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Preserved Sm-Nd Isotopic Composition as Useful Provenance Indicators in Neoproterozoic Sandstones in the Voltaian Basin, Ghana

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ABSTRACT

The provenance of sandstones derived from the Lower Voltaian Kwahu-Morago Group and the Middle Voltaian Oti-Pendjari Group of the Neoproterozoic Voltaian Basin are discriminated by their Sm-Nd Isotopic compositions. Plots from the Sm-Nd data suggested provenance of the Kwahu-Morago Group to be from the Birimian metasediments and associated "basin type" granitoids. The Sm-Nd studies have further revealed an average T_{DM} model age of whole rock samples in the Kwahu-Morago Group to be 2.2 Ga which shows that this portion of the Voltaian Supergroup represents eroded remnants of "basin type" granitoids. Sm-Nd data from the Oti-Pendjari Group suggested provenance from the Birimian volcanic rocks and probably with contribution from the Pan African rocks. Its average T_{DM} model age of whole rock samples was 2.0 Ga, which generally falls in the range of the model ages for the basement Birimian volcanic rocks as well as the model ages for the granitoid rocks and thus suggests the major source rock of the Oti-Pendjari Group as coming from the volcanic belts. The model ages for both groups seem to indicate clastic supply from an early Proterozoic crustal provenance. This study shows that whole rock isotopic analyses can also be complementary in providing an insight into the origin and development of sedimentary successions.

Keywords: Isotope; Model Age; Provenance; Sandstone; Voltaian Basin

1. Introduction

Sm-Nd model ages provide a good basis for determining the average crustal residence age of clastic sediments [1]. One of the strengths of the Sm-Nd model age method, as applied to whole-rock systems, is that it provides the opportunity to see back through erosion, sedimentation, high-grade metamorphism and even crustal melting events which may reset other dating tools [2].

Obtaining direct whole-rock age constraints on the source region is a helpful tool. The sediments of the Voltaian Basin in Ghana is partly postulated to have probably been derived from the surrounding crystalline Birimian rocks [3,4]. To test this hypothesis and also deal with the relatively complex situation posed by the high compositional maturity [4,5] of the Voltaian sandstones, we conducted Sm-Nd isotope analyses on selected samples and used the data to evaluate the possible provenance of the sandstones.

2. Geological Setting and Study Area

The Voltaian Basin [6-10] is among the smaller of a series of depositional basins developed on the West African craton (**Figure 1**). It is ~5 km thick succession of Neoproterozoic to Lower Palaeozoic (?) sandstones and mudstones with subordinate proportions of limestone, which occupies a surface area of ~115,000 km^2 in Ghana [3]. The basement rocks of the Neoproterozoic to early Cambrian Voltaian Basin are the easternmost portion of Paleoproterozoic rocks of the West African craton. Other surrounding rocks of the Voltaian Basin are the Buem Formation, the Togo Formation, and the Benin-Nigeria Province on the east.

The study area, bounded by 6˚30'N and 6˚45'N latitude and 0˚30'W and 0˚45'W longitude, is located in the southeastern part of the Voltaian Basin (**Figure 2**). Two sandstone groups outcrop over most of the area (**Figure 3**). There is completely no exposed section through the Voltaian Supergroup due to deep weathering and low topographic relief. Correlations within the Supergroup and the groups of the area within it are therefore difficult.

Two divisions were identified in the present work; the Lower Voltaian Kwahu-Morago Group (correlative to Kwahu Sandstone Member of Anani, [4]) and the Middle Voltaian Oti-Pendjari Group. The former corresponds to

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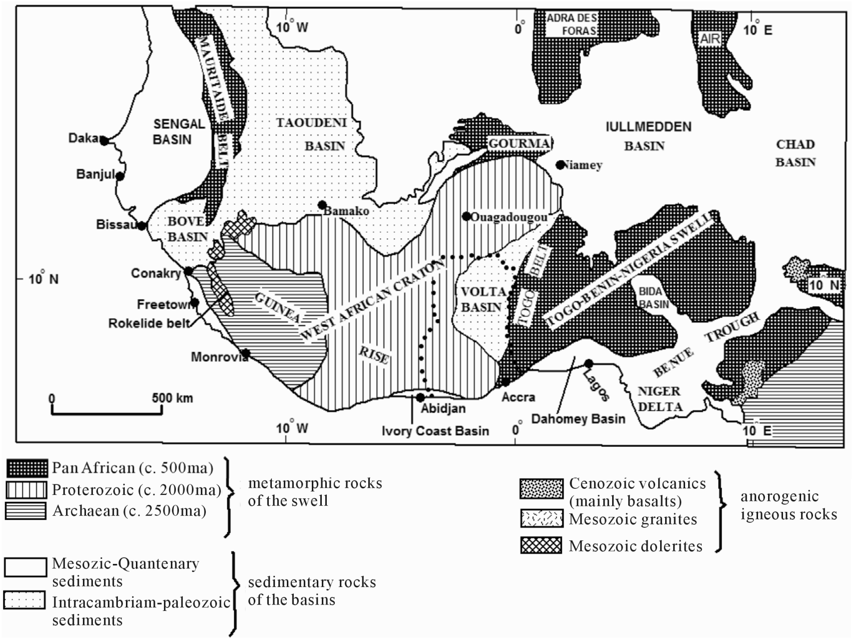


Figure 1. Main geological units of West Africa showing the Voltaian Basin (After Wright *et al.* 1985).

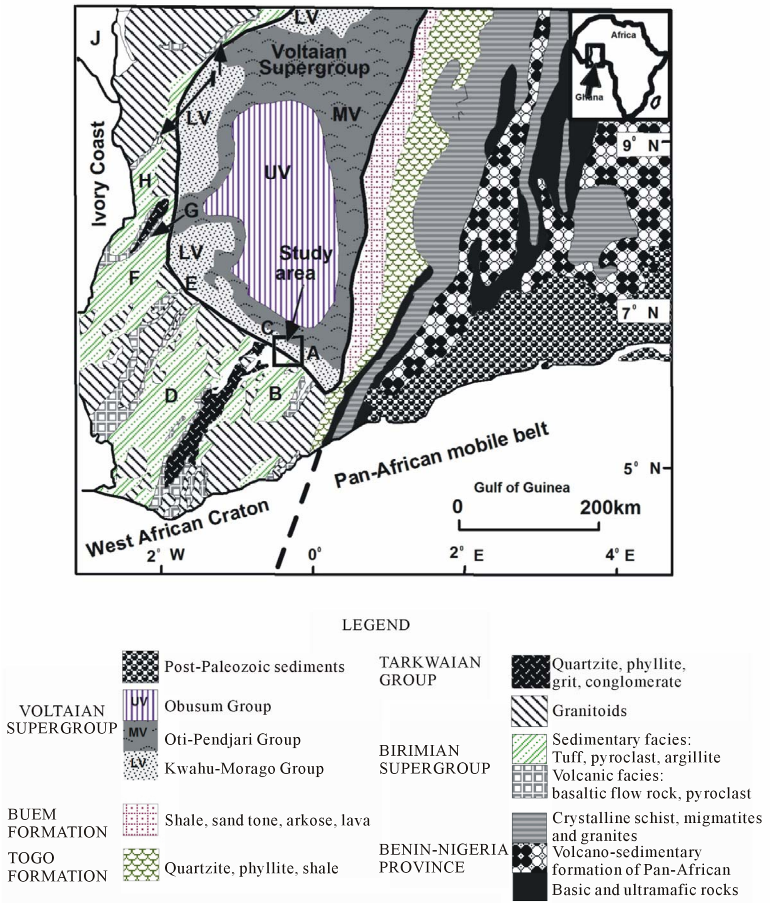


Figure 2. Generalized geological map of the eastern section of West African Craton (Modified after Ako *et al.*, 1985 and partly modified). Belts and basins in the Birimian are defined after Leube *et al.* (1990) as follows: A—Kibi-Winneba belt; B—Cape Coast basin; C—Ashanti belt; D—Kumasi basin; E—Sefwi belt; F—Sunyani basin; G—Bui belt; H—Maluwe basin; I— Bole Navrongo belt; J—Lawra belt.

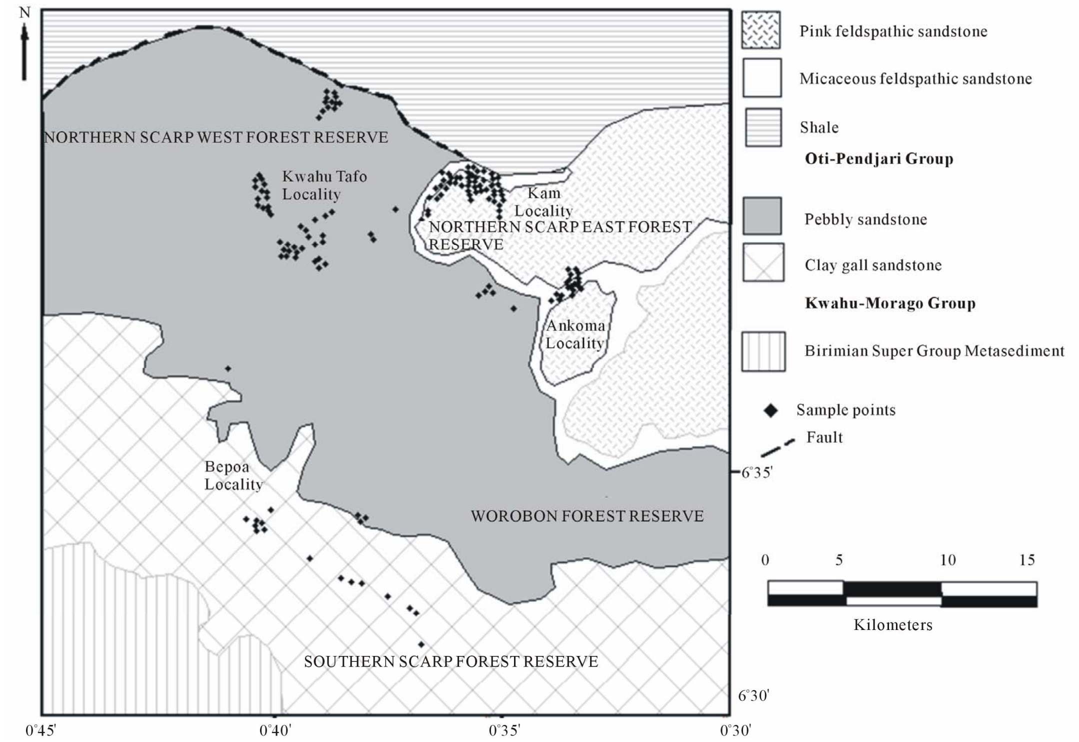


Figure 3. Geological map of the study area in the southeastern part of the Voltaian Basin.

the Lower Voltaian Formation of Kete [11] and Saunders, [12] and the latter also corresponds to the Anyaboni Formation of Saunders, [12] and correlative to the Upper Voltaian Formation of Kete [11].

3. Sample Preparations and Analytical Procedures

Fresh sandstone samples were selected from both the Kwahu-Morago Group and the Oti-Pendjari Group. Twelve samples were selected for analysis comprising seven from the Kwahu-Morago Group and five from the Oti-Pendjari Group. Each sample of the size of about a "cigarette packet" was thoroughly washed clean with third (3rd) grade water and then dried completely. This was followed by a systematic crushing of each rock using a clean hammer, stainless mortar and pestles to reduce each rock into tiny chips and finally a vibrating sample mill (T1-100) was used to reduce each sample into a smooth powder. About 100 - 200 mg of each rock powder was completely dissolved in a mixture of HF, $HClO_4$ and HCL with 40%, 70% and 30% concentrations respectively, using a teflon beaker. All sample solutions were placed in an oven of 100˚C for 7 days. By this method, the sample is completely decomposed. Each sample was duplicated by the same procedure described above, such that two weighed aliquots of each sample was obtained. However, one fraction of each sample was "spiked" with an enriched isotope for isotope dilution analysis according to the procedure described in Dickin, [2], and the other left "unspiked" for accurate isotope ratio analysis.

Sm and Nd were extracted from the samples after the procedure of Kagami *et al*. [13]. This is based on the use of ion exchange column for the REE separation, followed by chromatography of reverse phase in order to separate Sm and Nd. The isotopic ratios were measured with a thermal ionization mass spectrometer Finigan/MAT 261. Nd isotopic ratios were carefully measured several times for each sample. Ratios of $^{143}Nd/^{144}Nd$ errors quoted at the lowest 2σ values for several runs are shown in Table 1. $^{143}Nd/^{144}Nd$ are reported with respect to JNdi-1 (Geological Survey of Japan (GSJ) standard) = 0.512116, which corresponds to 0.511858 of La Jolla [14]. Sm and Nd concentrations were determined by isotope dilution with a mixed ^{149}Sm and ^{145}Nd spike.

T_{DM}(depleted mantle) model ages are calculated by substituting the appropriate DM (depleted mantle) values in place of $(^{143}Nd/^{144}Nd)_{CHUR}$ and $(^{147}Sm/^{144}Nd)_{CHUR}$ in the following equation;

$$T_{CHUR} = \frac{1}{\lambda} \ln\left[\frac{\left(^{143}Nd/^{144}Nd\right)_{\text{sample, today}} - \left(^{143}Nd/^{144}Nd\right)_{\text{CHUR,today}}}{\left(^{147}Sm/^{144}Nd\right)_{\text{sample, today}} - \left(^{147}Sm/^{144}Nd\right)_{\text{CHUR,today}}} + 1\right]$$

(where CHUR means the CHondritic Uniform Reservoir).

T_{CHUR} equation is quoted in Rollinson [15]. Parameters used in calculating T_{DM} are those of Goldstein *et al*., [16]; $(^{143}Nd/^{144}Nd)_{DM,today} = 0.51316$, $(^{147}Sm/^{144}Nd)_{DM,today} = 0.215$ and the decay constant $l = 6.54 \times 10^{-12yr-1}$.

4. Results and Discussion

The Sm and Nd concentrations and the Nd isotopic compositions of the Kwahu-Morago Group and the Oti-Pendjari Group are listed in **Table 1**. Twelve samples were analysed however, four samples (two from Kwahu-Morago and two from Oti-Pendjari groups) had extremely high 2σ values or in other cases the Sm or Nd concentrations were undetectable and therefore were omitted in the list.

Kwahu-Morago Group and Oti-Pendjari Group

The Sm-Nd isotopic analyses and model ages determined for both the Kwahu-Morago and Oti-Pendjari Groups have been used in evaluating the source of the sandstones. A plot of the fractionation factor $f^{Sm/Nd}$ against $\varepsilon_{Nd}(0)$ indicates an old upper crust source for both groups (**Figure 4(a)**) whiles a $\varepsilon_{Nd}(0)$ versus $^{147}Sm/^{114}Nd$ plot underscores a Birimian metasediment/granitoids and Birimian metavolcanic source rocks for both groups (**Figure 4(b)**). Sm and Nd contents of the Kwahu-Morago Group range between 0.6 to1.2 ppm and 3.2 to 6.1 ppm respectively, and tend to be much lower than those of the Oti-Pendjari Group which has high Sm and Nd contents ranging between 2.4 to 6.7 ppm and 11.8 to 34.7 ppm respectively. Both groups however, show similar $^{147}Sm/^{144}Nd$ ratios (**Table 1**). The low Sm and Nd contents of the Kwahu-Morago Group seem to reflect some relationship to its highly mineralogical matured coarse-to medium grained contents as noted inAnani, [4] and referred to as the Kwahu sandstone member. The Oti-Pendjari Group, described by Anani, [4] as the Anyaboni sandstone member is characterized by relatively higher Sm and Nd contents which is probably due to its fine-to medium grained arkosic and mafic contents. Both groups have an appreciable amount of accessory minerals. The most common assemblages in both cases are zircon, tourmaline and rutile.

From **Table 1**, calculated T_{DM} model ages for the Kwahu-Morago Group ranges from 2.1 - 2.3 Ga. These are quite compatible to the model ages indicated by Kalsbeek and Frei [17]. This may therefore suggest that the Kwahu-Morago group is possibly derived from a Proterozoic crustal source rock (**Figure 4(a)**). **Figure 4(b)** further shows a Birimian metasediment and granitoid mixed source region for the Kwahu-Morago Group.

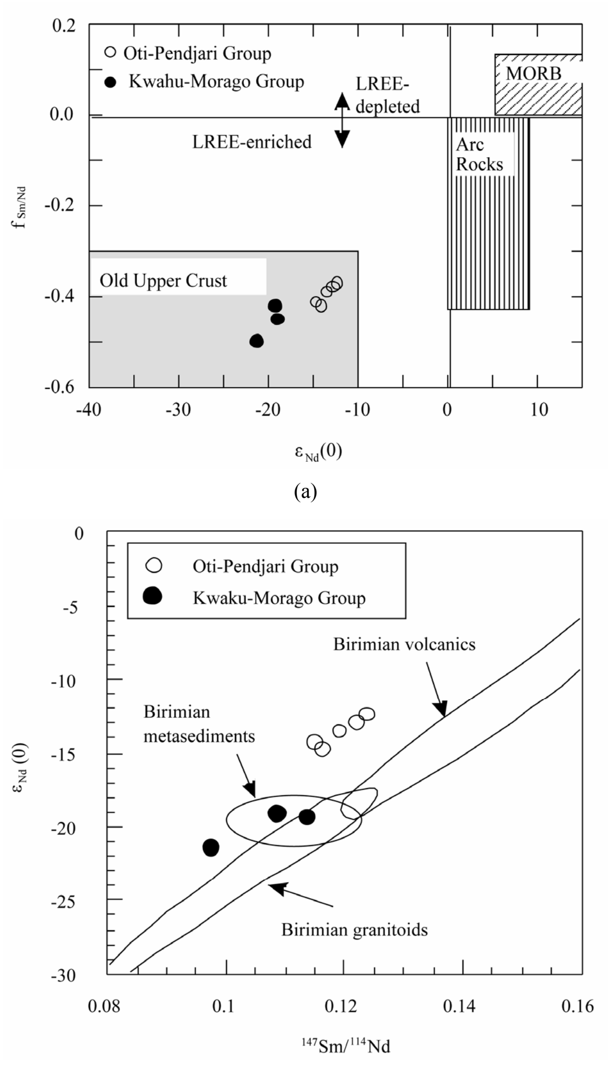
Again from **Table 1**, the Oti-Pendjari Group displays T_{DM} model ages that range from ~1.9 to 2.0 Ga. These seem to straddle around those of Kalsbeek and Frei [17]. The disparity in the T_{DM}, displayed by the Oti-Pendjari Group may be due to a mix of source rock input, both from the Birimian and the Pan-African rocks with age around 2.2 Ma and ~600 Ma respectively [3]. In **Figure 4(b)**, all of the points from Oti-Pendjari Group plot just outside of the region of the Birimian volcanic rocks. This may be due to the possible addition of source rock input from the Pan African younger rocks to the Birimian older rocks, thus confirming the findings of Kalsbeek *et al*., [3].

Dabart *et al*., [18] however, pointed out that in mature sediments, the presence of heavy minerals is liable to influence the isotopic signature. As a result, isotopic heterogeneities can arise between fine- and coarse-grained facies developed in sedimentary sequences. These heterogeneities do not reflect changes in the source areas, but rather are linked to sedimentary processes, such as

Table 1. Isotopic data.

Sample No.	Deposition/Strat. Age (Ga)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd} (0)	ε_{Nd} (t)	$f^{Sm/Nd}$	T_{DM} (Ga)
Oti-Pendjari Sandstone (depositional age (t) = 0.6 Ga)									
CD 077	0.6	6.678	34.705	0.1163	0.511885 ± 14	−14.69	−8.54	−0.41	1.96
CD 110	0.6	4.715	24.811	0.1149	0.511907 ± 14	−14.26	−8.00	−0.42	1.9
CD 106	0.6	5.779	28.225	0.1238	0.512004 ± 14	−12.37	−6.79	−0.37	1.93
CD 107	0.6	5.265	26.719	0.1191	0.511947 ± 14	−13.48	−7.54	−0.39	1.92
CD 073	0.6	2.393	11.846	0.1221	0.511977 ± 27	−12.89	−7.18	−0.38	1.93
Kwahu-Morago Sandstone (depositional age (t) = 1.0 Ga)									
CD 012	1.0	0.85	5.276	0.0974	0.511541 ± 14	−21.4	−8.71	−0.5	2.09
CD 051	1.0	0.582	3.242	0.1086	0.511660 ± 14	−19.08	−7.82	−0.45	2.14
CD 041	1.0	1.152	6.123	0.1137	0.511649 ± 14	−19.29	−8.69	−0.42	2.26

Analysed at the Graduate School of Science and Technology, Niigata University, Japan.



(a)

(b)

Figure 4. Diagrams illustrating the Sm-Nd isotopic compositions of sandstones from the Kwahu-Morago and the Oti-Pendjari Groups.

grain-size segregation due to hydrodynamic processes. The model ages for both groups seem to indicate clastic-supply from an early Proterozoic crustal provenance. Sm-Nd ratios of the Kwahu-Morago Group samples are all within the range of values expected for detritus derived from Proterozoic continental provenance. The Sm-Nd studies have also revealed an average T_{DM} model age of whole rock samples in the Kwahu-Morago Group to be 2.2 Ga (**Table 1**); it is shown in (**Figure 4**) that this portion of the Voltaian Supergroup represents eroded remnants of both the metasediments and related "basin type" granitoids.

The Sm-Nd ratios of the fine grained Oti-Pendjari Group seem to vary over only a narrow range (**Table 1**). The narrow range of Sm-Nd ratios is typical of fine-grained sedimentary material and is usually interpreted as the result of efficient mixing of the sedimentary material during transport and deposition [19]. The Sm-Nd studies also show an average T_{DM} model age of whole rock samples in the Oti-Pendjari Group to be 2.0 Ga (**Table 1**). This obviously confirms a crustal provenance source of the Oti-Pendjari Group. **Figure 4(b)** suggests crustal supply from the Birimian volcanic rocks and probably some from the Pan African rocks.

5. Conclusion

The overall Sm and Nd isotopic data obtained on the Voltaian sandstones from this study shows that the possible sources of the Kwahu-Morago Group are the Birimian meta-sediments and its associated "basin type" granitoids. The Oti-Pendjari Group received crustal supply from the Birimian volcanic rocks and some contribution from the Pan African rocks. Thus Sm-Nd isotopic compositions are useful indicators for determining the provenance of silici clastic sedimentary rocks.

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