Ghana J. Sci. **51** (2011), 89-100

GEOCHEMISTRY OF PEGMATITES ASSOCIATED WITH THE CAPE COAST GRANITE COMPLEX IN THE EGYAA AND AKIM ODA AREAS OF SOUTHERN GHANA

P. M. NUDE*, J. E. K. HANSON, S. B. DAMPARE, T. T. AKITI, S. OSAE, E. S. NYARKO, N. ZKARIA AND S. ENTI-BROWN.

*(P.M.N.: Department of Earth Science, University of Ghana, P. O. Box LG 58, Legon, Ghana; J.F. K. H.,E.S.N., N.Z., & S. E-B: Nuclear Chemistry and Environmental Research Center, Ghana Atomic Energy Commission, P. O. Box LG 80, Legon- Accra, Ghana; S. B. D., T. T. A. & S. O.: Graduate School of Nuclear and Allied Sciences, University of Ghana, AE 1, Atomic- Kwabenya, Ghana)*Corresponding Author's e-mail; pmnude@ug.edu.gh)*

Abstract

The Cape Coast granite complex, which is associated with metasedimentary rocks of the Birirmian in Ghana, is characterised by various minor intrusions that include pegmatites. The pegmatites, which are feldspar-rich, occur within, and at the margins of the granite batholiths and the surrounding schists. The major and trace element compositions of the pegmatites sampled from Egyaa and Akim Oda areas have been determined. The data indicates that the pegmatites from these areas have granitic compositions. The rocks are medium-K to high-K, calc-alkaline, S-type granitoids that are peraluminous and magnesian. Lower values of molar CaO/ (MgO + FeO_{tot}) coupled with higher values of molar Al_2O_3/(MgO + FeO_{tot}) suggest their derivation from partial melting from metapelitic sources, with the Birimian metasedimentary rocks being the likely source material. The rocks are depleted in Rb, Ba, Nb, Ce and Ti but rich in U, K, La, Hf and Y relative to primitive mantle. The data suggest that the pegmatites from these areas are late orogenic, and were emplaced at upper to middle crustal levels in a volcanic arc geotectonic environment.

Introduction

The Cape Coast granite complex which is associated with the metasedimentary rocks of the Birimian in Ghana is one of the two major types of Eburnean granitoids that outcrop in parts of southern and northern Ghana (Morgans, 1962; Kesse, 1985; Leube *et al.*, 1986). The Cape Coast granite complex is characterised by various minor intrusions that include microgranites and pegmatite bosses (Kesse, 1985). The pegmatites are noted to be mostly related to the margins of the granite batholiths and outcrop within both the granites and the surrounding rocks as discrete bosses or as sparsely narrow veins or discontinuous small patches (Morgans, 1962).

The associations of minerals such as gold, bauxite, manganese, and diamond with the rocks of the Birimian and its associated intrusives make them economically important and, therefore, the rocks have been extensively explored for these minerals (Kesse, 1985). The Egyaa and Akim Oda areas are underlain by Birimian rocks, which have been intruded by the Cape Coast granitoids that also contain many pegmatite intrusions. Previous studies on the pegmatites focused on minerals of economic importance such as feldspar, beryl, kaolin, columbite-tantalite and uranium (Kesse, 1985). As such, there is lack of published information on the geochemical characteristics and, therefore, source and tectonic settings, and mode of emplacement of the pegmatites still remain unresolved. In the study the major element and trace element concentrations of representative pegmatite samples taken from Egyaa in the southern end, and Akim Oda to the northeast of the Cape Coast granite batholiths were determined. Data collected were used to determine the composition andgeochemical characteristics of the pegmatites and to infer their possible sources and emplacement.

Geological

In southern Ghana, the Birimian is characterised by sedimentary basins, which separate a series of sub-parallel, roughly equally spaced, north-easterly-trending volcanic belts. The sedimentary basins are composed of volcaniclastics, wackes and argillites which are metamorphosed to greenschist-amphibolite facies. (Leube *et al.*, 1990). The volcanic belts consist predominantly of metamorphosed tholeiitic lavas and minor volcaniclastics of greenschist facies (Leube *et al.*, 1990; Sylvester & Attoh, 1992). Intruding the Birimian rocks are migmatitic bodies and porphyritic granitoids that have generally been classified into two broad categories. These are: (a) hornblende-rich varieties that are closely associated with the meta-volcanic rocks and known as the 'Dixcove granites' or 'belt' type granitoids, and (b) mica–rich varieties which tend to border the volcanic belt and are in the meta-sedimentary units, referred to as 'Cape Coast granite' or 'basin' type granitoids (Leube *et al.*, 1990; Taylor *et al.*, 1992; Hirdes *et al.*, 1992).

The belt granitoids are small discordant to semi-discordant, late or post-tectonic soda-rich hornblende-biotite granites or granodiorites which grade into quartz diorite and hornblende diorite. They are generally massive but in shear zones and strongly foliated. The basin granitiods have been described as large concordant and syn-tectonic batholitic granitoids, commonly banded and foliated. There are two-mica potassic granitoids, containing both biotite and muscovite, with the biotite dominating (Leube *et al.*, 1990). The granitoids contain post orogenic aplite, prophyry and pegmatite intrusions at many localities (Hirdes *et al.*, 1990).

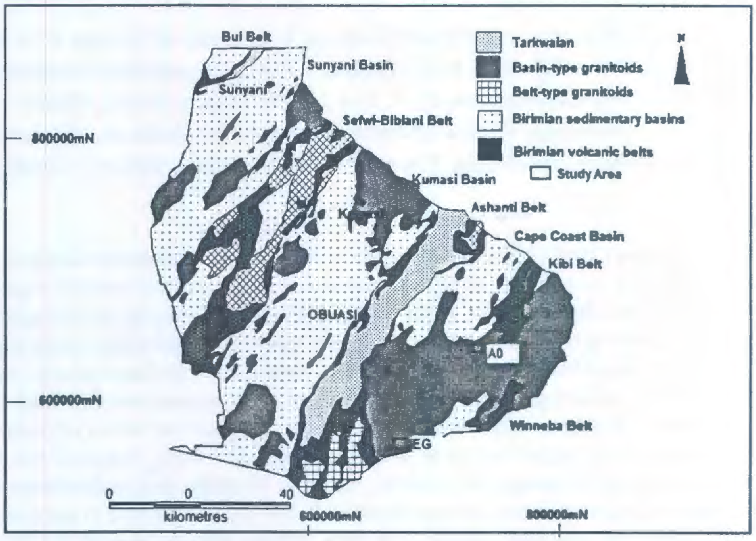

Fig. 1. Geological map of southern Ghana showing the distribution of the volcanic and sedimentary basins and associated granitiods. Inset are Egyaa (EG) andAkim Oda (AO) sampling localities

The Egyaa and Akim Oda areas, from which the samples for the present study were taken are within the 'basin' type or Cape Coast granite complex, specifically at the southern and northern portions of the Cape Coast basin, respectively (Fig. 1). In these areas meta-sedimentary rocks comprising tuffaceous meta-graywackes with subordinate quartzites and interbedded grey and black phyllites and schists predominate. In the Egyaa areas, the pegmatite distributions are related to the margin of the Cape Coast batholiths where the pegmatites occur within the granites and the surrounding schists. The pegmatites found here barely exceed 30 m in width and 500 m along strike. The discontinuous nature along strike is due to either normal faulting or limitations in strike extent. In the field, the pegmatites occur as blocky outcrops or as boulders with abundant muscovite floats.

In the Akim-Oda areas, the pegmatites are associated with the northern margin of the Cape Coast batholith. The batholith in this area is interpreted as relatively shallow dipping with the incorporation of roof pendants of Birimian metasediments. The pegmatites occur as dykes or bosses, and are principally composed of feldspar, quartz and mica with the weathered varieties commonly associated with small detrital columbite-tantalite in the regolith.

Experimental

Samples and analytical methods

Samples. Representative and fresh pegmatite samples were taken from Eygaa in the southern area and Akim Oda in the northern section of the Cape Coast batholiths. The pegmatites are medium to coarse grained rocks composed of quartz, microcline, albite, muscovite and beryl with accessory garnet, apatite, tourmaline, columbite-tantalite, spodumene and rare biotite. Quartz occurs variously as white or milky-grey or as smoky-grey varieties, and normally intergrown with microcline or occurs in pods with muscovite, beryl and apatite. Microcline is often perthitic, and albite is found as replacement to microcline or as pods with muscovite. Muscovite is widespread and found normally with quartz as residual pods or as radial aggregates. Beryl occurs in a variety of forms; it occurs as poikilitic, prismatic or as schlierens. Columbite-tantalite occurs as small anhedral crystals intergrown with quartz.

Analytical methods. Major element oxides and selected trace elements (Rb, Sr, Zr, Nb, Co, Ni, Cu, Zn, V, Cr, Ga, Rb, Y, Mo, Sn, Cs, La, Ce, Hf, Ta, Bi, Th, U and Ba) concentrations in representative samples were determined from pressed powders by X-ray fluorescence (XRF) spectrometry at the Ghana Geology Survey Department. Pellets used in analysis were prepared by measuring 4.0 g of the sample to which one gram of Hoechst wax was added, as a binding agent. The mixture was put into a stainless steel container with two Teflon balls and tightly enclosed. The tightly enclosed stainless steel container was then taken to a Retsch shaker to obtain a homogenous mixture by vigorously shaking for 3 mins. The homogenized mixture was poured into a mortar and piston and sent to a compressor to compress the mixture with a pressure of about 5.0 Pa to obtain the pellets. The chemical compositional analysis of each of the powdered samples was determined using Spectro X-Lab 2000 type 78000811 X-Ray Fluorescence Spectrometer connected to a Pentium III desktop computer.

Results

Characteristics of major elements

The major element composition of the representative samples are listed in Table 1. Totals of the major elements excluding volatiles for all the rocks range from 87.21 to 94.54 weight per cent, consistent with the richness of volatiles in pegmatites. The rocks are evolved, rich in Al_2O_3 (12.58 - 24.8 wt) and K_2O (2.74 - 9.39 wt %) and show relatively high CIPW normative corundum (1.0 – 9.93), orthoclase (19.1 - 55.14) and albite (7.1 - 35.9). Figure 2 is Harker plots showing evolutionary trend of the rocks. Major oxides such MnO, MgO, Al_2O_3 and Na_2O show linear relationship with SiO_2. This phenomenon is interpreted to be due to fractional crystallization in the rocks.

TABLE 1

Major element compositions and CIPW norms in representative samples of the pegmatites

	EG03	*EG04*	*EG05*	*EG09*	*EG010*	*EG011*	*AO05*	*AO 06*	*AO07*	*AO08*	*AO09*
SiO_2	60.81	58.46	53.15	71.4	59.4	64.17	55.09	57.32	58.4	75.34	63.77
TiO_2	0.01	0.01	0.59	0.02	0.02	0.02	0.64	0.2	0.22	0.07	0.01
Al_2O_3	15.3	18.82	14.93	16.2	24.8	17.74	14.63	18.63	18.45	12.58	16.2
Fe_2O_3	0.35	0.6	6.55	0.64	0.51	0.95	6.06	2.23	1.89	0.79	0.58
MnO	0.04	0.01	0.17	0.01	0.02	0.03	0.09	0.07	0.05	0.02	0.06
MgO	0.61	0.74	3.23	0.98	0.63	0.89	3.74	1.85	1.28	0.85	0.46
CaO	0.14	0.2	1.49	0.12	0.18	0.46	1.54	1.84	1.38	0.14	0.13
Na_2O	2.54	4.89	0.83	1.7	2.7	2.32	3.1	3.5	3.55	0.84	4.24
K_2O	9.33	2.74	5.11	3.24	4.85	3.69	2.98	2.83	2.81	3.24	3.51
P_2O_5	0.56	0.52	1.2	0.04	0.03	0.73	0.12	0.24	0.04	0.05	0.06
SO_3	0.31	0.2	0.18	0.2	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Cl	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.02	0.01
Total	90.2	87.21	87.44	94.54	93.29	91.20	88.20	88.91	88.27	94.13	89.22
ANK	1.07	1.71	2.16	2.56	2.56	2.27	1.76	2.11	2.08	2.57	1.50
ACNK	1.05	1.65	1.55	2.48	2.47	2.05	1.31	1.53	1.62	2.45	1.47
					CIPW Norm						
Q	9.26	18.2	21.79	47.3	23.7	34.86	15.24	19.36	21.66	56.37	24.62
C	1.02	7.81	8.03	9.72	14.8	9.93	3.792	7.04	7.15	7.56	5.33
Or	55.14	16.19	30.2	19.1	28.7	21.81	17.61	16.72	16.61	19.15	20.74
Ab	21.49	41.38	7.02	14.4	22.8	19.63	26.23	29.62	30.04	7.11	35.88
An	0	0	0	0.33	0.7	0	6.86	7.56	6.59	0.37	0.253
Hy	1.87	2.34	12.8	2.96	1.99	3.02	13.43	6.25	4.48	2.69	1.72
Mt	0.51	0.87	9.5	0.93	0.74	1.38	8.79	3.23	2.74	1.15	0.84
Il	0.02	0.02	1.12	0.04	0.04	0.04	1.22	0.38	0.42	0.13	0.02
Ap	0.25	0.36	2.68	0.09	0.07	0.83	0.28	0.57	0.09	0.12	0.14

From Fig. 2, all the samples plot in the medium- to high-K field with the majority plotting in the high-K field. The Egyaa samples are relatively more enriched in K_2O than the Akim Oda samples. Normative feldspar compositions of the pegmatites indicate potassic affinities with the samples plotting in the granite field (Fig. 3). The Akim Oda samples contain higher normative An relative to the Egyaa samples. A plot of Al saturation index (Fig. 4) of Maniar and Piccoli (1989) shows that the rocks are peraluminous and S-type granitoids. This is consistent with the presence of muscovite in the modal mineralogy of rocks and corundum in the norm. On the AFM

TABLE 2
Trace element concentrations in representative samples of the pegmatites

	EG03	*EG04*	*EG05*	*EG09*	*EG010*	*EG011*	*AO05*	*AO 06*	*AO07*	*AO08*	*AO09*
p.p.m.											
Nb	1.00	1.00	106.81	1.00	1.00	11.9	93.2	62.9	107.9	7.52	31.1
Zr	1.00	1.00	10.9	1.00	1.00	1.00	9.41	5.32	2.02	0.82	1.00
Y	234	33.7	83.7	57.7	114	147	568.9	389.6	856.5	74.2	13.1
Sr	1352	515	1334	241	326	960	130	172	142	117	474
Ba	46	20.7	289.2	4.12	6.73	105	16.4	28.6	32.8	4.83	38.0
Rb	0.92	0.61	0.72	0.73	0.70	1.00	0.43	0.40	0.60	0.23	0.22
Hf	3.00	3.00	21.8	3.00	3.00	3.00	28.4	3.00	3.00	5.51	3.00
Ta	1.90	0.90	4.21	1.61	1.00	3.30	3.30	6.71	4.11	1.42	3.91
Pb	6.60	5.21	17.7	13.0	6.11	35.9	4.72	45.1	11.9	3.72	50.5
V	9.90	5.12	96.8	7.41	3.50	5.20	101	31.9	6	6.9	7.6
Cr	400	268	207	548	169	335	665	370	584	314	179
Co	4.10	6.41	33.8	6.30	4.61	5.70	29.9	10.9	6.74	6.73	3.20
Ni	45.3	60.4	53.4	124.1	45.3	48.7	165.9	68.3	49.7	75.7	47.6
Cu	13.8	13.3	21.6	15.4	11.5	11.3	19.9	16.0	17.9	24.2	12.1
Zn	10.5	69.6	352.2	13.8	8.12	101	104.1	32.7	41.6	38.1	18.7
Ga	15.9	41.0	23.8	24.8	35.4	44.1	20.4	41.7	30.5	25.1	33.5
As	0.81	0.40	0.60	0.52	2.12	0.52	0.60	0.60	0.72	0.40	0.60
Sn	3.20	4.30	1.70	10.2	3.20	4.11	8.72	3.00	4.50	6.70	3.60
Bi	33.2	6.90	9.50	13.1	15.4	9.50	17.0	21.1	21.9	5.50	21.3
Cs	6.4	43.5	121.9	23.3	36.4	121	8	21.5	23.4	15.7	23.4
La	80.1	12.7	332	139	205	625	832	655	1166	403	15.1
Ce	6.30	5.00	14.4	2.00	2.00	2.00	16.2	4.20	2.91	4.80	3.90
Mo	4.20	32.0	23.5	32.0	27.5	90.4	8.80	47.8	16.1	16.5	52.0
Th	0.70	0.60	1.60	0.60	0.60	0.70	0.71	7.60	0.60	0.60	2.20
U	5.30	3.90	9.50	2.00	2.00	13.5	2.00	3.90	1.30	20	5.60

diagram (Fig. 5), the rocks plot within the calc-alkaline field with most samples clustering close to the alkaline corner. The $FeO_t/(FeO_t+MgO)$ versus SiO_2 plot (Fig. 6) shows that the rocks are magnesian granitoids in the classification of Frost *et al.* (2001).

Characteristics of trace element

The concentrations of selected trace elements in the pegmatites are shown in Table 2. The rocks have relatively high absolute concentrations of Y (13.1-568 p.p.m.), Sr (117 - 1352 p.p.m.) Cr (169 - 665 p.p.m.). Barium, La and Nb concentrations

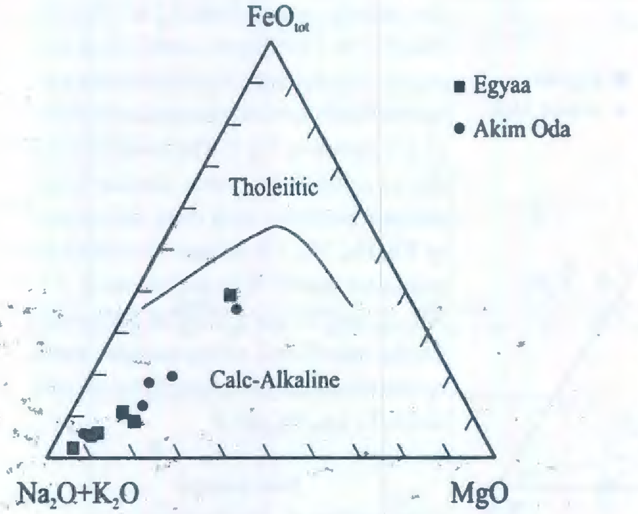

Fig. 5. AFM (A = $Na_2O + K_2O$), F = FeO_{tot}, M = MgO) diagram, showing a calc-alkaline affinity of the pegmatite samples. The calc- alkaline and tholeiitic series differentiation line is from Irvine and Barager (1971).

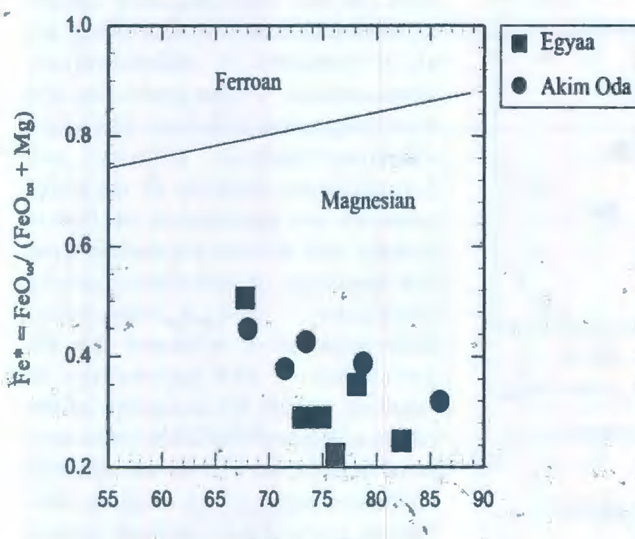

Fig. 6. $FeO_t/(FeO_t+MgO)$ versus SiO_2 classification of Frost et al. (2001) showing the magnesian affinity of the pegmatites

in granitic rocks is determined by the composition of the source region and the nature of the melting process.

The rock samples from this study were derived from partial melts of metapelitic sources with little contribution from partial melts from greywackes (Fig. 8). Experimental results have shown that granitoid magmas can be generated from a wide range of common crustal rocks (Wolf & Wyllie, 1994; Gardien *et al.*, 1995; Patino & Beard, 1996; Singh & Johannes, 1996). Peraluminous granites for example can be formed from hydrous melting of mafic rocks, or pelitic rocks. Experimental and geochemical studies also show that partial melting of detrital sediments especially shales and greywackes, are major sources of per-aluminous and S–type granitoids (Condie *et al.*, 1999). Pegmatites are generally shown to form by fractional crystallization process or direct anatexis of rocks with the appropriate compositions (Simmons *et al.*, 1995).

From the data, it is compelling to suggest that the pegmatites from Egyaa and Akim Oda have been generated from Birimian metasedimentary rocks. The magnesian characteristic shown by the rocks reflects the affinity to hydrous oxidizing sources that are broadly subduction related (Frost *et al.*, 2001). Considering the geochemical characteristics, the pegmatites correspond to the typical peraluminous pegmatites in the classification of Cerny and Ercit (2005). These authors also argue that peraluminous S-type pegmatites are formed from upper crustal to middle-crust supracrustal rocks. Major and trace element data of the pegmatites agree with the anatexis of metapelitic sources with possible contribution from greywacke sources.

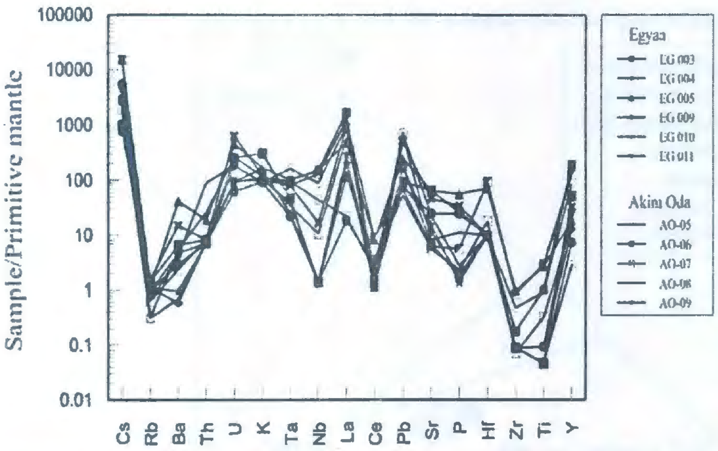

Fig. 7. Primitive mantle-normalized trace element plot of Pearce et al. (1984) for the pegmatite samples

Tectonic implications

The overall geochemical features of the pegmatites from this study are compatible with the composition of calc-alkaline magmas of orogenic tectonic setting. In the R1 - R2 discrimination diagram (Fig. 9) of De La Roche *et al.* (1980), the pegmatites mostly cluster within the late orogenic field, with one sample plotting in the syn-collision field. In the Rb versus Y+Nb discrimination diagram (Fig. 10) of Pearce *et al.* (1984), the pegmatites plot within the ocean ridge granite field with one sample plotting within the volcanic arc granite + syn-collisional granite field. These fields (late orogenic and syn-collision fields) are all synonymous to volcanic arc granite (VAG) and ocean ridge granite (ORG) in the scheme of Pearce *et al.* (1984) and Pearce (1996). In the ORG-normalised plot (Fig. 11), most of the pegmatite samples show enrichment in K_2O, Ta (and Nb) and Y, and depletion in Rb, Ba, Ce, Hf and Zr relative to ocean ridge granite. This indicates that the pegmatites are not typical ocean ridge granites. It appears the interplay of tectonic setting and petrological processes may have influenced the compositions of these granitic pegmatites.

The basin granitoids from which these pegmatites were derived are believed to have formed during the 2.1 Ga Eburnean orogeny, and are considered to be syn-orogenic (Hirdes *et al.*, 1992). It is, therefore, consistent that the pegmatites being late crystallizing melts of granitoids could be late orogenic. The two samples showing the within-plate features in the Nb versus Y discrimination (Fig. 10) may be an evolved trend of the calc-alkaline suites.

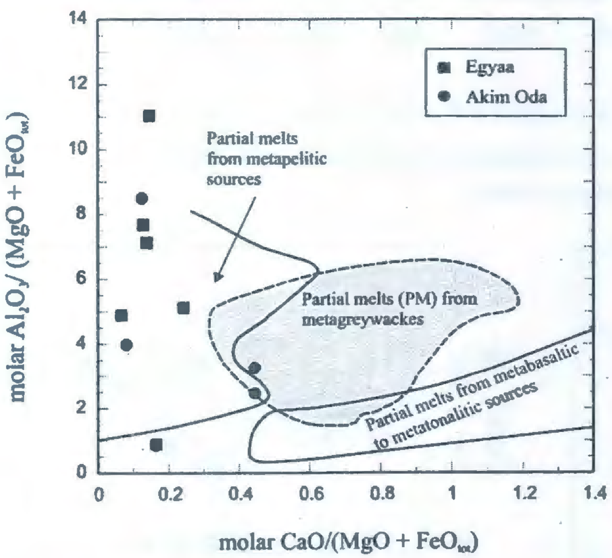

Fig. 8. Chemical composition of the pegmatites samples in the molar Al_2O_3/ ($MgO + FeO_{tot}$) – CaO/ ($MgO + FeO_{tot}$) of Altherr et al., (2000). Composition fields of partial melts were obtained from various source rocks (Wolf and Willie, 1994; Garden *et al.*, 1995; Patino Douce and Beard, 1996; Singh and Johannes, 1996).

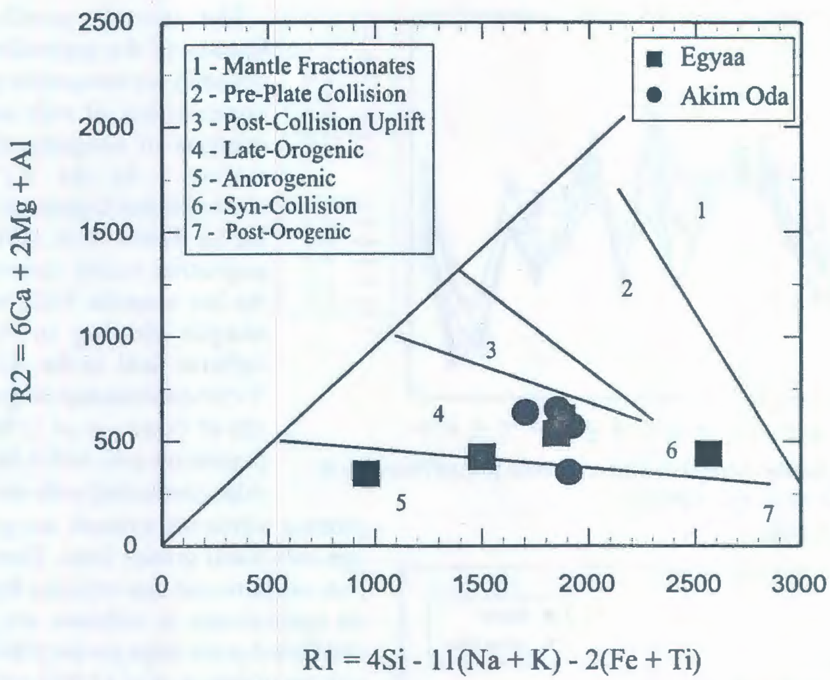

Fig. 9. Plot of the pegmatite samples in the R1 – R2 mulitcation diagram (Roche *et al.*, 1980) with tectonic discrimination fields after Batchelor *et al.* (1985).

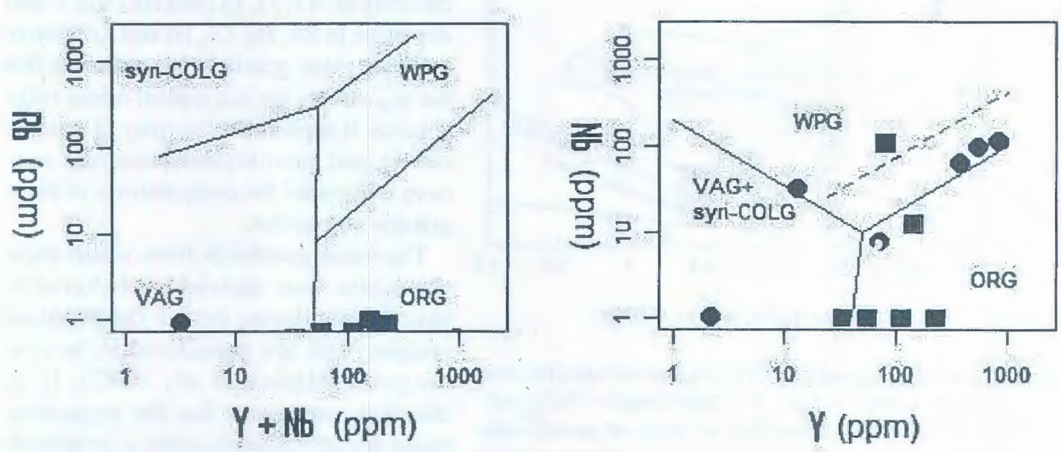

Fig. 10. Plot of the pegmatite samples in the Rb versus Y + Nb and Nb versus Y tectonic discrimination diagrams (after Pearce et al., 1984). Syn-COLG=syn-collision granite, WPG=within-plate granite, VAG= volcanic arc granite and ORG= ocean ridge granite. Symbols are as in Fig. 9.

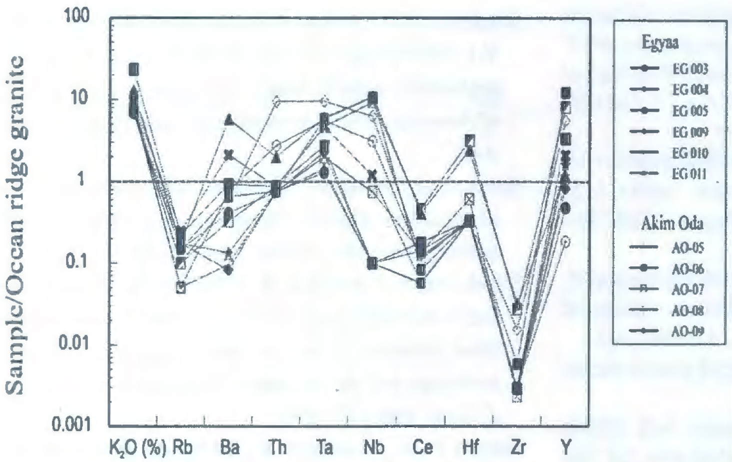

Fig. 11. Ocean ridge granite (ORG)-normalized spider diagram of the Egyaa and Akim Oda pegmatites. The ORG normalization values are from Pearce et al. (1984).

Conclusion

The new geochemical data on the pegmatite samples from Egyaa and Akim-Oda areas show that the rocks are composed principally of feldspars, quartz and mica. The rocks are calc-alkaline, medium to high-K, peraluminous and S-type granitoids. The pegmatites are muscovite pegmatites that were generated by differentiation of fertile granites derived from partial melting of Birirmian metasedimentary rocks at upper to middle crustal levels. Considering the magnesian nature, the melting of the metasedimentary sources may have been promoted by hydrous conditions. The trace element patterns and characteristics are consistent with the generation of the pegmatites in a volcanic arc geotectonic setting.

References

Batchelor, B. & Bowden P. (1985) Petrogentic interpretation of granitoid rock series using malticationic parameters. *Chem. Geol.* **48,** 43–55.

Chappell, B.W. & White, A. J. R. (1974) Two contrasting granite types. *Pacif.Geol.* **8,** 173 –173.

Cerny, P. and Ercit, T. S. (2005).*adian Mineralo.* **43,** 2005–2026.

Condie, K. C., Latysh, N., Van Schmus, W. R., Kozuch, M. & Selverstone, J. (1999) Geochemistry, Nd and Sr isotopes, and U/Pb zircon ages of granitoid and sedimentary xenoliths from Navajo Volcanic Field, Four Corners area, Southwestern United States. *Chem. Geol.* **156,** 95-133.

De La Roche, H., Leterrier, J., Grandcluade, P. & Marchal, M. (1980) A classification of granitic and plutonic rocks using R1R2-diagrams and major element analysis. Its relationships and current nomenclature. *Chem. Geol.*, **29,** 183-210.

Frost, B. R., Barnes, C. G., Collins, W. J., Arculus, R. J., Ellis, D. J. & Frost, C. D. (2001) A chemical classification for igneous rocks. *J. Petrol.*, **42,** 2035–2048.

Gardien, V., Thompson, A. B., Grujic, D. & Ulmer, P. (1995)Experimental melting of biotite+plagioclase+quartz± muscovite assemblage and implications for crustal melting. *J. Geophy. Res.* **100,** 15581–15591.

Hirdes, W. Davis, D: W. & Eisenlohr, B. N. (1992) Reassessment of Proterozoic granitoids ages in Ghana on the basis of U/Pb zircon and monazite dating. *Precambrian Res.***56,** 89–96.

Irvine, T.N. & Barager, W.R.A. (1971) *A* guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sci.*, **8,** 523-548.

Kesse, G. O. (1995) *The mineral and rock resources of Ghana.* A.A. Balkema Press. Rotterdam, Netherlands, 610 pp.

Leube, A. & Hirdes, W. (1986) *The early Proterozoic (Birimian and Tarkwaian) of Ghana and some aspects of its associated gold mineralization.* Extended abstracts Geocongress '86, Johannesburg, pp. 315–319.

Leube, A., Hirdes, W., Mauer, R., & Kesse, G.O. (1990) The Early Proterozoic Birimian Supergroup of Ghana and some aspects of its associated gold mineralization. *Precambrian Res.* **46,** 139–165.

Maniar, P. D. & Piccoli, P. M. (1989) Tectonic discrimination of granitoids. *Geol. Soc. Am.Bull.* **101,** 635–643.

MORGANS, M. W. (1962) The Investigation of Alluvial columbite and columbite bearing pegmatites of ¼° Field Sheet 57, Nsaba N.W., *Ghana Geological Survey Department Archive Report No. 17*, 2nd edn. Edition

O'CONNOR, J. T. (1965) A classification of quartz- rich igneous rocks based on feldspar ratios. *U.S. Geological Survey Professional Paper*, 525B, 79–84.

PARTINO DOUCE, A. E., BEARD, J. S. (1996) Effects of *P*, $f(O_2)$ and Mg/Fe ratio on dehydration melting of model metagreywackes. *J. Petrol.*, **37**, 999–1024.

PEARCE, J.A. (1996) Source and setting of granitic rocks. *Episode*, **19**, 120–125.

PEARCE, J.A., HARRIS, N.B.W. & TINDLE, A.G. (1984) Trace element discrimination diagrams for the interpretation of granitic rocks. *J. Petrol.* **25**, 956–983.

PECERILLO, A., & TAYLOR, S.R. (1976) Geochemistry of Eocene cal-alkaline volcanic rocks from the Kastamonu area, northern Turkey. *Contr. Mineral Petrol.* **58**, 63–81.

SIMMONS, W.B., FOORD, E.E., FALSTER, A.U. & KING, V.T. (1995) Evidence for an anatectic origin of granitic pegmatites, western Maine, USA. *Geological Society of America Annual Meeting, Abstract Programs 27, A411.*

SINGH, J., & JOHANNESES, W. (1996) Dehydration melting of tonalities: Part II. Composition of melts and solids. *Contr Min. Petrol,* 125, 26–44.

SYLVESTER, P. J. & ATTOH, K. (1992) Lithostrstigraphy and composition of 2.1 Ga greenstone belts of the West African craton and their bearing on crustal evolution and the Archean- Proterozoic boundary. *J. Geol.* **100**, 377–393.

TAYLOR P. N., MOORBATH S., LEUBE, A., & HIRDES, W. (1992) Early Proterozoic crustal evolution in the Birimian of Ghana; constraints from geochronology and isotope geology. *Precambrian Res.* **56**, 77–111.

WOLF, M.B. & WYLLIE, J. P. (1994) Dehydration-melting of amphibolites at 10 kbars: the effects of temperature and time. *Contr. Min. Petrol.* **115**, 369–383.

Received 6 Oct 11; revised 24 Oct 11.