Heavy mineral analysis of alluvial sediments from the Akwatia area of the Birim diamondiferous field, Ghana

Samuel DAMPARE*, Daniel ASIEDU**, Bruce BANOENG-YAKUBO** and Tsugio SHIBATA***

*Graduate School of Natural Science and Technology, Okayama University, Okayama 700-8530
**Department of Geology, University of Ghana, P.O. Box LG 58, Legon, Ghana
***Department of Earth Sciences, Okayama University, Okayama 700-8530

Heavy mineral analysis was carried out on Pliocene to Recent alluvial sediments from the Birim diamondiferous field of Ghana. The main objective of the study was to examine the mineral composition of heavy fractions in order to identify: (1) the heavy mineral assemblage that occur in the sediments, (2) particular diamond indicator minerals associated with the diamonds, and (3) the provenance of the alluvial sediments. The heavy minerals are essentially composed of staurolite, ilmenite and magnetite in varying proportions, with trace amounts of leucoxene, rutile, garnet and zircon. The heavy mineral assemblage and chemical compositions of ilmenite and garnet suggest their derivation from phyllites and schists which reflect directly the composition of the basement rocks developed in the study area. The absence of diamond indicator minerals such as apatite, pyrope garnet, chromian spinel, and picroilmenite in the heavy fraction is unlikely to be due to their destruction during intense weathering and/or diagenesis but rather their non-occurrence in the area.

Keywords: Heavy minerals, provenance, sediments, diamonds, Ghana

I. Introduction

The properties of heavy minerals allow an insight into the petrological character of sediment source terrains and permit their extensive use in tracing provenance. An association of characteristic heavy minerals is intimately related to particular source lithologies and may often be correlated with an identifiable source terrain although factors such as source area climate, hydraulic sorting, and post-depositional diagenetic effects can control heavy mineral assemblages in sediments (Morton, 1985). For example, zircon, rutile and tourmaline, particularly if rounded, are of typical sedimentary provenance whereas garnet, epidote, kyanite, sillimanite and andalusite suggest high-grade metamorphic provenance.

Diamonds in Ghana occur mainly in alluvium overlying Paleoproterozoic rocks (Fig. 1a) in the Birim diamondiferous field and the Bonsa diamondiferous field (Kesse, 1985). However, diamonds of Ghana are mostly produced from the Akwatia area of the Birim diamondiferous field. In spite of the high diamond production in the country, the primary source(s) of the diamonds has remained enigmatic (Kesse, 1985). All the previous studies on heavy mineral concentrates from the Akwatia area have revealed that no classical kimberlitic indicator minerals such as pyrope garnet, chromian spinel, chrome diopside and picroilmenite were found to be associated with the sediments. The principal heavy minerals found in association with the Akwatia diamonds are, in approximate order of abundance, are staurolite, ilmenite, limonite, rutile, rutile-quartz intergrowth, and tourmaline (Junner, 1943; Kaminsky et al., 1996). All the studies of heavy mineral concentrates have dealth with coarse sand- and pebble-size fractions alone (e.g., Junner, 1943; Appiah et al., 1996; Kaminsky et al., 1996). However, a number of heavy mineral species have an affinity to certain grain sizes; e.g., zircon tends to occur as small grains whereas staurolite, kyanite and sillimanite often appear as fairly large fragments.
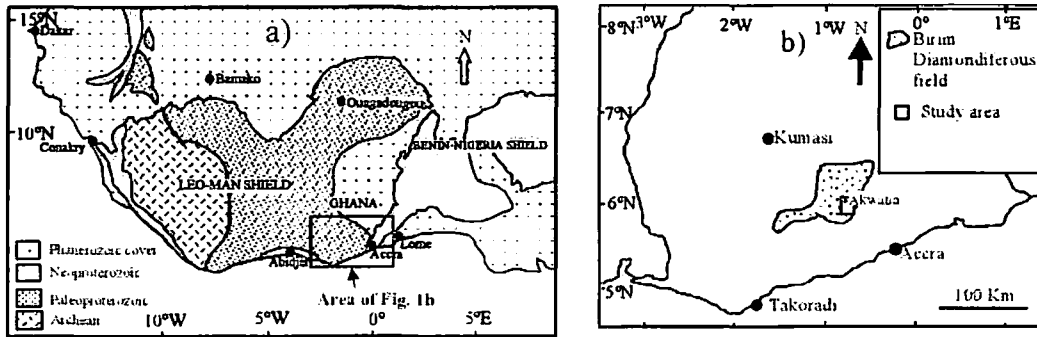
Fig 1 Simplified geological map of West Africa (a) and location map of the study area (b).

On the heavy mineral analysis of coarse sand fraction, Kaminsky et al. (1996) concluded that the absence of diamond indicator minerals in the Akwatia sediments might be due to the analyzed size fraction and/or the development of mature crusts of weathering within the region and consequent destruction of the indicator minerals. Accordingly, the main objective of this study was to examine the mineralogical composition of the medium- to fine-grained heavy fractions of the alluvial sediments in Akwatia, in order to identify the mineral associations that occur in the alluvial sediments developed in the area. Another objective was to identify the particular diamond indicator minerals that would point to primary diamond sources.

II. Geology

The Birim diamondiferous is situated in the Birim River valley in the Eastern Region of Ghana and is approximately 110 km northwest of Accra. The study area lies within the Birim diamondiferous field, which in turn occurs within the Paleoproterozoic Birimian rocks of Ghana (Fig. 1). The geological, geochronological, and provenance studies of the Birimian rocks in the study area have been covered by various workers (e.g. Junner, 1943; Asiedu et al., 2004: Dampare et al., 2005).

The Birim Supergroup in the study area is mainly composed of metasedimentary rocks which comprise tuffaceous metagreywackes with subordinate quartzites and interbedded grey and black phyllites and schists. These are the oldest rocks in the area. Mafic to ultramafic lavas and sub-volcanic rocks probably of the same age as the metasedimentary rocks (Junner, 1943; Dampare, 2001) also occur in the area. The southern portion of the study area is intruded by Paleoproterozoic granitoids. The superficial deposits in the area include gravels, sands,

clays, laterite and soils. These Pliocene to Recent deposits host most of the diamonds produced from the diamond field.

III. Field and Analytical Procedures

1. Field procedure

The heavy mineral study consisted of eight samples from Akwatia-Osenase-Atiankama Nkwanta area of the Birim diamondiferous field (Fig. 2). Five of the samples are pit gravels while the remaining three are sediments taken from active streams. The gravel layer was selected for this study because diamonds in the area have been found by previous workers to be associated with the gravel layer (Junner, 1943; Kesse, 1985; Appiah et al., 1996; Kaminsky et al., 1996). Obviously other heavy minerals accompanying the diamonds are also likely to be found in the gravels.

Three active streams were sampled, making sure that all the various lithological units of the area had been taken care of. All the streams where there had ever been a mining activity were not sampled. This is because the streams' courses have been diverted and re-diverted several times, thus, their sediments contaminated or destroyed. At each sampling site approximately 2 kg of the gravel was taken out and panned. The panning was carefully done such that most of the heavy minerals were not lost or washed away, periodically skimming the lighter material from the surface of the sample. In cases where large-sized particles are included in the mixture, a locally made jig of wood-framed screen of 2mm aperture was first used to remove them before conventional panning was done. The panned concentrate was then bagged and labelled. Field treatment of pit samples followed the same procedure as the stream sediments. The locations were
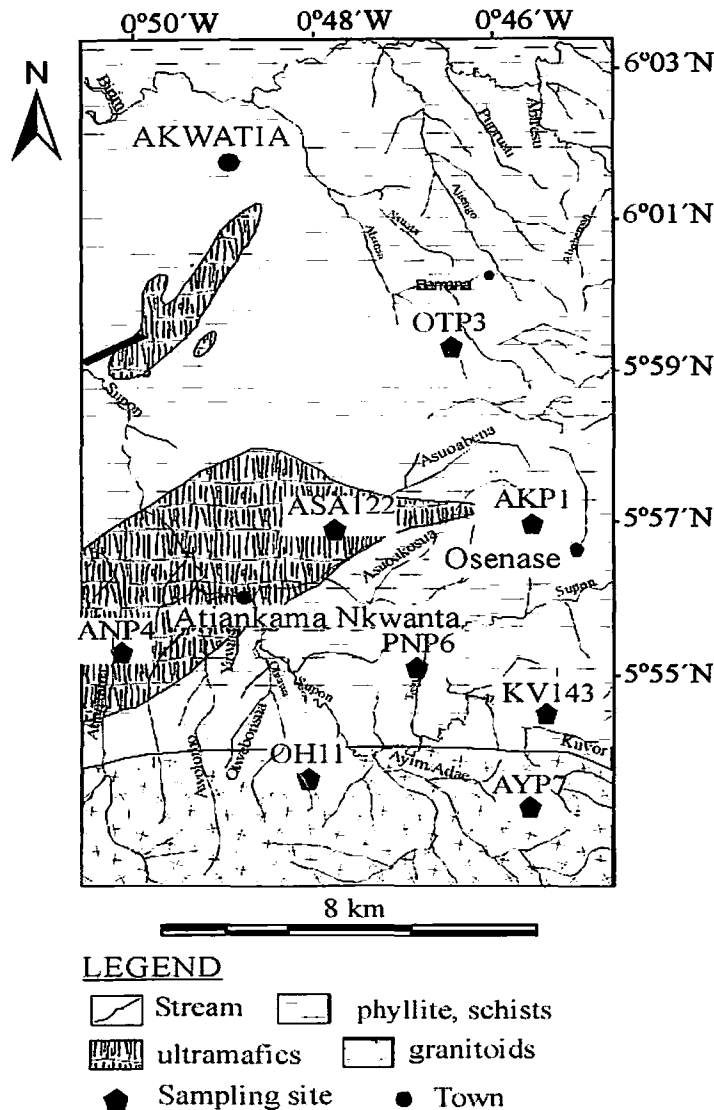
Fig. 2. Geological and drainage map of the study area

also recorded and the pits logged (Appendix 1). A 12 Channel Garmin GPS with 15 m accuracy was used to take locations of the sample sites. Site details such as packing, texture, trap description, location etc. were also recorded. The sampling equipment was thoroughly washed or cleaned between sample sites in order to avoid contamination of one sample by the other.

2. Analytical procedure

The unwanted finer particles were removed from the loose sands and disaggregated materials by a spay of water using a sieve of 0.063 mm. The medium- to fine-sand fraction (0.063-0.5 mm) was extracted from the dry samples by standard sieving (Ingram, 1971) for this work. The heavy mineral separation then followed. The sample was quartered to ensure uniformity in the grain

distribution, and a maximum of 10g weight taken. Gravity settling method, with bromoform (tribromoethane) of specific gravity 2.89, was used for the separation of the heavy minerals. A settling time of 3 to 6 hrs was allowed for complete separation of lighter grains from heavy ones. The heavy mineral separation was carried out at the Department of Earth Sciences, Okayama University.

The heavy fraction of each of the samples was divided into two. Thin-sections were prepared for one half of the samples by mounting the grains in epoxy casting resin (Middleton and Kraus, 1980). The mineralogical and chemical analyses of the other half were carried out at the Geological Survey of Denmark and Greenland, Copenhagen, using Computer Controlled Scanning Electron Microscopy (CCSEM). The samples were thin-sectioned and polished for the CCSEM study. The SEM

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Table 1. Mineralogical composition of the heavy fraction (in vol. %)

Sample No.	ASA122	KV143	OH11	AKP1	OTP3	ANP4	PNP6	AYP7
Ilmenite	8.1	73.1	9.1	20.9	1.7	5.2	27.7	4.8
Leucoxene	0.0	3.0	0.0	0.3	0.0	0.3	0.1	0.5
Rutile	1.8	3.5	0.0	0.1	0.4	0.0	0.0	0.0
Ti magnetite	0.4	3.2	0.5	7.9	0.4	4.2	13.6	0.0
Magnetite	0.0	9.5	0.0	8.1	66.5	71.0	22.3	0.0
Chromite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pyrite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phosphate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Monazite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sphene	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Garnet	0.2	0.0	0.6	0.2	0.5	1.1	2.7	0.0
Kya/Sill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Staurolite	83.5	5.4	81.8	38.4	11.6	0.2	8.3	88.1
Zircon	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Silicate	4.8	1.5	8.1	18.6	4.8	3.7	12.4	6.6
Unclassified	1.1	0.9	0.0	5.4	14.1	14.1	13.0	0.0
No of analyzed grains	698	784	559	1481	880	1474	1478	633
% of HM in raw sand	2.5	2.6	2.7	6.6	12.3	14.1	13.2	12.7
Mineral association	St-il	il-Mg-St	St-il	St-il-Mg	Mg-St	Mg-il	Mg-il-St	St-il

HM, heavy mineral; St, staurolite; il, Ilmenite; Mg, magnetite

analyse over 500 grains per polished thin-section, group the grains into 17 mineral categories (i.e., ilmenite, leucoxene, rutile, sphene, other Ti-Fe oxides, magnetite, chromite, zircon, monazite, Y-phosphate, apatite, pyrite, garnet, sillimanite, staurolite, other silicates and unclassified), and calculate the content of these groups and their chemical composition.

IV. Results

The results of the modal mineralogy and mineral chemistry are presented in Table 1 and Table 2, respectively.

1. Heavy mineral assemblages

Both stream sediment and pit samples show similar heavy mineral assemblages. The heavy mineral fraction is essentially composed of staurolite, ilmenite and magnetite in varying proportions (Table 1). These occur in four sets of mineral associations: staurolite-ilmenite (3 samples; Fig. 3), staurolite-ilmenite-magnetite (3 sample), magnetite-ilmenite (1 sample) and magnetite-staurolite (1 sample). Other heavy minerals that occur in minor and trace amounts include leucoxene, rutile, garnet and zircon (Table 1). These heavy mineral assemblages are similar to those reported for coarser sand fraction (Kaminsky et al., 1996). The samples with low staurolite contents, however, show high "unclassified" contents (Table 1). The thin-section study indicates that the

Fig. 3. Concentrate sample ASA122 heavy fraction, staurolite-ilmenite association. Mag. X 15.

"unclassified" group is dominated by hematite and limonite.

2. Major mineral constituents

Staurolite is present in all the analysed samples. It occurs as irregular, angular to sub-rounded and somewhat platy grains. The grains occur in shades of yellow colours: pale yellow through golden yellow to dark yellowish brown. Chemically, they are composed essentially of Si, Al and Fe, with the Mg content of about 1.4 wt% (Table 2a). Ilmenite is also present in all the analysed samples. It usually occurs in the form of tabular crystals as well as rhombohedral habit, which appear to be flattened octahedral. These shapes are typical of ilmenite originating from metamorphic rocks and phyllites

Table 2a. Mineral chemistry (average) of staurolite and zircon from the Akwatia sediments

	Staurolite								Zircon	
	ASA122 N=583	KV143 N=42	OH11 N=457	AKP1 N=569	OTP3 N=102	ANP4 N=3	PNP6 N=123	AYP7 N=558	KV143 N=1	ANP4 N=1
TiO_2	0.6	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.0	0.2
Fe_2O_3	14.7	15.3	15.0	15.5	16.0	15.9	15.3	15.4	0.3	2.1
MnO	0.3	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.0
Cr_2O_3	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.0	0.0
SiO_2	33.4	31.8	33.4	33.1	31.9	31.7	33.2	32.2	30.1	29.0
Al_2O_3	47.4	48.3	47.2	46.6	47.5	48.2	46.8	47.9	0.2	0.2
MgO	1.4	1.4	1.4	1.4	1.4	1.3	1.4	1.4	0.0	0.0
CaO	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.3
ZrO_2	0.2	0.3	0.2	0.3	0.3	0.2	0.3	0.3	65.1	61.5
Total	98.3	98.0	98.2	97.9	98.0	98.3	98.0	98.1	95.8	93.3

Table 2b. Mineral chemistry (average) of ilmenite and garnet from the Akwatia sediments

	Ilmenite								Garnet					
	ASA122 N=57	KV143 N=573	OH11 N=51	AKP1 N=310	OTP3 N=15	ANP4 N=77	PNP6 N=409	AYP7 N=30	ASA122 N=1	OH11 N=3	AKP1 N=3	OTP3 N=4	ANP4 N=16	PNP6 N=40
TiO_2	54.6	55.2	51.1	51.3	48.1	50.6	50.1	56.1	0.2	0.1	0.4	0.7	0.6	1.8
Fe_2O_3	34.2	33.5	35.9	35.6	36.4	37.4	36.1	33.7	27.5	33.0	27.0	46.6	42.7	28.4
MnO	2.2	0.9	1.0	1.0	1.0	2.0	1.8	1.2	5.4	2.6	0.1	0.1	0.1	0.1
Cr_2O_3	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3
SiO_2	5.5	6.4	8.1	7.4	9.1	5.5	7.1	4.8	37.8	37.0	42.3	32.6	35.0	41.0
Al_2O_3	1.3	1.6	2.0	2.1	2.6	1.5	2.2	1.9	19.7	19.3	23.6	17.6	18.5	22.3
MgO	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	2.0	2.4	1.9	0.0	0.1	2.1
CaO	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	5.2	3.1	0.5	0.1	0.1	0.6
ZrO_2	0.2	0.2	0.2	0.3	0.3	0.4	0.3	0.3	0.0	0.1	0.2	0.0	0.3	0.3
Total	98.4	98.3	98.7	98.2	97.9	97.8	97.9	98.4	97.9	97.7	96.3	98.0	97.7	96.9

(Kaminsky et al., 1996). Rutile was found in appreciable amounts in two of the steam sediment samples (Table 1). It is, however, absent in most of the analysed samples. It is a mineral characteristic of metamorphic schists and phyllites. The rutile grains present in the samples elongated, ellipsoidal and well-rounded. It occurs in shades of red and brown.

V. Provenance

The main mineralogical components of (unweathered) kimberlites are pyroxene, garnet, olivine and phlogopite. Important accessory minerals are spinel, ilmenite, perovskite, apatite and diamond. None of these heavy minerals were observed in appreciable amounts in the analyzed samples. The heavy mineral assemblages of the analyzed samples are dominated by only few stable minerals species (i.e., ilmenite, staurolite, and magnetite). The absence of unstable heavy minerals in the heavy fraction may be ascribed to one of the following: (a) source area lithology; viz. low-grade metamorphic terrains, carbonate rocks, polycyclic sediments – none of which contains significant proportions of unstable minerals, or (b) pre-depositional loss, viz. intense chemical weathering in catchment regions, low relief, slow depositional rate, corrosive groundwater – any of these factors could lead to the breakdown of unstable minerals before sedimentation takes place. However, it is unlikely that the original (pre-diagenesis) heavy mineral assemblage of the Akwatia sediments included appreciable amounts of the diamond indicator minerals garnet, apatite and spinel because these minerals are considered to be stable in the generalized order of chemical stability of heavy minerals (Pettijohn et al.,

Table 2c. Mineral chemistry (average) of magnetite and Ti-magnetite from the Akwatia sediments

| | Magnetite | | | | | | Ti Magnetite | | | | | | |
| | ASA122 | KV143 | AKP1 | OTP3 | ANP4 | PNP6 | ASA122 | KV143 | OH11 | AKP1 | OTP3 | ANP4 | PNP6 |
	N=1	N=74	N=120	N=585	N=1047	N=330	N=3	N=25	N=3	N=117	N=4	N=62	N=201
TiO_2	0.6	3.1	0.5	0.3	0.4	0.7	37.2	41.5	40.0	39.2	39.5	39.9	38.8
Fe_2O_3	70.3	66.3	61.6	63.5	63.7	61.0	33.2	33.2	26.5	35.6	36.8	37.4	34.7
MnO	0.3	2.2	0.2	0.2	0.2	0.3	1.8	0.7	1.2	0.8	0.7	1.6	1.6
Cr_2O_3	0.3	1.3	0.3	0.7	0.5	0.3	0.2	0.1	0.0	0.2	0.2	0.2	0.1
SiO_2	14.0	9.7	17.0	15.6	15.3	19.1	21.2	20.7	27.8	16.7	18.3	12.5	17.8
Al_2O_3	11.7	12.5	16.9	16.6	16.2	15.1	2.7	1.8	1.7	4.4	2.0	3.7	3.8
MgO	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.0	0.2	0.2	0.4	0.2
CaO	0.3	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2
ZrO_2	0.4	0.3	0.5	0.4	0.4	0.5	0.5	0.3	0.5	0.4	0.2	0.5	0.3
Total	98.1	95.8	97.4	97.5	97.1	97.3	97.1	98.6	97.9	97.6	98.1	96.4	97.5

Table 2d. Mineral chemistry (average) of leucoxene and rutile from the Akwatia sediments

| | Leucoxene | | | | | Rutile | | | | |
| | KV143 | AKP1 | ANP4 | PNP6 | AYP7 | ASA122 | KV143 | AKP1 | OTP3 | PNP6 |
	N=24	N=1	N=4	N=1	N=3	N=13	N=27	N=1	N=4	N=1
TiO_2	81.8	74.6	73.0	69.8	66.9	88.6	89.1	90.7	92.2	88.7
Fe_2O_3	8.3	11.9	2.7	10.3	0.4	3.5	0.9	2.5	1.3	2.5
MnO	0.1	0.5	0.1	0.5	0.4	0.2	0.3	0.1	0.1	0.1
Cr_2O_3	0.7	0.5	0.5	0.0	0.0	0.5	0.6	0.4	0.2	0.6
SiO_2	4.6	6.4	18.0	12.0	28.4	3.5	5.5	2.6	1.4	4.1
Al_2O_3	1.9	3.2	2.6	3.8	1.4	1.4	1.0	1.6	0.9	1.3
MgO	0.3	0.4	0.3	0.1	0.2	0.6	0.4	0.1	0.1	0.4
CaO	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.2	0.3
ZrO_2	0.3	0.2	0.4	0.3	0.4	0.1	0.2	0.3	0.7	0.3
Total	98.2	97.8	97.7	96.9	98.3	98.5	98.2	98.4	97.1	98.3

1973). Moreover, these minerals (i.e., garnet, apatite and spinel) are considered to be more stable than staurolite under deep burial and saline or alkaline pore fluids (Morton, 1985; Mange and Maurer, 1992). However, staurolite appears to be more stable than spinel, apatite and garnet under acid leaching (Morton, 1985).

Varietal studies of heavy minerals may be of greater importance in provenance studies than those that take the entire heavy mineral assemblage into consideration because focusing on one particular mineral or mineral group helps to minimize the effects of the hydraulic factor and other (e.g., diagenetic) factors acting to modify the members of the original heavy mineral suite (Mange and Maurer, 1992). One of the best known applications of varietal studies in diamond exploration is the use of chemical compositions of resistate indicator minerals (RIMs). Chemical signatures of RIMs such as spinel, garnet and ilmenite in sediments can be used to infer

whether they were derived from kimberlites and lamproites.

The main criterion for distinguishing ilmenite from kimberlites from those from other environments is the MgO (> 10%), FeO (< 30%), Cr (> 0.5%) and NiO (> 0.06%) contents. The ilmenites from the analyzed samples have the following contents: MgO < 0.5%, FeO > 30%, and Cr < 0.5 suggesting that they are unlikely to be derived from kimberlites. Basu and Molinaroli (1991) have indicated that ilmenite grains with TiO_2 contents between 50 and 60% are more prevalent in metamorphic rocks although their occurrence in igneous rocks is by no means rare. They indicated that TiO_2 contents of ilmenite in igneous rocks mostly range from 40 to 50 wt %. Therefore, the high TiO_2 content (average, 52 wt %) of the Akwatia ilmenites (Table 2b) suggests their derivation from metamorphic rocks. In metamorphic rocks, ilmenite is

commonly found in those with pelitic and mafic compositions and particularly in those of the granulite facies; ilmenite is not present in metabasites formed under the conditions below the mid-greenschist facies (Asiedu et al., 2000).

Garnet occurs widely in potential source rocks and its compositions are somewhat controlled by paragenesis, although there exist some overlaps among garnets occurring in rocks of different paragenesis. Garnets from kimberlites are pyrope in composition with high chromium content (Cr_2O_3, 1 – 4%). The Akwatia garnets are almandine in composition (Table 2b) and therefore are unlikely to have been derived from a kimberlitic source. Almandine is typical of garnetiferous schists and gneisses, although it also occurs in some calc-alkaline granites and rhyolites (Takeuchi, 1994). The almandine garnets of the Akwatia sediments may have been derived from schists resulting fro regional metamorphism of argillaceous sediments, although their derivation granites cannot be discounted.

VI. Conclusion

Heavy mineral analysis on the medium- to fine-sand size alluvial sediments from the Birim diamondiferous field, Ghana permits the following interpretations:

(1) The heavy minerals suite is essentially composed of staurolite, ilmenite and magnetite in varying proportions with trace amounts of rutile, leucoxene, garnet and zircon. This heavy mineral assemblage is similar to that observed in coarser sand fractions (Kaminsky et al., 1996).

(2) The heavy mineral composition directly reflects the composition of the metamorphic basement rocks developed in the region, i.e., phyllites and schists.

(3) Diamond indicator minerals are absent in the heavy mineral fraction. The absence of indicator minerals is not due to intense chemical weathering and/or diagenesis but is most likely due to their not occurring in the area at all, because these minerals (i.e., apatite, spinel, and garnet) have similar chemical stability as staurolite which dominates the heavy fractions in most of the samples. In addition, the ilmenite and garnet grains present in the Akwatia sediments have chemical compositions unlike those observed in kimberlites.

Acknowledgement

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Appendix 1. Summary of logged pits for the Akwatia sediments

Sample No.	Coordinates		Layer thickness (in meters)	
	Longitude	Latitude	Overburden	Gravel
OTP3	05° 55' 14.3" N	000° 48' 44.0" W	1.75	0.8
AKP1	05° 55' 40.6" N	000° 46' 28.4" W	1.09	0.75
ANP4	05° 56' 41.4" N	000° 49' 57.60" W	0.55	0.47
PNP6	05° 55' 39.3" N	000° 47' 38.1" W	0.71	1.45
AYP7	05° 54' 33.2" N	000° 46' 28.6" W	0.53	0.72