby the Tarkwaian rocks occupy the center of the belt and the Birimian volcanic rocks flank the margins of the belt. The Tarkwaian sediments are considered as erosional products of the volcanic belts deposited in long intramontane basins (Klemd et al., 1993; Hirdes and Nunoo, 1994).

The southern Ashanti volcanic belt is dissected into three branches referred to as Axim branch, Cape Three Point branch and Butre branch (from west to east), with three plutons occupying positions between the greenstone branches (Loh and Hirdes, 1996). The volcanic branches comprise calc-alkaline basaltic and andesitic lavas, and volcaniclastic wackes. The three plutons, which are locally termed as the Prince's Town pluton, the Dixcove pluton and the Ketan pluton, are largely tonalitic, tonalitic – granodioritic, and tonalitic – granodioritic in composition, respectively. According to Loh and Hirdes (1996), normal faults/thrust zones usually mark the contacts between the volcanic branches and the associated granitoids.

Economically, gold and manganese occur in the southern Ashanti belt. Some of the gold deposits are structurally-controlled and mostly occur in the transition zones between the volcanic belts and the basin sediments (e.g., Kesse, 1985; Leube et al., 1990; Hirdes et al., 1993; Oberthür et al, 1996). The two most important regional structural controls of the gold deposits in the southern Ashanti belt seem to be the Axim high-strain zone along the western flank of the Ashanti belt, and the sheared granitoid/greenstone settings (Loh and Hirdes, 1996). The gold-bearing quartz-pebble conglomerates of the Tarwaian also contribute to the gold production from the volcanic belt. Studies carried out on gold mineralization in the Ashanti belt have suggested that the gold-bearing fluids are coeval with (peak)-greenschist-facies metamorphism (e.g. Mumin and Fleet, 1995; Loh and Hirdes, 1996). It has also been indicated that higher grade mineral assemblages are mostly restricted to the contact aureoles of the belt type granitoids (e.g., Junner, 1935; Leube et al., 1990). The metamorphic study by John et al. (1999) over the entire stretch of the southern Ashanti belt indicates that the southern Ashanti belt rocks have experienced a clockwise P–T path through peak-amphibolite-facies conditions to retrograde greenschist-facies conditions. A minimum peak-metamorphic condition of amphibolite-facies grade at 500-650°C and 5–6kbar was proposed for the Eburnean tectono-thermal event.

The geochemistry of the volcanic rocks, particularly trace element signatures of the Ashanti belt point to a primitive island arc tectonic setting environment for the Birimian rocks (e.g., Sylvester and Attoh, 1992; Loh and Hirdes, 1996).

## III. Analytical methods

A number of rock samples from the Prince's Town pluton, outcropping in the Axim area, were studied petrographically. Nine representative samples were subsequently selected for geochemical studies. Standard procedures were followed during preparation of thin sections for microscopic studies and whole-rock geochemical analysis. Powdered samples were obtained by mechanical crushing and pulverization of specimens using an agate mortar.

The preparation of glass beads for X-ray fluorescence (XRF) analysis followed the procedure outlined below. About 0.5 g of heated rock powder was weighed, and mixed with a 5.0 g lithium tetraborate flux to give a flux to rock ratio of 10:1. The mixture was then fused in an induction furnace for about 6 minutes, and the resulting melt was cooled to form a glass disc. Whole rock major element analysis was performed on the fused discs by automated XRF spectrometer, Philips PW1480, installed at the Department of Earth Sciences, Okayama University. The analytical equipment was calibrated using geochemical standards. The precision was better than 1% for all analysed elements.

## IV. Petrography

The Prince's Town granitoid consists of granitic to dioritic rocks, which are generally massive but occasionally display alignment of ferromagnesian minerals. They are mostly greenish with pinkish tints, and are typically medium-grained but some of the granodiorites and the tonalities are coarse-grained.

The rocks contain mainly plagioclase, K-feldspar, quartz, amphibole, biotite and opaques. Accessory phases include zircon, apatite and sphene. Plagioclase occurs as euhedral grains which display a variety of textures, including albite twinning and compositional zoning. Plagioclase is often sericitized and carbonated, and/or saussuritized, with the alteration being intense at the core. Fresh plagioclase crystals also occur in the rocks. K-feldspar partly displays a microperthitic to perthitic texture and is normally wrapped around euhedral plagioclase grains. Microcline is sericitized, carbonated saussuritized; fresh types are also present. In some of the rocks, feldspar exhibits a myrmekitic texture. The amphiboles are brownish-green in colour and have prismatic shapes, and are partially altered to epidote and chlorite. Biotite, mostly flaky, is often reddish-brown, and is commonly altered to epidote and chlorite. Some of the biotites exhibit a poikilitic texture. Quartz is anhedral and displays undulatory extinction as well as sutured grained boundaries. Some of the quartz grains have been recrystallized and form fine-grained mosaics in the rocks. In the quartz diorites, quartz frequently occurs as interstitial grains between plagioclase crystals. Apatite mostly occurs as stubby-prismatic grains. Sphene and zircon are present as subhedral and euhedral crystals, respectively. Some opaques occur as pods in chloritized biotite.

## V. Geochemistry

Major element compositions of the rocks analyzed in the present study are given in Table 1. All the analyzed samples from the Prince's Town pluton have $SiO_2$ content of 62.96-70.49%; $TiO_2$ of 0.27-0.38%; $Al_2O_3$ of 14.50-16.33%; total iron as $Fe_2O_3$ of 3.10-5.80%; MnO of 0.06-0.11%; MgO of 1.53-2.89%; CaO of 3.30-5.74%; ($Na_2O$+$K_2O$) content of 5.01-6.96% and $Na_2O/K_2O$ ratios from 1.34 to 2.70; and $P_2O_5$ of 0.10-0.13%. The Mg# of the rocks ranges from 53 to 48.

The major element compostions (Fig. 3) reveal an evolutionary trend for the rocks. $Al_2O_3$, $Fe_2O_3$ (total), MnO, MgO, CaO, $TiO_2$ and $P_2O_5$ apparently decrease with increasing $SiO_2$ content, whereas $K_2O$ and $Na_2O$

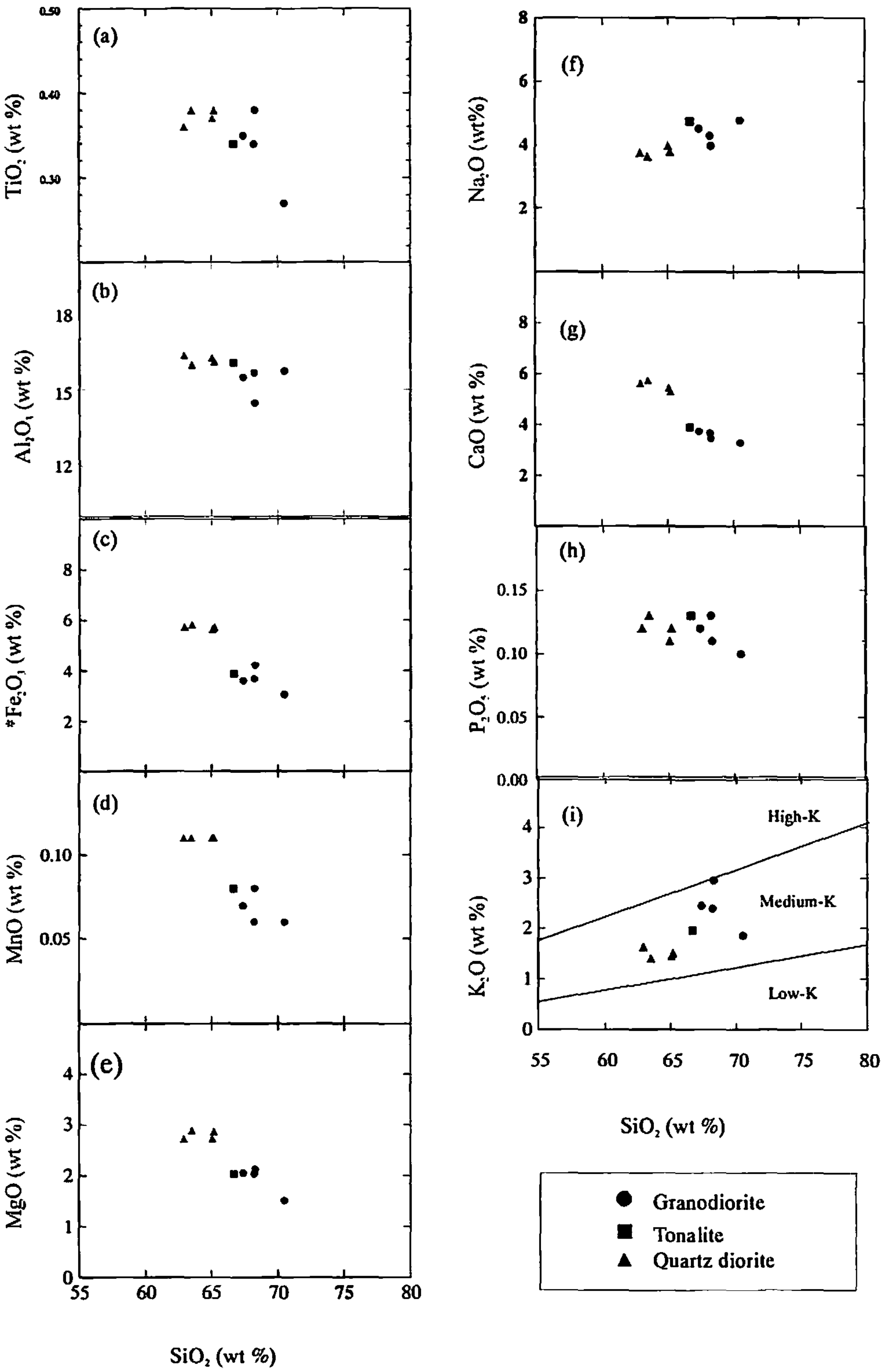

Fig. 3. The Harker diagrams showing variations of major element oxides with silica for the Prince's Town plutonic rocks. The $K_2O$ vs. $SiO_2$ diagram (Fig. 3i) after Le Maitre (1989) indicate a medium-K affinity for the plutonic rocks.

Table 1. Major element abundances and CIPW normative mineral assemblages in the representative samples from the Prince's Town granitoid suite

| Rock type | Tonalite | Grano-diorite | Grano-diorite | Grano-diorite | Grano-diorite | Quartz diorite | Quartz diorite | Quartz diorite | Quartz diorite |
|---|---|---|---|---|---|---|---|---|---|
| Sample No. | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 |
| wt % | | | | | | | | | |
| $SiO_2$ | 66.66 | 70.49 | 67.33 | 68.17 | 68.30 | 62.96 | 65.07 | 65.22 | 63.52 |
| $TiO_2$ | 0.34 | 0.27 | 0.35 | 0.34 | 0.38 | 0.36 | 0.37 | 0.38 | 0.38 |
| $Al_2O_3$ | 16.05 | 15.72 | 15.49 | 15.67 | 14.50 | 16.33 | 16.25 | 16.10 | 16.00 |
| $^*Fe_2O_3$ | 3.91 | 3.10 | 3.61 | 3.69 | 4.23 | 5.75 | 5.63 | 5.70 | 5.80 |
| MnO | 0.08 | 0.06 | 0.07 | 0.08 | 0.08 | 0.11 | 0.11 | 0.11 | 0.11 |
| MgO | 2.05 | 1.53 | 2.06 | 2.04 | 2.14 | 2.72 | 2.73 | 2.87 | 2.89 |
| CaO | 3.90 | 3.30 | 3.76 | 3.70 | 3.48 | 5.63 | 5.46 | 5.32 | 5.74 |
| $Na_2O$ | 4.74 | 4.75 | 4.50 | 4.26 | 3.95 | 3.74 | 3.95 | 3.75 | 3.61 |
| $K_2O$ | 1.98 | 1.87 | 2.46 | 2.41 | 2.95 | 1.64 | 1.46 | 1.51 | 1.40 |
| $P_2O_5$ | 0.13 | 0.10 | 0.12 | 0.13 | 0.11 | 0.12 | 0.11 | 0.12 | 0.13 |
| Total | 99.84 | 101.20 | 99.74 | 100.49 | 100.13 | 99.35 | 101.14 | 101.08 | 99.58 |
| Mg# | 50.92 | 49.39 | 53.08 | 52.31 | 50.06 | 48.39 | 49.03 | 49.92 | 49.68 |
| A/CNK | 0.95 | 0.99 | 0.92 | 0.96 | 0.91 | 0.9 | 0.91 | 0.92 | 0.89 |
| DI | 70.80 | 75.32 | 72.62 | 71.89 | 73.10 | 58.69 | 60.30 | 59.90 | 57.82 |
| CIPW Norm (vol %) | | | | | | | | | |
| Q | 19.34 | 25.16 | 20.30 | 22.32 | 23.61 | 17.77 | 19.46 | 20.50 | 19.66 |
| or | 12.57 | 11.59 | 15.59 | 15.16 | 18.67 | 10.68 | 9.32 | 9.66 | 9.12 |
| ab | 42.09 | 41.20 | 39.92 | 37.50 | 34.98 | 34.09 | 35.31 | 33.56 | 32.91 |
| an | 16.60 | 15.30 | 14.72 | 16.30 | 13.04 | 23.44 | 22.35 | 22.73 | 23.85 |
| C | 0.00 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| di | 1.23 | 0.00 | 2.05 | 0.66 | 2.27 | 2.92 | 2.77 | 2.01 | 2.98 |
| hy | 7.17 | 5.90 | 6.45 | 7.09 | 5.94 | 9.90 | 9.64 | 10.34 | 10.24 |
| mt | 0.36 | 0.28 | 0.33 | 0.34 | 0.86 | 0.54 | 0.51 | 0.53 | 0.54 |
| il | 0.37 | 0.29 | 0.39 | 0.37 | 0.42 | 0.41 | 0.41 | 0.42 | 0.43 |
| ap | 0.27 | 0.19 | 0.25 | 0.26 | 0.22 | 0.25 | 0.23 | 0.24 | 0.27 |

*Total iron as $Fe_2O_3$; CIPW norms were calculated using a $Fe^{3+}/Fe^{2+}$ ratio of 0.15 (Tate et al., 1999)

Mg# = $100^*(MgO/40.32)/(\{Fe_2O_3/79.85\} + MgO/40.32)$; A/CNK = Molecular $Al_2O_3/(CaO + Na_2O)$

A/CNK = Molecular $Al_2O_3/(CaO + Na_2O)$; DI = Differentiation index; Q, quartz; or, orthoclase; ab, albite an, anorthite; C, corundum; di, diopside; hy, hypersthene; mt, magnetite; il, ilmenite; ap, apatite

increase with $SiO_2$. The Overall decreasing trend of $Fe_2O_3$ (total) and MgO suggests high fractionation of mafic minerals like biotite, magnetite, etc.

The Cross-Iddings-Pirsson- Washington (CIPW) norm calculations were performed using ferric-ferrous iron ratio of 0.15 to mollify any effect that might have resulted from post-emplacement oxidation processes (Tate et al., 1999). The normative mineral assemblages are also presented in Table. 1. The rocks are quartz-normative and contain normative hypersthene in the range of 7.7-13.2 wt. %. Normative anorthite ranges from 13.1 to 23.5 wt. %. Normative diopside occurs in almost all the rocks, except one granodioritic sample (D2). Interestingly, D2 is the only sample which contains normative corundum (0.12%).

## 1. Alteration

Alteration of plutonic rocks is a common phenomenon, especially in older rocks. It is usually evidenced by high loss on ignition (LOI) values and increased scatter and mobility of major and large ion lithophile elements (LILE). Some studies have noted, however, that even for rocks of ancient heritage, the concentrations of such 'mobile' elements are commonly not significantly changed from their primary abundances (e.g., Whalen et al., 1999). Owing to the relatively immobile nature of high field strength (HFSE) and rare earth elements (REE) under most conditions (e.g., Pearce and Cann, 1973; Whalen et al., 1999), they have often been used for igneous petrogenetic and tectonic studies. Major elements, on the other hand, have mostly been used to give background information due to their high susceptibility to mobility during processes such as metamorphism and hydrothermal activities. However, if the mobility of major elements is minimal, they could still reflect the primary igneous processes involved in the formation of the rocks.

Mauer (1990) indicated that the belt-type granitoids of Ghana have generally undergone the greenschist-facies metamorphism but secondary overprint of magmatic minerals occurred under isochemical conditions. Thus, the geochemical constituents of such rocks could still be used for petrogenetic studies. Nevertheless, the extent to which the Prince's Town rocks had been altered was investigated using the chemical index of alteration (CIA) calculations of Nesbitt and Young (1982). The CIA is defined as molar [$100^*Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)$], where $CaO^*$ is the contribution of CaO from silicates only. According to Nesbitt and Young (1982), the CIA values for unaltered granite and basic rock are 50 and 42 respectively, while a CIA value of any rock exceeding, 60 indicates a significant alteration. The CIA values for the Prince's Town rocks range from 47 to 50, indicating minimum alteration. Also, on the molar $Al_2O_3$-($CaO+Na_2O$)-$K_2O$ triangular plot (Nesbitt and Young, 1984, 1989), the rocks show minimal deviation from the standard granitoid compositions (Fig. 4). Therefore, the geochemical data of the plutonic rocks indicate minimal effects of weathering and are reliable for geochemical deductions.

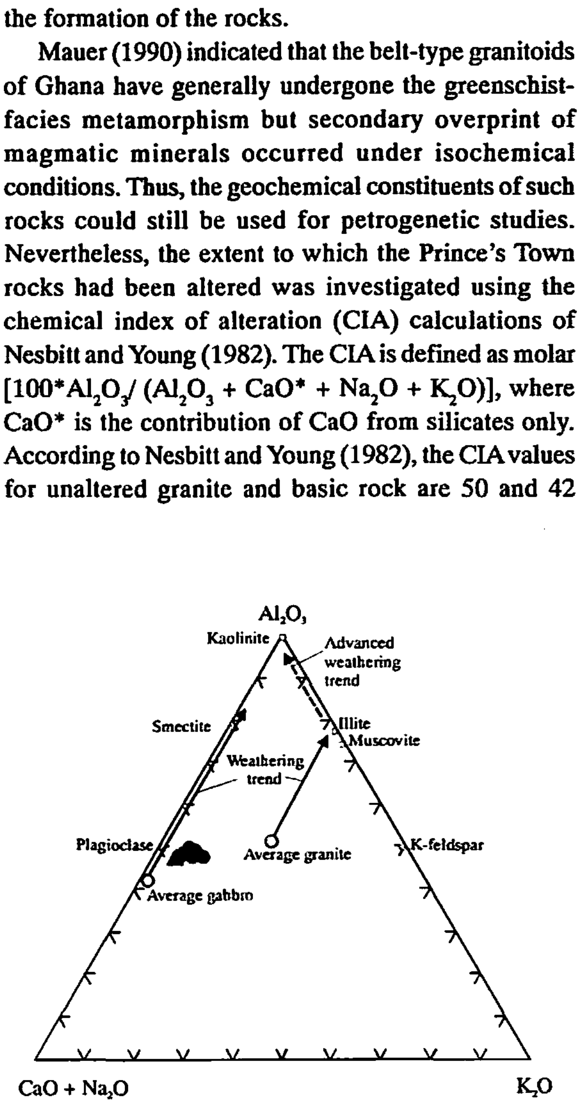

Fig. 4. The plot of the Prince's Town plutonic rocks on the molar ($Na_2O$ + CaO) - $Al_2O_3$ - $K_2O$ diagram of Nesbitt and Young (1984, 1989) showing the weathering trends for average granite and gabbro. The rocks show little deviation from average gabbroic and granitic compositions, and also indicate minimum weathering effects. Symbols as in Fig. 3.

## 2. Physical conditions of crystallization

One of the approaches we take in estimating the approximate depth of generation of granitic magmas is to use normative quartz (Q), albite (ab) and orthoclase (or) compositions of the rocks and compare with experimental results involving water-saturated minima in the granite system. The Prince's Town plutonic rocks are plotted on the ternary Q-Ab-Or diagram (Fig. 5). The cotectic line at $P_{H2O}$ = 3, 4 and 10 kbar (dashed lines) and the temperature minima for $P_{H2O}$ = 0.5, 1, 2, 5, 20 and 30 kbar (plus signs) in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$SiO_2$-$H_2O$ (Tuttle and Bowen, 1958; Luth et al., 1964; Huang and Wyllie, 1975; Steiner et al., 1975) are also shown. The rocks, however, contain a substantial amount of normative anorthite, and therefore, more appropriate to visualize them in the $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$-$SiO_2$-$H_2O$ system (i.e, in the An-Ab-Or-Q tetrahedron). The solid line in Figure 5a represents the projection of the 5 kbar isobaric cotectic curve, defined by the intersection of the cotectic surfaces plagioclase + quartz + liquid + vapor, plagioclase + alkali feldspar + liquid + vapor, and quartz + alkali feldspar + liquid + vapor in the system $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$-$SiO_2$-$H_2O$, onto the Q-Ab-Or base of the An-Ab-Or-Q tetrahedron. On the An-Ab-Or-Q diagram, the rocks plot between 4 and 7kb minima, and mostly close to the 5 kb isobaric curve on the plagioclase + quartz + liquid + vapour surface. One sample, however, plots on the cotectic surface defined by quartz + alkali feldspar + liquid + vapor. The estimated pressure suggests that the rocks may have originated at a lower crustal level.

The crystallizing temperature of the rocks can be estimated using the minimum pressure of 5 kbar (Fig 5b). The samples mostly fall between 670°C and 685°C, but close to the 670°C isothermal line. The remaining samples plot in the thermal valley of the 670°C

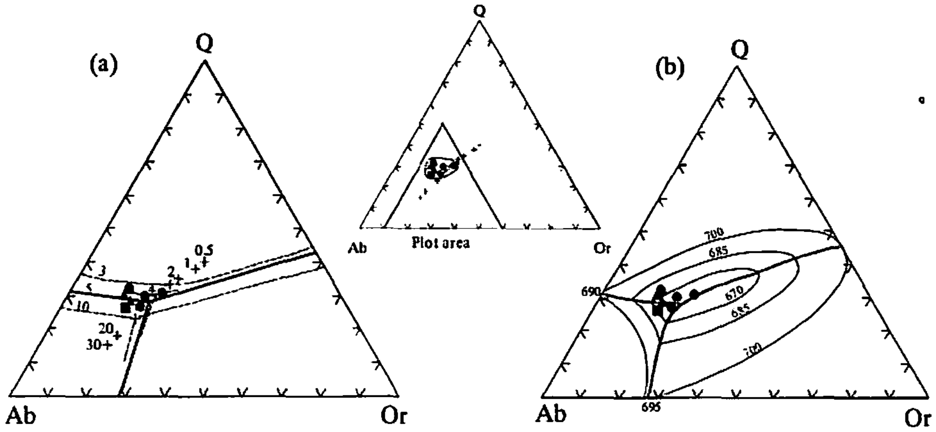

Fig. 5. The normative Q-Ab-Or ternary diagrams for the Prince's Town granitoids. (a) The cotectic lines in the system Q-Ab-Or-An-$H_2O$ at 5 Kb $P_{H_2O}$, projected onto the plane Q-Ab-Or, are displayed (solid lines). Other temperature minima in the system have also been indicated by plus (after Tuttle and Bowen, 1958; Luth et al., 1964; Steiner et al., 1975; Huang and Willie, 1975). (b) Isotherms on the 5 Kb minimum pressure showing the approximate temperature of crystallization of the plutonic rocks. Symbols as in Fig. 3.

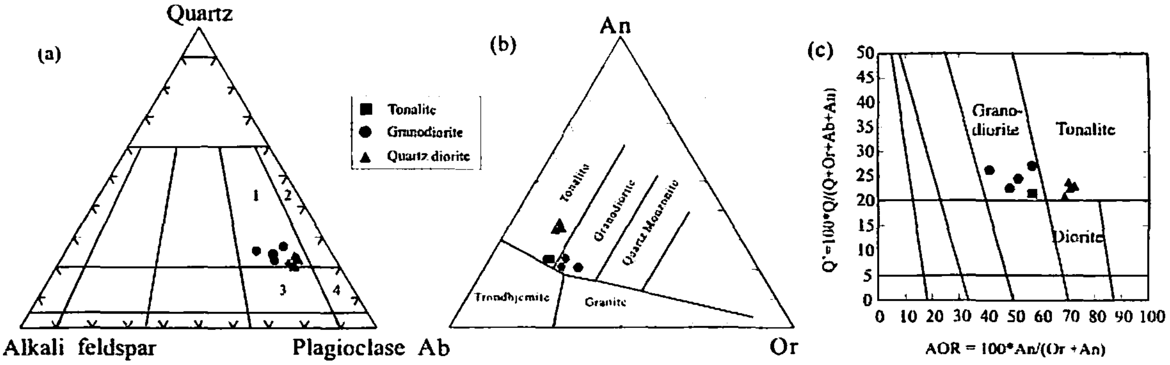

Fig. 6. (a) Mesonormative QAP diagram (after Le Maitre, 1989) showing granodioritic composition for the Prince's Town rocks. Fields: 1 - granodiorite, 2 - tonalite, 3 - quartz monzodiorite, 4 - quartz diorite. (b) Normative Ab-An-Or classification diagram (after O'Connor, 1965; Barker, 1979) showing the fields of the Prince's Town granitoids. (c) Molar norm compositions in the Q' - ANOR diagram of Streckeisen and Le Maitre (1979).

isotherm. Overall, the granitoids appear to have crystallized at a maximum temperature of 685°C and a minimum temperature, a little above the 640°C eutectic temperature for a hypogranitic system. The inferred pressure, 4-7 kb, suggests a lower crustal source for the rocks. A similar result was obtained by Opare-Addo et al. (1993), who indicated that the belt-type Dixcove granitoids of Ghana crystallized under shallow conditions, with the pressure usually being less than 5 kb.

## VI. Discussions

### 1. Classification

Various schemes, which involve parameters such as presumed origin of granitoids, mineralogy, geochemistry, and tectonic environment, have been proposed for the classification of granitoids. In this study, the Prince's Town plutonic rocks have been classified in selected geochemical schemes.

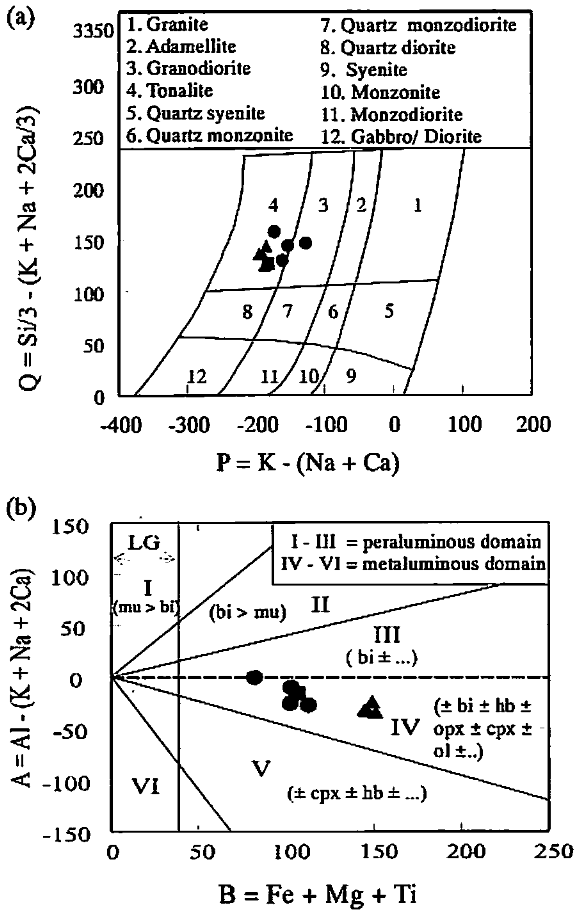

Fig. 7. Composition of the Prince's Town rocks in the cationic classification scheme of Debon and Le Fort (1988): (a) Q - P modal distribution diagram. (b) "Characteristic minerals" (A - B) diagram. VI, exceptional composition, LG field is for leuco granitoids. Symbols as in Fig. 3.

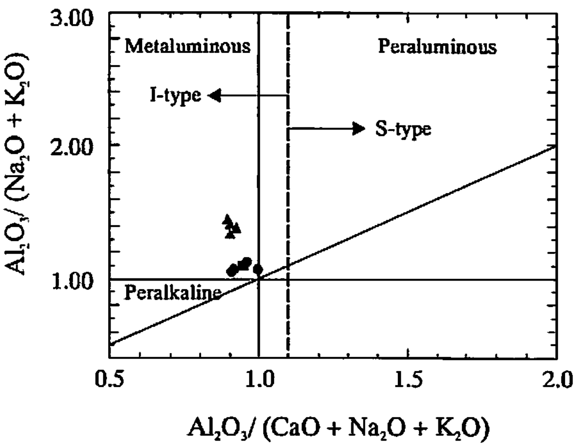

Fig. 8. Plot of alumina saturation vs. alkalinity for the Prince's Town rocks (after Maniar and Piccoli, 1989). The rocks are predominantly metaluminous and also fall within the I-type granite field of Chappel and White (1974)'s granite classification. Symbols as in Fig. 3.

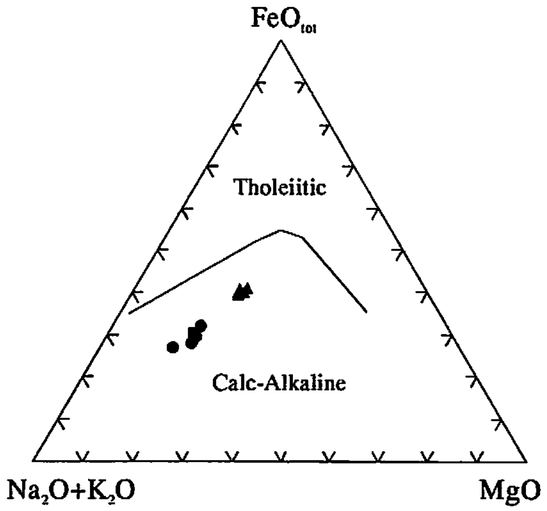

Fig. 9. AFM (A= $Na_2O$ + $K_2O$), F= $FeO_{tot}$, M= MgO) diagram, showing a calc-alkaline affinity for the Prince's Town plutonic rocks. The calc-alkaline and the tholeiitic series differentiation line is from Irvine and Barager (1971). Symbols as in Fig. 3.

The classification of the rocks, based on the quartz-alkali feldspar-plagioclase (QAP) scheme defined by Le Maitre (1989), is shown in Figure 6a.The classification used here is based on mesonormative compositions, indicated as volume percentages. In the QAP diagram (Fig. 6a.), the rocks plot in the field of granodiorite, with some close to the boundary with quartz monzodiorite. When the rocks are plotted in the Ab-An-Or diagram (O'Connor, 1965; Barker, 1979), they showed tonalitic and granodioritic affinities (Fig. 6b). Also, on Q'/ANOR classification diagram of Streckeinsen and Le Maitre (1979), the rocks are classified as granodiorites and tonalities (Fig. 6c).

Debon and Le Fort (1983) developed several major element-based chemical-mineralogical plots which are useful in providing information about plutonic magmatism, particularly with respect to rock names and magmatic associations (Whalen, 1993). The Q-P and A-B diagrams of Debon and Le Fort (1983), which use a measure of "quartz" [Q=Si/3-(K + Na + 2Ca/3)], dark minerals [B=Fe + Mg + Ti, P =K- (Na + Ca)], and aluminous character [A=Al-(K + Na + 2Ca)] have been employed to classify the Prince's Town

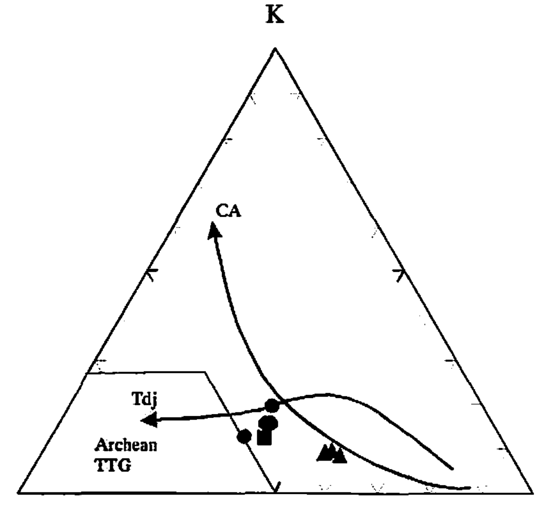

Fig. 10. Molecular Na - K - Ca plot for the Prince's Town plutonic rocks, showing sodic or trondhjemitic (Tdj) affinities rather than potassic affinities. The shaded field for Archean TTG and the calc-alkaline trend (CA) are from Martin (1995). Symbols as in Fig. 3.

rocks. On the Q-P multication diagram (Fig. 7a), the rocks mostly plot in the field of tonalite, with some almost on the tonalite-granodiorite divide; one sample is classified as a granodiorite. On the A-B diagram (Fig. 7b), the rocks demonstrate metaluminous character and also plot in field IV, reflecting the presence of biotite ± amphibole ± clinopyroxene. The metaluminous character of the rocks is corroborated by their lack of normative corundum (< 1%) and the position in the A/CNK-A/NK diagram of Maniar and Piccoli (1989), which further indicates that the rocks are of I-type character (Fig. 8).

The Prince's Town rocks show a sub-alkaline affinity on the total alkalis versus silica diagram (not shown), and define a calc-alkaline trend in the AFM (Fig. 9) of Irvine and Barager (1971). When the data are plotted in the $K_2O$ versus $SiO_2$ diagram (Le Maitre, 1989) (Fig.3i), all the rocks indicate a medium-K affinity. On a Na–K–Ca plot (Fig. 10), the rocks define a Na-enrichment or trondhjemitic trend rather than a potassic affinity, but are mostly less sodic and more calcic than those typical for the Archean trondhjemite–tonalite–granodiorite (TTG) suite, as defined by Martin (1995).

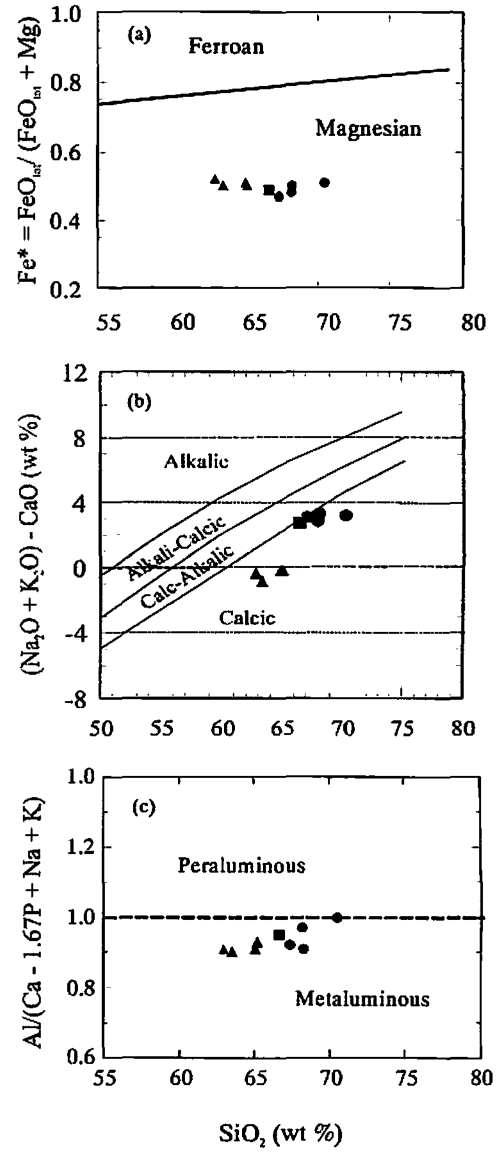

Fig. 11. Chemical classification of the Prince's Town plutonic rocks on the basis of Fe-number (Fe*), a modified alkali-lime index (MALI) and aluminum saturation index (ASI) after Frost et al. (2001). (a) The Fe* - $SiO_2$ diagram showing a magnesian affinity. (b) The MALI - $SiO_2$ diagram indicating calcic characteristic of the rocks. (c) The ASI - $SiO_2$ diagram showing a predominantly metaluminous character of the plutonic rocks. Symbols as in Fig. 3.

Frost et al. (2001) proposed a classification scheme based on major elements and using factors defined as the iron number or Fe*, modified alkali-lime index (MALI), and aluminum saturation index (ASI). The Fe-number [FeO/(FeO + MgO)] or Fe* [(FeO$_{tot}$/ FeO$_{tot}$ + MgO)] classifies samples as either ferroan or magnesian. The Fe-number or Fe* provides information

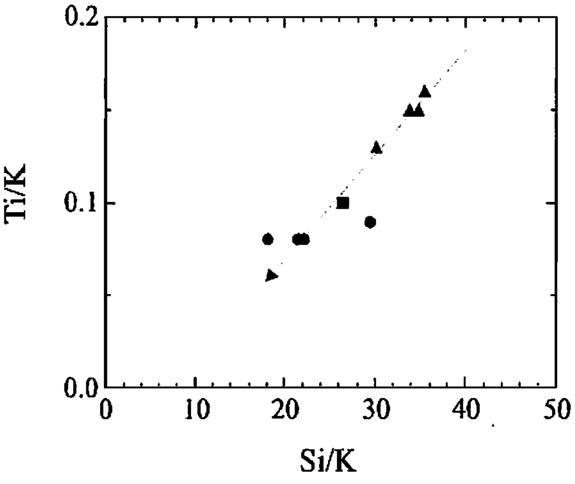

Fig. 12. The Si/K - Ti/K element ratio plot for the Prince's Town plutonic rocks, depicting a nearly continuous trend characteristic of rocks developed from a common source. Symbols as in Fig. 3.

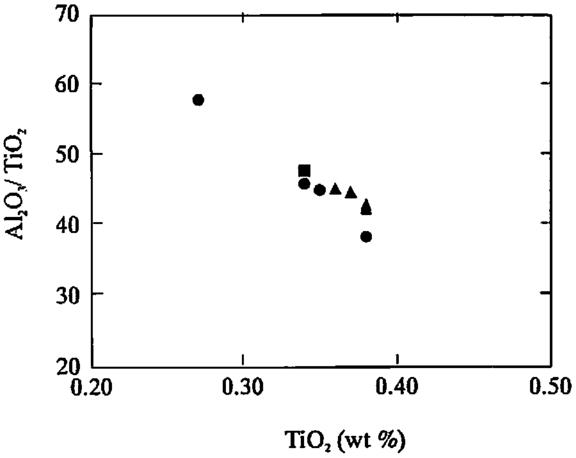

Fig. 13. $Al_2O_3/TiO_2$ vs. $TiO_2$ diagram for the Prince's Town plutonic rocks showing a curvilinear trend characteristic of plutonic rocks developed through magmatic differentiation. Symbols as in Fig. 3.

about the differentiation history of a granitic magma. The MALI is defined by ($Na_2O$ + $K_2O$-CaO) and divides samples into alkalic, alkalic, calc-alkalic, and calcic affinities. MALI is used to interpret magma sources. ASI (Al/Ca -1.67P + Na +K) differentiates peralkaline, metaluminous and peraluminous suites. Peraluminous suites have ASI>1.0, metaluminous suites have ASI<1.0 and (Na + K)<Al, and peralkaline suites have ASI<1.0 and (Na + K)>Al. The ASI index is a reflection of micas and accessory minerals in the rock, and is related to magma sources and conditions of melting. On the classification scheme of Frost et al. (2001), the Prince's Town rocks are magnesian, calcic and metaluminous in nature. Some of the rocks fall close to the boundary between calcic and calcic-alkalic (Fig. 11a-c).

## 2. Source rock characteristics and petrogenesis

Immobile to mobile elements ratios, which are commonly referred to as Pearce element ratios (after Pearce, 1983), can be used to infer the magmatic source of igneous rocks. Rocks from the same magmatic source have similar Pearce element ratios and plot along linear trends of magmatic differentiation. In granites, Ti, P and Si are considered to be immobile elements, whereas K, Na and Ca are mobile elements (Rollinson, 1993). The Ti/K and Si/K cationic ratios computed for the rocks showed similar values, ranging from 0.09 to 0.16 and 18.2 to 35.5, respectively. On the Ti/K and Si/K cationic plot (Fig. 12), the rocks broadly define a continuous trend, with the rock composition at the minimum point along the differentiation line being granodioritic. The close similarities of the different rock types of the pluton, including their calc-alkaline, metaluminous and magnesian affinity suggest that the rocks were probably generated by similar processes from a common source. The cogenetic relation for the rocks is also supported by their nearly linear trend in the $Al_2O_3/TiO_2$ vs. $TiO_2$ plot (Fig. 13) (El-Sayed et al., 1992).

The Prince's Town plutonic rocks display the mineralogical and chemical characteristic of I-type granitoids (e.g., Chapell and White, 1974) derived from partial melting of igneous protolith. Their calc-alkaline medium-K and metaluminous character requires a metaluminous and medium-K source material or protolith. The nature of the igneous rocks can be constrained using the geochemical and isotopic signatures of the plutonic rocks. Partial melting experiments conducted at geologically realistic temperatures and pressures have indicated that granitoid magmas can be generated from a wide range of common crustal rocks (e.g. Wolf and Wyllie, 1994; Gardien et al., 1995; Patiño Douce and Beard, 1996; Singh and Johannes, 1996). The geochemistry and mineralogy of the resulting granitic rocks are indicative of the nature of the protoliths from which they were derived, as well as the dynamic conditions under which magmas were formed, evolved and eventually solidified (Roberts et al., 2000). Variables such as $H_2O$ content, pressure, temperature and oxygen fugacity may be important during melting of source rocks. Compositional differences in melts generated by partial melting of different source rocks, such as amphibolites, tonalitic gneisses, metapelites and metagreywackes, under variable melting conditions can be visualised in terms of molar CaO/(MgO + $FeO_{tot}$) vs. molar $Al_2O_3$/(MgO + $FeO_{tot}$) (Altherr et al., 2000; Fig. 14). Figure 14 indicates that the Prince's Town rocks were likely derived from partial melting of metaplutonic or metavolcanic rocks, possibly with contribution from metagreywacke (at least for the granodioritic-tonalitic types) but preclude any contribution from metapelitic sources. Experimental and geochemical studies suggest that partial melting of detrital sediments, especially shales and greywackes, are the major sources of peraluminous and S-type granitoids (Condie et al. 1999;, Frost et al., 2001). The metaluminous and I-type character of the rocks may suggest insignificant contribution from greywackes, if any at all.

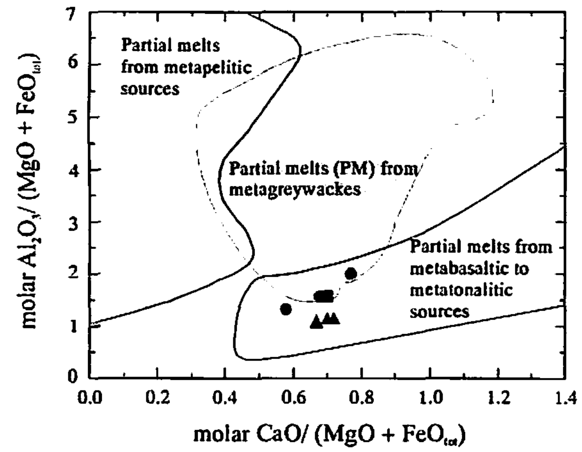

Fig. 14. Chemical composition of the Prince's Town plutonic rocks in a molar $Al_2O_3$/(MgO + $FeO_{tot}$) - CaO/(MgO + $FeO_{tot}$) of Altherr et al. (2000). Composition fields of partial melts were obtained by various source rocks (Wolf and Willie, 1994; Garden et al., 1995; Patino Douce and Beard, 1996; Singh and Johannes, 1996). Symbols as in Figure 3.

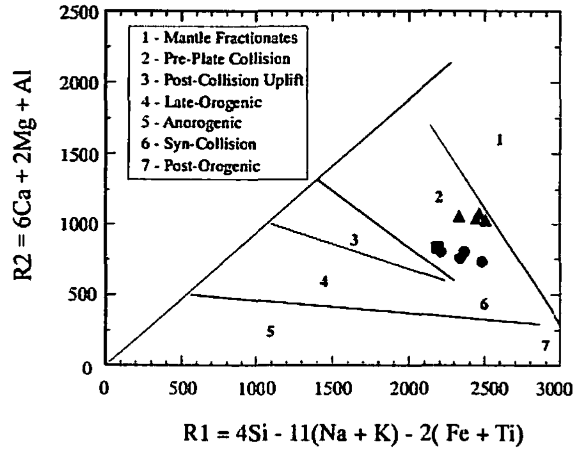

Fig. 15. The Prince's Town plutonic rocks in the R1-R2 multicationic diagram (De La Roche et al., 1980) with the tectonic discrimination fields by Batchelor and Bowden (1985). Same symbols as in Figure 3.

Mauer (1990) indicated that the belt type granitoids and tholeiitic basalts of Ghana are genetically closely related, and that the granitoids were derived from partial melting of the latter. This claim is corroborated by Hirdes et al. (1992), who also indicated from their isotopic data that the belt volcanic rocks and belt granitoids are coeval and comagmatic, and were formed at different stages of the same igneous event. Our data also suggest that the Prince's Town plutonics were mostly likely derived from the metavolcanics.

Major element variations show a nearly continuous trend for the rocks (mostly granodiorites and tonalites), indicating a single magmatic lineage. They must have been derived from partial melting under similar melting conditions (melt fraction, P–T and water saturation). However, the geochemical differences between samples (especially quartz diorite) may indicate that crystal fractionation probably took place during the ascent of the melts from the lower crust where they were generated up to the upper crust where they finally solidified. The abundance of hydrated minerals (amphibole and biotite) in the plutonic rocks suggests that the melting of the protolith took place under hydrous conditions. The roughly negative correlation between $SiO_2$ and $Fe_2O_3$, MgO and CaO contents in the rocks (Fig. 3) could indicate that fractional crystallization involving the assemblage plagioclase, amphibole and biotite took place. Frost et al. (2001) observed from their MALI diagram that most granitoids follow sub-parallel alkali-lime trends during differentiation. Hence, any observed crossing of trend divides or lines by a granitoid suite may indicate mixed magma sources or extreme differentiation of the parent magma for the rocks. The Prince's Town rocks tend to conform to the MALI differentiation trending lines (Fig. 11a)

Loh and Hirdes (1996) have suggested that the mafic lithologies (quartz diorites and diorites) of the Prince's

Town pluton may be different from those developed through the normal magmatic differentiation processes. Considering the fact that the mafic rocks mostly occur at the margin of the intrusive body, they contend that the marginal portions of this pluton could represent the hybrid rocks, resulting from the interaction between the granitoid magma and the mafic wallrocks. Although there appears to be some differences in the chemistry of the quartz diorites and the others rocks, Loh and Hirdes (1996)'s assertion could not be attested, probably due to limited number of samples in this study.

### 3. Tectonic setting

Several schemes exist for assigning granitoids to various tectonic environments by means of their geochemical characteristics (e.g., Pearce et al., 1984; Maniar and Piccoli, 1989; Pearce, 1996). Trace elements have been paramount in such schemes. However, a few of the major-element schemes have been useful in discriminating between the granitoids that belong to different tectonic environments. Accordingly, in order to infer the geotectonic environment of emplacement of the Prince's Town pluton, we have used the R1-R2 tectonic discrimination diagram of Batchelor and Bowden (1985), which was founded in the chemical classification scheme of De La Roche et al. (1980).

On the R1-R2 diagram, all the samples plot in the field 2 of pre-plate collision granites (Fig. 15), which is synonymous to the volcanic arc granite (VAG) in the scheme of Pearce et al. (1984) and Pearce (1996). The generation of normal calc-alkaline, I-type granitoids at pre-plate collisional settings is indicative of development of volcanic arcs in an oceanic setting or continental active margin setting. Such granitoids usually form by melting of asthenosphic mantle involving a subduction component. In the case of continental active margins, interactions of mantle–derived magmas with melts formed by anatexis of continental crust (hybridization) may be very important (e.g.,Pearce, 1996). Also, the magnesian character of the Prince's Town rocks could be a reflection of their close affinity to relatively hydrous, oxidizing magmas and source regions (Frost and Lindsley, 1991), which is in good agreement with the origins that are broadly subduction related (i.e., island arc magmas) (Frost et al., 2001).

The observed tectonic setting of the Prince's Town pluton is consistent with the previous studies carried out on the granitoids from the southern Ashanti belt (Loh and Hirdes, 1999) and other Birimian volcanic belts of Ghana. It has been suggested that the belt granitoids and volcanic rocks are coeval (Hirdes et al., 1992; Davis et al., 1994); it is, therefore, possible that the volcanic rocks were emplaced in the same geotectonic environment. Consequently, a volcanic arc setting could be inferred for the Ashanti volcanic belt, and this conforms to the studies that suggest that the Birimian volcanic belts represent island arc complexes (e.g., Sylvestor and Attoh, 1992; Pohl and Carlson, 1993).

## VII. Conclusion

The Prince's Town pluton exposed in the Axim area of the southern Ashanti greenstone belt consists of medium-K, I-type granitoid, emplaced at lower crustal levels and crystallized at temperatures below 700°C. The rocks are predominantly metaluminous, calc-alkaline, magnesian, and these together with their I-type characteristics are similar to the Cordilleran-type batholiths that are believed to be of magmatic arc origin (Pearce et al., 1984; Frost et al., 2001).

The Prince's Town rocks were largely derived from partial melting of metabasaltic and/or metatonalitic sources, with a probable contribution from metagreywackes (at least for the granodiorites and tonalities), but excluded any contribution from metapelitic rocks. The Birimian metavolcanic rocks with which they are associated, provide the most likely source material for the plutonic rocks.

The geochemical data indicate that the pluton was emplaced in a volcanic arc geotectonic environment. Taking cognizance of the fact that the belt granitoids and volcanic rocks of the Birimian terrain of Ghana are coeval (Hirdes et al., 1992; Davis et al., 1994), the inferred tectonic setting could be extended to the southern Ashanti belt, if not the entire Ashanti volcanic belt of Ghana. This work, therefore, agrees with the studies which indicate that the Birimian belts represent island arc complexes (e.g., Sylvestor and Attoh, 1992; Pohl and Carlson, 1993).

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