CHARACTERIZATION AND PALEOENVIRONMENT OF THE ANEMBALEMBA MEMBER IN THE KINKONY LAKE SECTOR (MAHAJANGA BASIN)

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ABSTRACT

The Campanian of the Mahajanga Basin is recognized by many authors as a very fossiliferous stage of the Upper Cretaceous. A large number of terrestrial vertebrates that flourished in the basin at this time have been discovered there, including dinosaurs. Previous taphonomic studies concluded that the majority of these large vertebrate fossils were collected from Facies 2 of the Anembalemba Member of the Maevarano Formation considered Campanian in age in this study. The investigations were carried out in the Lake Kinkony sector, a study area still little explored compared to that of Berivotra where outcrops of Upper Cretaceous layers including those of the Anembalemba Member abound and where dinosaur fossils and other terrestrial vertebrates are well preserved. The Anembalemba Member of the Lake Kinkony sector was then the subject of morphoscopic, mineralogical and geochemical analyses. It was deduced that the Anembalemba Member was deposited during a period of continental transgression in an alluvial plain. The climate there was hot and subtropical, as in the entire Mahajanga Basin. Following the morphology of the basin, the Maevarano Formation becomes thinner in this westernmost part of the basin, generating insufficient accommodation space for the effective burial of large terrestrial vertebrates. Also, the results of the geochemical analysis revealed that the deposits of the Anembalemba Member were exposed to the air for a quite long period, which does not allow good conservation of the fossils they contain.

Keywords: *Stratigraphy, Anembalemba Member, Late Cretaceous, Mahajanga Basin, Paleoenvironment*

1. INTRODUCTION

The study of the deposits of the Anembalemba Member of the Maevarano Formation aged Campanian (Hoffstetter, 1961; Karche and Mahe, 1967; Bésairie, 1972; Russell et al., 1976; Buffetaut and Taquet, 1979; Sues and Taquet, 1979; Papini & Benvenuti, 1998; Ramaniraka, 2022) is of great interest both from a geological and paleontological point of view since fossils of dinosaurs and other large terrestrial vertebrates have been discovered there (Déperet, 1896; Krause et al., 2006; 2007; 2019; Taylor & Francis, 2007; Gaffney et al., 2009; O'Connor and Forster, 2010; Brown, 2010; Marshall and Rogers, 2012; Obrist-Farner et al., 2017; Joyce et al., 2021). The MBP (Mahajanga Basin Project) was launched in 1993 to catalog the fossils of animals that flourished in the Mahajanga Basin, especially in the Late Cretaceous, and made it possible to recover and describe 125 previously unknown taxa including in particular crocodyliforms, non-avian dinosaurs and mammals (Thévenin, 1907; de la Bâthie, 1921; Lavocat, 1955; Obata, 1977; Sues, 1979; 1980; Ravoavy, 1991; Rogers et al., 2000; 2007; Krause et al., 1999; 2014; 2019; 2020) the majority of which were collected in Facies 2 of the Anembalemba Member (Rogers et al., 1997). Previous work has focused, for the most part, in the Berivotra sector, in the central part of the Mahajanga Basin, where Campanian outcrops are more numerous and evident

and where fossils of dinosaurs and large terrestrial vertebrates are the best preserved. Their discovery and the study of the formations which contain them make it possible to reconstruct the paleoenvironment of the Mahajanga Basin at the geological period when they lived there and thus to complete the existing data on the major geological events and their chronology, which affected the basin and those of East Africa.

This study will be more specifically focused on the "Characterization and the paleoenvironment of the Anembalemba Member in the Kinkony Lake sector (Mahajanga Basin)" in order to explain the uneven distribution of fossils of dinosaurs and large terrestrial vertebrates in the entire extent of the basin and provide additional data to reconstruct the paleoenvironment in its western part to which the Kinkony site belongs, during the Upper Cretaceous. To do this, the study will be mainly based on the lithological and geochemical analysis of samples collected from the study area as part of a geological and paleontological investigation in the Kinkony site.

2. LITERATURE REVIEW

The sedimentation in the Mahajanga Basin as well as its geomorphology were conditioned by the main tectonic movements generated by the different phases of rifting which led to its opening and which affected it.

Two major rifting episodes have been recorded (Coffin et al., 1992; Reeves et al., 2002; Geiger et al., Reeves, 2014). On the one hand, the syn-rift stage in the Permo-Triassic and Lower Jurassic corresponds to a period of extension and distension between Madagascar and Africa. It is characterized by variable subsidence from one zone to another of the basin as well as a syn-sedimentary play of brittle accidents (Razafimbelo, 2015). This first episode of oceanic rifting mainly affected the Somali and Comorian basins, leading to the separation of the Malagasy block from Continental Africa. Meanwhile, Madagascar and India follow a SSE trajectory along the Davie Ridge until Madagascar lies at a distance of approximately 400km from the eastern coast of Mozambique in the Lower Cretaceous. The ante-opening stage is also marked by a predominance of vertical movements in horst and graben as well as very diversified sedimentation (Perrodon, 1980; Razafimbelo, 2015). Active rifting ceased in the Early Cretaceous (Rogers, 2000). On the other hand, the post-rift stage corresponds to the end of syn-tectonic sedimentation. It is marked by a major distension during the Upper Cretaceous causing the separation of Madagascar and India. Thus, the Indian subcontinent quickly moved northeast towards Eurasia while Madagascar, belonging to the African plate, continued its movement northward until it reached its current position. It was during the dislocation of India and the Seychelles Islands that the opening of the Mascarene oceanic basin took place, with which large basaltic outpourings were associated with the Marion hot spot (Storey et al., 1997; Torsvik et al., 2000; Melluso et al., 2001; Bardintzeff et al., 2010; Cucciniello et al., 2013).

From a stratigraphic point of view, the Gondwanan Karroo formations were deposited during the pre-opening period. The sequence known in Madagascar has great similarities with the series described in Tanzania and Kenya (Kent, 1974; Datian et al., 2018). In the Mahajanga Basin, the Karroo presents from bottom to top: the Sakamena characterized by platety clay deposits and the presence of aestheria, and the Isalo characterized by intercalations of continental and marine facies from the Middle Triassic to the Middle Jurassic. The Post-Karroo formations were then deposited during the post-rift period. In the Mahajanga Basin, they consist from bottom to top of: the marine Jurassic, represented by alternations of calcareous and marly deposits rich in fossils, the Cretaceous, very fossiliferous, characterized by marine and continental episodes, and the marine Tertiary with some continental intercalations.

The Anembalemba Member which is the subject of this study belongs to the Maevarano Formation aged from the Campanian, a stage of the Upper Cretaceous. In the Mahajanga Basin, the three Upper Cretaceous stratigraphic units overlie Turonian basalts (Rogers et al., 2000). These are from bottom to top: the frankly continental Maevarano Formation (Ramaniraka, 2022), the marine Berivotra Formation (Rahantarisoa, 2007; 2022) and fossiliferous aged from the Maastrichtian, characterized by homogeneous sediments of marls and olive green to yellowish silty clays, and the marine Betsiboka Formation characterized by limestone deposits of Danian age.

In the type locality of Berivotra located in the central part of the Mahajanga Basin where the Maevarano Formation is the thickest and can reach a maximum thickness of 370 m (Bésairie, 1972), the Anembalemba Member is 10 to 115 m thick. It overcomes the Masorobe Member, at least 80 m thick, in the Berivotra sector.

The Anembalemba Member is topped by the Miadana Member, approximately 25.4 m thick, which only outcrops at Ambovondramanesy, approximately 4 km southeast of the village of Berivotra. The basal contact of the Anembalemba Member with that of Masorobe is marked by an erosional discontinuity and its upper contact is an erosional discontinuity with the Miadana Member or more often a continuous lateral disconformity with the Berivotra Formation when the latter is absent. A new Member, the Lake Kinkony Member, was described in 2013 (Rogers et al., 2013) in the Lake Kinkony study area and presents lithological similarities with the Miadana Member of the Berivotra sector. In the Lake Kinkony sector, the Anembalemba Member is then topped either by the Lake Kinkony Member, or directly by the Maastrichtian marls of the Berivotra Formation. At numerous outcrops of the Mahajanga Basin, the Anembalemba Member presents two distinct facies. Facies 1 is characterized by poorly sorted fine to coarse grains with a greater composition of sandstone than clay. The light gray to white clayey sandstones of Facies 1 often exhibit cross-stratification. Facies 2 of the Anembalemba Member consists of poorly sorted fine to coarse grained sandstone clays of olive green color and often has a massive structure.

3. METHODOLOGY

3.1. Description of the study area

The study area is located in the western part of the Mahajanga Basin and is called in previous work (Gaffney et al., 2009; Rogers et al., 2013) the "Kinkony Lake study area" since it is located near Kinkony Lake. As part of the MBP (Mahajanga Basin Project) research, 4 study areas were actually defined. These are, from East to West, the sites of Befandrama, Berivotra, Masiakakoho (near Bongomilitera) and Kinkony Lake on which this study will focus (Figure 1). Among these 4 sites, the study area of Lake Kinkony is the one located furthest to the West and is therefore closest to the town of Soalala which constitutes the South-Western limit of the Mahajanga Basin limited to the North- East by the Ampasindava peninsula. From an administrative point of view, it is located in the Commune of Katsepy, in the District of Mitsinjo, in the Boeny region.

The relief of the study area is gentle and intersected by shallow valleys and streams. Its altitude varies between 0 and 104 m and the highest part is located southeast of Mitsinjo. It presents a great similarity with that of the Berivotra sector with its flat-topped hills forming a gently dipping cuesta relief inclined towards the northwest following the monoclinal arrangement of the layers which form it.

From a geological point of view, the relief of the study area is formed by sandstones of Campanian age and Maastrichtian marls sometimes covered by Danian limestone deposits. The harder formations protect the softer formations they surmount from water and wind erosion, the top of the plateaus is often made up of Danian limestone. When these are absent, the underlying layers are more directly exposed and are more subject to the phenomenon of erosion, thus forming small hills of different altitudes. Recently, large deposits of alluvium resulting from accelerated erosion due to recent deforestation can be found in the study area.

The tropical climate which reigns in the study area favors the alteration of the formations which compose it. They are exposed to a hot season with abundant rains from November to April and a dry and cool season under the influence of the Alizée Wind from May to October. Throughout the year, the average temperature varies from 27.7° to 32°C. Under these conditions, lateritization is significantly stronger in the Kinkony Lake site than in the Berivotra sector. At several outcrops of the Maevarano Formation, the lateritic profile can then be well observed, often making it more difficult to distinguish the different members that constitute it in the study area.

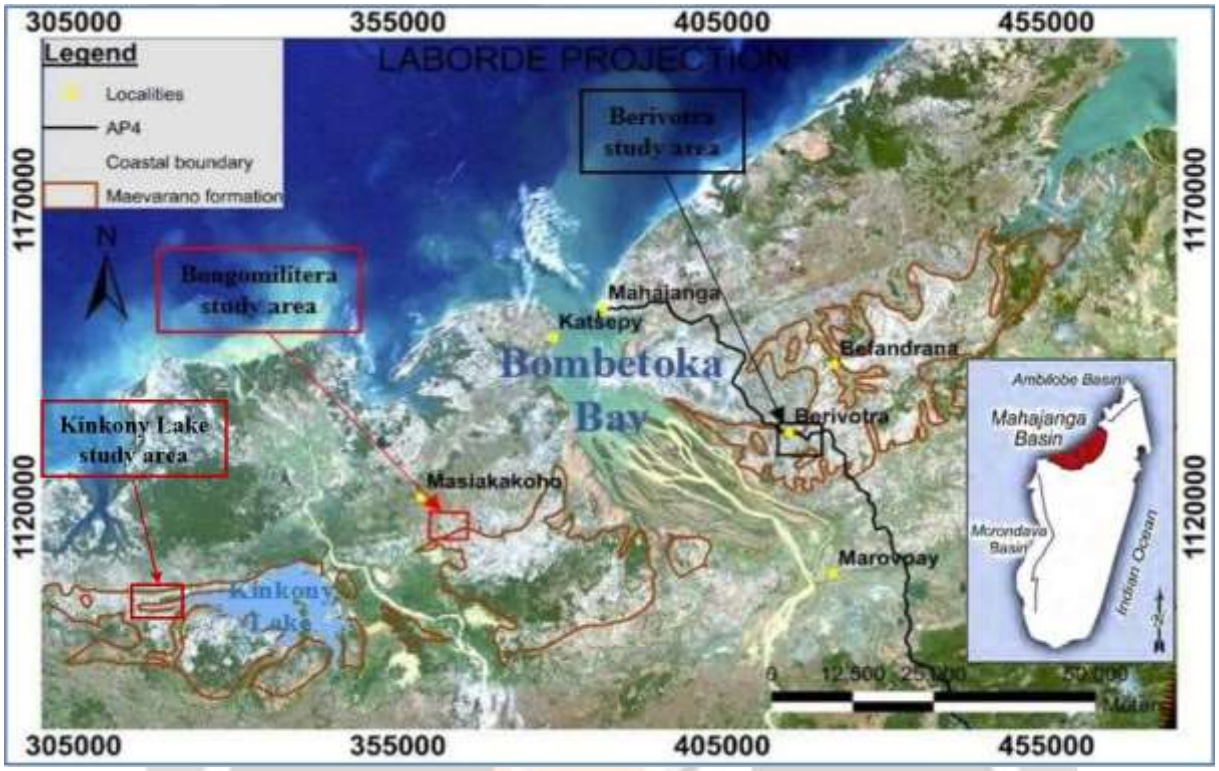

Figure 1. Location of the Kinkony Lake study area in the Mahajanga Basin with the delimitation of the Maevarano Formation by Bésairie in 1964

3.2. Sediment sampling and outcrops

A total of seven samples were collected from the Kinkony Lake area at four different outcrops (Table 1). These correspond to eroded hills like those of the landscape of the Berivotra site at which continental deposits aged from the Campanian were found. However, the formations of the Kinkony Lake study area are more subject to the phenomenon of alteration and the area undergoes strong lateritization (Figure 2) as in the case of the Bongomilitera site (Ramaniraka et al., 2022) due in particular to climatic conditions.

Table 1. List of Outcrops and Samples from the Kinkony Lake Study Area.

Outcrops	Location		Altitude (m)	Samples	Description
	X	Y			
A	322426	1105515	30	A01	Greenish gray sandstones-rich clays
				A02	White standstones-rich clays
				A03	White clayey sandstone with cross-stratifications
B	322427	1105524	34	A04	White clayey sandstone with cross-stratifications
C	322437	1105536	29	A05	Reddish gray clayey sandstone
D	322425	1105542	32	A06	Reddish-white sandstones-rich clays
				A07	Greenish gray sandstones-rich clays with reddish stains

Since no outcrop exposing the Anembalemba Member with its upper limit was found durint the investigation, either its contact with the Miadana Member (Kinknony Member) or with the Berivotra Formation and its lower limit being its contact with the Masorobe Member in the study area of Lake Kinkony, the samples were taken from West to East (Figure 3-A) in order to establish a stratigraphic section based on the reference section in the study area of Berivotra and that of the Bongomilitera study area.

A correlation will then be established between the section thus obtained and that of Kinkony 1 (Figure 3-B) drawn up during previous work (Rogers et al., 2013) in the same sector while respecting the principle of continuity of layers and the principle of paleontological identity.

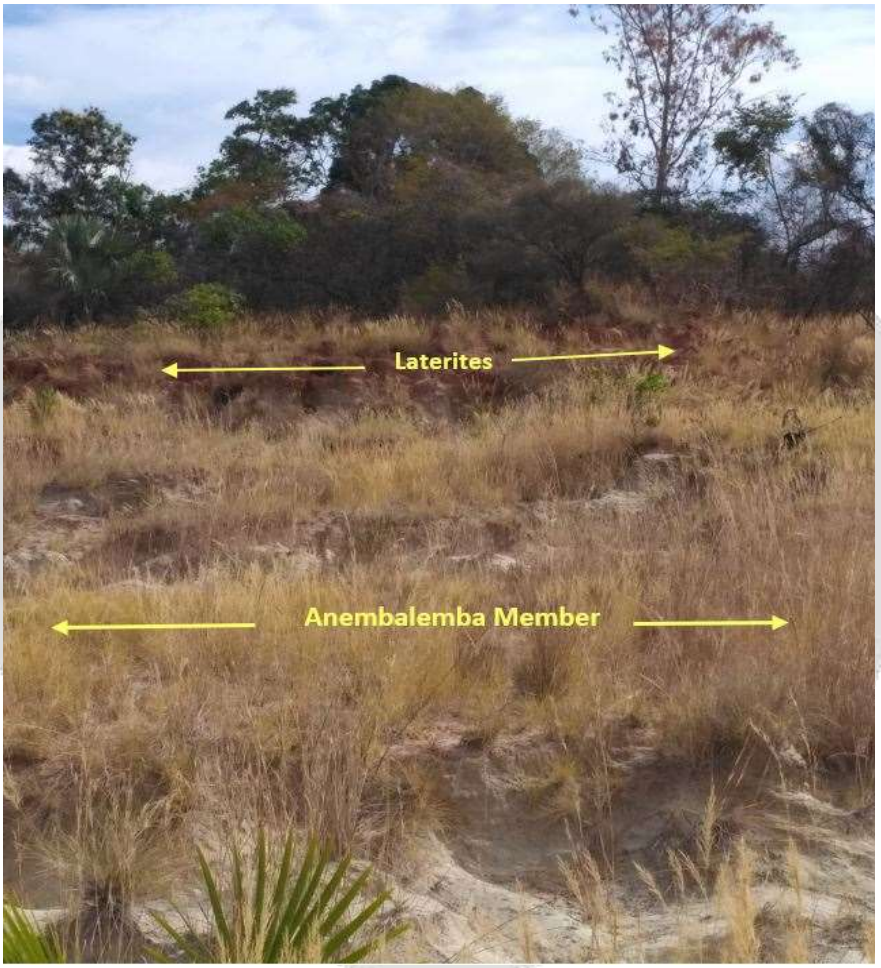

Figure 2. Lateritization at Anembalemba Member's outcrop in the Kinkony Lake area

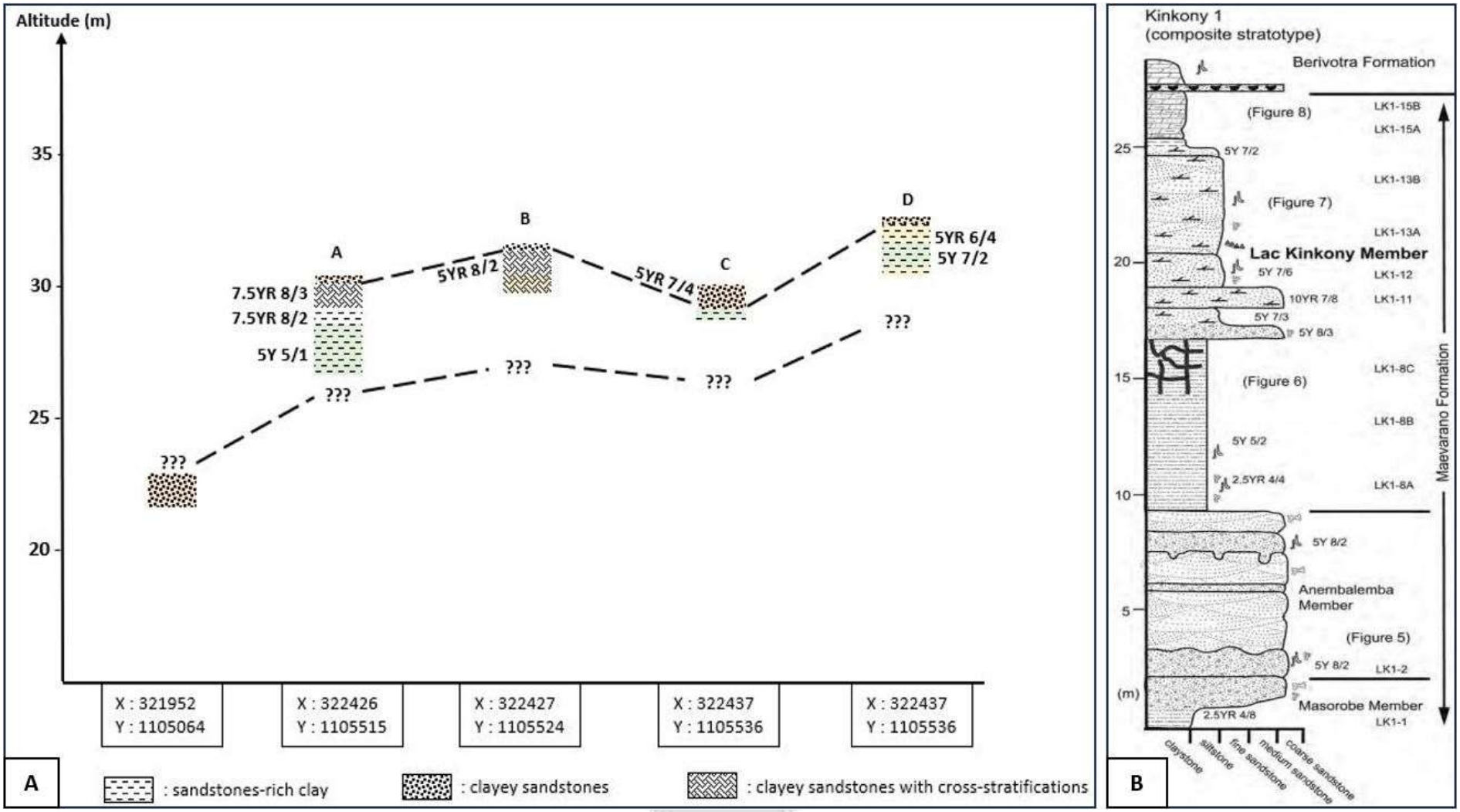

Figure 3. (A) Correlation between different outcrops layers in the Kinkony Lake Sector and (B) Maevarano Formation's representation in Kinkony 1 section (Rogers et al., 2013)

3.3. Morphoscopy and mineralogy

The morphoscopic study of sediments consists in observing the grains using a binocular magnifier in order to describe their shape, that is to say their sphericity as well as their degree of bluntness, to classify (Wentoworth , 1922) and to sort them out (Folk, 1957; 1980). The description thus obtained provides important information on their conditions of deposition and transport.

This process is followed by a more in-depth observation of the main components and minerals present in the studied samples using a petrographic microscope in plane-polarized light (PPL) and cross-polarized light (XPL). These two modes of observation make it possible to confirm the characteristics of the grains, in particular concerning their shape and their classification, but also to highlight different details from a mineralogical point of view. If an adjustment of the microscope in PPL makes it possible to observe the relief of minerals and to check the presence or absence of iron oxide and/or other signs of deterioration (Figure 4-A), an adjustment in XPL makes it possible to observe birefringence, extinction angles, twinnings and cleavages which are significant in accurately determining the minerals and elements present (Figure 4-B).

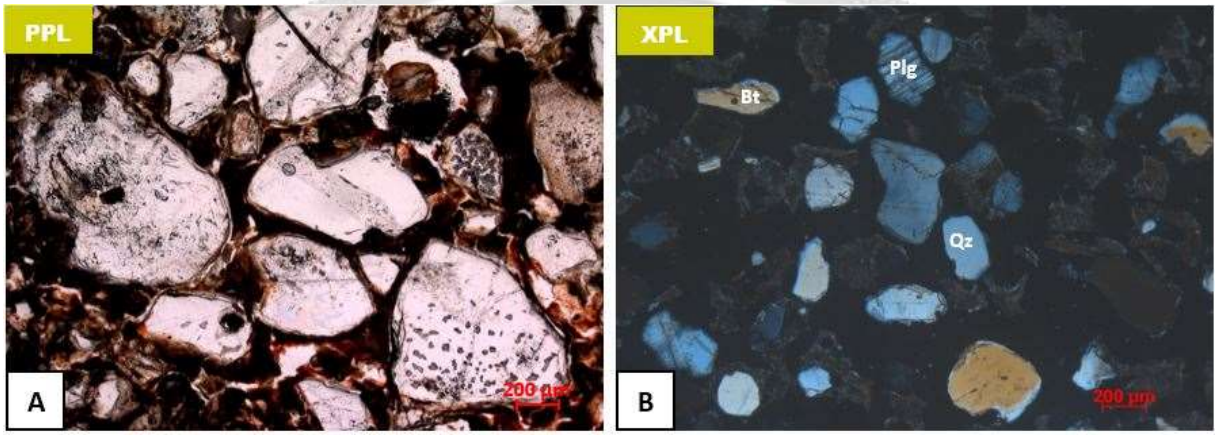

Figure 4. (A) A07 thin section in PPL showing signs of alteration on some minerals and presence of iron oxide responsible for the faint orange color at the edges of some grains and (B) A04 thin section in XPL showing poorly sorted grains mainly made of quartz.

The deposits studied being mainly continental deposits, but sometimes outcropping nearby or with marine deposits which overlie them, the minerals in the Table 2 based on previous work (Barker, 2014 ; MacKenzie et al., 2017), are the most observed under the petrographic microscope: quartz, feldspars, micas and more rarely calcite.

Table 2. 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°	One
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	3 perfect	3rd order	_	Lamellar

	moderately low	(very high)

Observation of the sediments with a binocular magnifier and a petrographic microscope made it possible to deduce that the Anembalemba Member is made up mainly of sandstones and clays with grains of variable dimensions mixed between them. They are classified either among lutites for dimensions less than 0.063 mm, or among arenites for dimensions between 0.063 and 2 mm depending on the dominant proportion. The mixture of these grains of different sizes in the same formation also shows that they are poorly sorted, except for the case of A04 for which the grains are exceptionally fairly well sorted. The morphoscopic study also reveals that the majority of grains observed are sub-rounded to sub-angular and show a shiny appearance (Table 3).

Table 3. Grains description of the sandstones samples collected from the Kinkony Lake Study Area.

Samples	Grain-Size (mm)	Classification (Wentworth)	Grain form (Tricart, 1959)	Surface aspect	Grain sorting (Folk)
A01	0.053 – 2	Coarse silt to very coarse sand	Sub-angular	Shiny	Very poorly sorted
A02	0.053 – 1	Coarse silt to coarse sand	Sub-angular	Shiny	Poorly sorted
A03	0.0125 – 2	Very fine silt to very coarse sand	Sub-rounded to sub-angular	Shiny	Poorly sorted
A04	0.053 – 0.5	Coarse silt to medium-grained sand	Sub-rounded to sub-angular	Shiny	Poorly sorted
A05	0.053 – 2	Coarse silt to very corse sand	Sub-rounded	Shiny	Very poorly sorted
A06	0.053 – 1	Coarse silt to coarse sand	Sub-rounded	Shiny	Poorly sorted
A07	0.053 – 1	Corse silt to coarse sand	Sub-rounded to sub-angular	Shiny	Poorly sorted

3.4. Geochemical Analysis

In the field, for a first determination of the nature of the sediments, they were tested and did not react to hydrochloric acid to exclude the possibility that they were marl or other limestone formations. A priori, the sediments studied are then sandstones, clayey sandstones or sandstone clays according to a first macroscopic observation.

In this study, the geochemical analysis focuses on the major elements in order to obtain relevant information on the depositional conditions and the paleoenvironment during this Campanian period. This involves defining in particular the level (in %) of silica, calcium, iron, magnesium and aluminum (Table 4).

Table 4. Geochemical analysis of major elements.

Samples	Fe_2O_3 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	SiO_2 (%)
A01	8.86	28.19	0.01	0.92	51.46
A02	4.88	38.06	0	0.83	62.37
A03	6.94	31.19	0	1.08	45.11
A04	5.97	42.19	0	0.50	59.5
A05	1.91	23.64	0	0.85	79.19
A06	11.26	29.47	0	0.43	45.89

A07	5.26	27.47	1.04	0.56	65.26

4. RESULTS AND INTERPRETATION

4.1. Mineralogical Composition

For the seven samples taken in the Anembalemba Member, it was observed that quartz with the chemical formula SiO_2 is the predominant mineral over the other minerals. Moreover, the geochemical analysis of the major elements showed a very high percentage of SiO_2 ranging from 45.11 to 79.19% confirming this predominance of the quartz. Taking into account this composition and the grain size varying between 0.053 to 2 mm but with a greater proportion of grains with a size greater than 0.063 mm, we have arenites. Depending on the percentage of fine grains and coarser grains, the samples are clayey sandstones (A03, A04 and A05) and sandstones-rich clays (A01, A02, A06 and A07).

For most of the samples, the CaO level is zero and only two of them (A01 and A02) contain CaO but in a very small quantity (0.01 and 1.04%). This also explains the virtual absence of calcite when observed under an optical microscope, the mineral characteristic of carbonate formations and marine formations. Thus, the sedimentary deposits studied are continental deposits, especially since they present, in addition to quartz, elements which support their continental origin including biotite and other micas as well as plagioclase.

4.2. Conditions and Environment of Deposition of the Anembalemba Member in the Kinkony Lake Study Area

In the Lake Kinkony sector, the contact of the Anembalemba Member with the Masorobe Member is not very clear. The Masorobe Member observed in the field (X: 321952; Y: 1105064) and outcropping near the first outcrop of the Anembalemba Member studied in this manuscript (X: 322426; Y: 1105515) presents towards its upper limit clayey sandstones deposits resembling those of sample A05 (X: 322437; Y: 1105536) considered as belonging to the Anembalemba Member given that it overcomes at its outcrop formations similar to those of A01 according to the principle of continuity of the layers. The outcrops were observed from East to West following this same principle and the lithology of the study area is then described from bottom to top as follows:

- The Masorobe Member is composed of reddish gray clayey sandstones and outcrops with a thickness of at least 0.5 m. Its contact with Anembalemba Member is difficult to determine.
- The Anembalemba Member is formed towards its base by sandstones-rich clays of a greenish gray color sometimes with reddish stains with a thickness of 1.10 m to 1.40 m (A01, A07).
- They are overlied by a thin layer of white sandstones-rich clays (A02, A06) with a thickness of approximately 0.8 m.
- They are then topped by white clayey sandstones with cross-stratifications (A03, A04) with a thickness of at least 1 m.
- Finally, the series ends with deposits of reddish gray clayey sandstones with a thickness of at least 0.4 m in the locality.

On the one hand, the characteristics observed in the deposits of layers A01 and A07 are very similar to those observed at the outcrops of Berivotra and Bongomilitera which correspond to Facies 2 of the Anembalemba Member. This would explain their very poorly sorted grains and their massive structure meaning that their deposition took place quickly. On the other hand, the layers corresponding to A03 and A04 present better sorted grains than those of A01 and A07, as well as cross-stratifications. Those characteristics are specific to Facies 1 of the Anembalemba Member observed in the Berivotra and Bongomilitera sectors.

5. DISCUSSION

The lithostratigraphic, grain size and geochemical studies carried out on the sediments of the Anembalemba Member and their outcrops make it possible to obtain important information on the Campanian paleoenvironment in the Kinkony Lake sector of the Mahajanga Basin. The way in which the layers of the

Anembalemba Member are arranged as well as their main characteristics indicate that a calm and stable period (deposition of fine clay particles) precedes a period of major floods (massive deposits with poorly sorted grains) during the establishment of Facies 2 deposits. The formations of the Anembalemba Member were deposited during a period of continental transgression, confirming the continental facies of the Campanian in the Mahajanga Basin. A large part of the continental elements are then transported by fluvial waters towards the sea with a fairly strong current as revealed in prior taphonomic study on fossil vertebrates from the basin's Campanian (Rabenorosoa, 2009). The outcrop of cross-stratified clayey sandstones of the Anembalemba Member at several localities in the Kinkony Lake sector and throughout the Mahajanga Basin allows us to deduce that during the establishment of the Anembalemba Member, the depositional environment is essentially an alluvial plain in which the phases of deposition and transport of sediments alternate.

Also, the geochemical analysis of the major elements which constitute the sediments collected from the Anembalemba Member of the Kinkony Lake sector revealed the presence of Mg0 in the samples, which gives a significant index in terms of paleoclimate. Even in small quantities or in trace amounts, Mg0 effectively indicates that the sediments were deposited in a warm and subtropical climate environment as in the entire Mahajanga Basin at that time.

Regarding the rarity of fossil vertebrates from the Anembalemba Member in the Kinkony Lake sector, although certain remains were found there during previous work (Rogers et al., 2013), compared to the case of the Berivotra sector, this can be explained by less favorable depositionnal and conservation conditions. Indeed, this study showed that the thickness of the Anembalemba Member is significantly lower than in the Berivotra sector due to the fact that the entire Maevarano Formation becomes naturally thinner as we move towards the southwest of the Mahajanga Basin, or towards the town of Soalala. This thinning is conditioned by the topography and geomorphology of the Basin. In the Kinkony Lake sector, the accommodation space available did not necessarily allow the effective burial of large vertebrates. If, however, it did take place, the geochemical results (Table 4) also show considerable contents of Fe_2O_3 and Al_2O_3, indicating too much exposure of the sediments of interest to air and alteration, which also explains their slightly reddish tint at many outcrops in the area.

6. CONCLUSION

This study focused on the description and characterization of the sedimentary deposits of the Anembalemba Member of the Maevarano Formation in the Lake Kinkony sector, the study site located furthest west of the Mahajanga Basin and one least explored. The interpretation of the results of the morphoscopic, lithostratigraphic, mineralogical and geochemical study of the sediments of interest led to the following conclusions:

i. The Anembalemba Member of the Kinkony Lake Sector was deposited during a period of continental transgression and therefore has a frankly continental facies.
ii. Its depositional environment is made up of alluvial plains in which there was a calm and stable period favoring the deposition of fine clay particles, but then followed by a period of major floods marked by massive deposits with very poorly sorted grains. Then, the strength of the fluvial water current increased to transport a large quantity of continental elements towards the sea following the morphology of the basin until the end of the Campanian.
iii. The presence of MgO indicates that the climate which reigned during the deposition of the sediments of the Anembalemba Member was warm and subtropical.
iv. The environmental conditions were not favorable for the burial and preservation of large fossil vertebrates. They were linked in particular to insufficient accommodation space and great exposure to the air and to alteration indicated by considerable levels of Fe_20_3 and Al_20_3.

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