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PALAEOMAGNETISM OF NEOPROTEROZOIC FORMATIONS IN THE VOLTA BASIN

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ABSTRACT

The Volta basin lies on the southern part of the West African craton, more precisely on the Leo (or Man) craton. The Dahomeyides chain is thrust onto its eastern fringe. The Volta basin is filled with Neoproterozoic to Cambro-Ordovician sediments. From bottom to top they are: the Boumbouaka Supergroup made of sandstone, micro-conglomerates, siltstones, shales and limestone lenses; the Pendjari or Oti Supergroup composed of a triad made of a diamictite, a cap carbonate and a silexitic complex that passes upwards to siltstones and shales; the Tamale Supergroup representing the molasse of the Dahomeyides chain. The three supergroups were sampled for palaeomagnetic study. The magnetic mineralogical study shows magnetite and hematite as carriers of magnetization. Mean palaeomagnetic directions are calculated on the high temperature components and yield a mean palaeopole, Plon=349.3°, Plat=44.1°, dp=26.6°, dm=33.7°, for formations with ages between 993±62 Ma and 660±9 Ma and a mean palaeopole, Plon=119.5°, Plat=71.2°, dp=19.8°, dm=38.1°, for sites dated between 635 Ma and 600 Ma which are, respectively, the ages of the marinoan glaciations in Volta basin and the Pan-African deformation, responsible of the Dahomeyides chain. The palaeolatitudes of the older formations about 44.9° S and that of the younger sites about 9.1° S show a migration of the West African craton from medium to low latitude during the Neoproterozoic, in conformity with the Snowball Earth hypothesis.

KEYWORDS: West African craton, Volta basin, Virtual Geomagnetic Pole, Palaeolatitude, Snowball Earth.

INTRODUCTION

The Volta basin is located in the southern part of the West African craton and stretches between longitudes 2° W and 3° E and latitudes 6 and 13° N (Fig. I). Its monoclinal western part grades eastwards to the folded external units of the Dahomeyides chain. The lithostratigraphy of the basin includes Neoproterozoic to Cambro-Ordivician sediments represented from bottom to top by the Boumbouaka, Oti and Tamale Supergroups which are separated by cartographic and/or erosional unconformities (Affaton, 1990). The base of the Middle Supergroup consists of a triad made of glaciogenic formations, cap carbonate and silexite that define a lithostratigraphic marker horizon in many basins on the West African craton. The glaciogenic formation in the Volta basin is considered the equivalent of that Jbeliat Group described in the Taoudeni basin situated in the north and attributed to the Marinoan glaciation (Deynoux et al., 2006).

In the Snowball Earth hypothesis (Kirschvink, 1992), the Sturtian and Marinoan glaciogenic formations are considered to be formed at low latitude (Hoffman et al., 1998). In order to constrain the palaeolatitude of formation of deposits in the Volta basin that include glacial sediments attributed to the Marinoan (Porter et al., 2004; Nedelec et al., 2007), seven sites were sampled for a palaeomagnetic study. Two sites, Boumbouaka 1 and 2 were located in the Boumbouaka Group of the Lower Supergroup. Four sites, Buipe, Koundjouare and Barkoissi 1 and 2 are attached to the triad of the Middle Supergroup. Buipe and Koundjouare belong to the cap carbonate of the glaciogenic formation and Barkoissi 1 and 2 to the horizon overlying the cap carbonate. The Kabalipe site is located in the Tamale Supergroup which constitutes the molasse of the Dahomeyides chain dated at Cambro-Ordovician.

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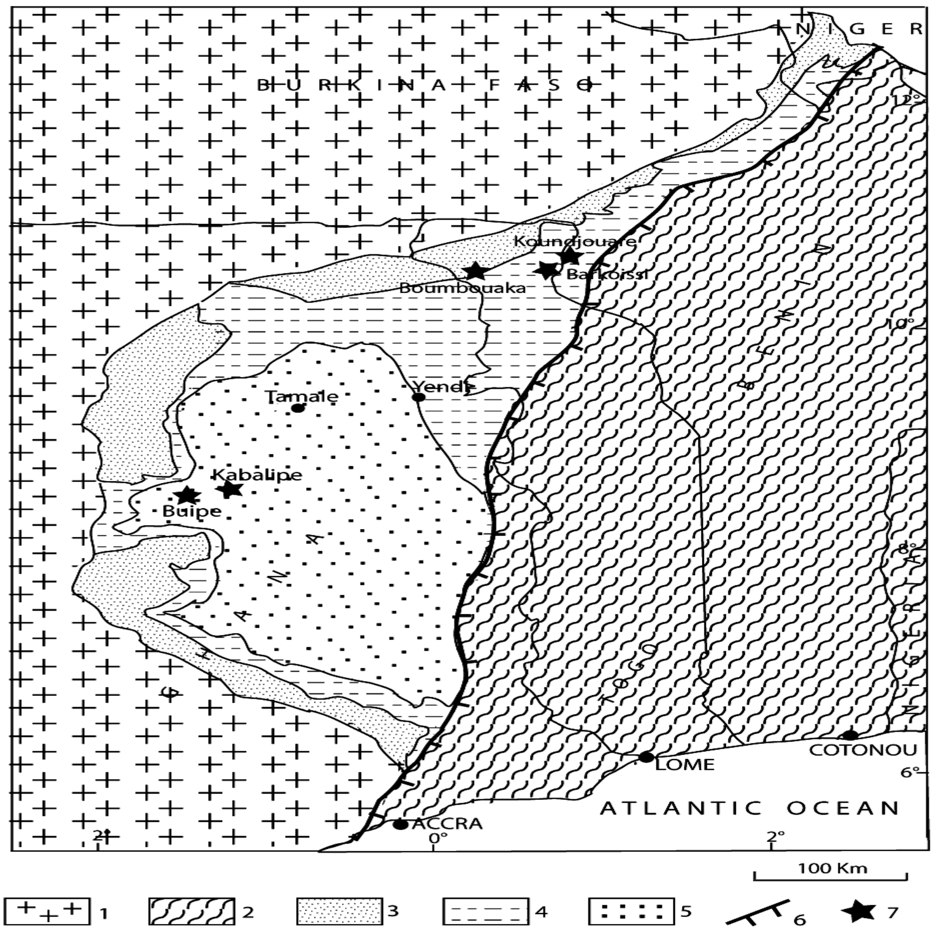

Fig. 1. Geological map of Volta Basin, after Affaton (1990), simplified.
1- Birimian basement; 2- Dahomeyides belt; 3- Boumbouaka Supergroup; 4- Oti Supergroup; 5- Tamale Supergroup; 6- Thrust contact; 7- Location.

GEOLOGY OF THE VOLTA BASIN

Lithostratigraphy

The lithostratigraphy of the Volta basin (Fig. 2) consists of three supergroups separated by unconformities. The Boumbouaka lower Supergroup, about 1000 m thick, starts with the Dapaong Group which is made of sandstone, micro-conglomerates, siltstones and shale. It passes upwards to the Fosse-aux-Lions Group composed of conglomerates, micro-conglomeratic sandstone, shale and siltstones containing limestone lenses. At the upper part, the Mount Bombouaka Group (or Yembouré) is made of feldspathic sandstone, ferruginous sandstone containing silty and /or conglomeratic intercalations, siltstones and more or less ferruginous shale. The Fosse-aux-Lions ferruginous Group is dated by the Rb-Sr method on fine argillaceous fractions at 993±62 Ma (Clauer, 1976). The Pendjari (or Oti or Afram) middle Supergroup, about 2500 to 4000 m thick, rests in cartographic and/or erosional unconformity pro-parte of glacial origin on the Boumbouaka Supergroup or directly on the Eburnean basement. It starts with the Sud-Bamboli Formation composed of glaciogenic sediments and cap carbonate and passes to the Barkoissi Formation made of clayey silexite containing intercalations of shale, siltstones and sometimes limestone. At the top, the Formation is made of siltstones and shales with intercalations of limestone lenses, sandstone or phospharenites and silexite bearing conglomerate. This Formation contains Chuaria Circularis, fossils of Vendian age (Amard and Affaton, 1984). It is dated by the Rb-Sr method on fine illite fraction at 660±9 Ma (Clauer, 1976). The Tamale upper Supergroup, about 500 m thick, rests in angular unconformity on the Pendjari Supergroup. It starts with the Yendi Group made up of conglomerates, shales and siltstones. At the upper part, the Kebia Group is composed of diamictites, polygenic conglomerate and sandstones passing upwards to micaceous sandstones, shales and siltstones then to finely bedded sandstones with intercalations of shales and massive feldspathic sandstones. This supergroup which represents the molasse filling the basin results from the active erosion of the adjacent Dahomeyides chain (Affaton, 1990). It is of Cambro-Ordovician age.

Petrography

The studied specimens included clastic rocks and non clastic rocks (Fig. 3). The clastic rocks of Boumbouaka 1 and 2 are made of fine grained sandstones to siltites (ph. A). Quartz is the dominant mineral. Feldspars and micas are present in very small amount. The quartz and feldspar grains are sub-angular to sub-blunt. The cement is made of sparitic carbonate. It is abundant in some samples which can be classified as sandy carbonates. Grains of iron oxides are frequent. The carbonate rocks described are from the Buipe and Koundjouare display micritic to microsparitic limestone facies which have parallel or locally discordant laminae. These laminae are formed by an alternation of horizons with and without peloids (ph. B). The samples also show horizons (levels) containing needles and stars of epigenized gypsum and also of detrital quartz (ph. C). Keystone-vugs or geodes, empty or infilled with microsparite or sparite, that is sometimes associated with quartz, are present in places (ph. B). Facies with algal mat structures appear in some samples (ph. D). These algal levels can alternate with peloids bearing levels. Lithoclasts and probably bioclasts bearing limestone facies and rare quartz and feldspar clastic grains are present. They are cemented by microsparite or sparite (ph. E and F). The lithoclasts can be micritic or recrystallized into sparite. Fibrous calcite generally, fills fissures observed in some samples. Styloliths are accompanied by iron oxide (ph. F).

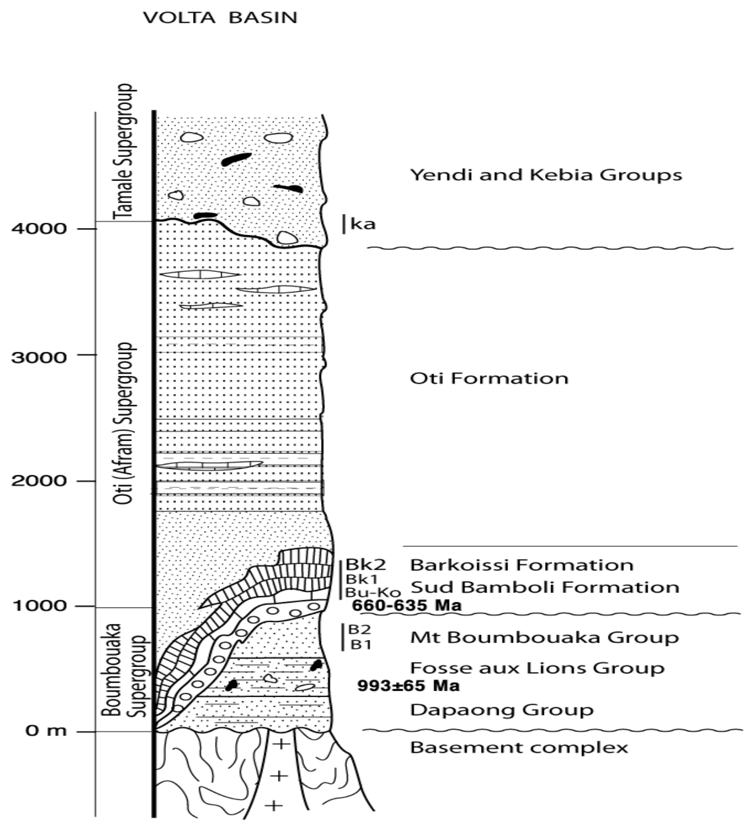

Fig. 2. Simplified lithostratigraphy of Volta basin, after Affaton (1990)
Locations: B1-Boumbouaka 1; B2- Boumbouaka 2; Bu- Buipe; Ko- Koundjouare; BK1- Barkoissi 1; Bk2- Barkoissi 2; Ka- Kabalipe

PALAEOMAGNETISM

Eighty three core samples made of sandstones, carbonates and silexites were taken at 7 sites (Boumbouaka 1 and 2, Buipe, Koundjouare, Barkoissi 1 and 2 and Kabalipe (Fig.1) and processed in the Geophysics and Planetology laboratory at the CEREGE (Aix-en-Provence, France).

Method

The samples were taken in the field using a portable petrol powered drill oriented with a solar or magnetic orienter and were cut in small cylindrical specimens (2.5 cm × 2.3 cm) then stored in a non-magnetic chamber in which the measures of magnetization were taken. Samples were subjected to thermal demagnetization in order to isolate the Characteristic Remanent Magnetization (CRM). The magnetization of the silexite samples from the Barkoissi 1 and 2 sites was measured using a JR5 (Agico) continuous rotation magnetometer. That of the carbonates and sandstones from other sites was done with a SQUID (2G enterprises) cryogenic magnetometer. The directions of the Characteristic Remanent Magnetization (CRM) are determined by principal component analysis (Kirschvink, 1980) after selection of the linear segments on Zijderveld's (1967) orthogonal projection. The mean direction at each site was calculated using Fischer's (1953) statistics. The data were processed using Cogne's (2003) Paleomac 6.1 software.

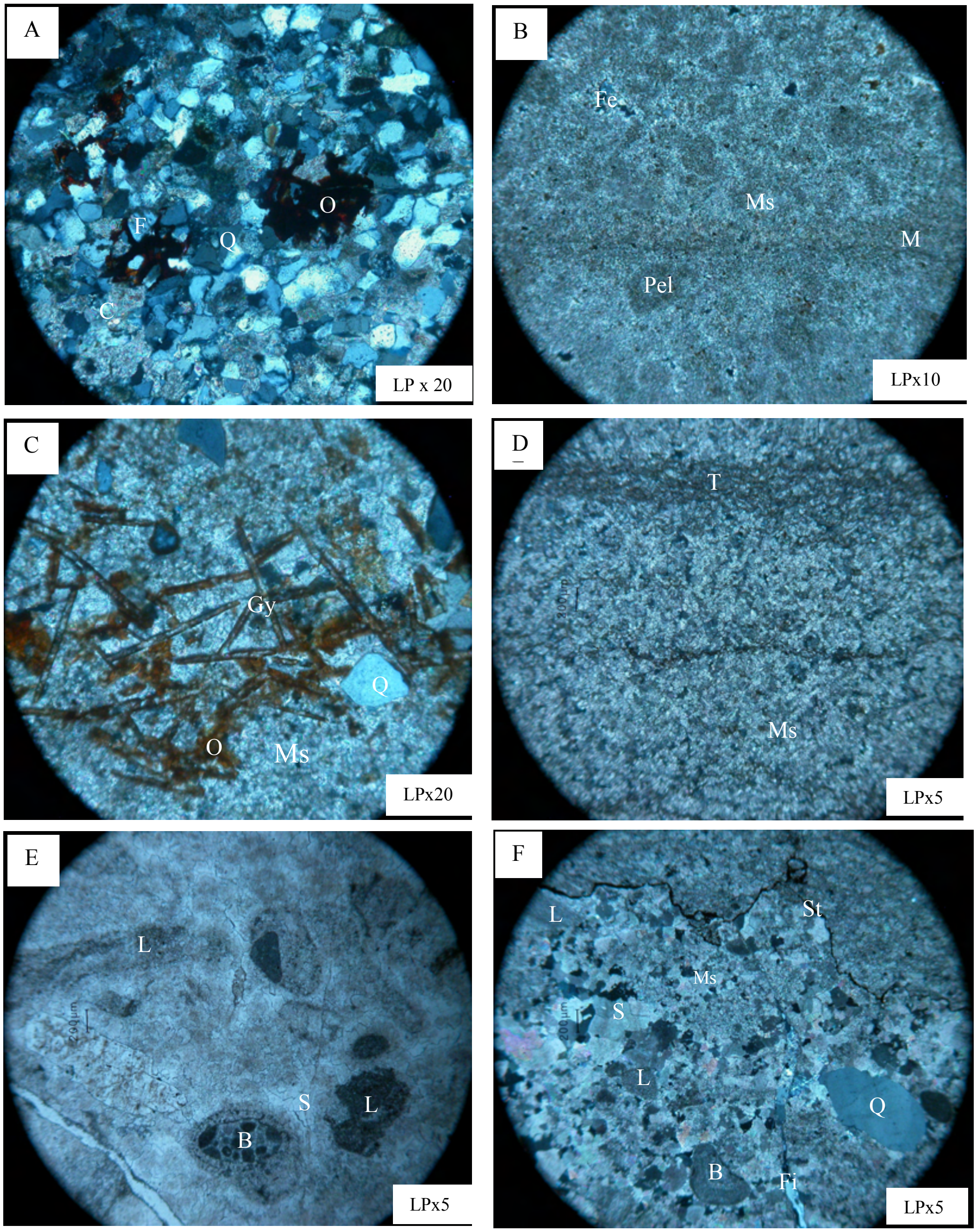

Fig. 3. Optical microscopic observations of Boumbouaka sandstones, Buipe and Koundjouare carbonates.
A: Boumbouaka sandstone; B-D: Buipe carbonate; E and F: Koundjouare carbonate.
Q- quartz; F- feldspar; C-calcite; G- gypsum; O- iron oxide; S- sparite;
Ms- microsparite; M- micrite; Fe- fenestrae; Pe- peloid; T- algal mat; L- lithoclast;
B- bioclast; Fi- fissure.

Three methods were used to determine the mineral carriers of magnetization. Two to three specimens from each site were subjected to thermomagnetic studies usiging an MFK1-MFA susceptibilimeter equipped with a CS3 furnace. The Lowrie's (1990) method was also used with application of fields 3T, 0.4T, and 0.12T respectively to three orthogonal axes of the sample. The acquisition of IRM by the samples was realized using an MMPMQ field pulse magnetizer. Finally, hysteresis cycles were produced using a micromag vibrating sample magnetometer (maximum field 1T).

RESULTS

The samples carry a Natural Remanent Magnetization (NRM) with intensity between 0.4 and 8.2×10^{-3} A/m. The mean at each site is shown in Table I.

Magnetic mineralogy

Thermomagnetism

Nineteen samples, reduced to powder, were processed in argon and heated to temperatures of up to 670° C then cooled to room temperature. The results show a generally weak initial susceptibility signal situated between 0.3 and 14.1^{-10} m^3. The curves obtained are either reversible (Fig. 4a) or irreversible (Fig. 4b). The irreversible curves show an increase in susceptibility between 400° and 500°C during heating and about 580°C during cooling (Fig. 4b). Such an increase in susceptibility has been observed in the Gourma basin (Boudzoumou et al., submitted) and has no influence in the magnetization direction. Magnetite and hematite are indentified by the drop of the susceptibility respectively at 580°C (Fig. 4b) and at 650°C (Fig. 4a).

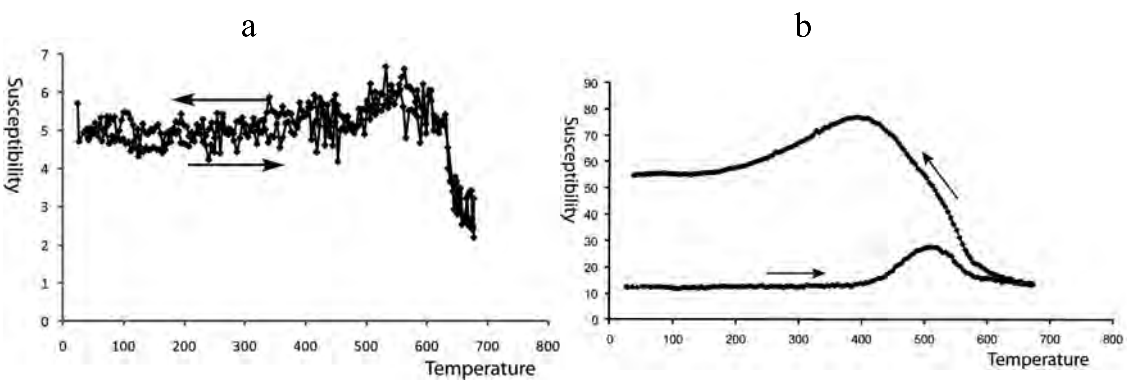

Fig. 4: Susceptibility / temperature curves of the specimens. Susceptibility is in 10^{-3} S.I; Temperature is in degrees Celsius a- Boumbouaka 2-08; b- Koundjouare 7156.

Lowrie's test.

Lowrie's (1990) test is applied to 9 samples. Depending on the sample, the highest intensity is carried by the hard (Fig. 5a, b), the medium (Fig. 5c) and the soft fraction (Fig. 5d). The release temperatures for the hard fraction lie between 650°C and 670°C. Those for the medium fraction are, depending on the sample, situated at 575°C (Fig. 5 c, d) and at 650°C (Fig. 5 a, b). The soft fraction shows a release temperature of 575°C (Fig. 5a-d). These release temperatures lie between 575°C and 670°C and are characteristic of magnetite and hematite minerals respectively.

Hysteresis cycles

The hysteresis cycles were realized on 9 samples subjected to a 1000 mT field. The results reveal saturated and non-saturated magnetic minerals. The curves obtained, corrected for slope, are variable in shape (Fig. 6): (I) A normal shape (Fig. 6a); (2) A wasp shaped size (Fig. 6b) attributed to a bimodal distribution of the hard and soft coercive fractions that may be due to a difference in grain size of the same mineral or to different magnetic minerals (Raposo et al., 2003, 2006; Piper and Darabi, 2005) like magnetite and hematite; (3) The specimens show a largely open shape (Fig. 6c) that characterizes the presence of strong coercivity ferromagnetic grains such as hematite.

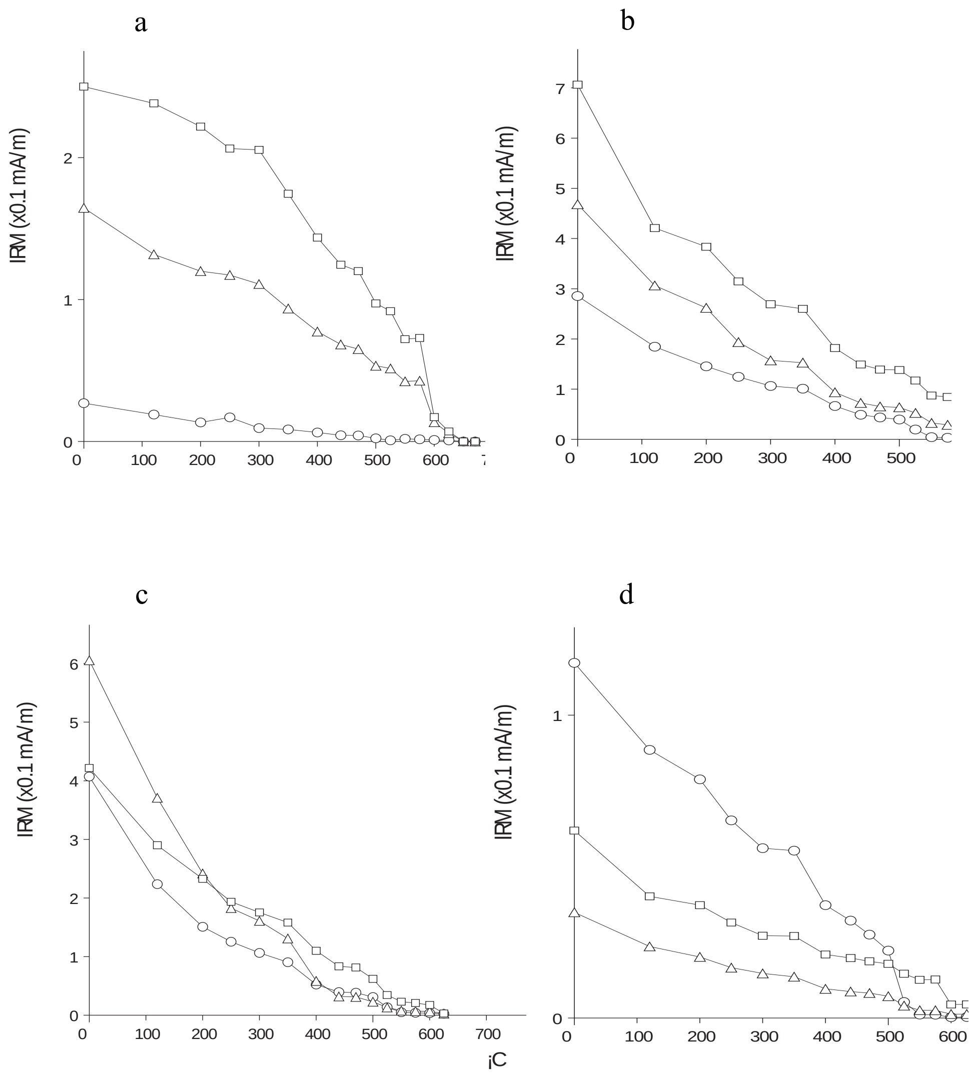

Fig. 5: Example of thermal demagnetization of three axes of isotherm remanent magnetization based on Lowrie (1990) method applied to some specimens.□ : hard fraction; △: medium fraction; ○: soft fraction. (a) Buipe; (b) Boumbouaka 2 ;(c) Boumbouaka 1; (d) Buipe.

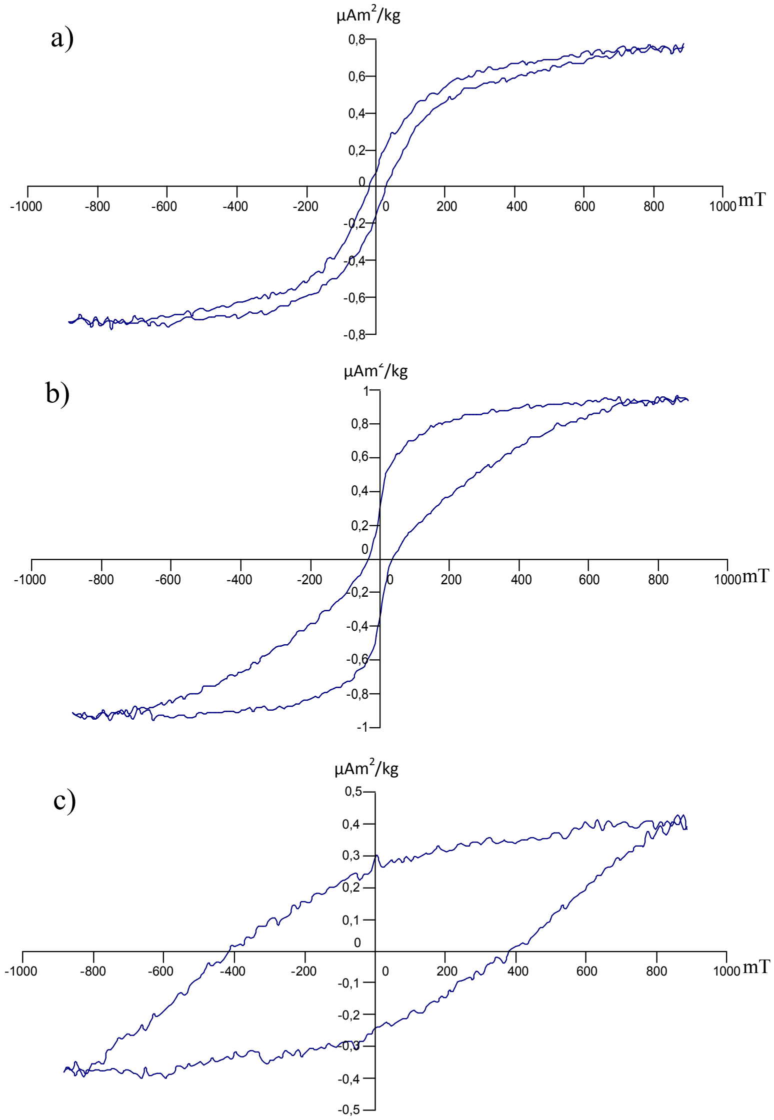

Fig. 6 : Hysteresis curves with dip correction of some specimens of the sites.
(a) Boumbouaka 01-04 ; (b) Barkoissi 01-04 ; (c) Barkoissi 02-01.

PALAEOMAGNETIC DATA

The thermal demagnetization curves indicate one to three principal components, carriers of magnetization. In the samples with one component, the latter is destroyed at temperatures, either of 575°C or of 670°C characteristic of magnetite and hematite respectively (Fig.7a). For the samples with two components (Fig. 7b), the first component is destroyed at 470°C. It is a carrier of secondary magnetization. The second component is destroyed at 575°C or 670°C. In the samples with three components, the first two components are destroyed at 300 and 470°C respectively. The last component is destroyed at 575°C or 670°C.

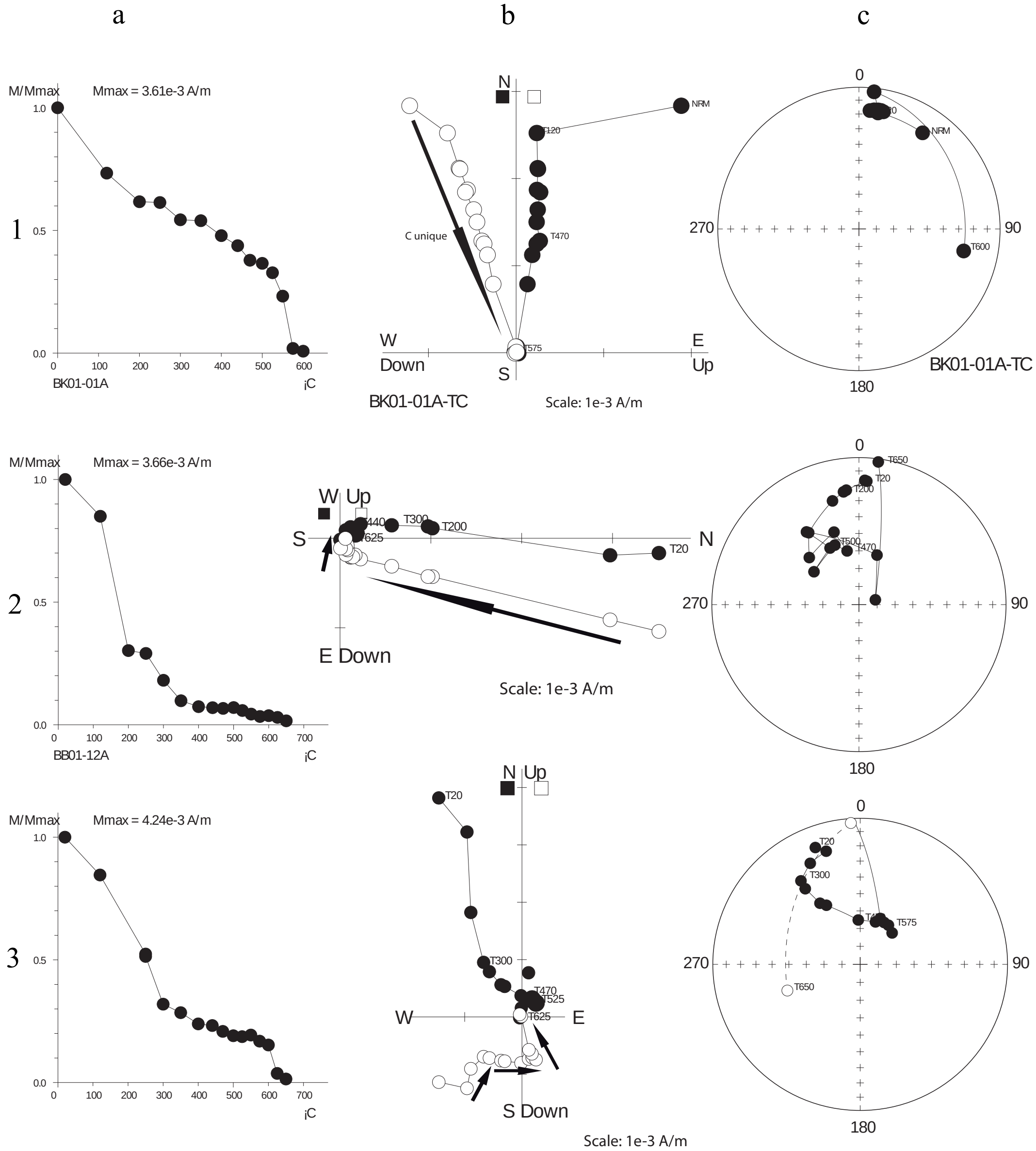

Fig.7. Thermal demagnetization of characteristic samples from Barkoissi 1 and Boumbouaka 1 sites. a) Intensity curves as a function of temperature; b) [Zijderveld's diagrams (The open/ full circles correspond to projections in the lower / upper hemisphere): 1b - one component; 2b- two components; 3b- three components]; c) Stereographic projections of demagnetization data.

INTERPRETATION AND DISCUSSION

Interpretation

The mean direction of the sites are calculated from the high temperature components (500 to 575°C or 600 to 670°C) that are susceptible to carry a primary magnetization. They are listed in Table I and shown (Fig. 8) after dip correction.

The Boumbouaka 1 and 2 sites are attached to the Boumbouaka Group of the Lower Supergroup (Fig. 2) which is dated between 993± 65 Ma, Rb-Sr age from underlying fine shale fractions

Table 1: Mean directions of Volta basin sites.

				Palaeomagnetic directions								Virtual Geomagnetic Poles						
				In situ				After dip correction				In situ		After dip correction				
Sites	N/n	Jr (10^{-3}A/m)	Mx	D	I	K	α_{95}	D	I	K	α_{95}	Lon	Lat	Lon	Lat	dp	dm	Plat
Volta Basin																		
Bb 1	10/14	8.2	m,h	335.2	66.8	12.1	15.4	341.7	67.0	12.9	15.3	337.2	45.9	342.6	47.9	21.0	25.5	49.6
Bb 2	12/16	5.2	m,h	342.7	73.7	88.4	4.6	339.7	77.1	88.4	4.6	355.2	39.9	355.2	39.9	9.8	10.9	59.7
Bu	6/25	0.4	m,h	23.5	-1.6	20.9	15.0	23.8	5.1	18.2	16.1	102.5	65.5	102.5	65.5	8.1	16.1	2.6
Ko	8/12	0.6	m	188.1	20.2	6.6	23.2	188.1	20.2	6.6	23.2	339.0	-67.6	339.0	-67.6	12.8	24.3	10.5
Bk 1	4/9	1.4	m,h	6.0	20.6	21.8	20.1	5.5	16.2	20.4	20.8	111.4	84.2	111.4	84.2	11.0	21.4	8.3
Bk 2	6/7	2.4	m,h	18.3	19.3	25.8	13.4	17.0	17.1	21.3	14.8	94.6	73.2	94.6	73.2	7.9	15.3	8.7

N: number of samples used in Fisher's calculation : n : number samples processed; Jr : natural remanent magnetization; Mx : magnetic minerals (m=magnetite, h=hematite) ; D and I: declination and inclination ; K : precision parameter ; α_{95}: semi-angle of 95% confidence cone ; Lon/ Lat: Longitude/ Latitude of the VGP; dp/dm : semi axes at 95% confidence level ; Plat : palaeolatitude; Bb1: Boumbouaka 1; Bb2: Boumbouaka 2; Bu: Buipe; Ko: Koundjouare; Bk1: Barkoissi1; Bk2: Barkoissi 2;

(Clauer, 1976) and 660 ±9 Ma, Rb-Sr age on illites from shale in the overlying Oti Formation (Clauer, 1976). The Boumbouaka site 1 yields the trend D=341.7°, I=67°, k=12.9, α_{95}=15.3° and the Boumbouaka 2 site, D=352.1°, I=74°, k=48.3, α_{95}=6° (Fig.8a,b). The Buipe and Koundjouare sites are stratigraphic equivalents and form the cap carbonate of the Marinoan diamictite that belongs to the triad at the base of the middle Supergroup (Fig. 2). The mean direction of Buipe is D=23.8°, I=5.1°, k=18.2, α_{95}=16.1°, (Fig. 8c). The average trend of Koundjouare, D=188.1°, I=20.2°, k=6.6, α_{95}=23.2°, (Fig. 8d) is at the antipode of its stratigraphic equivalent Buipe. The Barkoissi 1 and 2 sites are attached to the silexites forming the upper member of the triad. The mean direction of Barkoissi 1, D=5.5°, I=16.2°, k=20.4, α_{95}=20.8°, is close to the current field (Fig. 8e). That of Barkoissi 2 is D=17.0°, I=17.1°, k=21.3, α_{95}=14.8° (Fig. 8f). Overlying all the sites described so far, is the Kabalipe one attached to the Tamale Supergroup. It consists of fluvio-glacial conglomerate dated Cambro-Ordovician and represents the molasse of the Dahomeyides chain. This site is used to perform the conglomerate test. The directions measured are those of the blocs. They show a dispersion of individual direction. This dispersion suggests that the conglomerate was not remagnetized after its formation. The conglomerate test is, in this case, positive, and thus confirms that the directions, obtained from the sites underlying the Kabalipe conglomerate, have not been remagnetized after the deposition of the conglomerate.

The mean direction obtained yield the Virtual Geomagnetic Poles (VGP) (Table I) presented on stereographic projection (Fig.9) with Africa Apparent Polar Wander Path (Besse and Coutillot 2002). The palaeopoles of Boumbouaka 1 and 2 yield, Plon=342.6°, Plat=47.9°, dp=21°, dm=25.5° and Plon=355.2°, Plat=39.9°, dp= 9.8°, dm=10.9°, respectively. The Buipe and Koundjouare (this latter brought to its antipode) poles are located in the NE quadrant and give, Plon=102.5°, Plat=65.5°, dp=8.1°, dm=16.1° and Plon=159°, Plat=67.6°, dp=12.8° and dm=24.3°, respectively. The palaeopoles of Barkoissi 1 and 2 joints those of the underlying formations of Buipe and Koundjouare. The VGP of Barkoissi1 is Plon=111.4°, Plat=84.2°, dp=11°, dm=21.4° while Barkoissi 2 gives, Plon=94.6°, Plat=73.2°, dp=7.9°, dm=15.3°. The palaeolatitudes of the Boumbouaka 1 and 2 sites have high values situated at 49.6°S and 59.7°S respectively. On the contrary, those of the other sites, Buipe, Koundjouare, Barkoissi 1 and 2, yield low values between 2.6°S and 10.5°S.

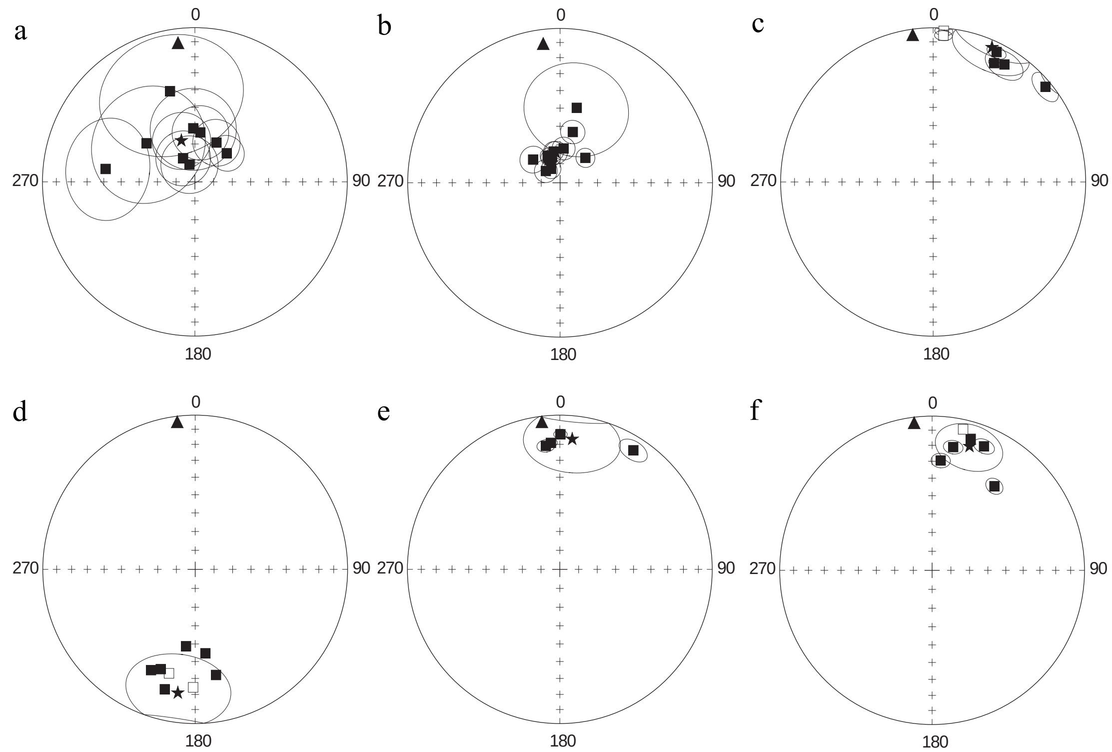

Fig. 8. Stereographic projections of individual trends and mean trend site, after dip correction, of Volta basin, in stratigraphic increasing order. ★ Fisher (1953) mean direction calculed after bring data in the same polarity:
▲ Current geomagnetic field; ■ □ individual samples; a- Boumbouaka 1; b- Boumbouaka 2; c- Buipe; d- Koundjouaré ; e- Barkoissi 1; f- Barkoissi 2.

DISCUSSION

The data provided by magnetic mineralogy show that magnetization is carried by magnetite and hematite. One, two or three components were identified in the samples. The mean directions of the sites are located mainly in the NW and NE quadrants. Only the Koundjouare site occurs in the SW quadrant. The oldest formations of Boumbouaka 1 and 2 consist of fine to very fine sandstone, feldspathic with carbonate cement. They define VGP, Plon=342.6°, Plat=47.9°, dp=21°, dm=25.5° and Plon=355.2°, Plat=39.9°, dp=9.8°, dm=10.9° respectively, yielding high palaeolatitude values of 49.6°S and 59.6°S. These high palaeolatitudes are those that are attributed to the West African craton in models of the reconstruction of the supercontinent of Rodinia before 750 Ma. Such high palaeolatitudes found at Boumbouaka 1 and 2 well confirm the age between 993±65 and 660±9 Ma attributed to these two virtual geomagnetic poles. Nevertheless, the two VGP are close to those of the Adma Diorite, Plon=344°, Plat=34°, dp=16°, dm=17°, described in the Adrar of Iforas, dated between 620 and 590 Ma (Morel, 1981).

The Buipe and Koundjouare sites, made of carbonate, and Barkoissi 1 and 2, made of silexites, are attributed to the triad of the middle Supergroup dated Marinoan to post-marinoan (Porter et al., 2004; Nedelec et al., 2007). The VGP of Buipe, Plon=102.5°, Plat=65.5°, dp=8.1°, dm=16.1°, Koundjouare in antipode, Plon=159°, Plat=67.6°, dp=12.8°, dm=24.3° and Barkoissi 2, Plon=94.6°, Plat=73.2°, dp=7.9°, dm=15.3° are grouped in the NW quadrant (Fig. 9). These sites define VGP's dated between 635 Ma, Marinoan age of the glaciomarine formation, and 600 Ma, age of Pan-African deformation that affects these formations. The palaeolatitudes obtained from these sites are situated between 2.6° S and 10.5° S .These values are very different from those obtained at the two sites at Boumbouaka 1 and 2. They place the West African craton in subequatorial palaeolatitudes as was determined in the Gourma sub-basin (Boudzoumou et al., submitted).

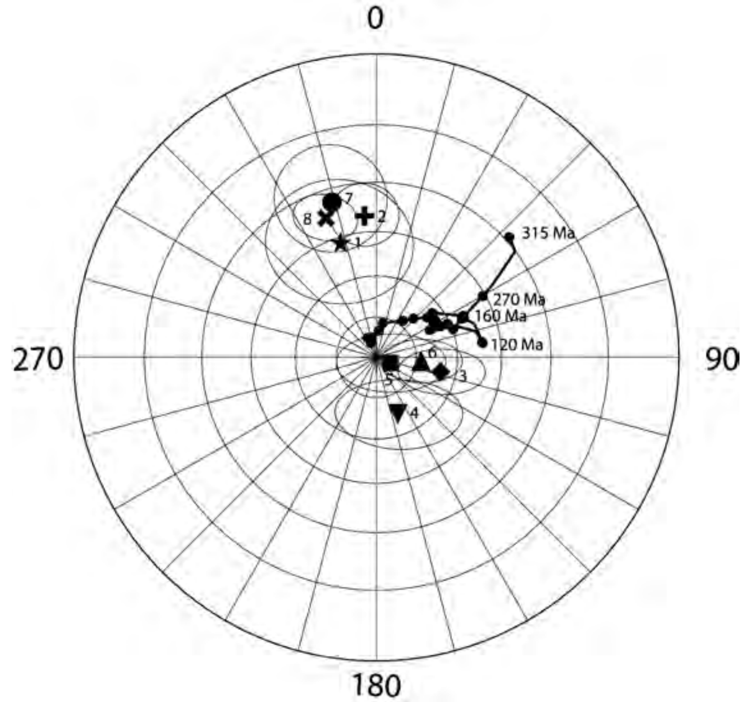

Fig. 9. VGP of Volta basin sites, Adma diorite of Adrar of Iforas and Puga cap carbonate of amazonian craton with Africa APWP (Besse and Courtillot, 2002). Lower hemisphere, Equiangular. Sites:1- Boumbouaka 1; 2- Boumbouaka 2; 3- Buipe; 4- Koundjouare; 5- Barkoissi 1; 6- Barkoissi 2; 7- Adma diorite (Morel, 1981) ; 8- Puga cap carbonate B (Trindade et al., 2004).

CONCLUSION

The palaeomagnetic study of the Volta basin has improved the data base of the Neoproterozoic Formations of the West African craton. The magnetic mineralogy consists of magnetite and hematite, carriers of magnetization.

The mean direction obtained from the high temperature components allow the calculation of the VGP's at the different sites. The Boumbouaka sites 1 and 2 are made of fine to very fine grained sandstones and define a medium palaeopole of Plon=349.3°, Plat=44.1°, dp=15.4°, dm=18.2° dated between 993±65 Ma and 660±9 Ma.

The associated palaeolatitude is 44.9°S which places the West African craton in a medium palaeolatitude as in the reconstruction models of the Rodinia supercontinent before its fragmentation (Meert and Torsvik, 2003). The Marinoan cap carbonate of Buipe and Koundjouare and the Barkoissi 2 silexites that overlie them give a medium palaeopole of Plon=119.5°, Plat=71.2°, dp=9.7°, dm=18.6° dated between 635 Ma and 600 Ma. This palaeopole is associated with a palaeolatitude of 9.1°S which now places the West African craton at a low palaeolatitude in conformity with the Snowball Earth hypothesis which stipulates that all continental masses were located at low latitudes during the Marinoan epoch (Kirchvink, 1992; Hoffman et al., 1998; Hoffman and Schrag, 2002). The two palaeolatitudes of the two medium palaeopoles show a migration of the West African craton from medium to low latitude toward the end of the Neoproterozoic.

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