CHARACTERIZATION OF THE MAEVARANO FORMATION'S ANEMBALEMBA MEMBER (CAMPANIAN) IN BONGOMILITERA SITE

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ABSTRACT

Studies have been conducted in the Mahajanga Basin for the diversity of fossils it contains, both vertebrates and invertebrates. They have mainly been concentrated in the pilot site of Berivotra, in the central part of the basin, where fossils are abundant and well preserved. This study focuses on the characterization of the Maevarano Formation's Anembalemba Member in the Bongomilitera sector, localized in the Commune of Masiakakoho, in the southwestern part of the basin, where expeditions are still rare. A comparison was made between the sedimentary deposits of the two sectors, and the morphoscopic, mineralogical, and geochemical studies of the sediments revealed that there is an obvious concordance between their lithology and their stratigraphic columns. However, the study area's strata are more subject to weathering and natural conditions do not allow the burial, formation, and conservation of large vertebrate fossils there. The paleoenvironmental reconstruction, based on the study of grains transport and deposit conditions in the area, confirms the existence of a relatively calm period followed by a great flood towards the end of the Campanian. These deposits correspond to the Anembalemba Member, which abounds in dinosaur bones in the Berivotra sector but does not present any in the Bongomilitera sector.

Keywords: *Stratigraphy, Geochemistry, Maevarano Formation, Mahajanga Basin, Vertebrate fossil, Paleoenvironment*

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1. INTRODUCTION

Several studies and expeditions (Déperet, 1896; Collignon, 1951; Lavocat, 1955; Bésairie, 1972; Obata, 1977; Asama et al., 1981; Lalaharisaina, 1994; Bignot et al., 1996; Curry, 1997; Papini and Benvenuti, 1998; Abramovich et al., 2003; Rahantarisoa, 2007; Ravoavy, 1991; Rogers, 1997; 1998; 2000) stated that the Campanian of the Mahajanga Basin in Madagascar is very fossiliferous. Belonging to the Upper Cretaceous, this stratigraphic stage contains part of the history of the Cretaceous-Tertiary biological crisis, responsible in particular for the extinction of dinosaurs (Archibald, 1996) 65 My ago. This is in the Anembalemba Member from this floor that a large majority of the fossils of dinosaurs and large terrestrial vertebrates that lived in the basin, were collected. However, these fossils are not distributed homogeneously throughout the basin and previous research was mainly concentrated on the Berivotra sector due to the fact that the fossils are particularly well preserved and the outcrops are clearer and more numerous there, some even run along the AP4.

This study then focuses on the Anembalemba Member of the Bongomilitera sector, in the Commune of Masiakakoho (District of Mitsinjo), one of the potential sites likely to contain dinosaur fossils like that of Berivotra, but further south-west. Studies and expeditions conducted in this sector are still very rare. Hence the interest of having carried out an investigation there in order to characterize the Anembalemba Member and make a comparison with that of the Berivotra sector by studying its lithology, its deposit conditions, and its composition. The paleoenvironmental reconstitution of the area is also important in the context of this study, with the aim of completing and updating the existing data on the Maevarano Formation in the Mahajanga Basin and attempting to explain the concentration of fossils in some sites more than others.

2. GEOLOGICAL BACKGROUND

2.1. Setting-up of Mahajanga Basin

The rifting between Madagascar and Africa (Coffin et al., 1992; Reeves et al., 2002; Geiger et al., Reeves, 2014) is at the origin of three large depocenters which constitute the western basins of Madagascar. From north to south, they are: the Antsiranana Basin, the Mahajanga Basin, and the Morondava Basin (Figure 1-A).

The opening of the Mahajanga Basin happened in two stages:

- A synsedimentary stage in the Permo-Trias and the Lower Jurassic, characterized by the synsedimentary play of brittle accidents;
- A postrift stage at the end of the Cretaceous, marked by the end of syntectonic sedimentation.

2.2. Structural Framework and Geomorphology of Mahajanga Basin

The main tectonic movements generated by the rifting phases control the sedimentation in the Mahajanga Basin (Figure 1-B), which is then made up of a succession of monocline formations concave towards the sea ranging from the Upper Permian to the present. The general arrangement WSW-ENE to SW-NE of its relief is controlled by the tectonic direction of the subsidence flexures. The central horst of Sahondralava-Ihopy was described from the analysis of seismic profiles (Boast and Nairn, 1982). It was in activity during the period of filling of the basin and constitutes the limit between the sub-basin of Mitsinjo in the SW and that of Loza-Mahavavy in the NE.

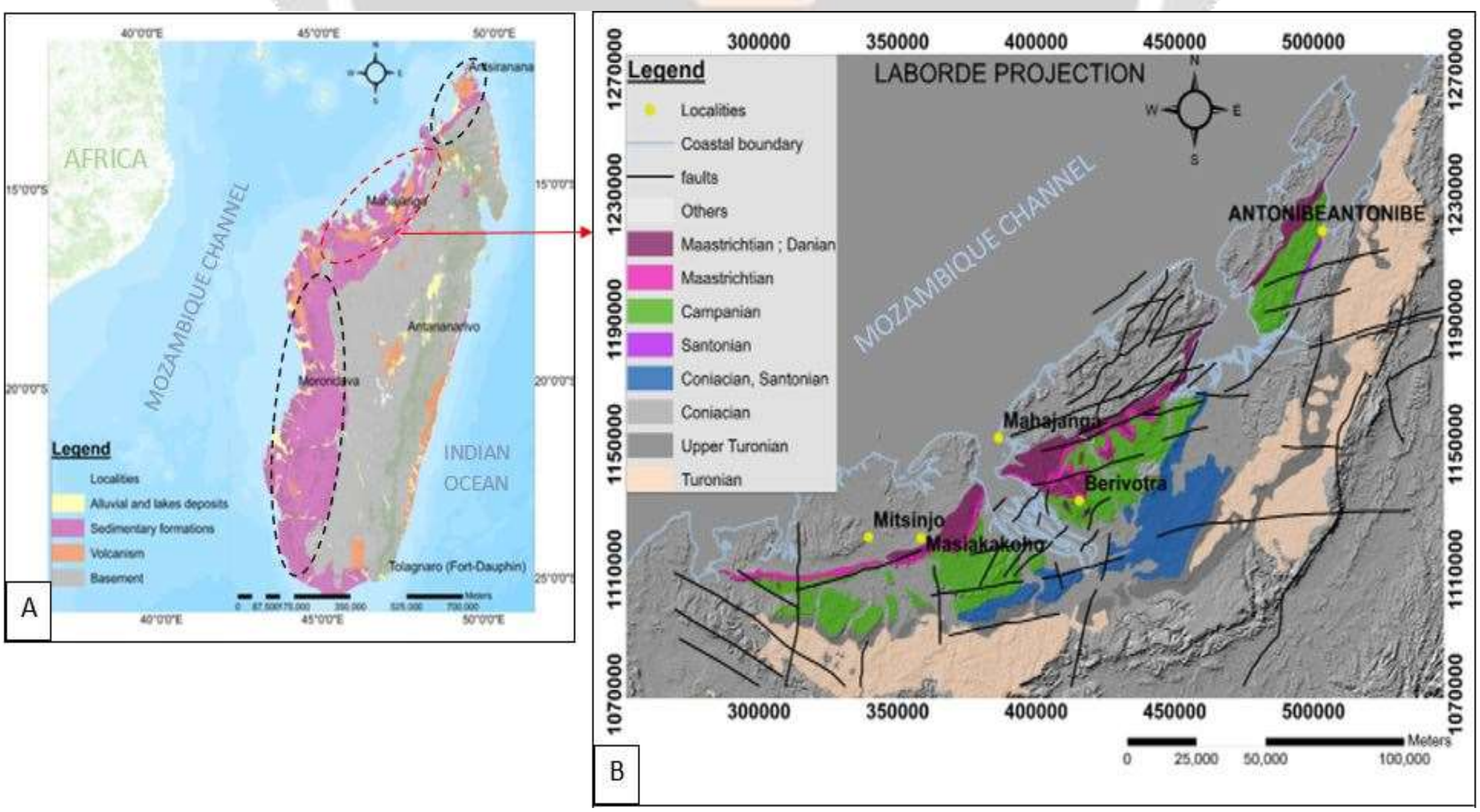

Figure 1. (A) Simplified geological map of Madagascar with its 3 western basins and (B) Structural map of the Mahajanga Basin with the formations of the Late Cretaceous (Bésairie, 1964)

2.3. Lithostratigraphy of Mahajanga Basin

Following the Panafrican orogeny, the crystalline basement of Madagascar, Precambrian age (Tucker et al., 2014), remained exposed until the Carboniferous. In the basin, essentially continental assemblages similar to the Karroo series of southern Africa (Kent, 1974; Rakotosolofo et al., 1999) are deposited first on the crystalline basement. These are from bottom to top:

- The Sakamena group, aged from the Upper Permian to the Lower Triassic, which only outcrops in the northern part of the basin, consisting of shale clay in platelets;
- The Isalo group ranging from the Middle Triassic to the Middle Jurassic, formed by sandstones.

At the end of syntectonic sedimentation, it is the post-Karroo formations, ranging from the Upper Jurassic to the present day, that surmount these Karroo formations. These are from bottom to top:

- Calcareous and marl deposits with levels of lignite and gypsum schist from the Middle and Upper Jurassic;
- The Cretaceous, very fossiliferous, marked by marine and continental episodes;
- The Tertiary, essentially marine, with some continental intercalations.

2.4. Upper Cretaceous of Mahajanga Basin

The Anembalemba Member studied in this article belongs to the Upper Cretaceous. Most of the previous research work on the Mahajanga Basin, leading to stratigraphic data (Piveteau, 926; Bésairie, 1972; Hartman et al., 1994; Bignot et al., 1996; Papini and Benvenuti, 1998; Rogers, 1999; 2000; Abramovich et al., 2003) and the reference sections (Figure 3) known to date, were made in the Berivotra sector, where outcrops are more numerous and evident, where the layers are the thickest, and where the microfossils (Lys, 1960; Möller and Wichmann, 1970; Bésairie, 1972; Perch-Nielsen, 1973; Randrianasolo, 1986) and fossils of large vertebrates (Perrier de la Bâthie, 1921; Forster et al., 1996; Dodson et al., 1998; Krause et al., 1999) including dinosaurs bones (Thévenin, 1907; Perrier de la Bâthie, 1921; Lavocat, 1955; Obata, 1977; Sues, 1979; 1980; Ravoavy, 1991) , are the best preserved.
According to Rogers (2000), the Upper Cretaceous of the Mahajanga Basin presents three stratigraphic formations. These are from bottom to top:

- The Maevarano Formation, dated to the Campanian (Bésairie, 1972), with continental facies;
- The Berivotra Formation, dated to the Maastrichtian, with marine facies and abundant invertebrate fossils;
- The Betsiboka Formation.

Rogers determined three members in the Campanian. These are from bottom to top:

- The Masorobe Member, comprising an alternation of sandstone and red clay;
- The Anembalemba Member, which is the subject of this study, consists of two distinct facies (Figure 2): facies 1, characterized by white clayey sandstones with cross-stratifications, and facies 2, characterized by sandstone clays rich in fossils, especially dinosaurs;
- The Miadana Member characterized by red sandstone clay. This member is not always present throughout the basin and only outcrops in the Berivotra sector to the south of Ambovondramanesy. The upper limit of the Anembalemba Member will then most often be contact between the Campanian and the Maastrichtian.

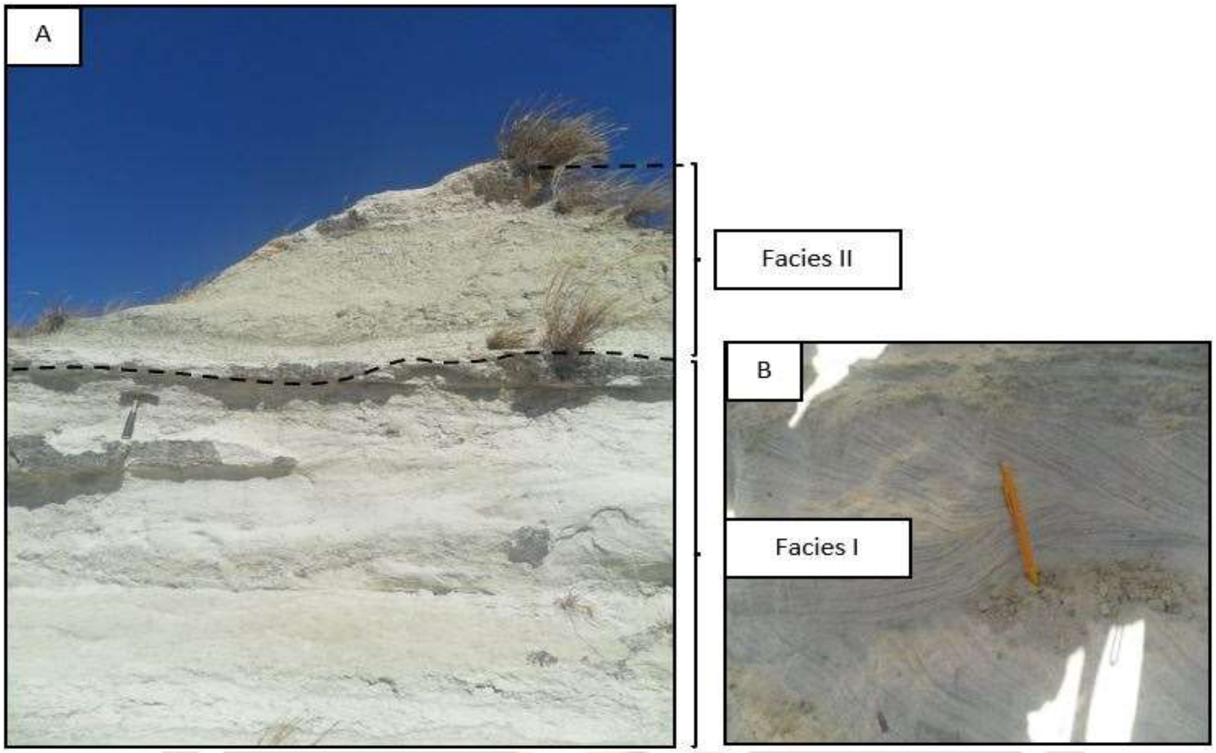

Figure 2. (A) Outcrop of the Anembalemba Member with its two facieses (X: 417005; Y: 1131455) and (B) Facies I characterized with clayey sandstones with cross-stratifications

Stages	Thickness	LOG	Lithological description
DANIAN	80 m		Alternation of chalky marls and thin marl limestone beds; organisms: Echinides, Bivalves Alternation of chalky marls and marl limestone Green clay marls
MAASTR ICHTIAN	40 m		Marl limestone with Bivalves mussels Gray marls Yellow marl limestone Gray marls a little sandy with Pycnodonta
CAMPANIAN	280 m		Thin gray sandstone Gray sandstone with reddish stains and limestone cement Gray or white sandstone, gray clayey sandstone, and gray-green to reddish sand clay, with bones Gray or reddish thin to coarse sandstone, clayey sandstone Gray or reddish sandstone, well consolidated clay sandstone and reddish or patched clay Thin to coarse sandstone, white, yellow gray, and especially reddish, with cross-stratifications; reddish clayey sandstone and clay Reddish well consolidated, thin to coarse sandstone, very sandy clay Gray or reddish thin to medium sandstone Clayey sandstone sometimes cross-stratified
			Gray clay

Figure 3. Lithostratigraphy of Mahajanga Basin's Upper Cretaceous (Rahantarisoa, 2007)

3. METHODOLOGY

3.1. Description of the Study Area

The study area (Figure 4) is located in the eastern part of the Mahajanga Basin, the Berivotra sector being in the central part. It is situated in the Bongomilitera sector of the Municipality of Masiakakoho, in the District of Mitsinjo, in the region of Boeny.
The site is part of the ones proposed by previous studies for future investigations to characterize the Campanian (Maevarano Formation) of the Mahajanga Basin. It is located east of Bombetoka Bay, with the Berivotra sector lying to the west of it.
The landscape of the study area is very similar to that of Berivotra and differs from the surrounding areas by the presence of numerous hills with flat tops (Figure 5-A). It presents a cuesta relief favored by the monocline and concordant arrangement of its layers, with a shallow dip inclined to the northwest and of different hardnesses exposed to erosion.
This region of the island is characterized by a dry tropical climate with a rainy season lasting 5 months. The annual rainfall is 1500 to 1700 mm and the average temperature is high (26.5° to 27° C). These climatic conditions favor lateritization (Figure 5-B) in the area.
The relief consists of continental Campanian sandstones and Maastrichtian gypsum marls protected by layers of Danian limestone. These are the hard layers that make up the top of the cuestas and protect the soft layers below.
Currently, the coastal zone receives a massive influx of alluvium resulting from accelerated erosion due to recent deforestation, modifying the existing cartographic data and making it more difficult to sample the sediments of interest and their outcrop in the area.
In this study, the sediments of interest are continental Campanian sandstones, the stage to which the Anembalemba Member of the Maevarano Formation belongs. However, with the erosion favored by the climate and the geomorphology of the area, there are notable modifications to the initial delimitation of the Campanian by Bésairie in 1964 (Figure 4) and of its contact with the overlaying formations of the Maastrichtian, the main outcrops being hillsides strongly exposed to the agents of erosion (Figure 5-B).

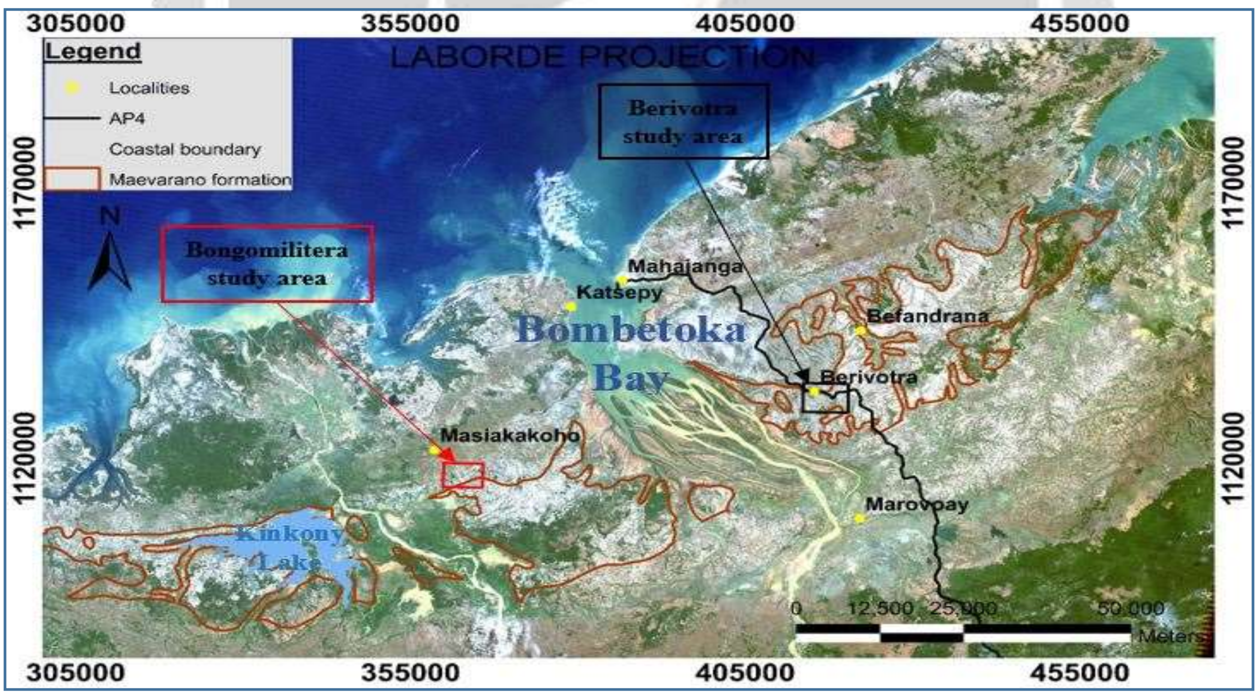

Figure 4. Location of the study area with the delimitation of the Campanian (Maevarano Formation) by Bésairie in 1964

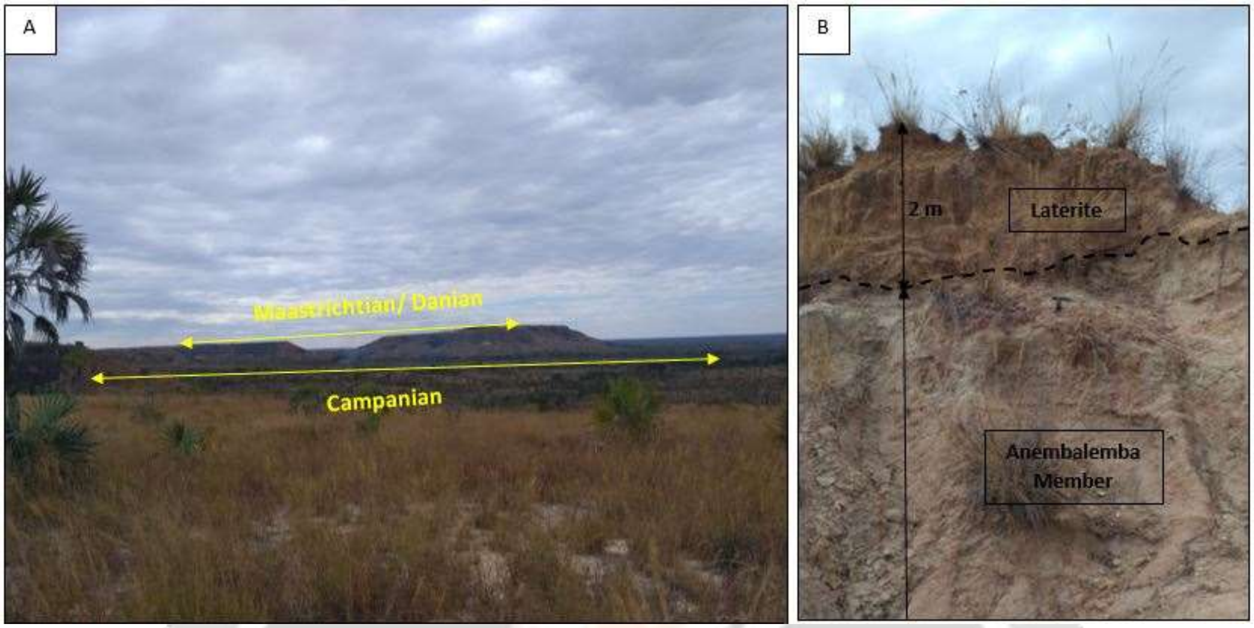

Figure 5. (A) General view of the Bongomilitera sector with its cuesta relief and (B) Outcrop of the Anembalemba Member with a thick level of laterite (X: 363016; Y: 1117190)

3.2. Sampling and Macroscopic Study of Sediments

A total of 7 samples (Table 1) were taken in the Bongomilitera sector at 4 different outcrops, which are all hillsides. A fifth outcrop was taken into account for a comparison between the different thicknesses and elevations of the Campanian layers in the study area. These layers were then correlated with those of the Berivotra sector (Figure 6).

Table 1. List of outcrops and samples of the Bongomilitera sector

Outcrops	Location		Samples	Description
	X	Y		
A	362831	1117019	BM7	Yellow-orange clayey marls with gypsum
B	362854	1117056	BM6	Gray-white oblique stratified sand clays
C	362917	1117101	BM1, BM2	Consolidated gray-green sandstones with reddish stains (BM1), with very thin limestone passages (BM2)
D	363016	1117196	BM3, BM4, BM5	3 different sandstones layers which are from the bottom to the top: consolidated gray-green clayey sandstones with reddish stains (BM3), Consolidated gray-green clayey sandstones (BM4), gray sandstones (BM5)
E	362989	1117084	-	Gray-green sandstones with reddish stains

BM7 is represented by silty marls with gypsum of an orange-yellow-gray color, and corresponds to the gray-orange silty marls of the Maastrichtian of the Berivotra sector, according to the principle of lateral continuity of the strata. It was taken from the contact between the Maastrichtian and the sandstones of the underlying Campanian level.
The rest of the samples are continental sandstones of the Maevarano Formation (Campanian). In the study area, we find the same white-gray, sometimes variegated, fine to medium sandstones as in the Berivotra sector's Anembalemba Member, the Miadana Member being locally absent, with a massive and consolidated structure. There is no distinction between facies 1 and facies 2. We can note the presence of grayish-white clayey sandstone with cross-stratifications identical to those of facies 1 of the Berivotra sector (Figure 2-B), only at outcrop B, the sampling point of BM6. Going upwards, the cross-stratifications fade and reddish spots appear until a massive structure of sandstone deposits is obtained.

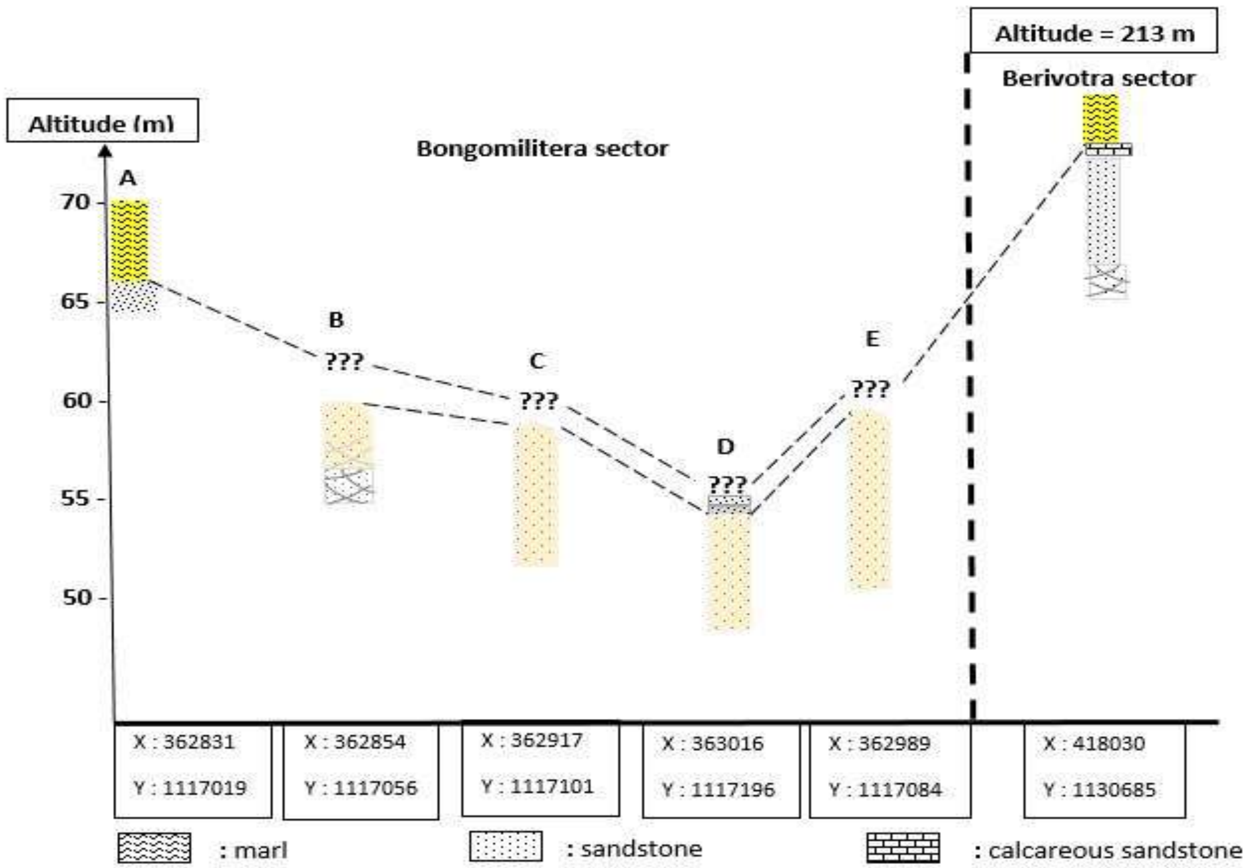

Figure 6. Correlation between layers in the Bongomilitera sector and the Berivotra sector

<u>Morphoscopic study</u>
A morphoscopic study was conducted on the Anembalemba Member's sandstones using a binocular magnifier in order to classify the grains (Wentoworth, 1922) to observe their sorting (Folk, 1957; 1980) and describe their shape, that is to say their sphericity and degree of bluntness using the visual characterization proposed by Tricart (1959), as well as the appearance of their surface. The description obtained (Table 2) is then used to characterize the conditions of sediments deposition and transport.
After observation, all the sediments sampled in the Anembalemba Member consist of sandstones made up of a mixture of grains of different dimensions, ranging from the size of "lutites", being clay and silt, (<0.063 mm) to that of arenite sands (0.063-2 mm). They are generally sub-angular in shape. Their surface has a shiny appearance with sometimes grains that have a matt appearance. The difference in grain size also showed that they are very poorly sorted, except for BM6, whose grains are relatively well sorted.

Table 2. Grains description of the sandstones samples from the Bongomilitera sector

Samples	Grain-Size (mm)	Classification (Wentworth)	Grain form (Tricart, 1959)	Surface aspect	Grain sorting (Folk)
BM1	0.1 – 1.5	Very fine to coarse sand	Sub-angular	Shiny	Poorly sorted
BM3	0.063 – 2	Very fine to very coarse sand	Sub-rounded to sub-angular	Shiny	Poorly sorted
BM4	0.063 – 1	Very fine to coarse sand	Sub-angular	Shiny	Poorly sorted
BM5	1 – 2	Coarse to very coarse sand	Sub-angular to angular	Shiny	Poorly sorted
BM6	0.053 – 0.2	Coarse silt with very fine sand	Sub-angular	Shiny	Well sorted

3.3. Microscopic Study

The sediments collected from the Campanian stage of the study area were prepared for observation under a petrographic microscope in plane-polarized light (PPL) and cross-polarized light (XPL) as part of a mineralogical study (Barker, 2014; MacKenzie et al., 2017). This is to determine the main components and minerals present in the samples, their texture, their shape and classify them. This method also helps to determine the conditions and nature of the sediment deposition environment depending on whether the grains are poorly or well sorted.

Observation in PPL makes it possible to highlight the different reliefs of the minerals as well as the presence of iron oxide and signs of deterioration for most of the samples (Figure 7-A). Observation in XPL (Figure 7-B) allows us to distinguish the various minerals present based on their color, their birefringence, their extinction angle, and the presence or absence of cleavage and twinning. In this study, the main minerals observed (Table 3) are quartz, which is the most abundant in almost all of the samples, feldspars, including plagioclases, biotite, and calcite.

Quartz is recognized in PPL by its low relief. Due to its hardness, it is an unalterable mineral that does not show signs of alteration at its surface, unlike feldspars. In XPL, these 2 minerals have an almost similar first-order gray tint. To differentiate them, feldspars often have twins that characterize them. Calcite is distinguished from other minerals by its high relief. It is a birefringent mineral that can be recognized by its color shades of the 3rd order or higher. In natural light, mica has low relief. Biotite, a variety of mica, shows direct pleochroism with a light-yellow tint that turns brown in XPL.

Table 3. Characteristics of the main minerals observed in thin section

Mineral	Color	Relief	Cleavage	Max birefringence	Extinction angle	Twinning
Quartz	Colorless	Low	None	1st order	0°	None
Alkali Feldspar	Colorless	Low	2 perfect	1st order	0°	Simple or tartan
Plagioclase	Colorless	Low	2 perfect	Variable	Variable	Lamellar
Biotite	Green to brown, pleochroic	Moderately low	Perfect basal	Upper 3rd order	_	Very rare

Calcite	Colorless	Low to moderately high	3 perfect	3rd order (very high)	_	Lamellar

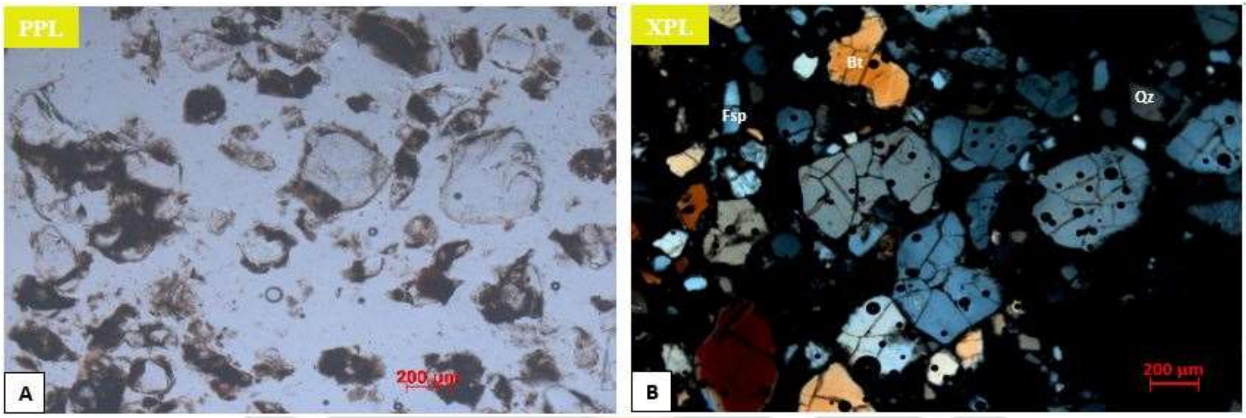

Figure 7. (A) BM1 thin section in plane-polarized light (PPL) showing signs of alteration on some minerals and presence of iron oxide responsible for the faint orange color at the edges of some grains and (B) BM3 thin section in crossed polars (XPL) showing very poorly sorted grains mainly made of quartz and feldspars

3.4. Geochemical Analysis

The geochemical analysis of the samples is carried out in the laboratory, with the exception of BM2. Like BM7, BM2 reacts to the hydrochloric acid test, which shows the presence of carbonates. However, the outcrops show that BM2 is temporary and only represents a fine limestone passage that crosses both Maastrichtian and Campanian formations (Figure 8) by entering cracks subsequent to the installation of the layers following a bed structure.

Figure 8. (A) Calcareous infiltrations in Maastrichtian marls (X: 362783, Y: 1117034) and (B) Calcareous infiltrations in Campanian sandstones (X: 363016, Y: 1117190)

The rest of the samples, being sandstones (BM1 to BM6) and marl (BM7), were treated in the laboratory with an alkaline fusion, either by attack with double carbonate of sodium and potassium, in order to determine the content of major elements (Table 4). The analysis will then give the composition in silica, calcium, iron, magnesium, and aluminum. This is in an attempt to determine the age of rocks and events through geochronology using the method of relative dating, as well as to study the paleoenvironment of the area.

Table 4. Geochemical analysis of major elements

Samples	Fe_2O_3 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	SiO_2 (%)
BM1	4.05	6.50	7.18	1.05	78.10
BM3	2.80	5.80	6.50	0.90	77.78
BM4	-	1.09	20.17	0.40	75.64
BM5	2.65	4.80	9.80	-	80.06
BM6	-	1.68	29.56	-	64.76
BM7	2.95	-	7.18	4.47	10

4. RESULTS

4.1. Mineralogical Composition

The mineralogical composition of the sediments was obtained from a microscopic study related to the geochemical analysis of major elements.
Observation under a petrographic microscope highlighted the predominance of quartz in all samples. Taking into account this characteristic and the grain size, we have arenite quartz and the sediments are clayey sandstones (BM1, BM3, and BM5) and sandstone clays (BM4 and BM6). This explains the high silica content ranging from 64 to 80%, quartz being a mineral consisting of crystallized silica (SiO_2).
Only in BM7 is this value relatively low (10%) and more or less proportional to that of calcium oxide (7.18%). This marl is then a calcareous clay. In XPL, we note the presence of gypsum, which has a first-order gray tint and birefringence very similar to those of quartz.
BM1 and BM3 have the same mineralogical composition, which suggests that they are locally the same formation. In addition to the predominant quartz, they contain abundant aluminosilicate minerals, which are feldspars under the microscope, and show the presence of ferromagnesians such as mica (biotite) in considerably lower proportions.
In XPL, BM4 shows a relatively abundant presence of calcites ($CaCO_3$), which are natural crystallized calcium carbonates, in addition to quartz. Geochemical analysis also gave a higher calcium oxide content (20.17%) than in other sandstones. This allows it to be classified among limestone sandstones (Figure 9-B).
The geochemical results of BM5 show a higher calcium content (9.8%) than that of BM1 and BM2, and observation under a petrographic microscope shows the presence of calcite with the quartz grains. However, this composition can be influenced by the calcareous infiltrations that cross the sandstone formations of the Campanian. Without matrix and cement, BM5 is in fact much more porous and permeable than BM1, BM3 and BM4, the diagenesis of which is more advanced given their quite consolidated appearance.

4.2. Conditions and Environment of Deposition of the Anembalemba Member

Sandstones are detrital rocks produced by the erosion of pre-existing rocks. The Campanian sandstones of the Bongomilitera sector, like those of the Berivotra sector, are of continental origin and were set up under continental transport and deposit conditions.
Macroscopic observation, morphoscopic and microscopic study of the sediments revealed a general sub-rounded aspect of the grains studied. Therefore, they are not unworn grains characteristic of an absence of transport or of a short transport of sediments, nor of dull-shine specific to long transport by water, but rather of an intermediate aspect. That induces the entrainment of grains by continental waters over a moderately long distance. The presence of clay and silt, which are very fine particles in the sedimentary deposits, induces a current strong enough to keep them in suspension during transport and a calm deposition environment to allow them to reach the bottom. It is also observed that the grains are very poorly sorted; that is to say, the sandstones and the clays are deposited at the same time, which induces rapid deposition.
However, BM6 presents grains which are clearly better sorted (Figure 9-A) than those of BM1, BM3, BM4 and BM5. Previous studies of the Berivotra area (Rogers, 2000) have shown that facies 1 of the Anembalemba Member has better sorted grains than those of its facies 2 (Figure 9-C, D). BM6 then corresponds to facies 1 of the Anembalemba Member, confirming its Campanian age, and its deposit is slower than that of the overlaying sandstone formations. Its cross-stratifications show an agitation at the level of the ridge line and result in a lateral migration of sedimentary forms while depositing the detrital material. The very poorly sorted grains of BM1, BM3, BM4 and BM5 result in a rapid and massive deposit similar to that of facies 2 of the Anembalemba Member.
The presence of iron in BM1, BM3 and BM5, demonstrated by geochemical analysis, allows us to deduce that these sandstone formations were in contact with the air. The red pigmentation observed with the naked eye on the sandstones as well as the orange spots on the edges of the minerals observed in XPL under a petrographic microscope also testify to this exposure to air. This is not the case with BM4 and BM6, in which the presence of iron was not detected.

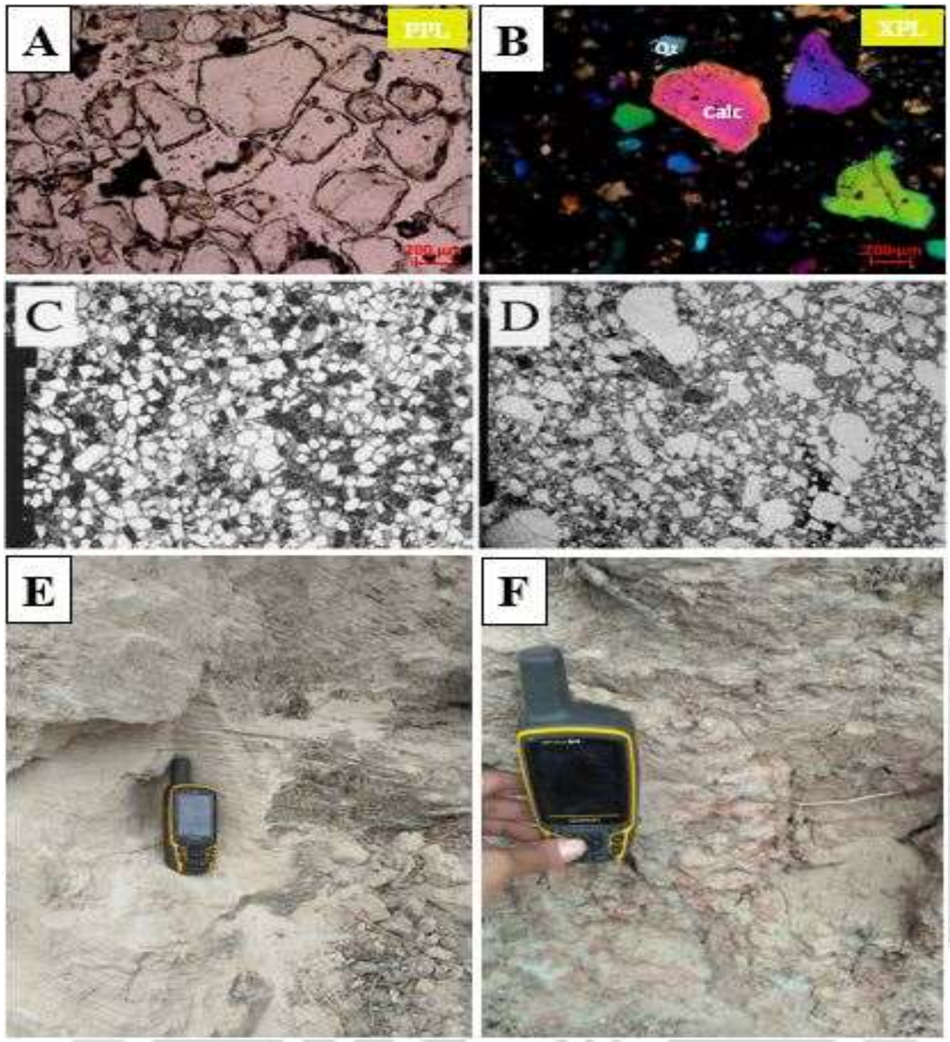

Figure 9. (A) Clayey sandstones of BM6 better sorted than (B) calcareous sandstones of BM4 observed in thin sections; (C), (D) Representative photomicrographs of facies 1 and facies 2 of the Anembalemba Member of Berivotra sector, respectively (Rogers et al., 2000), scale bar = 2.5 mm; (E) Facies 1 (BM6) of the Anembalemba Member with its cross-stratifications (X: 362854; Y: 1117056) and (F) Massive sandstone deposits overlying the facies 1 (X: 362855; Y: 1117053)

4.3. Chronostratigraphy of the Anembalemba Member's Formations

The absence of microfossils and macrofossils in the sandstone formations studied in the Bongomilitera sector does not allow determination of the geochronology by using radiometric dating. Rather, relative geochronology is used to determine their age. The lithology of the sediments studied in the study area matches that of the Berivotra sector and corresponds to the description given by the reference section (Figure 3), which confirms the Campanian age of the Upper Cretaceous of the sandstone deposits in the area and that it is indeed the Anembalemba Member, the Miadana Member, not outcropping in the area.

The characteristics of the sandstones that form this member show that it is clearly continental. Its upper limit is its direct contact with the transgressive marls of the Maastrichtian Berivotra Formation (Bésairie, 1972).

After correlation between the different outcrops, the thickness of the Anembalemba Member is at least 10 m in the area, and its lithostratigraphy is described as follows with the corresponding major geological events (Table 5):

- The basal formation consists of sandstone clay with cross-stratifications. The deposition of these sediments in a calm environment allows to deduce that the environment at that time was quite stable and favorable to the survival of any terrestrial animals;

- This formation is then surmounted by massive deposits of sandstone with grains that are poorly sorted compared to the preceding ones. In the area, it first presents gray-greenish clayey sandstones with reddish spots resulting in temporary exposure to the air. Greenish-gray sandstone deposits then form, showing no trace of contact with the atmosphere. This level contains many fossils of large vertebrates, including dinosaurs (Figure 10-B) and giant tortoises in the Berivotra sector, and its unconsolidated texture (Figure 10-A) at the level of certain outcrops testifies to a great flood at that time;
- Finally, a level of limestone sandstone is deposited on these formations. The presence of iron, responsible for the reddish tint in them, may induce contact with air. These sandstones are also hard and compact in the Berivotra sector, indicating that sedimentation has stopped.

This superposition of continental layers is covered by the Maastrichtian marls, which were deposited during a marine transgression.

Table 5. Chronostratigraphy of the Anembalemba Member

Stages	Ages (My)	Formations	Thickness (m)	Sections	Lithology	Geological events
MAASTRICHTIAN	65,5	BERIVOTRA FORMATION	?	(Not seen in this study)	Yellow marls with gypsum	Marine transgression
CAMPANIAN	70,8	MAEVARANO FORMATION (ANEMBALEMBA MEMBER)	10		Calcareous sandstones Consolidated gray-greenish clayey sandstones Consolidated gray-greenish clayey sandstones with reddish stains White-gray sandy clay with cross-stratifications	Cessation of sedimentation Great flood, continental transgression Development of terrestrial animals

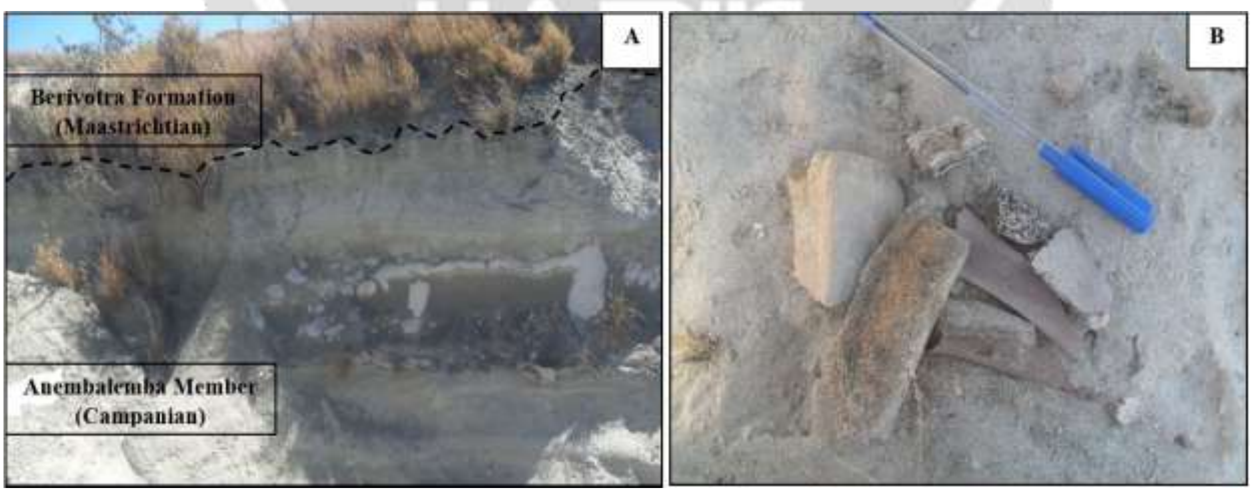

Figure 10. (A) Outcrop of the Anembalemba Member showing unconsolidated formation in the sector of Berivotra (X: 417958; Y: 1130779) and (B) Dinosaur fossils collected from Facies 2

5. DISCUSSION

5.1. The Paleoenvironment of the Area

Indices about the paleoenvironment of the area can be found from studies carried out in the sector. This involves reconstructing the ancient environment corresponding to the age of the sediments studied from their properties.
The characteristics of the formations encountered in the study area as well as the presence of cross-stratifications allow us to describe a fluvial deposition system (Wright et al., 1993; Miall, 2006; Willis et al., 2010) with the transport of detrital elements following streams and their deposition on river beds. This may imply that this sedimentary environment is a flood plain that first receives the sediments under stable conditions before receiving them abundantly during rapid discharges caused by large floods during the Campanian. It may correspond to a major flood or a great continental transgression, which was at the origin of the extinction of the dinosaurs in the Mahajanga Basin in the Upper Cretaceous during the fifth biological crisis of the Cretaceous-Tertiary.

5.2. Interpretation of the Absence of Dinosaur Fossils in the Bongomilitera Sector

While fossils of dinosaurs and other large vertebrates from the Upper Cretaceous are abundant in the Berivotra site, they are rare or even absent in the Bongomilitera area.
Preliminary taphonomic analysis (Rogers et al., 1997) revealed that the majority of fossils are concentrated in facies 2 of the Anembalemba Member. This can be explained by the good burial and conservation conditions it offers. Indeed, the dead or alive dinosaurs were trapped under the massive deposits resulting from the rapid release of sediments during great floods flooding the plain. A large quantity of detrital elements was then deposited to bury them and protect them from destruction by water and/or climatic hazards.
The absence of dinosaur fossils and large terrestrial vertebrates in the Bongomilitera sector therefore does not exclude the possibility that they lived there, but that the conditions for the formation and/or conservation of fossils in this part of the basin are poor.
It may be that the reduced thickness of the layers in this zone, conditioned by its geomorphology, does not allow good burial. If, however, it was successful, the characteristics of the layers, in particular too rich in iron, do not allow good conservation of animal remains, leading to their gradual decomposition.

5.3. Limitations of the Study

The results and interpretations discussed in this study are based only on the macroscopic observations of the sediments, the morphoscopic and microscopic study of the samples, the geochemical analysis of the major elements and the correlation with the previous studies' results. The complete history of the deposits in the Bongomilitera sector in order to better reconstruct the paleoenvironment of the area requires, in particular, additional grain-size analysis and more.
However, this study remains a step forward in the understanding of the conditions and deposition environments of the Maevarano Formation's Anembalemba Member, which hosts a wide variety of terrestrial vertebrate fossils in several sites of the Mahajanga Basin, making it important for completing and updating the existing geological and paleontological data.

6. CONCLUSION

This study looked at the characterization of the Anembalemba Member of the Bongomilitera sector, a very little studied site in the Mahajanga Basin. The characteristics of the deposits were observed by means of macroscopic, microscopic, and geochemical analysis of the sediments in order to provide a better understanding of their transport and deposition conditions in an attempt to reconstitute the paleoenvironment of the area.
The results obtained led to the following conclusions:

i. The Anembalemba Member is frankly continental and essentially made up of terrigenous deposits transported by fluvial currents over a certain distance and deposited in a flood plain. These characteristics make it possible to describe a stable environment which is then subject to a period of great flooding highlighted by massive deposits generated by rapid discharges.

ii. Its lithology matches perfectly with that of the Berivotra sector, confirming its Campanian age and its belonging to the Maevarano Formation. The Miadana Member, being absent in the area, the Anembalemba Member is directly surmounted by the Maastrichtian marls of the Berivotra Formation.

iii. The Anembalemba Member of the Bongomilitera sector does not provide favorable conditions for the formation and conservation of fossils of dinosaurs and large terrestrial vertebrates. This is due in particular to its considerably reduced thickness compared to that of Berivotra and the frequent exposure of its formations to the air, as evidenced by the presence of iron in its components, leading to further deterioration.

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