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GEOCHEMISTRY OF LOWER PROTEROZOIC GREYWACKES FROM THE BIRM DIAMONDIFEROUS FIELD, GHANA

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ABSTRACT:- *The Birim Diamondiferous field from which most of the alluvial diamonds are recovered is underlain by Lower Proterozoic Birimian metasedimentary and associated mafic rocks. Bulk rock geochemistry was carried out on the sandstones from the metasedimentary rocks to constrain the tectonic setting during the early Proterozoic. Bulk rock geochemical studies on greywackes show that they are characterized by moderately low but variable SiO2 contents, generally high Al2O3 and ferromagnesian element (e.g., Fe, Mg, Cr, V, Co, Sc) contents, and K2O/Na20 commonly less than 1. The geochemical data indicate that the greywackes were deposited in an active continental margin environment. The detritus were mainly derived from the upper continental crust but with an admixture of mafic component. Recent studies have shown that some of the mafics/ ultramafics are diamondiferous metakimberlites. The inferred tectonic (arc) setting makes the emplacement of the so-called Proterozoic diamondiferous metakimberlites unlikely, if we are to go by the Clifford's Rule. However, if these ultramafic rocks are really metakimberlites and the source of the diamonds, then the Clifford's Rule may not be applicable in the Ghanaian situation, and the Birim field may be one of the few exceptions to this general rule. This would, then, present a typical example of subduction zone related diamondiferous kimberlites.*

Keywords: Birim Diamondiferous field, Birimian, geochemistry, Ghana, tectornc setting

INTRODUCTION

The composition of detrital sediments is a function of a complex interplay of variables including source area composition, weathering, transportation and diagenesis (Bhatia, 1983; Sawyer, 1986). Since these variables are influenced by tectonic setting (Siever, 1979; Condie et aI" 1992), it has been advocated that tectonism primarily controls sediment composition (Dicldnson and Rich, 1972; Blatt et al., 1980). The close relationship between sediment composition and tectonic setting has been confirmed by various studies on modem sands of known tectonic settings (e.g., Potter, 1978; Dickinson and Valloni, 1980; Valloni and Maynard, 1981) apd various workers have utilized the composition of ancient sedimentary rocks to infer the tectonic setting of sedimentary basins (e.g., Schwab, 1975; Dickinson and Suczek, 1979).

The Birim diamondiferous field is situated in the Birim River valley, about 110 kIn northwest of Accra, Ghana (Fig. 1). Diamonds mined from this field contribute 98% of the total diamonds produced in Ghana, and more than 100 million carats of diamonds have been recovered from the placer deposits of the diamondiferous field since 1920 (Kesse, 1985). The Birimian were deformed, regionally metamorphosed and tectonically stabilized during the Eburnean (c. 2000 Ma) part of the Man Shield in the southern segment of the West African Craton. The Man Shield, which comprises a western domain of mairilyArchean rocks of Liberian age (3.0 - 2.5 Ga) and an eastern domain of early Proterozoic Birimian Supergroup, has remained stable since about 1.7 Ga (Leube et aI., 1990).

In Ghana, the Birimian comprises metavolcano-sedimentary and metavolcanic rocks. The former forms sedimentary basins, which separate a series of sub-parallel,

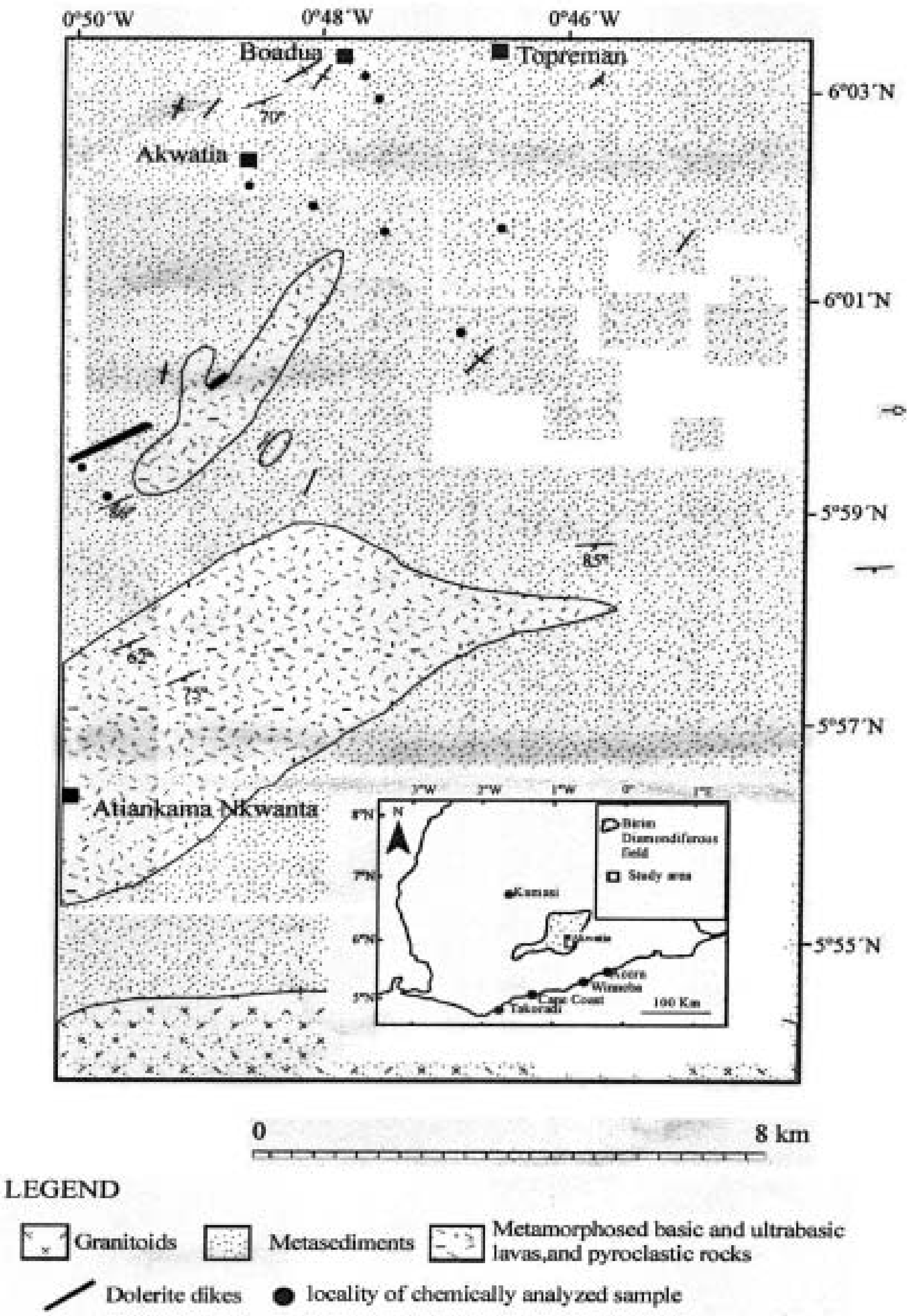


Figure 1: Simplified geological map of the study area. Inset: map of Ghana showing the Birim Diamondiferous Field and the study area

roughly equally spaced, northeasterly trending volcanic belts of mainly tholeiitic basalts (Taylor et al., 1992; Hirdes et al., 1992). The Birimian suffered intense deformation, typified by isoclinal folding and greenschist facies regional metamorphism, and is intruded by granitoids during the Ebumean tectono-metamorphic event. The Birimian geology of Ghana is summarized by Junner, 1935; Asihene and Barning, 1975; Kesse, 1985; Wright et al., 1985; Leube et aI., 1990.

Two contrasting concepts exist regarding the age relationship between the metavolcanics and the metasediments. Junner (1940) assert that the sedimentary series occupies the lower series and are older than the volcanic series, which occupies the upper position. However, Tagini (1971) in Leube et al. (1990) and the francophone geologists believe that the metavolcanics are rather older than the metasediments. Leube et al. (1990) proposed a new version of the stratigraphy, where the lavas and the sedimentary rocks are said to have been deposited contemporaneously as lateral facies equivalent. Also controversial is an appropriate tectonic model for the evolution of the Lower Proterozoic rocks in Ghana and the number of deformational phases involved. While Leube et al. (1990) propose a multi-rift or graben model with two distinct phases of deformation event, Eisenlohr and Hirdes (1992) suggest a single, progressive deformational event involving a series of deep-seated, partly blind thrusts, possibly in a foreland basin setting.

Geochronological studies of the Birimian Supergroup and associated granitoids in West Africa suggest they were formed during the time interval ~2.25 - 2.05 Ga (Abouchami et al., 1990; Liegeois et al., 1991; Boher et al., 1992; Hirdes et aI., 1992; Taylor et al., 1992; Davis et al., 1994). The rocks were probably deposited on an Archean basement in the early Proterozoic as sediments and volcanics in an extensive geosyncline and later defonned during the Eburnean tectono-thennal event. The purpose of this study is to report the petrographic and geochemical compositions of sandstones from the Lower Proterozoic Birimian rocks in the Al(Watia district. of the Birimc diamondiferous field (Fig. 1) and constrain the lithology of source rocks and the tectonic setting of the study area during the early Proterozoic. The secondary objective is to relate this tectonic setting to the emplacement of kimberlite during the early Proterozoic.

Geology of the study area

The rocks of the Birim diamondiferous field may be classified in order of increasing as follows: superficial deposits (Pliocene to Recent) comprising gravels, sands, clays, laterite and soils; basic intrusives (unknown age?) consisting of dolerite, epidiorite and other basic sills and dykes; acidic intrusives (Post-Birimian age) comprising granite, aplite, porphyry, pegmatite and quartz veins; and the Birimian rocks comprising metasediments and metavolcanics (i.e., basic subvolcanic and extrusive igneous rocks).

The gravels have been classified into three cycles depending on their location (Junner, 1943) as (i) terrace and valley gravels of the rivers and larger streams such as those of Birim, Supong, Pra and Moh Rivers; (ii) The hill-top gravel; and (iii) the gravels of the flats of smaller streams. Most of the diamonds recovered from the field are associated with these gravels.

The basement rocks of. the diamondiferous field are the Birimian rocks. Cape Coast granite intrudes the Birimian rocks south of the study area extending to the coast between Cape Coast and Winneba.

The Birimian in the study area is almost completely composed of metasediments with minor tuffs and basic to ultrabasic lavas and subvolcanic rocks. The metasediments consist of interbedded greywackes/ metagreywackes, grey and black phyllites, and minor black quartzites and schists. The greywackes are, carbonate-spotted, fine to coarse-grained, and show various degrees of shearing and metamorphism. Generally, the Birimian rocks show a regional northeast strike, with local variations due to complex folding and faultiJ;lg. The rocks generally exhibit up to greenschist-facies regional metamorphism in the northern part of the study area. These low-grade metamorphosed rocks commonly dip steeply to southeast though northwest local dips were observed at several places. The degree of metamorphism increases through the central part of the field to the south as the granitoid intrusion is approached (Fig. 1). Both the metasediments and the ultramafic intrusives close to the granite batholith display various degrees of contact metamorphism.

The metasediments are massive and show no sedimentary structures such as ripple marks and cross bedding probably due to recrystallisation. Graded bedding was observed in the least metamorphosed sandstone exposures. No key or marker beds were observed in the field making it very difficult to establish correlation between outcrops and hence, the stratigraphy of the area.

Sampling and analytical methods

Sampling was problematic due to scarcity of fresh rock exposures due to thick vegetation and deep tropical weathering. Prominent exposures are restricted to the Akwatia-Boadua area.'(Fig. 1) and a very few isolated places.

On the basis of the petrographic characteristics of the samples, eleven of the least metamorphosed and relatively fresh samples were selected for bulk-rock analysis. Bulk-rock chemical analyses of the samples were carried out at the National Nuclear Research Institute of the Ghana Atomic Energy Commission, Accra. Instrumental Neutron Activation Analysis (INAA) technique was used to determine major and trace elements concentrations. Loss on ignition was not determined.

Petrography

Description

The greywackes/metagreywackes are the dominant rocks among the metasedimentary series and form prominent exposures in the area under study. They are mostly gray, fine to coarse- grained, feldspathic and carbonate spotted. The rocks show various degrees of metamorphism and shearing. Flakes of black phyllitic material are present inmost cases.

The framework grains are made up of quartz, plagioclase, orthoclase, biotite, calcite, muscovite, sericite and chlorite. Grains are angular to sub-rounded in shape. Some of the grains are elongate within the direction of foliation/ schistosity where shearing has taken place.

Both mono crystalline and polycrystalline quartz grains were observed, although the former dominate. Monocrystalline quartz grains mostly show undulose extinction and are clear of inclusions. The polycrystalline quartz variety is mostly composed of three or more crystals with sutured intercrystalline boundaries. No embayment or overgrowths were observed on quartz grains.

In almost all the sections, plagioclase far exceeds K-feldspar. Plagioclase occurs as ovoid and lathe-like grains. Minor to complete alteration of the plagioclase is evident. Igneous and metamorphic fragments are present.

Pyrite and other opaque minerals occur in minor quantities in some of the samples. Biotite content is high (15%) in some of the samples. Biotite grains grow across each other in some cases. Calcite generally contains inclusions of quartz, opaque minerals and micas and appears to be replaced with quartz and matrix material in most sections. Some of the large calcite grains have iron stains at their borders/margins.

The matrix content is generally high (up to 60 volume percent) and highly variable, and its origin is in most cases problematic. It includes recrystallized matrix of fine-grained quartz, mica, feldspar, iron oxides and clay minerals (orthomatrix of Dickinson, 1970), grain-alteration and grain-replacement matrix composed of quartz, calcite, sericite, and chlorite (epimatrix of Dickinson, 1970) and deformed lithic grains (pseudomatrix of Diclcinson, 1970). The estimated modal abundances of essential minerals are shown in Table 1.

Table 1. Ranges of estimated modal compositions Of Petrographic constituents in the sandstones

Constituent	Range (%)
Quartz	20.0 - 40.0
Plagioclase	18.0 - 25.0
Orthoclase	4.0 - 8.0
Sericite	3.0 - 10.0
Muscovite	0.0 - 10.0
Calcite	7.0 - 15.0
Chlorite	0.0 - 4.0
Biotite	3.0 - 15.0
Pyrite	0.0 - 1.0
Opaque minerals	0.5 - 4.0
Rock fragments	0.0 - 5.0
Matrix	25.0 - 6.00

Interpretation

The relatively high proportion of strained monocrystalline quartz and strained polycrystalline quartz with sutured contacts between crystals over other rypes of quartz grains, coupled with the generally low content of lithic fragments may suggest their derivation from mainly acidic plutonic rocks. However, some or most of the strained quartz may be due to post-depositional deformation processes as the sandstones have undergone some degree of metamorphism. Lack of stretched quartz grains, and polycrystalline quartz grains with elongate crystals and straight intercrystalline boundaries rule out significant contribution from schistose and gneissic terrains.

The relationship between tectonic setting and sandstone composition is mainly based, on modal analysis of framework grains (Dickinson and Suczek, 1979). However, the modal data of the analyzed samples is not very accurate due to the metamorphosed nature of the sandstones (Bhatia, 1983). In addition, a large part of the matrix may have formed due to the degradation of lithic grains (Cummins, 1962; Hawkins and Whetten, 1969). These uncertainties together with the high matrix content ‘make it impossible to apply the discriminant diagram of Dickinson and Suczek (1979) to infer the tectonic setting.

Geochemistry

The wackes (Table 2) have moderately low SiO2 concentrations of 42 - 65 wt percent but generally between 55 - 65 wt percent, although one of the samples has SiO2 concentration of70 wt. The concentrations of Al2O3 are negatively correlated with SiO2 (Table 3) and range from about 11 to 31 wt percent. Al_2O_3/SiO_2 ratios are variable and range from 0.5 to 0.74 and K_2O/Na_2O ratios are commonly less than 1. The TiO_2 and Fe_2O_3+MgO contents are generally high; averaging 0.7 and 12.7 wt percent respectively. The abundances of ferromagnesian trace elements (e.g., Cr, V, CO and Sc) are also generally high; upto-530 ppm, 230 ppm, 165 pprii and 23 ppm for Cr, V, Co and Sc respectively.

Table 2: Representative chemical compositions of the analyzed sandstones

	PKX 10	AB 7	GCD 25	24B	APT26	BOA 20
SiO_2	44.03	61.6	55.34	53.7	60.24	58.09
TiO_2	1.08	0.63	0.94	0.84	0.52	0.07
Al_2O_3	28.71	14	20.08	25.2	14.49	13.3
Fe_2O_3*	7.69	6.21	5.68	6	8.56	7.05
MnO	0.09	0.07	0.1	0.06	0.18	0.09
MgO	7.03	4.94	7.85	5.16	5.19	6.35
CaO	4.69	1.6	3.66	2.65	2.1	4.26
Na_2O	3.61	2.56	3.13	2.88	2.29	3.66
K_2O	1.72	1.98	1.94	2.18	2.59	2.87
Total	98.92	93.2	98.72	98.7	96.16	95.74
Sc	16.06	15	14.97	15.9	22.62	23.41
V	221	114	168.1	165	149.1	171.6
Cr	149.4	114	159.6	126	229.8	301.9
Co	68.53	62.5	59.36	56	165.9	69.37
Ga	50.43	70.2	67.39	67.9	65.34	66.6
Zr	416.2	519	422.7	415	511	419.6
Hf	4.23	2.97	4.32	2.75	6.75	3.37
Ta	4.23	3.68	3.65	3.03	5.68	17.22
Ba	551.5	756	735.5	696	1032	801
La	22.94	15.7	20.89	21	61.39	16.83
Ce	51.7	22.7	31.03	31.3	114.4	39.83
Nd	18.42	14.5	15.35	17.1	35.09	16.57
Sm	4.64	3.41	3.68	4.01	5.31	3.87
Eu	1.6	1.13	1.13	1.19	1.23	1.31
Gd	6.02	4.26	4.29	4.89	5.67	4.92
Tb	0.74	0.67	0.73	0.78	0.79	0.82
Dy	3.78	2.28	3.9	2.31	3.17	2.43
Gd	6.02	4.26	4.29	4.89	5.67	4.92
Tb	0.74	0.67	0.73	0.78	0.79	0.82
Dy	3.78	2.28	3.9	2.31	3.17	2.43
Yb	1.24	1.21	1.36	1.28	1.69	1.26
Lu	0.19	0.16	0.2	0.19	0.25	0.19

*Total Fe as Fe_2O_3

Table 3: Linear correlation coefficients for selected element distribution in the analyzed samples

SiO_2 – Al_2O_3	-0.94
TiO_2 – Al_2O_3	0.8
Fe_2O_3 + MgO - Al_2O_3	0.59
V – Al_2O_3	0.87
Al_2O_3 – La	-0.11
Al_2O_3 – Yb	-0.27
Al_2O_3 – total REE	-0.02
Zr – La	0.5
ZR – Yb	0.63
Zr – total REE	0.46
Zr – Hf	-0.3
Cr – V	-0.29
Cr – Co	0.01
Cr – Sc	0.32
V – Co	0.06
V – Sc	0.23
Co – Sc	0.66

Chemical Classification

Various workers (e.g., Crook, 1974; Pettijohn et al., 1972; Blatt et al.:,.1980) have devised plots to chemically classify sedimentary rocks. On the chemical classification diagram of Blatt et al. (1980), the analyzed samples plot in the greywacke field close to the Fe_2O_3 + MgO boundary (Fig. 2a). The Na_2O - K_2O diagram of Crook (1974) indicate that the Birimian wackes are quartz-intermediate (Fig. 2b). Combining the two diagrams, the Birimian wackes can be described as ferromagnesian rich quartz-intermediate greywacke.

Compositional trends

Before we can begin to understand how the geochemical data monitor the provenance of the Birimian greywackes we need to know which minerals control which element

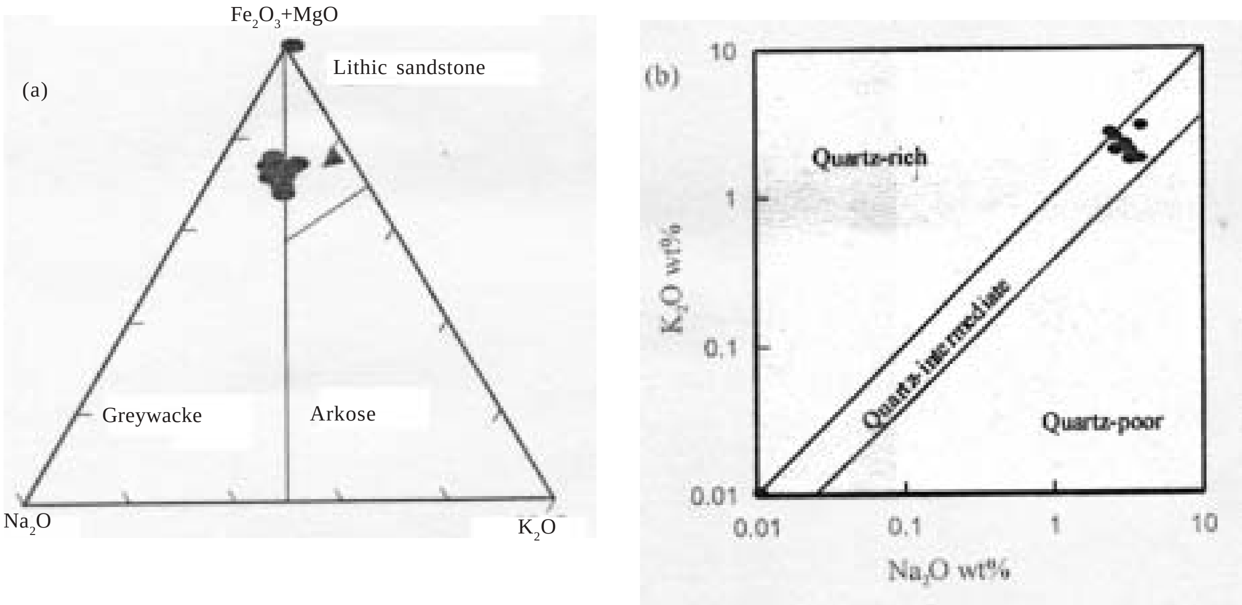


Fig. 2: Major element chemical classification of the sandstones (diagrams from Blatt et al., 1980; Crook, 1974)

distribution in the analyzed samples. The TiO_2 contents of the greywackes show strong correlation with the Al_2O_3 contents (Table 3). This correlation suggests that Ti is mainly contained in phyllosilicates, possibly biotite (Asiedu et al., 2000; Condie et al., 1992). Also, moderately strong correlation of FezO3+MgO and V contents to AlzO3 imply that V, Fe and Mg are mostly housed in phyllosilicates rather than in accessory minerals such as oxides, non-aluminous silicate minerals and pyrites (Table 3). There is lack of correlation of Al_2O_3 to La, Yb and total REE but moderate correlation of Zr to La, Yb and total REE (Table 3). This feature suggests that zircon is more important than phyllosilicates in housing REEs (Asiedu et al., 2000; Condie et al., 1992).

The Zr and Hf contents show poor correlation, and ferromagnesian trace element abundances (i.e., Cr, V, Co, and Sc) generally show poor inter-relationships. These poor inter-relationships may be the result of good mixing of the sediment prior to deposition.

Chemical discrimination of provenance

Previous chemical studies have related greywacke compositions to different tectonic environments (e.g., Bhatia, 1983; Roser and Korsch, 1986). It is, therefore, possible to compare the chemical compositions of the studied greywackes with those of greywackes deposited in known tectonic settings.

The major element geochemistry of sandstones has been found to reflect the tectonic setting of the basin (Bhatia, 1983; Roser and Korsch, 1986). Roser and Korsch (1986) plotted SiO_2 content (volatile-free) versus K2OINa20 to distinguish sediments from different tectonic settings. Rather than using diagrams that rely on few diagnostic elemental ratios, Floyd et al. (1991) proposed the use of a full range of elemental compositions for tectonic setting discrimination. Figure 3 shows the average composition of the Birimian greywackes normalized to the average major element compositions of greywackes from different tectonic setting (Floyd et al., 1991). From the diagram, the Birimian greywackes compares well with those from continental island arc including active continental margin (CAAM). Such an interpretation is compatible with the quartz-intermediate nature of the sandstones (Crook, 1974).

The relatively insensitive nature of the rare earth elements (REE) to remobilization during alteration and metamorphism makes them useful for inference of tectonic setting and provenance type (Condie and Allen, 1984; Taylor and McLennan, 1985; Vance and Condie, 1987; Cullers et al., 1987). Nesbitt (1979) has shown that although REE may be locally remobilized in a weathering profile, there are no selective losses of REE during weathering, and thus weathering probably does not produce Eu anomalies. The chondrite-normalized REE distribution patterns for the eleven analyzed samples are similar and are characterized by light REE enrichment, slightly negative

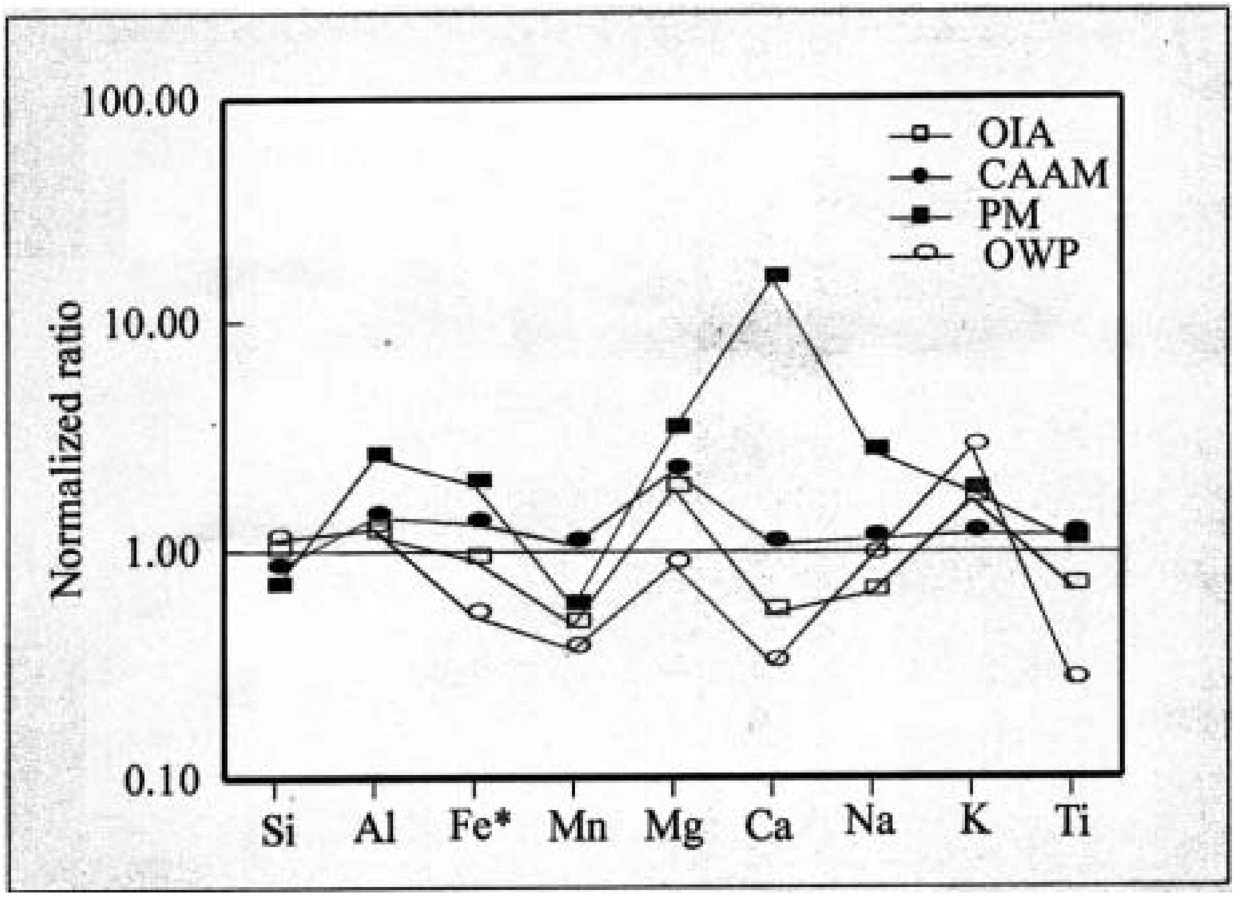
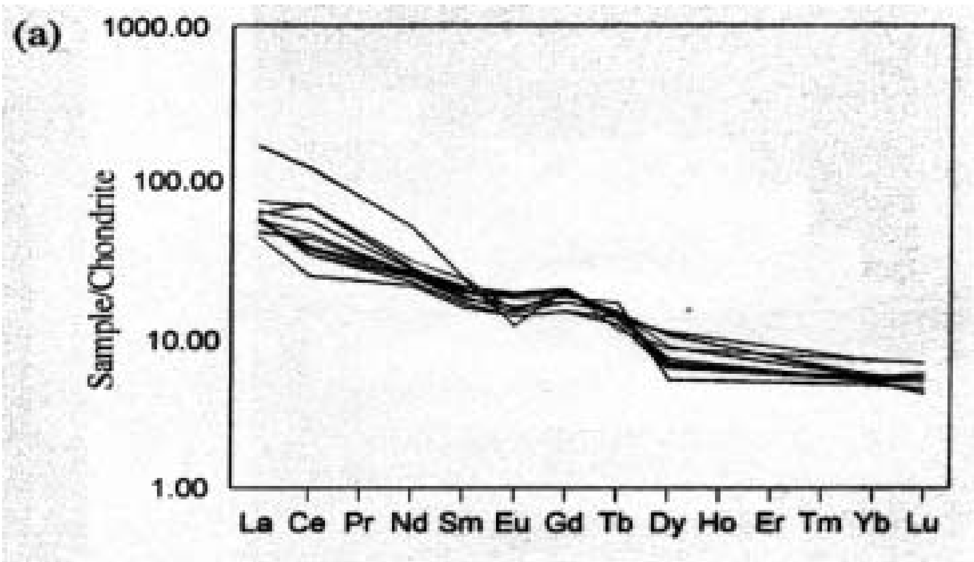


Fig. 3. Major element patterns for the greywackes normalized to those of passive margin (PM), continental arc + active margin (CAAM), and oceanic island arc (alA). Standards from Floyd et al. (1991).

Eu anomalies and slightly heavy REE depletion (Fig. 4a). The average REE pattern of the greywackes is similar to those of average early Proterozoic upper continental crust and post-Archean shales (Fig. 4b) suggesting their derivation from mainly the upper continental crust and their deposition in continental margins (Taylor and McLennan, 1985). Continental margins can be categorised as active or passive (Taylor and McLennan, 1985). Compared to the average post-Archean shales (typical of passive margin sediments) the studied greywackes have relatively lower La_N/Sm_N (2.74-3.57) and higher Eu/Eu* (0.54-0.99) ratios suggesting their deposition in an active continental margin rather than passive margin environment. The studied greywackes have relatively higher abundances of ferromagnesian elements compared to those from the average upper continental crust, suggesting significant mafic input possibly of mantle-derivation rocks.

Tectonic setting and the emplacement of kimberlite Diamond occurrences in the metasediments and the associated ultramafics in the study area have been reported by several authors (e.g., Appiah et al., 1996; Grantham, 1956; Junner, 1943). This was confirmed during our fieldwork as illegal miners recovered diamondsffom these rocks. The occurrence of diamond at great depths in the weathered parts of t4e metasediment rocks but notably not in fresh rocks has been attributed to the infiltration down cracks and root-holes of diamonds littered on surface by past alluviation (Grantham, 1956). Although diamonds in the ultramafics also occur in the weathered parts, it is believed that they are insitu and have not resulted from any infiltration or mechanical action, as they show no abrasion (Kaminsky et al., 1996).



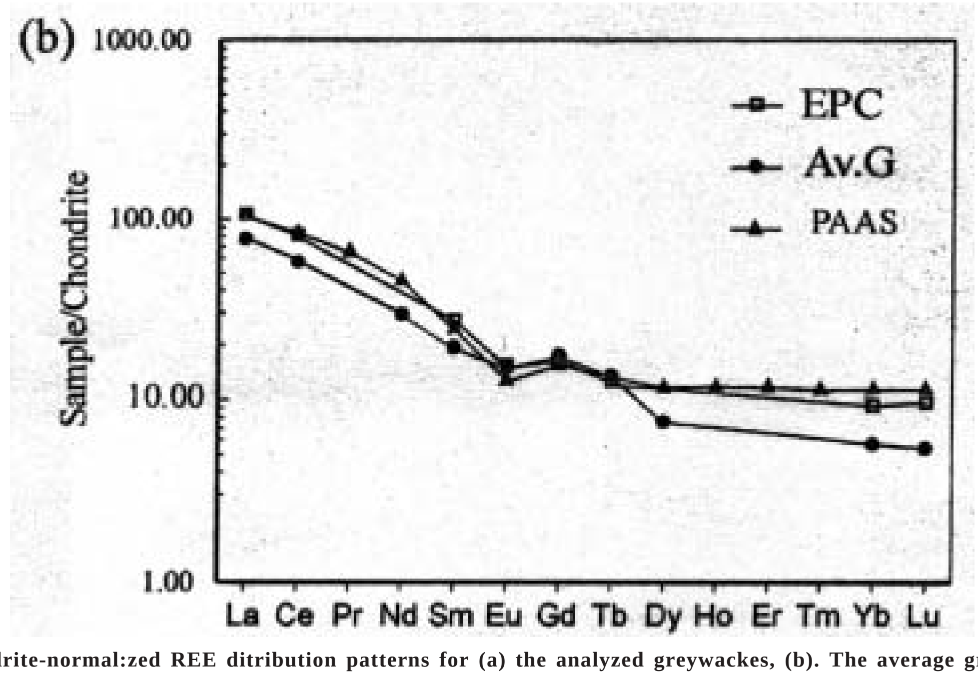


Figure 4: Chondrite-normal:zed REE ditribution patterns for (a) the analyzed greywackes, (b). The average greywackes compared to those of the early Proterozoic upper continental crust (EPC) and post-Archean Australian Shales (PAAS). Data for the EPC from Condie (1991) and PAAS from Taylor and McLennan (1985).

Appiah et al. (1996) have indicated that the major and minor elemental composition of the ultramafics fit well with kimberlite. These rocks that have appropriately been termed as metakimberlites (McKitrick, 1993 in Appiah et al., 1996), are believed to be some of the ultimate sources of Birim diamonds (Appiah et al., 1996; Kaminslcy et al., 1996). The age of these rocks has been constraint. to be Early Proterozoic, as they have been metamorphosed by the Eburnean Cape Coast gratritoids.

According to Clifford's Rule (Clifford, 1966; Kirkley and Gunney, 1992), economic ldmberlites are confined to craton regions mostly underlain by Archean basement. Hence, the most favourable location for diamond-bearing kimberlites is "on-craton" as opposed to "off-craton". Meanwhile, the Birim diamondiferous field is not underlain by Archean crust, thus presenting an unfavourable geologic condition for emplacement of kimberlite.

The inferred active continental margin tectonic setting of the greywackes also makes it very difficult to understand how the emplacement of diamondiferous kimberlite could occur in the study area during the Proterozoic era. In any case, if the diamondiferous ultramafics are really metakimberlites, then the Akwatia metakimberlites are an example of subduction zone related kimberlites, and that the Birim diamondiferous field may be one of the exceptions to the Clifford's rule.

CONCLUSIONS

The major, trace and rare earth elemental composition of the stUdied samples (Akwatia greywackes) indicate that:

- The sediments were most likely deposited in an active continental margin tectonic setting
- The sediments were mostly derived from the upper continental crust but with significant contribution from mantle-derived rocks.

The inferred active continental margin environment for the Birimian in the study does not favour the emplacement of kimberlite in the study area during the early Proterozoic era, i.e., if the Clifford's Rule is to be applied. This rule is, however, challenged by the presence of the so- called Proterozoic diamondiferous metakimberlites in the area. Thus, generalizations based on Clifford's rule in kimberlite emplacement could be very misleading, and the Ghanaian situation may be one of the exceptions to the rule. Also, if the ultramafic rocks indeed are metakimberlites, then the Birim dianlondiferous field gives an example of subduction zone kimberlite volcanism.

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