Stratigraphic Analysis of Upper Cretaceous Rocks in the Mahajanga Basin, Northwestern Madagascar: Implications for Ancient and Modern Faunas

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ABSTRACT

Upper Cretaceous strata of the Mahajanga Basin, northwestern Madagascar, yield some of the most significant and exquisitely preserved vertebrate fossils known from Gondwana. The sedimentology of these strata and their stratigraphic relations have been the focus of renewed geological investigations during the course of five expeditions since 1993. We here designate stratotypes and formalize the terrestrial Maevarano Formation, with three new members (Masorobe, Anembalemba, Miadana), and the overlying marine Berivotra Formation. The Maevarano Formation accumulated on a broad, semiarid alluvial plain bounded to the southeast by crystalline highlands and to the northwest by the Mozambique Channel. The Berivotra Formation was deposited in an open marine setting that evolved from a clastic- to a carbonate-dominated shelf, resulting in deposition of the overlying Betsiboka limestone of Danian age. New stratigraphic data clearly indicate that the Maevarano Formation correlates, at least in part, with the Maastrichtian Berivotra Formation, and this in turn indicates that the most fossiliferous portions of the Maevarano Formation are Maastrichtian in age, rather than Campanian as previously reported. This revised age for the Maevarano vertebrate assemblage indicates that it is approximately contemporaneous with the vertebrate fauna recovered from the Deccan basalt volcano-sedimentary sequence of India. The comparable age of these two faunas is significant because the faunas appear to be more similar to one another than either is to those from any other major Gondwanan landmass. The revised age of the Maevarano Formation, when considered in the light of our recent fossil discoveries, further indicates that the ancestral stocks of Madagascar's overwhelmingly endemic modern vertebrate fauna arrived on the island in post-Mesozoic times. The basal stocks of the modern vertebrate fauna are conspicuously absent in the Maevarano Formation. Finally, the revised age of the Maevarano Formation serves to expand our global perspective on the K/T event by clarifying the age of a diverse, and arguably the best preserved, sample of Gondwanan vertebrates from the terminal Cretaceous.

Introduction

Over the past century, Upper Cretaceous strata in the Mahajanga Basin of northwestern Madagascar (fig. 1) have yielded small but intriguing samples of terrestrial and freshwater vertebrates, most notably dinosaurs (Depéret 1896*a*, 1896*b*; Thévenin 1907; Perrier de la Bathie 1919; Piveteau 1926; Lavocat 1955*a*, 1955*b*; Hoffstetter 1961; Collignon 1968; Russell et al. 1976; Obata and Kanie 1977; Buffetaut and Taquet 1979; Sues and Taquet 1979; Sues 1980; Asama et al. 1981; Ravoavy 1991). Recent joint expeditions of the State University of New York at Stony Brook and the University of Antananarivo to the Mahajanga Basin have targeted several of the more productive fossil-bearing horizons, and this ongoing research (the "Mahajanga Basin Project") has already more than quadrupled the previously known species diversity of Late Cretaceous vertebrates from the island. These discoveries have begun to shed light on important aspects of the evolutionary and biogeographic history of the vertebrates of Gondwana in general and Madagascar in particular (Krause et al. 1994, 1997*a*, 1997*b*, 1999; Forster et al. 1996, 1998; Sampson et al. 1996, 1998; Curry 1997; Asher and Krause 1998; Dodson

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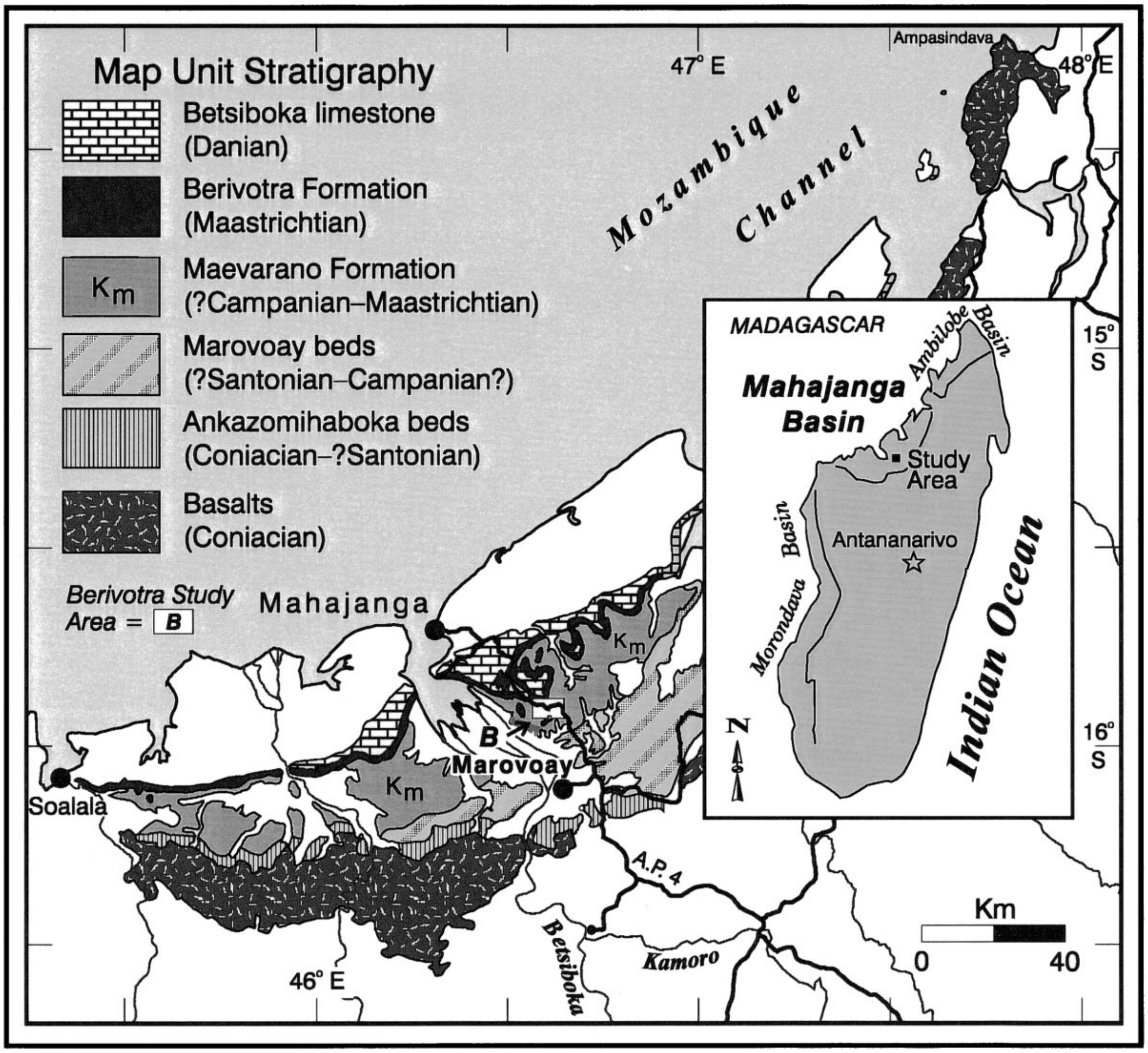


Figure 1. Late Cretaceous and Paleocene geology of the Mahajanga Basin, northwestern Madagascar. Map units were compiled from 1 : 500,000–scale maps after Besairie (1968, 1969, 1971). The three major sedimentary basins of western Madagascar are shown on the inset map of the island. Basins are delimited by the contact of Cretaceous-Jurassic strata in the Morondava and Mahajanga basins and the base of the "Karoo Facies" in the Ambilobe (Diego) Basin (after Besairie 1961).

et al. 1998; Gottfried and Krause 1998; Gottfried et al. 1998; Buckley and Brochu 1999).

In contrast, relatively few studies with sedimentologic or stratigraphic objectives have been initiated in the Mahajanga Basin, and consequently, there remains confusion with regard to stratigraphic nomenclature and regional correlation. Reliable age control has been particularly elusive, and a better understanding of chronostratigraphy, especially in the nonmarine record, is crucial to casting phylogenetic and biogeographic hypotheses within a meaningful temporal framework. A case in point, the dinosaur-bearing Maevarano Formation (stratotype described here) was initially considered to be Turonian by Depéret (1896*b*; followed by Thévenin 1907) and later modified to Turonian to Santonian by Lemoine (1911; followed by Perrier de la Bathie 1919; and by von Huene and Matley 1933), Santonian by de Lapparent (1957), and Campanian by Hoffstetter (1961). A Campanian age for the Maevarano Formation appears to have been accepted by Karche and Mahe (1967), Besairie (1972), and all subsequent workers (e.g., Brenon 1972; Russell et al. 1976; Buffetaut and Taquet 1979; Sues and Taquet 1979). However, on the basis of new data reported here, it is now apparent that relegation of the Maevarano Formation to the Campanian is an oversimplification of stratigraphic relations.

In this report, we examine the existing stratigraphic nomenclature in the Mahajanga Basin and suggest several amendments that pertain to the Upper Cretaceous section. In particular, we formalize the Maevarano Formation and the overlying Berivotra Formation by designating stratotypes, and we propose three new members within the Maevarano Formation, namely, the Masorobe, Anembalemba, and Miadana members. Formalization of lithostratigraphic units is deemed appropriate because (1) the two formations and three new members under consideration are characterized by distinctive and readily observable lithic properties, (2) contacts of the two formations have already been mapped on a regional scale (Service Géologique de Madagascar 1960), and (3) relegation to formal status is preferable to maintaining a confusing mix of informal terminology tainted with chronostratigraphic implications. With a better appreciation of the basic lithostratigraphy, we present new interpretations of depositional environments and establish a more realistic framework for regional correlation. Our new stratigraphic framework suggests a revised age, Maastrichtian, for the richly fossiliferous beds in the upper portion of the Maevarano Formation. This new age determination has profound biogeographic implications for both ancient and modern Malagasy faunas.

Regional Setting

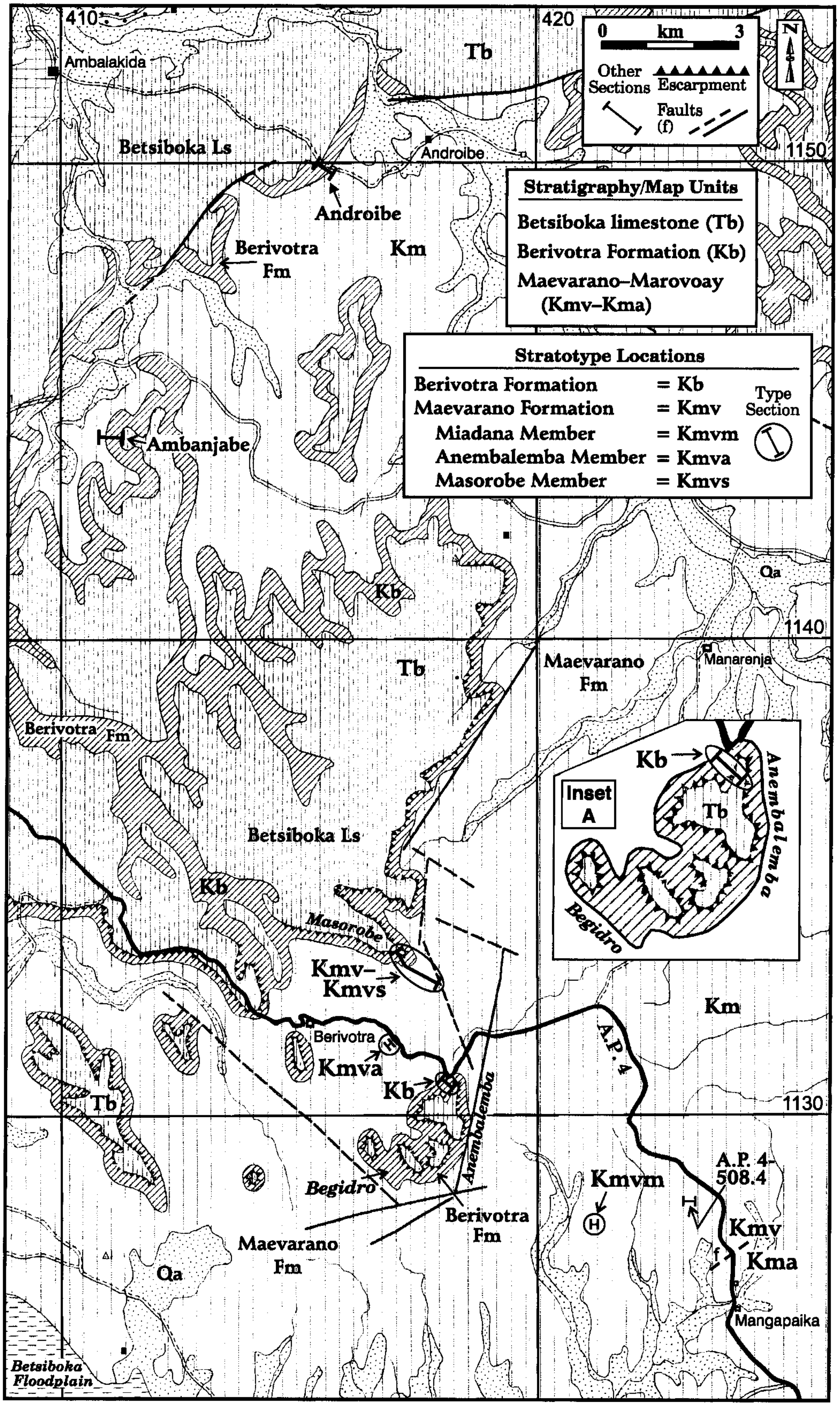
Extension and rifting between Madagascar and Africa began during the Permo-Triassic. Geophysical data summarized in Coffin and Rabinowitz (1988, 1992), Lalaharisaina and Ferrand (1994), Storey et al. (1995, 1997), Roeser et al. (1996), and Krause et al. (1997*a*) indicate that sea floor spreading between the conjugate-rifted margins of southern Somalia, Kenya, and Tanzania (Western Somali Basin) and northern Madagascar was initiated by the Late Jurassic (~165 Ma). This first episode of oceanic rifting was focused in the Somali and Comoros basins and led to separation of the Indo-Madagascar block from mainland Africa. Madagascar-India followed a south-southeastward trajectory along the Davie Fracture Zone until coming to rest some 400 km off the east coast of Mozambique in the Early Cretaceous (130–125 Ma). A second major rifting event in the Late Cretaceous led to the separation of Madagascar and India. This episode of sea floor spreading was centered in the Mascarene Basin and was accompanied by an outpouring of flood basalts on the island of Madagascar. Dates from these flood basalts cluster in age around 87.6 ± 0.6 Ma (weighted mean) (Storey et al. 1997). With this second episode of rifting, the Indian subcontinent moved rapidly northeastward toward Eurasia (Randrianasolo et al. 1981; Storetvedt et al. 1992; Storey et al. 1995, 1997). Madagascar, as part of the African Plate, continued to move northward to its present position between 12° and 26° south.

Rifting between Madagascar and Africa created three major sedimentary depocenters along Madagascar's western margin—the Morondava, Mahajanga, and Ambilobe basins (fig. 1). Nonmarine Permo-Triassic sediments accumulated in these basins during early stage rifting (Boast and Nairn 1982; Wescott and Diggens 1997). Marine conditions were established in parts of the intervening rift by the Middle Jurassic. In the Early Cretaceous, active rifting ceased, and the western coast of Madagascar evolved into a passive margin that experienced transgressive-regressive cyclicity until the end of the Cretaceous (Lalaharisaina and Ferrand 1994). The marginal basins of Madagascar were largely inundated by marine waters by the end of the Cretaceous, and marine conditions persisted throughout much of the Paleogene and into the Neogene.

The Mahajanga Basin extends for approximately 400 km along Madagascar's northwestern coast, stretching from the town of Soalala on the south to the Ampasindava Peninsula on the north (fig. 1). The Sahondralava-Ihopy horst, which was active during the filling of the basin, delimits the boundary between two subbasins—the southwestern Mitsinjo subbasin and the northeastern Loza-Mahavavy subbasin (Boast and Nairn 1982). This report focuses on the outcrop belt within the Loza-Mahavavy subbasin, in the central portion of the Mahajanga Basin, where the Antananarivo-Mahajanga national route (A.P. 4) provides access to badland exposures and limestone-capped escarpments of Upper Cretaceous and Tertiary strata. Our investigation is centered in the richly fossiliferous outcrops that surround the village of Berivotra, but exposures to the north and south were also examined to gain a better understanding of the regional stratigraphy (fig. 2).

Lithostratigraphy

Previous Work. Formal stratigraphic terminology is currently employed for a relatively small fraction of the sedimentary succession in the Mahajanga Basin. The basal Sakamena Group (uppermost Permian–Lower Triassic), which is either in



410
420
0 km 3
N
Other Sections
Escarpment
Faults (f)
Tb
Ambalakida
Androibe
Betsiboka Ls
1150
Stratigraphy/Map Units
Betsiboka limestone (Tb)
Berivotra Formation (Kb)
Maevarano–Marovoay (Kmv–Kma)
Androibe
Berivotra Fm
Km
Stratotype Locations
Berivotra Formation = Kb
Maevarano Formation = Kmv
Miadana Member = Kmvm
Anembalemba Member = Kmva
Masorobe Member = Kmvs
Type Section
Ambanjabe
Kb
Qa
1140
Tb
Maevarano Fm
Manarenja
Berivotra Fm
Kb
Inset A
Tb
Anembalemba
Begidro
Betsiboka Ls
Kb
Masorobe
Kmv–Kmvs
Km
A.P. 4
Berivotra
Kmva
Kb
Tb
1130
Anembalemba
A.P. 4-508.4
Kmvm
Begidro
Berivotra Fm
Kmv
Maevarano Fm
f
Kma
Qa
Mangapaika
Betsiboka Floodplain

fault contact with or rests nonconformably on crystalline basement, is locally exposed only in northern reaches of the basin. The Isalo Group (Middle Triassic–Middle Jurassic), which consists of interfingering continental and marginal marine facies, rests unconformably on the Sakamena Group (Boast and Nairn 1982). The heterolithic nature of the Isalo Group has led to the recognition of several informal subunits (e.g., Isalo I, II, IIIa, and IIIb; see Besairie 1972; Boast and Nairn 1982). A thick succession of interbedded marine and terrestrial strata that accumulated from the Late Jurassic into the Cretaceous overlies the Isalo Group. A review of Besairie (1972) indicates that at least eight informal units are recognized in this heterolithic interval, with the Ankarafantsika and Amboromalandy sandstones (Turonian?) intercalated at the base of the Upper Cretaceous section. Flood basalts dated to ~88 Ma (early Coniacian based on the time scale of Gradstein et al. 1995) cap Turonian deposits throughout most of the Mahajanga Basin. These basalts have recently been linked to the onset of rifting between Madagascar and the Seychelles Island group-Indian subcontinent (Storey et al. 1995, 1997).

Four sedimentary units of Late Cretaceous age have traditionally been distinguished above the Coniacian flood basalts (Perrier de la Bathie 1919; Besairie 1938, 1972) (figs. 1, 3). Besairie (1972) subdivided the lower three of these four units, all of which are nonmarine, into three "séries." The basal unit was referred to as the "série d'Ankazomihaboka" and includes tan and brown cross-bedded sandstones and claystones of terrestrial origin. In the region immediately to the north of the Betsiboka River, beds of the "série d'Ankazomihaboka" crop out above and below the Coniacian basalts (see Besairie 1972, plate 34). The overlying "série de Marovoay," also terrestrial, consists of variegated purple, yellow, pink, and red beds of sandstone intercalated with thin beds of claystone. Surface exposures of the "série de Marovoay" exhibit abundant fluvial cross-bedding and evidence of pedogenesis. The sandstone-dominated "série de Maevarano" (the Maevarano Formation of this article) overlies the "série de Marovoay" and, according to Besairie (1972), can be distinguished by more pervasive fluvial cross-bedding and a significant carbonate content (presumably pedogenic). Obata and Kanie (1977) subdivided the "série de Maevarano" (which they referred to by its map unit designation of C^8; Service Géologique de Madagascar 1960) into informal lower and upper members, but they failed to designate type localities or to fully characterize lithological properties. These nonmarine units are disconformably overlain by calcareous claystones and shales of marine origin that Besairie (1972) referred to as the "marnes Maastrichtiennes" (the Berivotra Formation of this article).

Regional thickness trends and lateral facies relationships of these Upper Cretaceous units are poorly documented. In addition, neither stratotype localities nor reference sections have ever been designated, and the boundaries between these units have never been adequately described. As a consequence, some workers (e.g., Obata and Kanie 1977; Papini and Benvenuti 1998) have avoided usage of some or all of these terms and opted instead to use more generalized map unit designations (e.g., C^7, C^8, C^9) established by the Service Géologique de Madagascar (1960). To complicate matters further, virtually all previous workers (e.g., Besairie 1972; Obata and Kanie 1977; Krause and Hartman 1996; Papini and Benvenuti 1998) have correlated the lithologic transitions that bound these units with stage boundaries, and as a consequence, both the lithostratigraphy and the chronostratigraphy of the Upper Cretaceous section in the Mahajanga Basin are problematic and in need of revision.

Maevarano Formation. There is a general lack of information with regard to the original definition of the "série de Maevarano" (Besairie 1938, 1972). Besairie (1972) reported a thickness of approximately 370 m for this unit between the Mahajamba and Betsiboka rivers, but he did not describe any surface localities in detail, and he failed to indicate how and where this thickness estimate was derived. Besairie did provide a cursory description of a well log located on the Betsiboka delta plain (sondage de la Tuilerie), and based on his interpretation of this well, the "série de Maevarano" is at least 150 m thick. However, in the published description of this well log, Besairie (1972, p. 182) included marine microfossils of Maastrichtian age within the "série Campanienne de Maevarano." It thus ap-

Figure 2. Geological map of the Berivotra region (based on the Majunga-Ambalakida 1 : 100,000 sheet, Service Géologique de Madagascar 1960). Stratotype locations are indicated, as are supplementary sections (Ambanjabe, Androibe, A.P. 4-508.4). Inset *A* is an enlargement of the southern Berivotra field area showing the location of the Berivotra Formation stratotype on the northern edge of Anembalemba.

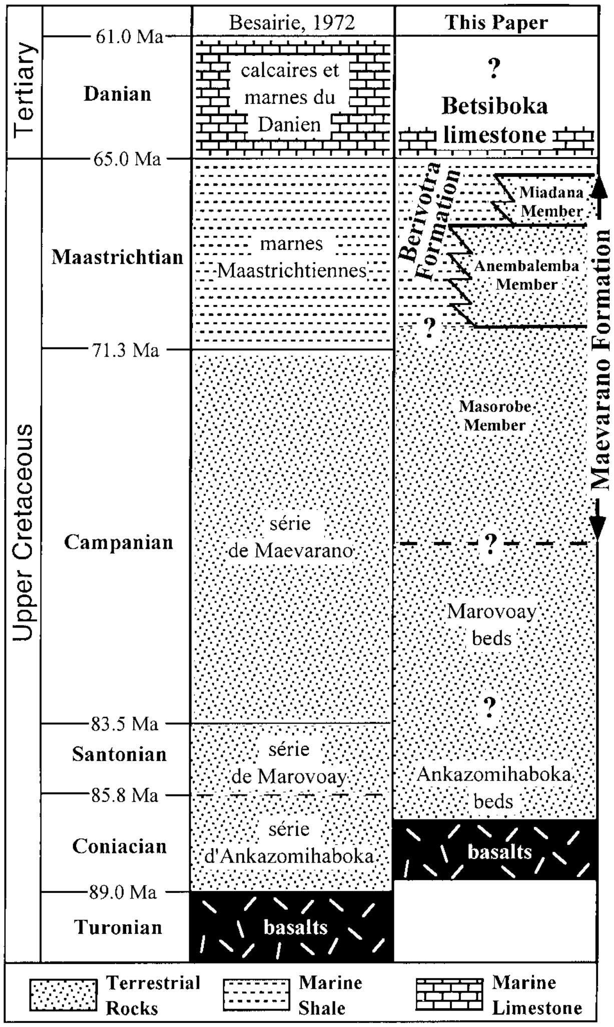


Figure 3. Stratigraphy of Upper Cretaceous and Paleocene strata of the Mahajanga Basin. The stratigraphic nomenclature and chronostratigraphic interpretations of Besairie (1972) are shown in relation to our findings. Before our study, the units under scrutiny were normally stacked with stage boundaries positioned at their contacts. Relegation of the basalts to the Coniacian is based on recent dating by Storey et al. (1995, 1997).

pears as though the Maevarano Formation and the overlying marine Berivotra Formation were combined in Besairie's analysis.

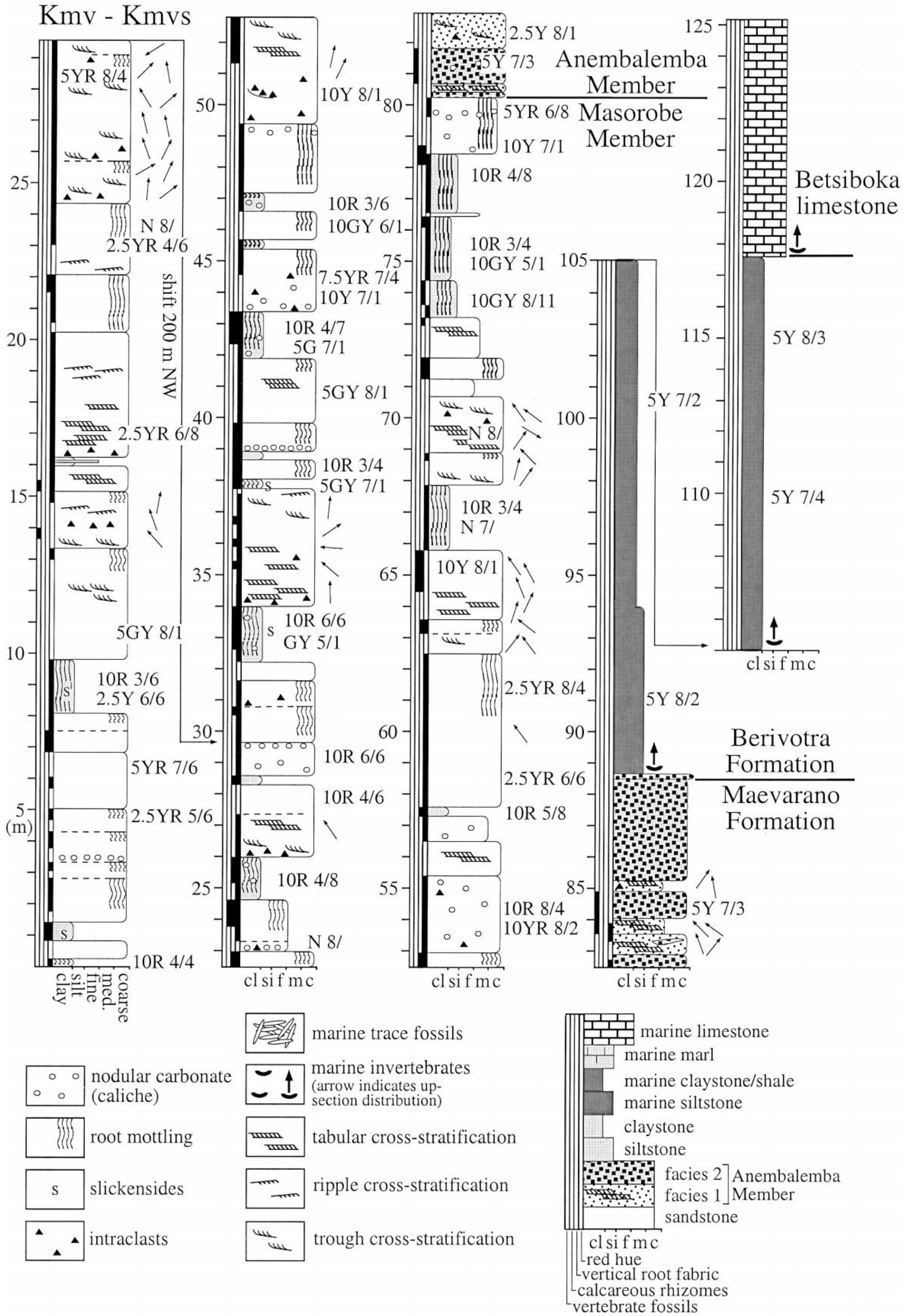
Our description of the Maevarano Formation is based on outcrop in the vicinity of the village of Berivotra (fig. 2). We are confident that the formation as defined here is equivalent to the "série de Maevarano" of Besairie (1972) and map unit C^8 of the Service Géologique de Madagascar (1960).

The proposed type section of the Maevarano Formation is located along the southern flank of a prominent ridge called Masorobe in the general vicinity of the village of Berivotra (fig. 2). The coordinates at the base of the section are 15°53′34.8″S, 46°36′15.4″E. Starting from this position, only one minor offset is required to access 88.5 m of continuous exposure to the upper contact with the Berivotra Formation (15°53′24.0″S, 46°35′53.3″E). A graphic stratigraphic log of the Maevarano Formation measured at the type locality is illustrated in figure 4.

Despite considerable effort, we have been unable to locate a depositional contact between the Maevarano Formation and the underlying Marovoay beds in outcrop anywhere within the central part of the Mahajanga Basin, and to complicate matters, a previously unrecognized normal fault coincides with the mapped contact between these two units in the vicinity of national route A.P. 4 (fig. 2). In contrast, the upper contact of the Maevarano Formation is readily accessible in the Berivotra region, and in the type section, it is a disconformity marked by the abrupt juxtaposition of silty olive yellow clay shales (Berivotra Formation) on a 5–20-cm-thick bed of very coarse to conglomeratic sandstone. This bed, which tends to cap local buttes, is well cemented with calcite and yields rounded pebbles of chert and polished bone, along with scattered teeth of selachians (Gottfried and Rabarison 1997; J. A. Rabarison, L. L. Randriamiaranana, and M. J. Gottfried, unpub. manuscript). Rounded and thoroughly bored cobbles of siltstone also occur on the contact. Some borings display the distinctive flask shape commonly attributed to pholadid bivalves. Locally, the contact is overlain by flattened cobbles of coarse-grained conglomeratic sandstone and large boulders of densely packed shell bed (fig. 5).

Coarse-grained, poorly sorted sandstone is the most conspicuous lithology in the Maevarano Formation type locality, with <20% of the stratotype composed of finer-grained sandstone, siltstone, or claystone (fig. 4). Sandstone beds in the type section range from massive to pervasively cross stratified. Cross-stratified intervals typically display small- to medium-scale tabular and trough cross-bed sets (see below). Angular to subrounded quartz and feldspar grains are the most abundant framework components, and clay appears to be the only cementing agent. X-ray diffraction analyses of the clay fraction indicate that smectite is the predominant clay mineral, with lesser amounts of illite and kaolinite. Pedogenic features are developed throughout the formation, but they are most common in the lower 80 m of the type section (fig. 4).

A shift from predominantly red-bed facies to a



Kmv - Kmvs
shift 200 m NW
Anembalemba Member
Masorobe Member
Betsiboka limestone
Berivotra Formation
Maevarano Formation
5YR 8/4
N 8/
2.5YR 4/6
2.5YR 6/8
5GY 8/1
10R 3/6
2.5Y 6/6
5YR 7/6
2.5YR 5/6
10R 4/4
10Y 8/1
10R 3/6
10GY 6/1
7.5YR 7/4
10Y 7/1
10R 4/7
5G 7/1
5GY 8/1
10R 3/4
5GY 7/1
10R 6/6
GY 5/1
10R 6/6
10R 4/6
10R 4/8
N 8/
2.5Y 8/1
5Y 7/3
5YR 6/8
10Y 7/1
10R 4/8
10R 3/4
10GY 5/1
10GY 8/11
N 8/
10R 3/4
N 7/
10Y 8/1
2.5YR 8/4
2.5YR 6/6
10R 5/8
10R 8/4
10YR 8/2
5Y 7/2
5Y 8/2
5Y 7/3
5Y 8/3
5Y 7/4
(m)
clay silt fine med. coarse
cl si f m c
nodular carbonate (caliche)
root mottling
slickensides
intraclasts
marine trace fossils
marine invertebrates (arrow indicates up-section distribution)
tabular cross-stratification
ripple cross-stratification
trough cross-stratification
marine limestone
marine marl
marine claystone/shale
marine siltstone
claystone
siltstone
facies 2
facies 1
Anembalemba Member
sandstone
red hue
vertical root fabric
calcareous rhizomes
vertebrate fossils

distinctive interval of green and light gray/white beds of sandstone occurs 80 m above the base of the Maevarano stratotype (fig. 4). This lithologic transition, which is easily traced throughout available exposures in the Berivotra field area, coincides with an increase in the richness of the Maevarano fossil record and serves as the contact between the newly proposed Masorobe and Anembalemba members (see below). Obata and Kanie (1977) recognized this same lithologic shift, and they used it to distinguish informal lower and upper members of the Maevarano Formation.

Masorobe Member. Exposures of the newly proposed Masorobe Member can be traced throughout the region surrounding the village of Berivotra. The type section is exposed on the south side of Masorobe and coincides with the lower 80 m of exposure in the Maevarano Formation type section (figs. 2, 4, see locality data above). The Masorobe Member is characteristically (but not exclusively) red in color and is composed of coarse-grained, poorly sorted sandstone with occasional intercalations of fine-grained sandstone, siltstone, and claystone. Paleosols are well developed within the member (fig. 6), and 36 discrete pedogenic horizons have been identified in the type section. Evidence of pedogenesis includes color banding, superbly developed root casts (with drab root halos and occasional calcareous encrustations), root mottling (often with a strong vertical fabric), caliche, and rare slickensides. Despite pervasive pedogenic alteration, some sandstone beds exhibit primary stratification that consists of small- to large-scale tabular and trough cross-bed sets (fig. 6*E*, 6*F*). The vector mean of 40 paleocurrent measurements taken from cross-stratified units is 347°. Vertebrate fossils are rare in the Masorobe Member, and they are generally isolated and of poor preservational quality. To date, no invertebrate fossils have been recovered.

Eighty meters of the Masorobe Member are exposed at the type section, but the basal contact is not exposed, and thus the full thickness and regional geometry of the unit cannot be determined. The upper contact of the Masorobe Member is defined by a disconformity positioned at 80.3 m in the Maevarano Formation type section (fig. 4). This disconformity separates a root-mottled fine- to coarse-grained sandstone facies with a red hue (5YR 6/8) from an overlying bed of coarse-grained sandstone with massive structure and an olive green color (5Y 5/3).

Anembalemba Member. Exposures of the Anembalemba Member can also be traced throughout the region surrounding the village of Berivotra. The type section is exposed along the western side of national route A.P. 4, near a prominent ridge called Anembalemba (fig. 2). Here, the Anembalemba Member is exposed in its entirety in a pyramid-shaped roadcut with the coordinates 15°54′14.2″S, 46°35′45.6″E (figs. 7*A*, 8*A*).

Two distinctive sandstone facies (here designated facies 1 and facies 2) characterize the Anembalemba Member (figs. 7*A*, 8). Facies 1 consists of fine- to coarse-grained, poorly sorted sandstone with a sizable clay component. The light gray to white (10GY 5/1 to N 8/) sandstones of facies 1 typically display small- to medium-scale tabular and trough cross stratification. Directional measurements ($n = 51$) derived from outcrops of facies 1 throughout the study area yield a vector mean of 337°. Facies 2 consists of fine- to coarse-grained clay-rich sandstone characterized by very poor sorting, massive structure and an olive green color (5GY 8/1). In all known exposures of the Anembalemba Member, cross-stratified beds of facies 1 and massive beds of facies 2 (and occasional beds characterized by a blend of features from both) are recurrently interbedded with erosional contacts. Bed thickness and lateral traceability varies from outcrop to outcrop, and load structures (including spectacular examples of ball and pillow structure) are relatively common (fig. 8*E*).

Vertebrate fossils are amazingly abundant within the Anembalemba Member (table 1), and in the past few years >25 taxa previously unknown from the Late Cretaceous of Madagascar have been recovered and described (e.g., Krause et al. 1994, 1997*a*,

Figure 4. Graphic stratigraphic log of the proposed stratotype of the Maevarano Formation and Masorobe Member. This measured section is located along the southern flank of a prominent ridge called Masorobe northeast of the village of Berivotra (fig. 2). The coordinates at the base of the section are 15°53′34.8″S, 46°36′15.4″E. Starting from this position, only one minor offset is required to access 88.5 m of continuous exposure to the upper contact with the Berivotra Formation. A shift from predominantly red-bed facies to a distinctive interval of green and light gray/white beds of sandstone occurs 80.3 m above the base of the Maevarano stratotype. This lithologic transition, which is easily traced throughout available exposures in the Berivotra field area, serves as the contact between the newly proposed Masorobe and Anembalemba members. Small arrows indicate paleocurrent measurements. Munsell color notation is also provided. Key also applies to figures 7 and 9.

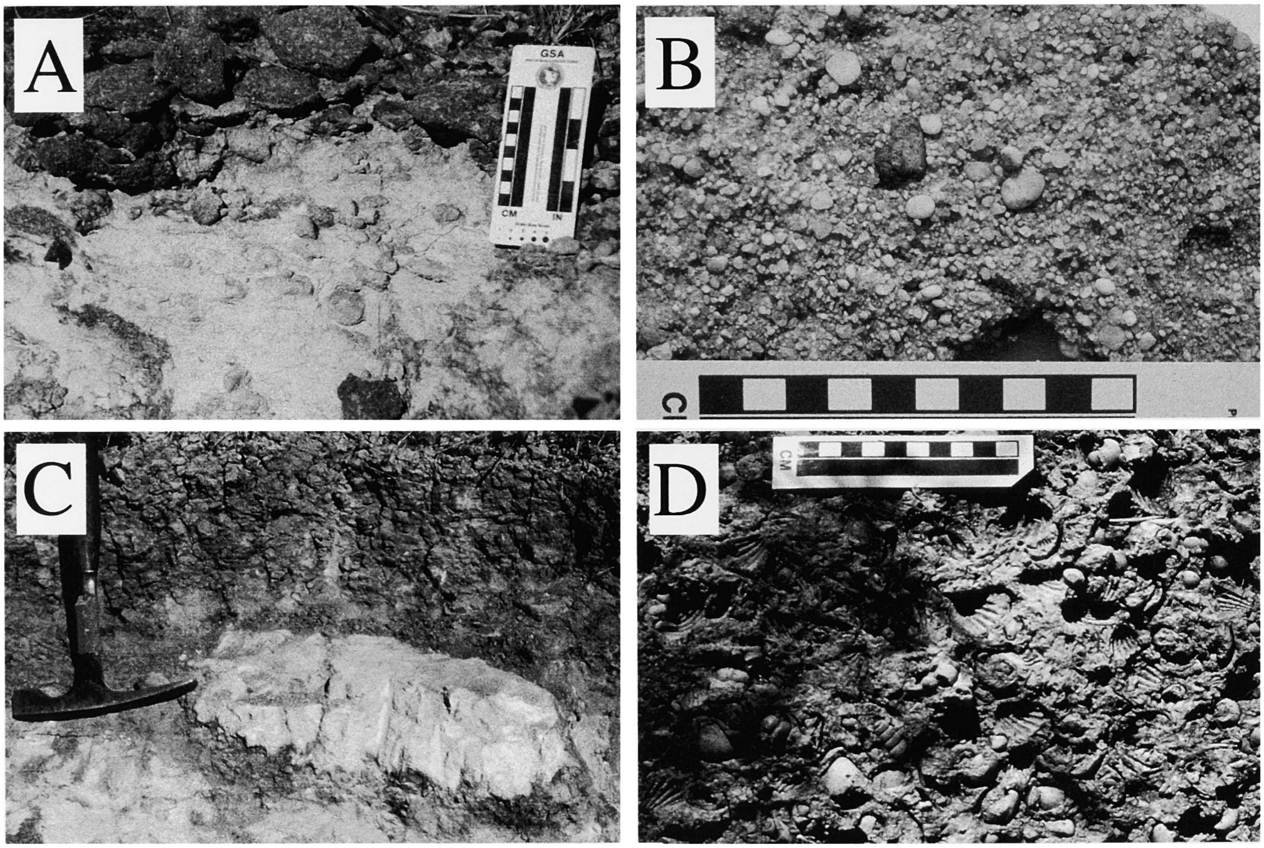


Figure 5. Outcrop views of the upper contact of the Maevarano Formation. We interpret the discontinuity that separates the Maevarano and Berivotra formations as a transgressive surface of erosion (ravinement). *A*, 5–20-cm-thick bed of very coarse-grained conglomeratic sandstone (*dark gray*) marks the contact throughout most of the Berivotra region. This bed, which tends to cap local buttes, is well cemented with calcite and yields rounded pebbles of chert and polished bone, along with scattered teeth of selachians (Gottfried and Rabarison 1997; J. A. Rabarison, L. L. Randriamiaranana, and M. J. Gottfried, unpub. manuscript). *B*, Close-up of capping bed showing rounded quartz pebbles and a polished bone pebble (*left of center*). *C*, Rounded and thoroughly bored cobbles of siltstone also occur on the contact (borings are visible on the lower surface). *D*, Locally, the contact is overlain by large boulders of densely packed shell bed.

1997*b*, 1999; Forster et al. 1996; Krause and Hartman 1996; Sampson et al. 1996). A preliminary taphonomic analysis (Rogers et al. 1997) indicates that the majority of fossils are concentrated in facies 2 (fig. 8*F*), although bones and teeth are also recovered in considerable abundance from facies 1. In contrast to this exceptionally rich vertebrate record, invertebrate fossils are uncommon within the Anembalemba Member, although rare gastropods and conchostracans have been reported (Krause and Hartman 1996), and bivalves are also preserved.

The Anembalemba Member is 12.6 m thick at the type locality (fig. 7*A*). Elsewhere in the Berivotra region, the member ranges from <10 to >15 m thick. The basal contact of the Anembalemba Member is an erosional discontinuity that locally exhibits >1 m of relief. The upper contact is a laterally continuous and essentially planar disconformity (see upper contact of Maevarano Formation described above) marked at the type locality by a conglomeratic bed of sandstone that yields polished bone pebbles and teeth of selachians.

Miadana Member. Exposures of the Miadana Member are limited to a few isolated hills located approximately 4 km to the southeast of the main Berivotra field area (fig. 2). The type section (fig. 7*B*) crops out on the east-facing slope of the second (western) prominent hill along the entrance road to the Miadana agricultural station (15°56′16.2″S, 46°38′0.1″E). Another representative section of the

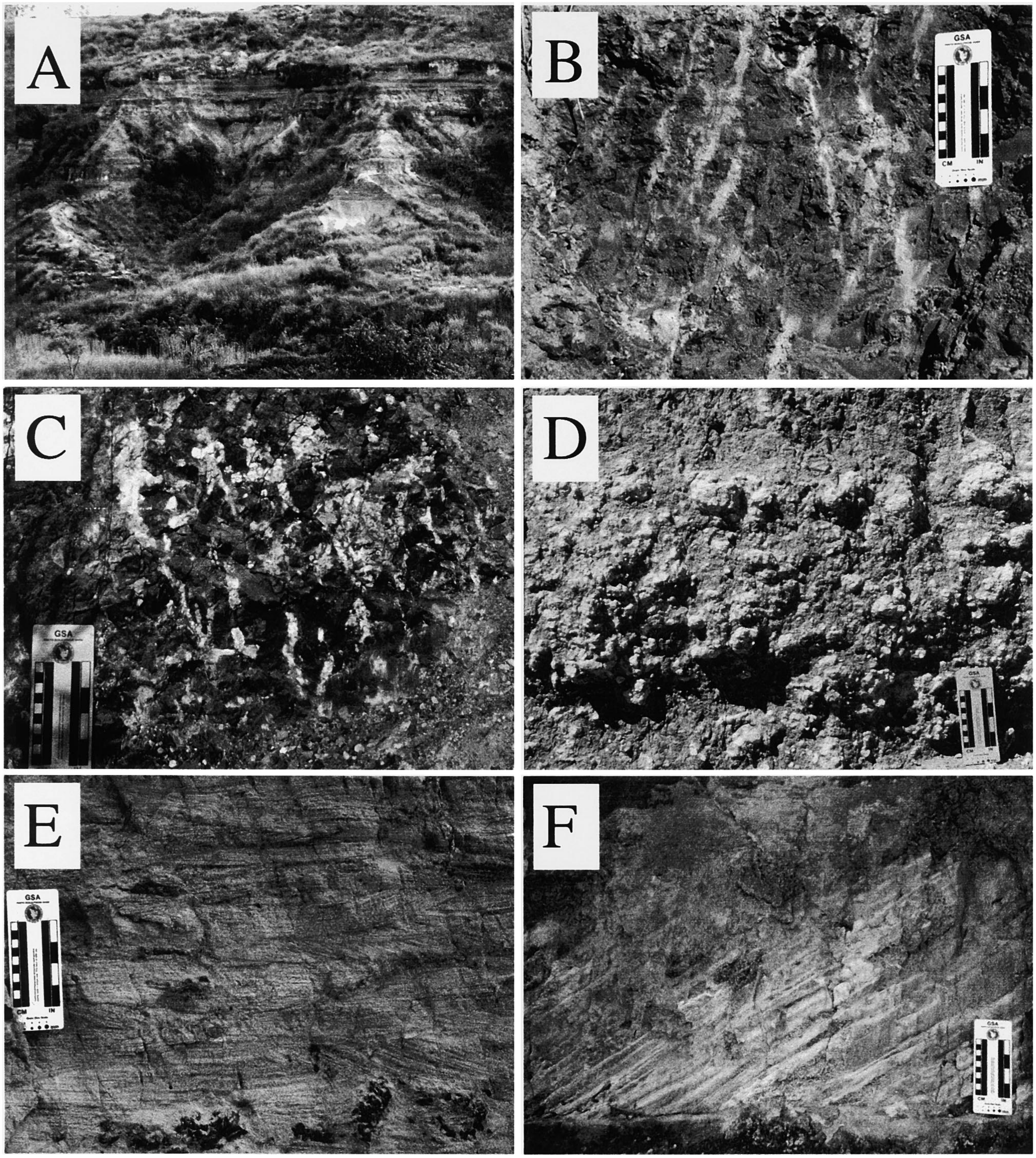


Figure 6. Outcrop views of the Masorobe Member of the Maevarano Formation. *A*, View of the base of the Maevarano Formation type section showing typical red-bed facies of the Masorobe Member. *B*, Paleosols are well developed within the Masorobe Member, and root mottling with a strong vertical fabric is pervasive. *C*, Calcareous rhizomes are locally abundant within the Masorobe Member. *D*, Several beds of caliche are present in the upper 55 m of the Masorobe Member (see fig. 4). *E*, *F*, Despite pervasive pedogenic alteration, some sandstone beds exhibit primary stratification in the form of small- to large-scale tabular and trough cross-bed sets. The vector mean of 40 paleocurrent measurements taken from cross-stratified units in the Masorobe Member is 347°.

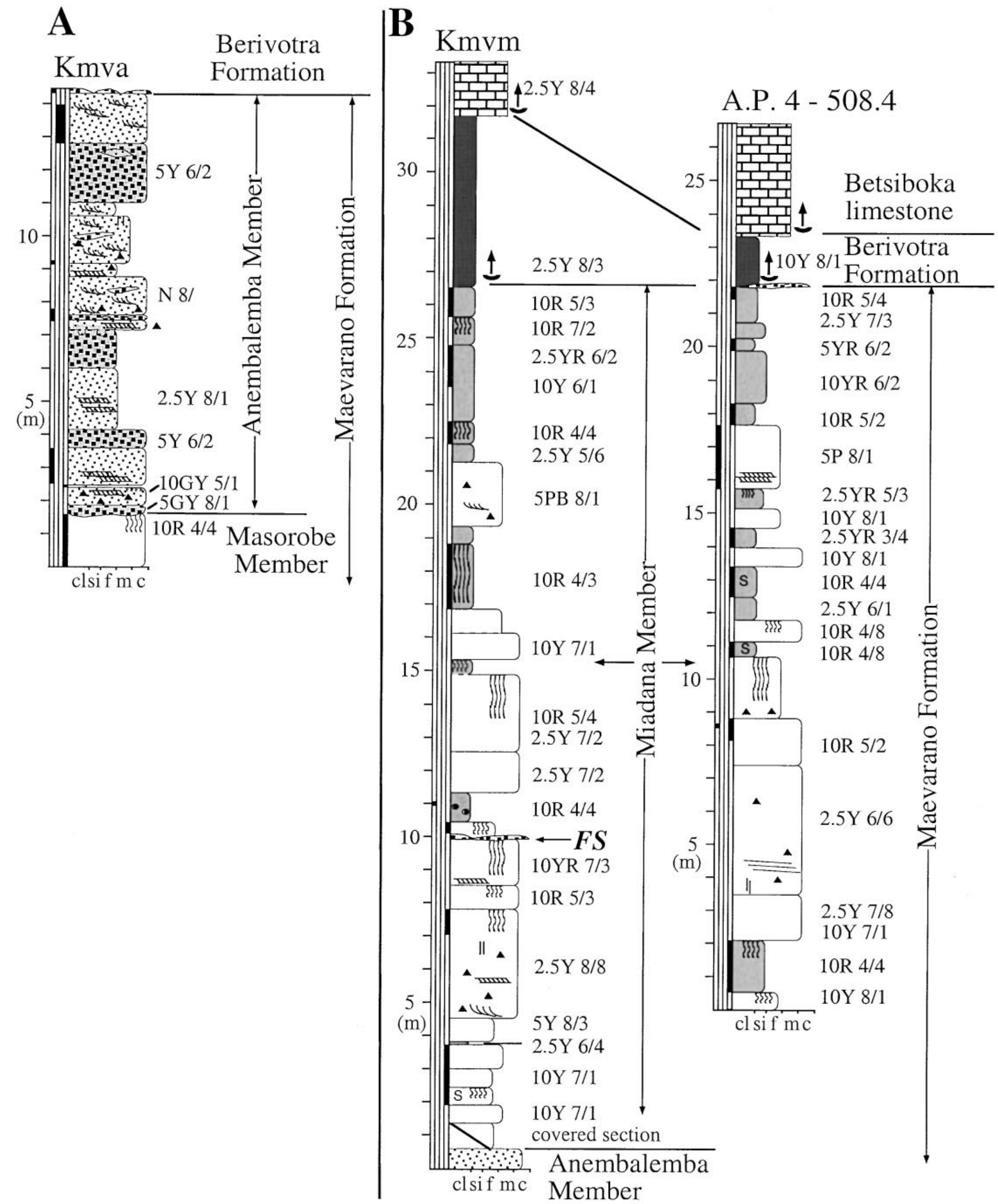


Figure 7. Graphic stratigraphic logs of Anembalemba and Miadana Members of the Maevarano Formation. *A*, Exposures of the Anembalemba Member can be traced throughout the region surrounding the village of Berivotra. The 12.6-m-thick type section (Kmva) is exposed along the southwestern side of national route A.P. 4, near a prominent ridge called Anembalemba (fig. 2; see text for GPS data). Two distinctive sandstone facies (here designated facies 1 and facies 2) characterize the Anembalemba Member (see fig. 8). Facies 1 consists of fine- to coarse-grained, poorly sorted sandstone that typically displays small- to medium-scale tabular and trough cross stratification. Directional measurements ($n = 51$) derived from outcrops of facies 1 yield a vector mean of 337°. Facies 2 consists of fine- to coarse-grained clay-rich sandstone characterized by very poor sorting, massive structure, and, generally, an olive green color. *B*, Exposures of the Miadana Member are limited to a few isolated hills located approximately 4 km to the southeast of the main Berivotra field area (fig. 2; see text for GPS data). The type section (Kmvm) crops out on the east-facing slope of the second (western) prominent hill along the entrance road to the Miadana agricultural sta-

Miadana Member can be accessed in the vicinity of kilometer marker 508 along national route A.P. 4 (15°55′51.4″S, 46°39′10.3″E).

The Miadana Member is 25.4 m thick at the type locality (fig. 7*B*) and consists of a mix of fine- to coarse-grained lithologies that vary in color from white (5PB 8/1) to greenish gray (2.5Y 7/2) to deep red (10R 5/3). Claystone beds make up >30% of the section, and sandstone beds are considerably finer grained than their counterparts in either the Masorobe or Anembalemba members. Most beds that comprise the Miadana Member are massive, with only rare examples of primary stratification in the form of faint localized cross-bedding. Several beds exhibit mottling, although the vertical root fabric so characteristic of the Masorobe Member is not apparent. A thin, localized bed of conglomeratic sandstone comparable to the conglomeratic facies that caps the Anembalemba Member crops out 10 m above the base of the Miadana Member type section (fig. 7*B*). This conglomeratic bed is cemented with calcite and yields smooth carbonate pebbles, shark teeth, and tooth plates of teleost fish.

The basal contact of the Miadana Member is obscured by modern soil and talus at the type locality, but at most 1 or 2 m of covered strata separate the base of the Miadana Member from underlying facies of the Anembalemba Member (the upper few meters of the Anembalemba Member crop out between the two hills bordering the entrance road to the Miadana agricultural station). The upper contact of the Miadana Member is a disconformity that separates red (10R 5/3) silty claystone from overlying olive yellow (2.5Y 8/3) claystone of the Berivotra Formation (fig. 7).

Berivotra Formation. The newly defined Berivotra Formation is equivalent to the "marnes Maastrichtiennes" of Besairie (1938, 1972). This fine-grained unit consists of tan to olive yellow siltstone, claystone, and marl. Beds are predominantly massive, although planar lamination is locally developed. Fossils are preserved throughout the Berivotra Formation, and they include brachiopods, bryozoa, echinoids, bivalves, gastropods, and rare fish elements. The formation is widely accessible in the Berivotra region and in areas to the north, but the quality of exposure is generally poor, and it is usually necessary to penetrate a surficial layer of burned and deeply cracked soil in order to access fresh rock.

The type section of the Berivotra Formation (figs. 9*A*, 10*A*) is located on the northwestern flank of Anembalemba along the mine access road that intersects route A.P. 4 near the Berivotra community church (fig. 2). The coordinates at the base of the section are 15°54′39.7″S, 46°36′20.3″E. The coordinates at the top of the type section are 15°54′42.5″S, 46°36′26.5″E. At the type locality, the Berivotra Formation is 29.5 m thick. The basal contact is a disconformity that separates light gray (N 8/) cross-stratified sandstones of the Anembalemba Member (facies 1) from overlying tan (5Y 7/4) clay-rich siltstone. Scattered sandstone cobbles with borings and rare shark teeth mantle this surface. A thin (<5 cm) bed of greenish gray (10Y 8/1) coarse-grained sandstone cemented by calcite crops out 80 cm above the basal contact. There is a transition from clay-rich siltstone to silty claystone approximately 10 m above the base of the section. Fossils of marine invertebrates (brachiopods, bryozoa, echinoids, bivalves, and gastropods) are relatively abundant above the basal siltstone-dominated interval, and rare vertebrate elements (fish centra, shark teeth) have also been recovered. The upper ~5 m of the type section consist of calcareous claystone with a very minor silt content, and the upper 30 cm of the unit preserve lenses of chalky carbonate. Exposures of the Berivotra Formation at the type locality grade rapidly upward into a 2–3-m ledge of thickly bedded to massive marine limestone (fig. 10). Elsewhere in the field area, up to 7 m of this resistant limestone unit cap the Berivotra Formation. Besairie (1972, p. 176–177) referred to this capping limestone bench and overlying carbonate facies as the "calcaires et marnes du Danien," and he reported a thickness for this unit of up to 80 m. Besairie further concluded that the resistant base of this carbonate interval marked the "limite supérieure du Maestrichtien" throughout

tion. Another representative section of the Miadana Member (A.P. 4-508.4) can be accessed in the vicinity of kilometer marker 508 along national route A.P. 4 (fig. 2; see text for GPS data). The Miadana Member is 25.4 m thick at the type locality and consists of a mix of fine- to coarse-grained lithologies. Claystone beds make up >30% of the section, and sandstone beds are for the most part finer grained than their counterparts in either the Masorobe or Anembalemba members. A thin bed of conglomeratic sandstone crops out 10 m above the base of type section, and this bed is interpreted to mark a marine flooding surface (*FS*). Key as in figure 4.

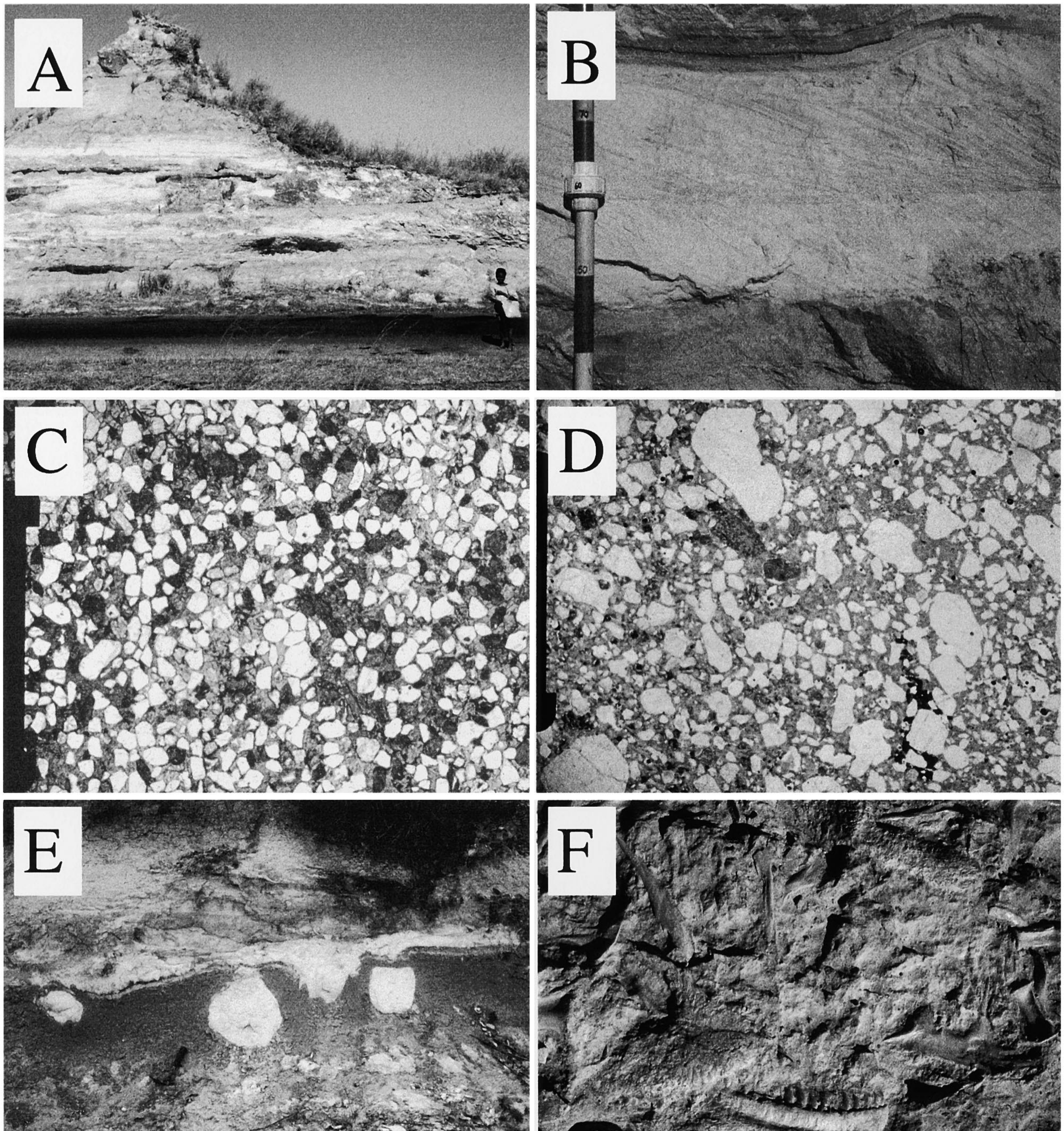


Figure 8. Outcrop and thin-section views of the Anembalemba Member of the Maevarano Formation. *A*, View of Anembalemba Member stratotype along national route A.P. 4. *B*, Close-up of cross-bedded sandstones of facies 1 (*light gray*) and massive green sandstones of facies 2 (*dark gray*). *C*, *D*, Representative photomicrographs of facies 1 and facies 2 of the Anembalemba Member, respectively. Quartz is the predominant framework grain, with lesser amount of K-feldspar (*stained*) and rare rock fragments. Facies 1 is typically better sorted than facies 2, and it has a lower clay content. Scale bar = 2.5 mm. *E*, Load structures, including spectacular examples of ball and pillow structure, are relatively common in the Anembalemba Member. *F*, Vertebrate fossils are amazingly abundant within the Anembalemba Member. A preliminary taphonomic analysis (Rogers et al. 1997) indicates that the majority of fossils are concentrated in facies 2, although bones and teeth are also recovered from facies 1. The bones in this photograph are primarily those of a skull of the abelisaurid theropod dinosaur *Majungatholus atopus*.

Table 1. Fossil Vertebrates from the Maevarano Formation, Upper Cretaceous (Maastrichtian), Mahajanga Basin, Northwestern Madagascar

- Osteichthyes
  - Actinopterygii
    - Ginglymodi (=Lepisosteiformes)
      - Lepisosteidae
        - *Lepisosteus* sp.
    - Pycnodontiformes
      - Pycnodontidae
        - cf. *Coelodus* sp.
  - Teleostei
    - Elopomorpha
      - Albuliformes
        - Phyllodontidae
          - cf. *Egertonia*
    - Osteoglossocephala
      - Ostarioclupeomorpha
        - Ostariophysi
          - Siluriformes
            - Gen. et sp. indet.
      - Euteleostei
        - Acanthomorpha
          - Gen. et sp. indet.
- Anura
  - Mesobatrachia
    - ?Pelobatidae
      - Gen. et sp. indet.
  - Neobatrachia
    - Gen. et sp. indet. A
    - Gen. et sp. indet. B
- Testudines
  - Pleurodira
    - Pelomedusoidea?
      - Gen. et sp. indet. A
      - Gen. et sp. indet. B
- Squamata
  - Serpentes
    - Alethinophidia
      - Madtsoiidae
        - *Madtsoia madagascariensis*
        - *Madtsoia* cf. *M. laurasiae*
        - Gen. et sp. indet. A
        - Gen. et sp. indet. B
- Crocodyliformes
  - Metasuchia
    - Trematochampsidae
      - *Trematochampsa oblita*
    - Peirosauridae?
      - Gen. et sp. indet.
    - Notosuchidae?
      - Gen. et sp. indet.
    - Incertae sedis
      - *Araripesuchus* sp.
      - *Mahajangasuchus insignis*
      - Gen. et sp. indet.
  - Eusuchia?
    - Gen. et sp. indet.
- Dinosauria
  - Saurischia
    - Sauropoda
      - Titanosauridae
        - Gen. et sp. indet. A
        - Gen. et sp. indet. B
    - Theropoda
      - Abelisauridae
        - *Majungatholus atopus*
      - Incertae sedis
        - Gen. et sp. indet. A
        - Gen. et sp. indet. B
      - Tetanurae
        - Aves
          - *Rahonavis ostromi*
        - Metornithes
          - Ornithothoraces
            - *Vorona berivotrensis*
          - Enantiornithes
            - Gen. et sp. indet. A
            - Gen. et sp. indet. B
- Mammalia
  - Allotheria
    - Multituberculata
      - Gen. et sp. indet.
  - Theria
    - Tribosphenida?
      - Gen. et sp. indet.
  - Incertae sedis
    - Gen. et sp. indet.
    - Gondwanatheria
      - Sudamericidae
        - *Lavanify miolaka*

the basin. We have traced this distinctive body of well-indurated limestone throughout the region to the east of the Betsiboka delta plain, but until an appropriate stratotype is identified and described, we propose to informally name this readily identifiable stratum the Betsiboka limestone. Fossils recovered from the Betsiboka limestone indicate that it is early Paleocene (Danian) in age (Besairie 1972; D. Neraudeau and J. H. Hartman, unpub. manuscript).

Additional outcrops of the Berivotra Formation were studied in the open-pit quarry of the SANCA Cimenterie (15°49′51.0″S, 46°20′8.2″E), which is located near the town of Amboanio, approximately 28 km northwest of the Berivotra field area. Here, the upper 6 m of the Berivotra Formation and the entire thickness of the overlying Betsiboka limestone are exposed (figs. 9*B*, 10*C*–10*F*). The Berivotra Formation is characterized by alternating beds of calcareous claystone and marl. Beds of claystone are typically massive and burrow mottled and preserve scattered shell fragments and rare shark teeth.

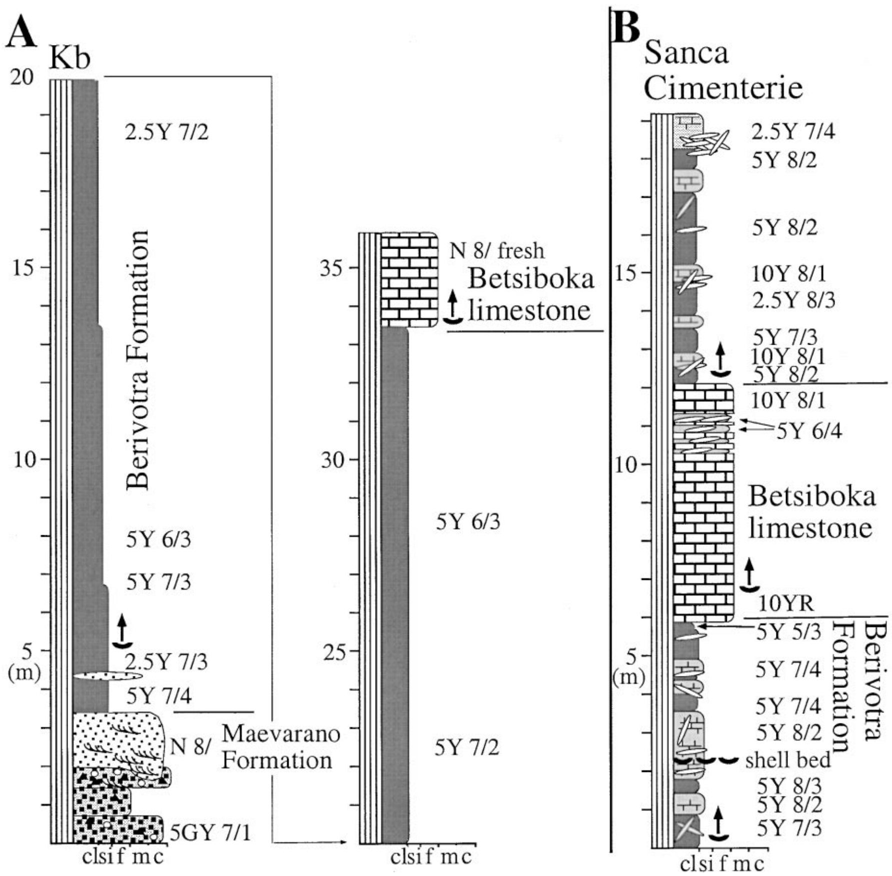


Figure 9. *A*, Graphic stratigraphic log of the Berivotra Formation stratotype. The stratotype is located on the northwestern flank of Anembalemba (fig. 2; see text for GPS data). At the type locality, the Berivotra Formation is 29.5 m thick. Exposures of the Berivotra Formation at the type locality grade rapidly upward into a 2–3-m ledge of thickly bedded to massive marine limestone, here informally designated the Betsiboka limestone. Fossils are preserved throughout the Berivotra Formation, and they include brachiopods, bryozoa, echinoids, bivalves, gastropods, and rare fish elements. The formation is widely accessible in the Berivotra region and in areas to the north. *B*, Graphic stratigraphic log of the Berivotra Formation and the overlying Betsiboka limestone as exposed in the quarry of the SANCA Cimenterie (see text for GPS data). The upper 6 m of the Berivotra Formation are characterized by alternating beds of massive calcareous claystone and marl, and here too the formation grades rapidly upward into the base of the Betsiboka limestone, which is approximately 6 m thick. The Betsiboka limestone is overlain by alternating beds of calcareous claystone and marl that preserve intricate networks of *Thallasinoides*. Key as in figure 4.

Intercalated beds of marl tend to form resistant ledges and are characterized by networks of *Thallasinoides*, which are indicative of firmground conditions (fig. 10*C*, 10*D*). A densely packed, 5–10-cm-thick shell bed dominated by disarticulated valves of *Alectryonia* crops out in a bed of marl 2.25 m above the base of the local exposures (figs. 9*B*, 10*E*). The upper 25 cm of the Berivotra Formation consists of calcareous claystone that grades rapidly upward over a span of 5–10 cm of marl into the base of the Betsiboka limestone (fig. 10*F*).

Depositional Framework

Previous Work. Besairie (1972) recognized the predominantly nonmarine nature of the Maevarano Formation and the marine affinities of the overlying Berivotra Formation, but he did not venture beyond these very general paleoenvironmental categorizations. Obata and Kanie (1977) concluded that the upper portions of the Maevarano Formation in the vicinity of Berivotra accumulated in a "calm lake." A curious array of geological evidence

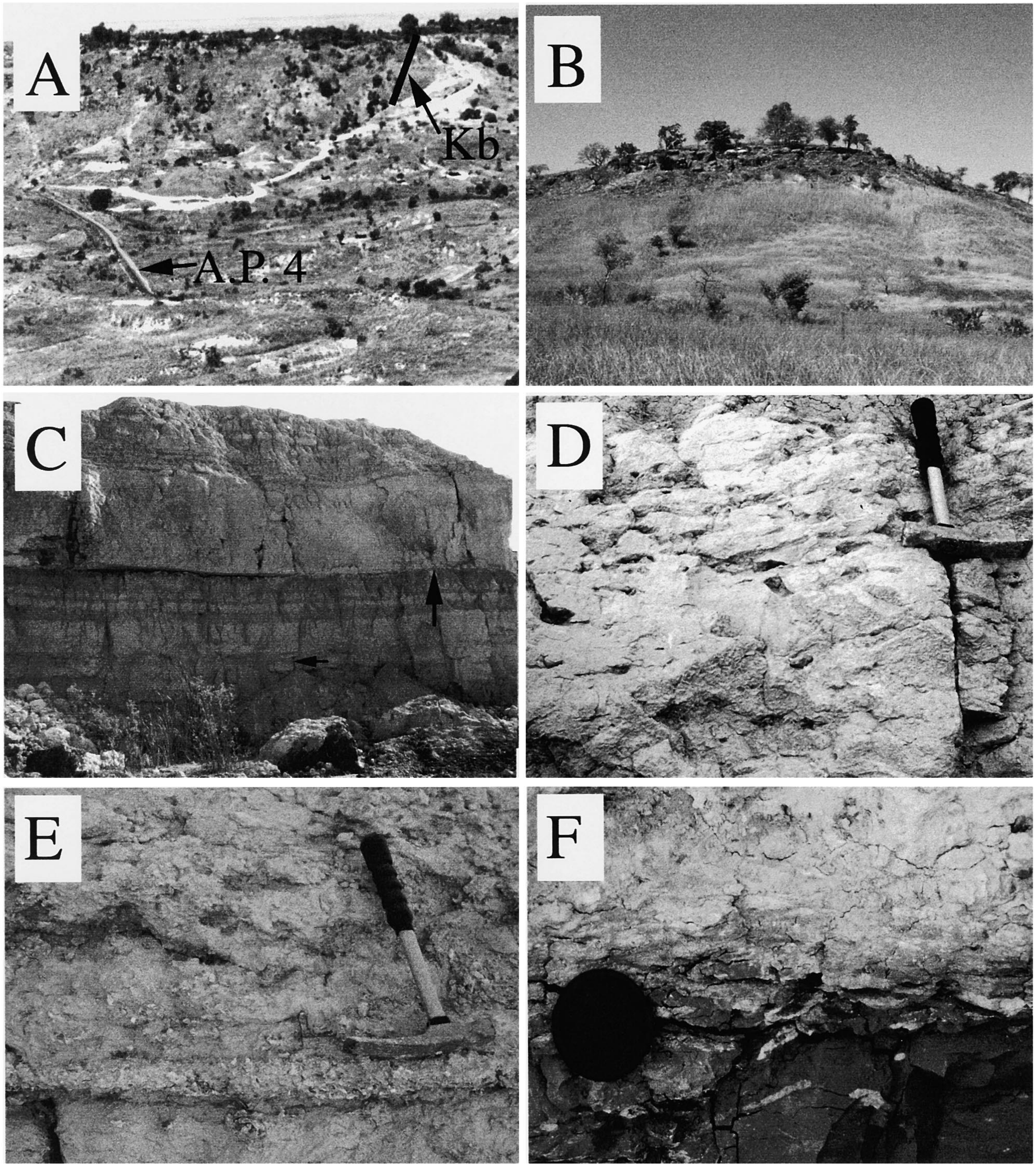


Figure 10. Outcrop views of the Berivotra Formation and Betsiboka limestone. *A*, View of the Anembalemba ridge and the Berivotra Formation stratotype (*Kb*). The entire section can be accessed along the mine access road that intersects national route A.P. 4. *B*, View of typical Berivotra Formation exposures (vegetated slope) with capping ledge of Betsiboka limestone (Ambanjabe locality; see fig. 2). *C*, Outcrop view of interbedded claystone and marl in the upper Berivotra Formation and the indurated ledge of the overlying Betsiboka limestone in the SANCA Cimenterie. Large arrow points to contact between these two units. Small arrow points to 60-cm pick. *D*, Bed of massive marl in the Berivotra Formation showing evidence of bioturbation. *E*, Densely packed shell bed dominated by disarticulated but relatively intact valves of *Alectryonia*. This shell bed crops out ~2.3 m above the base of exposures at the SANCA locality. *F*, Contact between the Berivotra Formation and the overlying Betsiboka limestone showing a rapid gradation from calcareous claystone to marly limestone.

was cited in support of their lacustrine interpretation, including "sandpipes" (root casts?), cross lamination, and idiomorphic crystals of barite. Hartman et al. (1994) interpreted the upper several meters of the Maevarano Formation in the vicinity of Berivotra as a distributary channel complex with localized deposits of river-dominated estuaries. A localized exposure of clay-draped cross beds led to this interpretation. Obata and Kanie (1977) and all subsequent workers followed Besairie (1972) in correlating stage boundaries with major lithologic shifts in the Upper Cretaceous section. Consequently, the Santonian-Campanian boundary was interpreted to coincide with the contact between the Marovoay beds and the Maevarano Formation, and the Campanian-Maastrichtian boundary was interpreted to coincide with the contact between the Maevarano Formation and overlying Berivotra Formation.

In a more recent survey of the Berivotra field area, Papini and Benvenuti (1998) proposed several new paleoenvironmental interpretations within the context of what they deemed a sequence stratigraphic framework. These authors subdivided the Upper Cretaceous section in the vicinity of Berivotra into eight units, each of which was interpreted to represent a distinct depositional setting, such as "aeolian-reworked fluvial" (their Unit 4), "fluvio-lacustrine" (their Unit 5), and "lagoonal" (their Unit 7 = Berivotra Formation and overlying Betsiboka limestone). These eight units were in turn relegated to four depositional sequences separated by sequence boundaries. In their analysis, the contacts of the Maevarano Formation were still interpreted to coincide with the Campanian and Maastrichtian stage boundaries (e.g., fig. 3 in Papini and Benvenuti 1998).

There are major problems with the depositional framework proposed by Papini and Benvenuti (1998). First of all, these authors failed to recognize the fault contact that separates the Marovoay beds from the Maevarano Formation along the Antananarivo-Mahajanga national road (A.P. 4), and they also failed to assimilate the faults already mapped along the east flank of Anembalemba by the Service Géologique de Madagascar (1960) (fig. 2). In doing so, they overlooked the down dropping of the Upper Cretaceous section to the south of the Berivotra escarpment (see below), and thus erroneously concluded both that their Unit 2 was the base of the Maevarano section, when in fact it is the top of the Maevarano Formation (Miadana Member), and that their Unit 3 represented a marine incursion within the Maevarano Formation, when in fact it consists of the overlying Berivotra Formation and Betsiboka limestone.

Another problem with the stratigraphic analysis of Papini and Benvenuti (1998) pertains to their uncritical application of sequence stratigraphic methodology. For example, the depositional sequences that they propose are purportedly bounded by nonmarine sequence boundaries, but these critical bounding surfaces are not described with regard to relief, lateral traceability, associated lags, degree of paleosol development, or any other geological attribute. Three transgressive surfaces are also reconstructed (but not described) in their analysis, but no effort is made to distinguish these surfaces (which by definition should underlie transgressive systems tracts) from more local marine flooding surfaces. Each depositional sequence proposed in their study also includes one or more systems tracts, but the reasoning behind systems tract differentiation in this complicated nonmarine record is not made explicit, and there is a general dearth of supporting sedimentological data. The authors themselves admit that "there is a lack of sufficient control on the lateral continuity of these units and of their bounding surfaces" (Papini and Benvenuti 1998, p. 242).

Paleoenvironments Reconsidered. In the area of study, the Maevarano Formation is entirely nonmarine, and it consists of facies that accumulated on a low-relief alluvial plain that was bounded to the southeast by crystalline highlands and to the northwest by the Mozambique Channel. Paleocurrent measurements indicate that the rivers that drained the crystalline uplands flowed transversely across the alluvial plain to the sea (Rogers and Hartman 1999).

Sandstone bodies of the Masorobe Member have sheetlike geometries, and those that exhibit remnant bedding are dominated by small- to medium-scale tabular and trough cross stratification (fig. 6). These sandstone bodies, which are interpreted as the deposits of broad and shallow low-sinuosity channel belts, are intercalated with floodplain deposits that are predominantly red in color and tabular in geometry. Facies of the Masorobe floodplain are typically massive, and root mottling is conspicuous, with casts of roots exhibiting a strong vertical fabric suggestive of tap roots. Some root casts are encrusted with $CaCO_3$, and these calcareous rhizomes are occasionally associated with beds of caliche (fig. 6). Pedogenic features indicate that vegetation was relatively abundant on the floodplain during deposition of the Masorobe Member and that the flora was adapted for a relatively dry climate. This interpretation is consistent with paleogeographic reconstructions (e.g., Scotese 1998) that position the Mahajanga Basin at approximately 30° S during the Late Cretaceous, which would place it within the influence of the subtropical desert belt.

An abrupt change in the nature of this alluvial record marks the boundary between the Masorobe and Anembalemba members. Throughout the study area, red beds of the Masorobe Member are disconformably overlain by the distinctive green and white sandstone facies of the Anembalemba Member (fig. 8). Sandstones of the Anembalemba Member are interpreted to have accumulated in a shallow and very broad channel-belt system characterized by an ephemeral and flood-prone discharge regime. In general, the two sandstone facies are interbedded in an erosive fashion, and erosional relief can be considerable and highly variable over short distances. Facies 1 of the Anembalemba Member, which is characteristically cross stratified and better sorted than facies 2, is interpreted to represent the product of "normal" downstream migration of bedforms. In contrast, facies 2, which is typically massive and very poorly sorted, is interpreted to represent events of rapid sediment dumping, presumably during floods (fig. 8). The massive nature of facies 2 is interpreted as an original depositional feature because there is virtually no evidence of pedogenic alteration or bioturbation. Rare collapse blocks of floodplain facies preserved as lag deposits indicate that the contemporaneous floodplain was oxidized and pedogenically modified. The flashy discharge that characterizes the ancient channel belts of the Anembalemba Member presumably reflects seasonality in the Late Cretaceous of northwestern Madagascar. It is tempting to equate this signal of ancient seasonality and discharge variability with the distinct rainy and dry seasons that influence large portions of the island of Madagascar today (Preston-Mafham 1991).

The Miadana Member is similar to the Masorobe and Anembalemba members in that it is essentially fluvial in origin. However, sandstone facies of the Miadana Member are finer grained than their counterparts in either the Masorobe or Anembalemba members, and beds of claystone and siltstone are more abundant (fig. 7). We interpret this overall decrease in grain size in the Miadana depositional system to reflect a lower gradient and a consequent decrease in stream competence. This interpretation is supported by stratigraphic data that clearly indicate that exposures of the Miadana Member are situated no more than 4 km inland of contemporaneous shoreline facies (see below). Accordingly, the Miadana Member is interpreted to represent deposition in a lower coastal plain setting.

From all indications, the Berivotra Formation was deposited in a marine environment. Papini and Benvenuti (1998, p. 240) concluded that this marine setting was restricted and possibly lagoonal based on the purported presence of a "paralic molluscan fauna." However, all of the fossils that we recovered from the Berivotra Formation, including planktonic foraminifera, ammonites, echinoids, bryozoa, gastropods, and bivalves, are consistent with deposition under normal marine conditions, presumably on an open marine shelf. This interpretation is certainly in agreement with the available geological evidence, as there is absolutely no indication of barrier island deposits or any other facies associations that would support an embayment or an estuarine interpretation.

The ~30-m-thick section of the Berivotra Formation exposed in the vicinity of the Berivotra type locality suggests an overall transgressive history. The base of the section is slightly coarser grained, being composed primarily of siltstone (fig. 9), and preserves scattered concentrations of large pycnodonte oysters. These basal facies, which are interpreted to represent deposits of the inner shelf, pass up-section into finer-grained beds of calcareous claystone that yield taxa indicative of more offshore conditions, such as planktonic foraminifera and ammonites. Alternating beds of claystone and marl in the SANCA quarry section suggest small-scale fluctuations in relative sea level during the overall Berivotra transgression. The gradational but rapid transition from the Berivotra Formation to the overlying Betsiboka limestone presumably coincides with the regional shutdown of clastic supply as coastal flooding ensued.

Revised Regional Correlation. Before our stratigraphic analysis, the Upper Cretaceous units in the central Mahajanga Basin were assumed to be stratified in layer-cake fashion with time-parallel boundaries (fig. 3). This simplistic reconstruction of stratigraphic relations led to erroneous chronostratigraphic interpretations, which were further confounded by the uncritical correlation of stage boundaries with major lithologic transitions. A revised view of the Upper Cretaceous stratigraphy in the central Mahajanga Basin is presented in figure 11.

Relatively few exposures of the Maevarano Formation occur outside of the main Berivotra field area, but the overlying Berivotra Formation is widely exposed, often in its entirety, and regional trends in the thickness of the Berivotra Formation have been determined. In the vicinity of the village

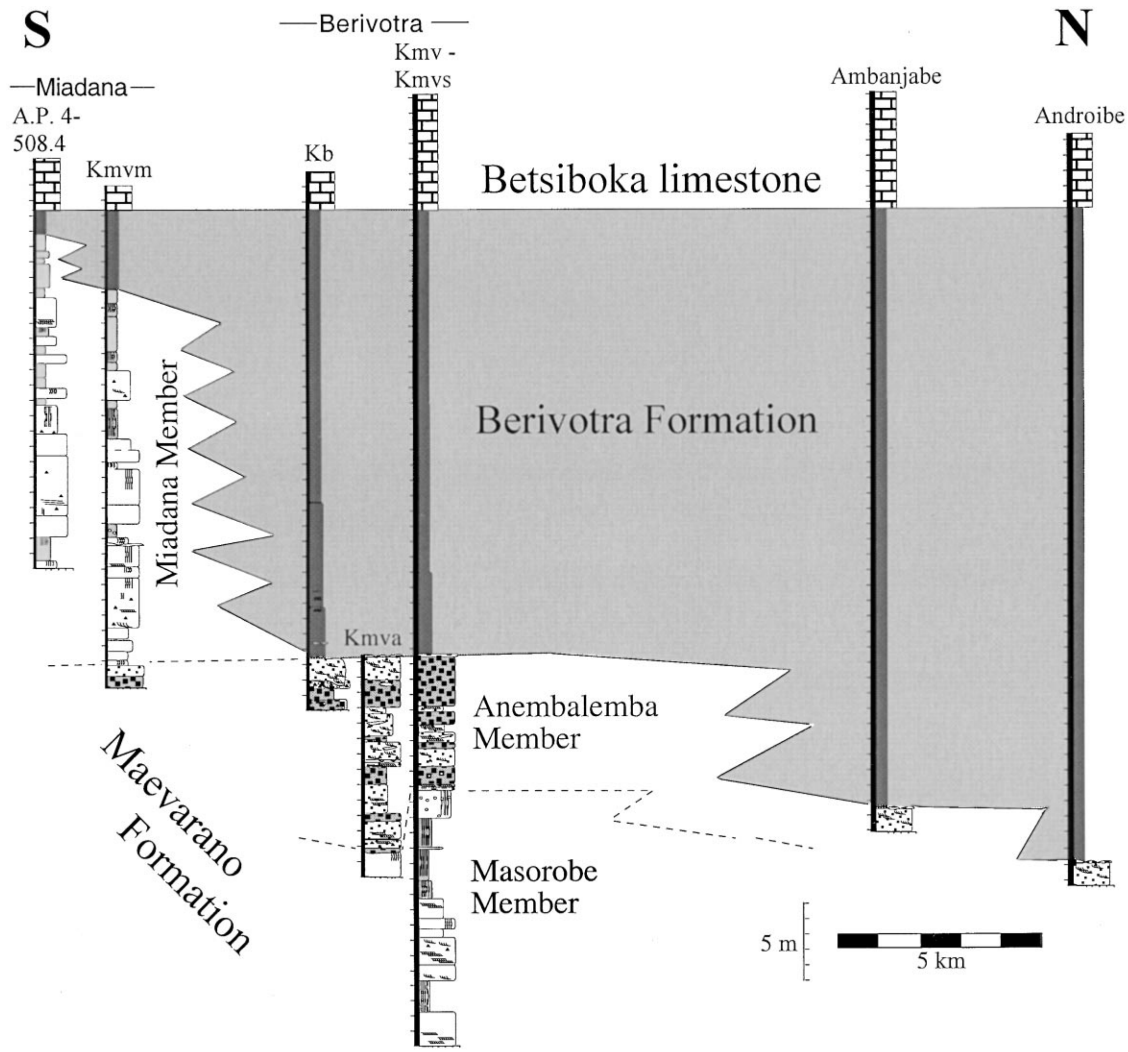


Figure 11. Regional cross section showing stratigraphic relations among Upper Cretaceous and Tertiary units in the Berivotra region (see fig. 2 for location of sections). Using the base of the Danian Betsiboka limestone as a datum, thickness data for the Berivotra Formation indicate that the disconformity that marks the contact between the Maevarano and Berivotra formations climbs stratigraphically several tens of meters from northwest to southeast. This in turn indicates that the Berivotra transgression proceeded diachronously from northwest to southeast. On the basis of this stratigraphy, exposures of the Miadana Member of the Maevarano Formation located in the Miadana Hills clearly correlate with exposures of the Maastrichtian Berivotra Formation in the main Berivotra field area. Regional thickness trends further suggest that exposures of the Anembalemba Member in the Berivotra field area correlate with exposures of the Berivotra Formation to the north.

of Berivotra, the Berivotra Formation is on average 30 m thick. To the north, the formation thickens by several tens of meters, to a maximum of ~60 m along the present day coast (R. R. Rogers, pers. observ.; Besairie 1972). Approximately 4 km to the south of the Berivotra field area, <2 m of the Berivotra Formation intervene between the Maevarano Formation and the Betsiboka limestone (figs. 7*B*, 11). Using the base of the Betsiboka limestone as a datum, thickness data for the Berivotra Formation indicate that the disconformity that marks the contact between the Maevarano and Berivotra formations climbs stratigraphically several tens of meters from northwest to southeast (fig. 11). This in turn indicates that the Berivotra transgression proceeded diachronously from northwest to southeast. On the basis of this stratigraphy, exposures of the Miadana Member of the Maevarano Formation located in the Miadana Hills clearly correlate with exposures of the Berivotra Formation in the main

Berivotra field area. Regional thickness trends further suggest that exposures of the Anembalemba Member in the Berivotra field area correlate with exposures of the Berivotra Formation to the north along the coast (fig. 11).

An additional line of reasoning based on the predicted response of the Maevarano depositional system to base level change can be applied to this proposed correlation. Recent conceptual treatments of the sequence stratigraphy of fluvial deposits (e.g., Wescott 1993; Wright and Marriott 1993; Shanley and McCabe 1994) and empirical studies (e.g., Shanley and McCabe 1991; Gibling and Bird 1994; Olsen et al. 1995; Rogers 1998) indicate that major changes in base level (sea level) can be distinguished in fully nonmarine records. Changes in the rate of addition of accommodation affect both fluvial architecture (channel stacking patterns and channel/floodplain ratio) and paleosol development. Trends in fluvial architecture are difficult to ascertain between the Masorobe and Anembalemba members. Both units are predominantly composed of coarse-grained, poorly sorted sandstone, and because of strong pedogenic overprinting, it is virtually impossible to conclusively differentiate between channel facies and coarse-grained floodplain facies within the Masorobe Member. Trends in paleosol development are more readily ascertained. Throughout the Berivotra field area, fluvial facies of the Masorobe Member that exhibit pervasive evidence of pedogenesis are disconformably overlain by fluvial facies of the Anembalemba Member that display well-preserved primary sedimentary structures and, in comparison, relatively little evidence of pedogenesis (figs. 4, 6, 8). The marked reduction in paleosol maturity that coincides with the Masorobe-Anembalemba contact may reflect an addition of accommodation, which would presumably coincide with increased rates of vertical aggradation. Along these same lines, the striking increase in the richness of the vertebrate fossil record that occurs across the Masorobe-Anembalemba contact may reflect the same addition of accommodation, with the potential for permanent burial of skeletal debris enhanced by increased rates of vertical aggradation in the Anembalemba channel belts. It is certainly feasible that the regional rise in base level that led to marine transgression and deposition of the lower Berivotra Formation also led to the abrupt decrease in paleosol maturity and increase in fossil richness that occurs across the Masorobe-Anembalemba contact.

Revised Age of the Maevarano Formation. Age estimates for the nonmarine Maevarano Formation have previously ranged from Turonian to Campanian (Depéret 1896*b*; Thévenin 1907; Lemoine 1911; Perrier de la Bathie 1921; von Huene and Matley 1933; de Lapparent 1957; Hoffstetter 1961). For the past few decades a Campanian age has been accepted by most workers (Hoffstetter 1961; Karche and Mahe 1967; Besairie 1972; Brenon 1972; Russell et al. 1976; Obata and Kanie 1977; Buffetaut and Taquet 1979; Sues and Taquet 1979; Krause and Hartman 1996; Papini and Benvenuti 1998), although relatively little can be gleaned from the literature regarding the reasoning behind this conclusion. Our work finally provides a reliable means of assessing the age of the Maevarano Formation, and data indicate that the richly fossiliferous upper part of the unit is in fact younger than previously surmised (Rogers and Hartman 1998).

Stratigraphic data demonstrate that the Miadana Member of the Maevarano Formation correlates with the upper part of the Berivotra Formation. Data further suggest that the underlying Anembalemba Member also correlates, at least in part, with the Berivotra Formation (fig. 11). At present, on the basis of fossils, the age of the entire Berivotra Formation can be confidently interpreted as Maastrichtian (Rahantarisoa 1994), and recent work on planktonic foraminifera indicates that exposures of the formation in the Berivotra region are late Maastrichtian in age (Rahantarisoa 1986, 1994; Bignot et al. 1996; Janin et al. 1996; W. Elder, written comm., 1995, 1997; K. McDougall and I. P. Silva, written comm., 1998). Foraminiferal assemblages derived from the upper Berivotra Formation span the late *Gansserina gansseri* Zone up to almost the top of the *Abathomphalus mayaroensis* Zone. *Racemiguembelina fructicosa*, among other species, are common to the *G. gansseri* Zone. There is also an increase in abundance of *Guembelitria* and calcispheres in the topmost samples from the formation (K. McDougall and I. P. Silva, written comm., 1998).

In addition to the above considerations, the age of the Maevarano Formation may now be inferred from a new record of a rare gastropod. *Solariella* aff. *S. antonibensis* Collignon occurs about 4 m below the top of the Anembalemba Member. Collignon (1951) first reported *S. antonibensis* in association with ammonites now interpreted as Maastrichtian in age (W. Elder, written comm., 1997; W. J. Kennedy, written comm., 1997). The apparent occurrence of this taxon in the Anembalemba Member and its reported association with the ammonite *Eubaculities laybrithicus* Morton are consistent with the upper part of the Maevarano Formation being Maastrichtian in age.

Paleobiogeographic Implications

The progressive isolation of Madagascar during Gondwanan fragmentation undoubtedly had profound effects on the evolutionary and biogeographic history of its terrestrial and freshwater vertebrate faunas. This biotic history can now be placed within a more refined temporal context owing to the revised chronostratigraphy of the Upper Cretaceous section in the Mahajanga Basin. First of all, the revised Maastrichtian age of the upper Maevarano Formation has a significant bearing on comparisons of the contained vertebrate assemblage with those from other landmasses, particularly the Indian subcontinent. The age of the Upper Cretaceous dinosaur-bearing strata of India (Deccan basalt volcano-sedimentary sequence [DBVSS] of Sahni and Khosla 1994) was originally interpreted as Turonian to Santonian by von Huene and Matley (1933, p. 71) on the basis of comparisons with dinosaurian taxa from Madagascar, then still considered to be Turonian to Santonian in age based on the work of Depéret (1896*a*, 1896*b*) and Lemoine (1911). Von Huene and Matley's assessment was based primarily on the purported presence of "*Titanosaurus*" *madagascariensis* (currently considered to be a nomen dubium; K. Curry Rogers, pers. comm.) on both landmasses. Building on doubts expressed by several other workers, a reappraisal of the Indian dinosaur fauna led Buffetaut (1987) to suggest that it was much younger than Turonian to Santonian and that it was likely Maastrichtian. This assessment was later corroborated and refined by radiometric and magnetostratigraphic data, as well as by additional paleontological evidence (both marine and nonmarine). The DBVSS is now considered to be of latest Maastrichtian age (65–67.5 Ma) and within the *Abathomphalus mayaorensis* foraminiferal zone (see reviews of evidence in Khajuria et al. 1994; and Chatterjee and Rudra 1996).

The Campanian age of the Maevarano Formation suggested by Hoffstetter (1961), and accepted by later workers, and the latest Maastrichtian age estimate for the DBVSS provided the basis for the assessment by Krause and Hartman (1996, p. 146) that "the Late Cretaceous fauna from Madagascar (known primarily from the Maevarano Formation) is older, possibly considerably older, than that from the Indian subcontinent." In light of our analysis here, however, it appears that the vertebrate fauna from the Maevarano Formation and the DBVSS are much closer in age than previously realized and, perhaps, even contemporaneous. This, in turn, taken in concert with current geophysical models concerning the fragmentation of Gondwana in which the Indian subcontinent was the last major landmass connected to Madagascar, affords the prediction, ceteris paribus, that the terrestrial vertebrate faunas from the Maevarano Formation of Madagascar and the DBVSS of peninsular India are more similar to one another than either is to those from any other major Gondwanan landmass (Krause and Hartman 1996; Krause et al. 1997*a*, 1997*b*).

This prediction is at variance with several previous geophysical and biogeographical models that, implicitly or explicitly, posited closer links of the Late Cretaceous vertebrate fauna of Madagascar with that of Africa, or both Africa and India, than with that of India alone. Briggs (1989) and Chatterjee and Scotese (1998), for instance, have suggested a direct faunal connection between the Indian subcontinent and northeastern Africa during the Late Cretaceous (Briggs [1989, fig. 5] cites the Late Cretaceous ["about 70 m.y.a."] paleogeographic reconstruction of Barron [1987*a*, 1987*b*] to support this conclusion, but Barron's Early Maastrichtian reconstruction does not place the Indian subcontinent adjacent to northern Africa). Le Loeuff (1991), on the basis of a biogeographical study employing a methodology called "parsimony analysis of endemicity," concluded that the vertebrate fauna from the Maevarano Formation is generally more similar to that from the Campanian-Maastrichtian of mainland Africa than to that from India and that it is more distantly related to the Campanian-Maastrichtian vertebrate fauna of South America than to those of either Africa or India. Taquet (1982) suggested that the Davie Ridge acted as a land bridge permitting exchange of dinosaurs between Africa and Madagascar during the Late Cretaceous. Finally, Sues (1980, p. 960), employing evidence from sauropods, agreed with the geophysical model of Smith and Hallam (1970), and stated "a land connection between India, Madagascar, and Africa until the end of the Cretaceous or even later."

Our recent discoveries and preliminary analyses indicate that (1) the theropod *Majungatholus atopus*, from the Maevarano Formation, is an abelisaurid closely related to *Indosuchus raptorius* from India and *Carnotaurus sastrei* from Patagonia (Sampson et al. 1996, 1998); (2) Gondwanatherian mammals, previously known only from the Campanian and Paleocene of South America (Krause and Bonaparte 1993), were also present in the Maastrichtian of Madagascar and India (Krause et al. 1997*a*); (3) pelobatid frogs, previously described from the DBVSS of India (Sahni et al. 1982), are probably represented in the Maevarano Formation assemblage (Asher and Krause 1998); and (4) peirosaurid crocodiles are known only from the Late Cretaceous of Madagascar and South America (Buckley and Brochu 1999; Krause et al. 1999). This evidence indicates stronger ties to India and South America than to Africa, although the paucity of vertebrates from the terminal stages of the Late Cretaceous of Africa precludes a definitive determination. Krause et al. (1997*a*, 1997*b*, 1999) and Sampson et al. (1998) have hypothesized that the biotic connections among Madagascar, India, and South America (see also, e.g., von Huene and Matley 1933; de Lapparent 1957; Charig 1973; Russell et al. 1976, and others) may be explicable in light of recent evidence that Indo-Madagascar may have retained a physical connection to Antarctica until well into the Late Cretaceous.

The revised age of the Maevarano Formation as Maastrichtian, combined with ongoing efforts to evaluate the phylogenetic and biogeographic history of Late Cretaceous and extant vertebrates, also has a bearing on the biogeographic history of extant Malagasy vertebrates. Preliminary analysis of the terrestrial and freshwater vertebrate fauna of the Maevarano Formation, which includes fishes, frogs, turtles, snakes, crocodiles, birds, and mammals (table 1), confirms the hypothesis that the basal stocks of the vast majority of extant Malagasy vertebrate higher taxa colonized the island in post-Mesozoic times (Krause et al. 1998, 1999). Regardless of the controversy surrounding the time of separation of Indo-Madagascar from Antarcto-Australia (ranging from 135 to 80 Ma), it appears that the Indian subcontinent rifted from Madagascar approximately 88 Ma. Madagascar was thus an island isolated in the Indian Ocean from that time, several million years before the deposition of the Maevarano Formation, until the present. The absence of ancestral elements of extant higher taxa of vertebrates in the Maastrichtian, combined with current geophysical evidence, suggests that the basal stocks of the modern taxa arrived during the Cenozoic and that they did so by crossing a significant marine barrier, not by crossing a land bridge.

Despite recent claims that the Davie Ridge may have served as a more or less continuous land bridge during the Late Cretaceous (Taquet 1982; Rage 1988) and Cenozoic (McCall 1997), there is no compelling geological evidence in support of such a notion (see discussion in Krause et al. 1997*b*). The Davie Ridge is a deep ocean-floor structure extending from about 4° or 5° to 20° S (Scrutton et al. 1981); it represents the transform fault between the African Plate and the Antarctic Plate (to which Madagascar and the Indian subcontinent were connected). The major islands in the Mozambique Channel, such as the Comoros Chain, are volcanic in origin and were emplaced <8 Ma (Nougier et al. 1986). The Mozambique Channel is 2 km deep in most areas and >3 km deep in many (see bathymetric map in Udintsev 1975, p. 19). Nairn et al. (1991) have stated that foraminifera recovered from the top of the Davie Ridge suggest water depths of >2 km since at least Eocene time. While there is evidence of previous subaerial exposure on a few seamounts along the Davie Ridge (Leclaire et al. 1989; Malod et al. 1991; Bassias 1992), such dots of land, each with areas of only a few square kilometers at most, in a vast expanse of ocean 400–1000 km wide, did not a land bridge make.

Finally, the revised, younger age of the Maevarano Formation may also have important consequences for the investigation of extinction events at or near the K/T boundary. Although latest Cretaceous vertebrates are known from several other major landmasses (e.g., Asia, Indian subcontinent), most questions concerning the end Cretaceous extinction of terrestrial and freshwater vertebrates have been addressed previously on the basis of discoveries made in the Western Interior of North America (e.g., Archibald 1996; Chatterjee and Rudra 1996; Hunter et al. 1997). Dodson and Dawson (1991), for instance, recently compiled a list of some 400 identifiable, articulated specimens of Maastrichtian dinosaurs; of these, only 100 are from the late Maastrichtian, and of these, 95 are from North America. As Archibald (1996, p. 16) logically concluded, "just about all of our knowledge of dinosaur extinction comes from the Western Interior" and a "single-region database cannot answer a global question." The K/T boundary has already been identified in the marine section of the Mahajanga Basin (e.g., Lys 1960; Collignon 1968; Bignot et al. 1996; Janin et al. 1996), and the revised Maastrichtian age of the Maevarano Formation demonstrates that the dinosaurs discovered in that rock unit were both among the last on Earth and from considerably farther south than any of the other areas sampled previously.

Summary and Conclusions

The richly fossiliferous and heretofore poorly known Maevarano Formation accumulated in the central portion of the Mahajanga Basin during the latest Cretaceous. Deposition occurred on an alluvial plain bounded by crystalline highlands to the southeast and the Mozambique Channel to the northwest. The basal Masorobe Member is characterized by red-bed facies that reflect pervasive pedogenesis. The scale of individual root traces and the density of root mottling indicate that vegetation was of a shrub or bush variety and was fairly abundant. Vertical root fabrics, combined with the presence of caliche, further indicate that the flora was adapted for relatively dry conditions. The overlying Anembalemba Member consists of complexly interbedded sandstone facies that accumulated in a broad channel-belt system characterized by shallow flow and an ephemeral discharge regime prone to floods. Paleocurrent measurements indicate that flow roughly paralleled the north-northwest course of modern drainage systems. Tetrapods that inhabited the Maevarano alluvial plain (table 1) frequented the aggrading Anembalemba channel belts, and the numerous bonebeds preserved in this member may reflect marked seasonality (and resultant resource instability and ecosystem stress) comparable to the distinct rainy and dry seasons that influence parts of Madagascar today. Uppermost strata of the Maevarano Formation, namely the Miadana Member, were deposited in a lower coastal plain setting within a few kilometers of the sea. The overall decrease in grain size in the Miadana Member relative to the underlying Anembalemba and Masorobe members is interpreted to reflect a lower gradient and a decrease in stream competence. A widely traceable discontinuity surface separates the Maevarano Formation from the overlying Berivotra Formation, which was deposited under marine conditions during a regional transgression. Planktonic foraminifera, ammonites, echinoids, bryozoa, gastropods, and bivalves indicate deposition on an open marine shelf. Fossil data further indicate that the formation accumulated during the latter part of the Maastrichtian. The gradational but rapid transition from the Berivotra Formation to the overlying Betsiboka limestone presumably coincides with the shutdown of clastic supply as coastal flooding ensued and rivers shifted from sediment delivery systems to sediment sinks. The deposition of carbonates persisted well into the Tertiary as marine waters inundated the Mahajanga Basin.

New stratigraphic data indicate that the Maevarano Formation accumulated at least in part during the same marine transgression that led to deposition of the Berivotra Formation. The Miadana Member is wholly correlative with the upper few decameters of the Berivotra Formation. Most, if not all, of the Anembalemba Member also correlates with the Berivotra Formation. This finding differs significantly from the overly simplified layer-cake model of previous workers and indicates that the most fossiliferous portions of the Maevarano Formation are Maastrichtian in age, rather than Campanian.

The Maastrichtian age of upper portions of the Maevarano Formation has several important biogeographic implications. First, it indicates that the Maevarano vertebrate assemblage is approximately contemporaneous in age with the vertebrate assemblages recovered from the Deccan basalt volcano-sedimentary sequence of India. This finding is certainly consistent with the striking similarities between the faunas from these two Gondwanan landmasses. Second, this new Maastrichtian (perhaps late Maastrichian) age designation, when considered in the light of recent fossil discoveries in the Maevarano Formation, indicates that the basal stocks of Madagascar's endemic extant vertebrate taxa arrived on the island after the end of the Cretaceous. This implies that the island is populated today by taxa that somehow crossed a significant marine barrier during post-Mesozoic time. Finally, the revised age of the Maevarano Formation serves to expand our global perspective on the K/T event by clarifying the Maastrichtian age of a diverse sample of vertebrate taxa from a relatively unexplored portion of Gondwana.

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