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The Toarcian–Bathonian succession of the Antsiranana Basin (NW Madagascar): Facies analysis and tectono-sedimentary history in the development of the East Africa-Madagascar conjugate margins

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Abstract

The latest Early to Middle Jurassic succession of the Antsiranana Basin (NW Madagascar) records the complex transition from the continental rifting of Gondwana to the drifting of Madagascar-India from East Africa. The Madagascan Late Paleozoic–Mesozoic successions have been included in several paleogeographic and geodynamic models explaining the evolution of the Gondwana margins. Nevertheless, in some cases, as for the Toarcian–Bathonian deposits of the Antsiranana Basin, no significant stratigraphic revision has been carried out since the early 1970s. New field surveys allow reconsidering the stratigraphic and structural context and the palaeoenvironmental meaning of Toarcian–Bathonian successions occurring in different parts of the basin. These successions rest on the Triassic-Early Jurassic Isalo Sandstone which records pre-breakup rift events with a dominantly fluvial deposition. This situation is similar to other continental rift basins of Gondwana. After a regional Toarcian transgression the different portions of the Antsiranana Basin were characterized by significantly diversified and coeval depositional environments. The basin can be subdivided in a SW and NE part separated by a NW–SE trending structural high. In the SW part of the basin (Ampasindava sub-basin) the so-called "Jurassique paralique" [Rerat, J.C., 1964. Note sur les variations de faciès des sèries jurassiques du nord de Madagascar. Comptes Rendus Semaine gèologique, Tananarive, pp. 15–22] or "*Facies Mixtes de la Presqu'ile de Ampasindava*" [Besairie, H., Collignon, M., 1972. Géologie de Madagascar; I. Les terrains sédimentaires. Annales Géologiques de Madagascar, 35, 1–463], a 1500 m thick prevalently terrigenous deposit, has been subdivided into four units. They document the long-lasting development of coastal–deltaic systems in a highly subsiding area. In the NE portion of the basin (Ankarana–Analamera sub-basin), a coeval mixed carbonate–terrigenous succession subdivided in five units for a total thickness of 500 m, was deposited during relative sea-level fluctuations in a ramp setting characterized by relatively lower subsidence.

The stratigraphic-depositional evolution was dependant on the presence of NW-trending, actively growing highs which fed the southwestern sub-basin. The clastic supply balanced the tectonically created accommodation space in this portion of the basin.

The revised and extended paleogeographical reconstruction has been included into a breakup model of the East Africa-Madagascar rift during the opening of the Mozambique Channel.

Keywords: Stratigraphy; Facies analysis; Jurassic paleogeography; Gondwana rifting; Antsiranana Basin; Madagascar

1. Introduction

The western margin of Madagascar is characterized by three contiguous sedimentary basins, the Morondava, Mahajanga and Antsiranana Basins (Fig. 1), which have been active since the Late Paleozoic.

The smallest of them, the ca. 300 km wide Antsiranana Basin, extends from the Ampasindava Peninsula in the SW to Antsiranana in the NE. Since the Permian the basin has been filled by 3–6 km thick sedimentary succession (Besairie and Collignon, 1972). The Antsiranana Basin, similar to other Madagascan Basins, records the development of the

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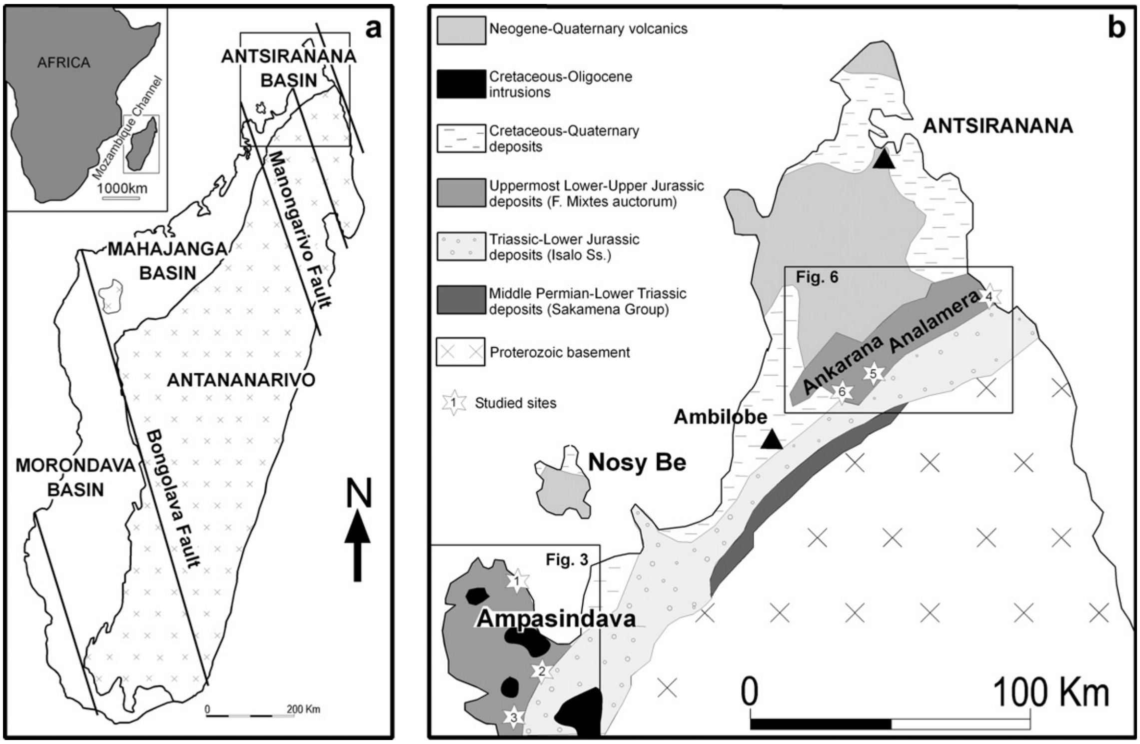

Fig. 1. (a) Distribution of the main sedimentary basins and fault zones in Madagascar; to notice the NW–SE trending major fault zones; (b) schematic geological map of the Antsiranana Basin.

East Africa-Madagascar conjugate margins (Coffin and Rabinowitz, 1988; Piqué, 1999; Reeves et al., 2002) through the following stages: (1) from the Late Carboniferous to the Early Jurassic the central part of Gondwana was affected by transtensional tectonics related to cratonic SW–NE mega-shear zones (Katz, 1987; Daly et al., 1989; Schandelmeier et al., 2004). As a consequence NE–SW strike-slip basins dominated by E–W extension developed in Gondwana and were subsequently filled with the Karoo deposits; (2) since the Middle–Late Jurassic, with the opening of the Mozambique Channel, the Madagascar block moved southward along the transcurrent Davie and DHOW fracture zones (Coffin and Rabinowitz, 1988; Malod et al., 1991; Luger et al., 1994; de Wit, 2003).

The latest Early Jurassic and Middle Jurassic represent therefore critical time intervals for the development of the East Africa-Madagascar conjugate margins, when the transition from a very long and complex continental rifting to the development of oceanic spreading and passive margins took place. An overall continuous geodynamic evolution since the Permian, has been proposed by some authors (Coffin and Rabinowitz, 1988; Hankel, 1994; Wopfner, 1994) whereas others (Geiger et al., 2004; Geiger and Schweigert, 2006) point to a significant interruption during the earliest Jurassic. The latter breakup model attributes the Permian–Triassic Basin to a pre-rifting stage of the Gondwana breakup whereas the effective breakup occurred as a short-lived rifting stage during the Toarcian–Aalenian. Drifting and oceanic spreading commenced during the Bajocian–Bathonian and lasted till the Cretaceous.

This study is based on the re-interpretation of a thick Lower–Middle Jurassic succession in the Antsiranana Basin, which has been described in previous works (Rerat, 1964; Besairie and Collignon, 1972). This succession rests unconformably on Middle Permian to Lower Jurassic Karoo deposits (Sakamena and Isalo groups; Besairie and Collignon, 1972; Wescott and Diggens, 1998) and started to develop during the Early–Middle Toarcian when shallow marine conditions established over the basin bringing to the deposition of mixed carbonate–terrigenous deposits (from SW to NE the Jangoa Limestone, Marivorahona Series p.p and Ankarabo Formation, Rerat, 1964; Fig. 2, Tables 1 and 2). Afterward, deposition to the SW (Ampasindava Peninsula) was characterized by dominantly coastal terrigenous deposits (Aalenian-Callovian *Facies Mixtes*; Rerat, 1964; conf. Besairie and Collignon, 1972) meanwhile mixed carbonate–terrigenous deposition persisted to NE (Marivorahona Series p.p, stratigraphically equivalent to Aalenian-Callovian Ankarana–Analamera Formation; Rerat, 1964). The *Facies Mixtes* of the Ampasindava Peninsula have been subdivided by Rerat (1964) in four formations, namely the Ampasimena, Andrahibo, Komamery, and Lavaloalika formations (Fig. 2, Table 1).

Stratigraphic and sedimentologic field data (Papini, 1995) allows to reconsider the tectono-sedimentary significance of these Lower–Middle Jurassic successions exposed in the different portions of the Antsiranana Basin, Ampasindava sub-basin and Ankarana–Analamera sub-basin in this study. Various sedimentary units have been established in the two sub-basins based on bounding surfaces and on

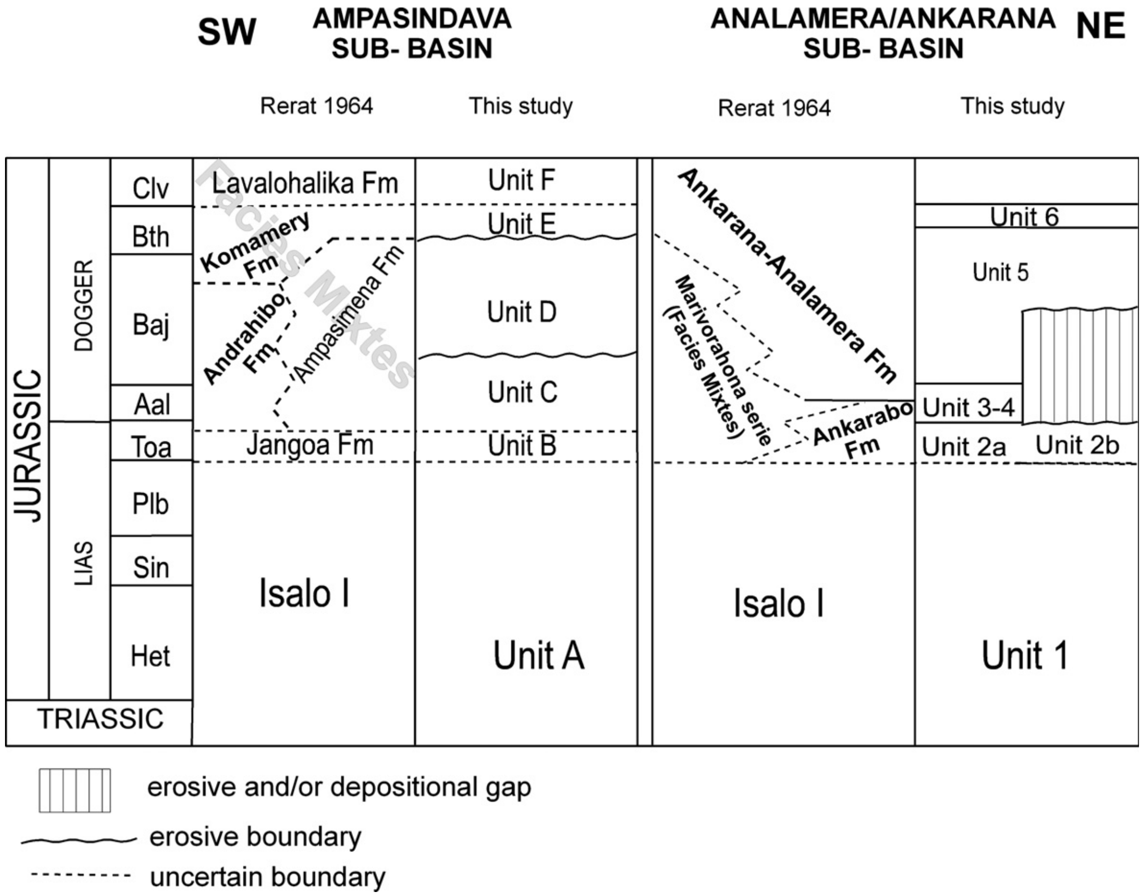

Fig. 2. Comparison of the stratigraphic subdivisions of the Lower–Middle Jurassic successions in the Antsiranana Basin. This succession rests unconformably on Middle Permian to Lower Jurassic Karoo deposits (Sakamena and Isalo groups, and started to develop during the Early–Middle Toarcian when shallow marine conditions established over the basin bringing to the deposition of mixed carbonate–terrigenous deposits.

the sedimentologic features of their deposits. This approach resulted in a quite different stratigraphic picture in respect to the framework of laterally equivalent lithostratigraphic units proposed by previous authors (Fig. 2). New stratigraphic and sedimentologic data on the Aalenian–Bajocian portion of these successions will be described in detail. This chronostratigraphic interval is particularly significant for the variation and cyclic arrangement of coeval facies occurring in these sub-basins. Similar to what has been described from the same chronostratigraphic interval in the Morondava Basin (Geiger et al., 2004; Geiger and Schweigert, 2006), the data provides from this study may help in reconsidering the tectono-sedimentary events of this area into the geodynamic context of the East Africa-Madagascar conjugate rifted margins.

2. Contributions from recent fieldwork in the Antsiranana Basin

2.1. The Ampasindava sub-basin: tectonic setting and revised lithostratigraphy (Fig. 3)

Field studies and photogeological analysis revise the morphostructural setting for this area (Fig. 3). According to Rerat (1964) the *Facies Mixtes* of the Ampasindava Peninsula is part of a homoclinal basin dipping toward W with an estimated thickness of 3000–6000 m. In contrast, our survey recognizes a dome structure with beds radially diverging from the center of the peninsula (Papini, 1995). In this area Besairie and Collignon (1972) report Oligocene alkaline lava flows and pyroclastics and their occurrence could explain the dome feature.

It should be noted that in our reconstruction the thickness of the uppermost latest Early to Middle Jurassic deposits does not exceed 1500 m.

On the Ampasindava Peninsula (Fig. 3) six informal sedimentary units (A–F) are recognized by Rerat (1964) and Besairie and Collignon (1972) (Fig. 2 and Table 1) based on lithologies.

A field control of the earlier descriptions has been performed in the Ambarata Bay, northern part of the Ampasindava Peninsula, and the survey was extended to the upstream reach of the Bemanevika estuary where units C and D can be observed (Figs. 3 and 4a). Further field controls on units D and E have been performed between Jojahely and Ankarami (Figs. 3 and 4b). A short lithologic description and interpretation in terms of depositional environments and chronologic calibration is given in Table

Table 1
Comparison of stratigraphic subdivisions established in the Ampasindava sub-basin in this study and by previous authors

Units from this study (units from previous studies)	Lithological description	Fossil content and age	Environment
Unit A (Isalo I Sandstone, Besairie and Collignon, 1972)	Cross-laminated whitish medium-coarse, locally microconglomeratic, quartzitic sandstones in bedsets up to 10 m thick. Reddish mudstones may be embedded within the sandstones	Barren, silicified tree trunks; Triassic-early "Lias"?	Alluvial plain
Unit B (Jangoa Limestone, Rerat, 1964; Besairie and Collignon, 1972)	Limestone interbedded within fine sandstones and claystones	Marine molluscs (in Besairie and Collignon, 1972): *Harpoceras* cf *metallarium, Spiriferina rostrata, Eopecten* cf *turberculosus, Rynchonella triplicata, Terebratula* cf *sarthacensis, Pholadomya* cf *voltisi, Protocardia striatulata, Gryphaea* cf *beaumonti*, lower–middle Toarcian	Mixed carbonate–terrigenous ramp
Unit C (Ampasimena Formation according to Rerat, 1964)	Dark grey calcilutite and marl (Fig. 5a) with subordinate cross-bedded sand indicating palaeocurrent direction toward NE	Vegetal remains (in Besairie and Collignon, 1972): *Equisetum jolyi, Pecopteris exilis, Yuccites* cf *hettangiensis, Yuccites* cf *angustifolius, Yuccites* cf *burgundiacus, Araucarites kutchensis, Brachyphyllum* cf *papareti, Pagiophyllum* sp., *Scleropteris* sp., *Sphenolepidium* sp. Marine molluscs (in Besairie and Collignon, 1972): *Catulloceras dumortieri, Harpoceras* cf *metallarium, Harpoceras* cf. *serpentinum* Toarcian-Aalenian	Coastal plain and shallow marine
Unit D (Andrahibo Formation, Ampasimena Formation according to Rerat, 1964)	Alternation of whitish sandstone and dark grey claystone. Sandstone are cross-bedded indicating palaeocurrents to SW	Barren, marine molluscs at Nosy Kisimamy (Besairie and Collignon, 1972) : *Gervillia iraonensis, Gervillia orientalis, Mactromya* sp., *Trigonia* sp. Bajocian-Bathonian?	
Unit E (Komamery Formation, Rerat, 1964; Besairie and Collignon, 1972)	Alternation of whitish medium-fine sandstone and grey claystone passing upward to marls	Dinosaur and marine invertebrate (*Macrocephalites* sp.) remains in the western portion of the Ampasindava Peninsula (Besairie and Collignon, 1972) Bathonian–Callovian	
Unit F (Lavalohalika Formation, Rerat, 1964)	Dark grey sandy clay with fine to coarse sandstones at the top	Barren Callovian	Coastal plain

1 (see also Fig. 2). Units D and E, surveyed in more detail, are described in the following section.

2.2. Facies analysis of units D and E

2.2.1. Unit D

Unit D is well exposed in the Ambarata Bay where three sub-units have been distinguished (Fig. 4a). Sub-unit D1 is about 70 m thick and rests erosively on unit C. It is characterized by alternations of white sandstones and black claystones (Fig. 5b). Sandstones are medium to coarse-grained and typically planar and trough-cross bedded with laminae dipping predominantly towards the SW. They are arranged in lenticular beds from 0.1 to 2 m thick stacked into major bedsets up to 10 m thick. Sandstones prevail on mudstones on which they rest through sharp, erosive surfaces. Claystones are generally massive and contain thin levels of siltstones and fine-grained sandstone. Sub-unit D2, about 40 m thick, is made of laminated black mudstones with thin layers of white or greyish siltstones, calcarenites and fine-grained cross-laminated sandstones. Locally, large mud volcanoes up to 3–4 m in diameter occur (Fig. 5c). Similarly to the sub-unit D1 no marine fossils have been found in sub-unit D2. Sub-unit D3, minimum 35 m thick, is composed of black mudstones and subordinate white sandstones (Fig. 5d). Sandstones are medium-fine grained, planar cross-laminated and arranged in lenticular beds to form tabular bedsets up to 10 m thick. Cross lamination indicates palaeocurrent to the NE. Mudstones are massive or thinly laminated with thin levels of siltstones. Locally convoluted beds are present. No macro- or microfossils have been detected in this sub-unit.

2.3. Further outcrops of unit D

Near Antsafiabe (Fig. 4b) deposits ascribed to unit D consist of about 90 m thick, thinly laminated mudstone arranged in 10 cm beds. These deposits are pervasively affected by pinkish–yellowish–reddish mottling. Thin levels of very fine yellowish sandstones occur in the uppermost part of these deposits.

2.4. Facies interpretation of unit D

The geologic mapping and the stratigraphic–sedimentological survey from this study (Figs. 2–4) have shown that unit D is equivalent to parts of the Rerat's Andrahibo and Ampasimena formations which are referred to a dominantly siliciclastic coastal plain and deltaic environment (Rerat, 1964). Strata on Nosy Kisimamy Island (north of Ampasindava Peninsula) which are younger than sub-unit D3 yielded a Bajocian–Bathonian pelecypod fauna (Table

Table 2
Comparison of stratigraphic subdivisions established in the Ankarana–Analamera sub-basin in this study and by previous authors

Units from this study (units from previous studies)	Lithological description	Fossil content and age	Environment
Unit 1 (Isalo I Sandstone, Besairie and Collignon, 1972)	Cross-laminated whitish medium-coarse, locally microconglomeratic, quartzitic sandstones in bedsets up to 10 m thick (Fig. 7c). Palaeocurrent toward NNE. Reddish mudstones may be embedded within the sandstones	Barren, silicified tree trunks; Triassic-early "Lias"?	Alluvial plain
Sub-unit 2a (Marivorahona Series, Rerat, 1964; Besairie and Collignon, 1972)	Alternation of well stratified silty claystones, clayey sandstones and marly limestone	Wood remains, bivalves and gastropods (Besairie and Collignon, 1972) Toarcian	Mixed carbonate–terrigenous ramp
Sub-unit 2b (Ankarabo Sandstone Rerat, 1964)	Cross-stratified quartzitic coarse-medium sandstones with carbonate cement (Fig. 9 a). Palaeocurrent toward WSW	Barren Toarcian? (Rerat, 1964; Besairie and Collignon, 1972)	Fluvio–deltaic
Unit 3 (Ankarana–Analamera Formation according to Rerat, 1964)	light grey marly limestone and subordinate calcarenitic beds	*Ludwigia murchisonæ, Tmetoceras scissum, Erycites onionotus, Sonninia aff. subdecorata, Posidonomya alpina* (Besairie and Collignon, 1972) *Nannofossils: Carinolithus magharensis (this study)* Aalenian	Mixed carbonate–terrigenous ramp
Unit 4 (Ankarana–Analamera Formation according to Rerat, 1964,)	Dark grey limestones passing upward into clayey-silty marlstones		
Unit 5 (Ankarana–Analamera Formation according to Rerat, 1964)	Alternation of oolithic limestone, marls and cross-stratified coarse-medium sandstones	*Ludwigia* sp., *Tmetoceras* sp., *Witchellia* sp., *Rhynchonella fageae, Macrocephalites* sp. (Rerat, 1964; Besairie and Collignon, 1972) Aalenian–Callovian	
Unit 6 (Ankarana–Analamera Formation according to Rerat, 1964)	Grey dolomitic limestone, locally sandy and oolitic limestone in meter thick tabular beds		Carbonate ramp

1; Besairie and Collignon, 1972). Apart from the age constraint the fossils indicate a marine influence in an overall alluvial-coastal environment documented by unit D. On the whole the palaeoflow directions in unit D shows sediment supply from NE. This sediment provenance contrasts with the scanty palaeocurrent data detected on top of unit C (Table 1) indicating sediment supply from an opposite direction.

The succession logged in the Ambarata Bay is referred to a fluvial-floodplain setting characterized by cyclic change of the depositional environment such as channels, floodplain and ponds. Cross-bedded sandstone in sub-unit D1 records small sinuous-crested dunes migrating in shallow channels. The associated claystones deposited mainly in a low-energy, poorly drained and poorly oxygenated floodplain, rich in organic material. Similar low-energy depositional conditions are hypothesized for sub-unit D2 formed by sediment settling in shallow ponds and lakes. Occasional mud volcanoes point to syn-depositional deformation presumably related to seismic shocks which induced large-scale fluid escape from underlying sediments. The depositional setting of sub-unit D3 was characterized by cyclic deposition of sandy channel belts and floodplain environments.

Unit D observed at the Ambarata Bay is characterized by the vertical stacking of sub-units showing a varying sandstones/claystones ratios which may be interpreted in terms of base-level variation. Thick and laterally extensive sandstones in D1 suggest a basin-ward shift of coarse-sediment supply during a period of a relative low-stand or a slow rise of the base-level. The interbedded claystones document the abrupt deactivation of the channel belts during short periods of increasing accommodation space. Dominant claystones in D2 record a time of a rising relative base-level with a more significant deactivation or landward shift of coarse-grained supply. Claystones/sandstones alternation in D3 suggests again a progressive increase of sandy supply to the fluvial feeder systems. Regarding the whole considered sedimentary section, sub-units D1, D2 and D3 outline a quasi-symmetrical sedimentary cycle whereas the internal alternation of sandstone and claystone outline short term increase in accommodation space throughout the section. We conclude that the whole section could record a base level-controlled cycle and the fining-upward sequences high-frequency pulses in basin subsidence due to tectonism. Similarly, different scale (tens to hundreds meters) fining-upward sequences in the Mesozoic successions of rift basins have been interpreted as response to fast subsidence rates during the rifting process (Surlyk and Clemmensen, 1983; Lambiase, 1990; Nottvedt et al., 1995). Fluid-escape structures occurring in the described section are evidence a tectonically-active setting.

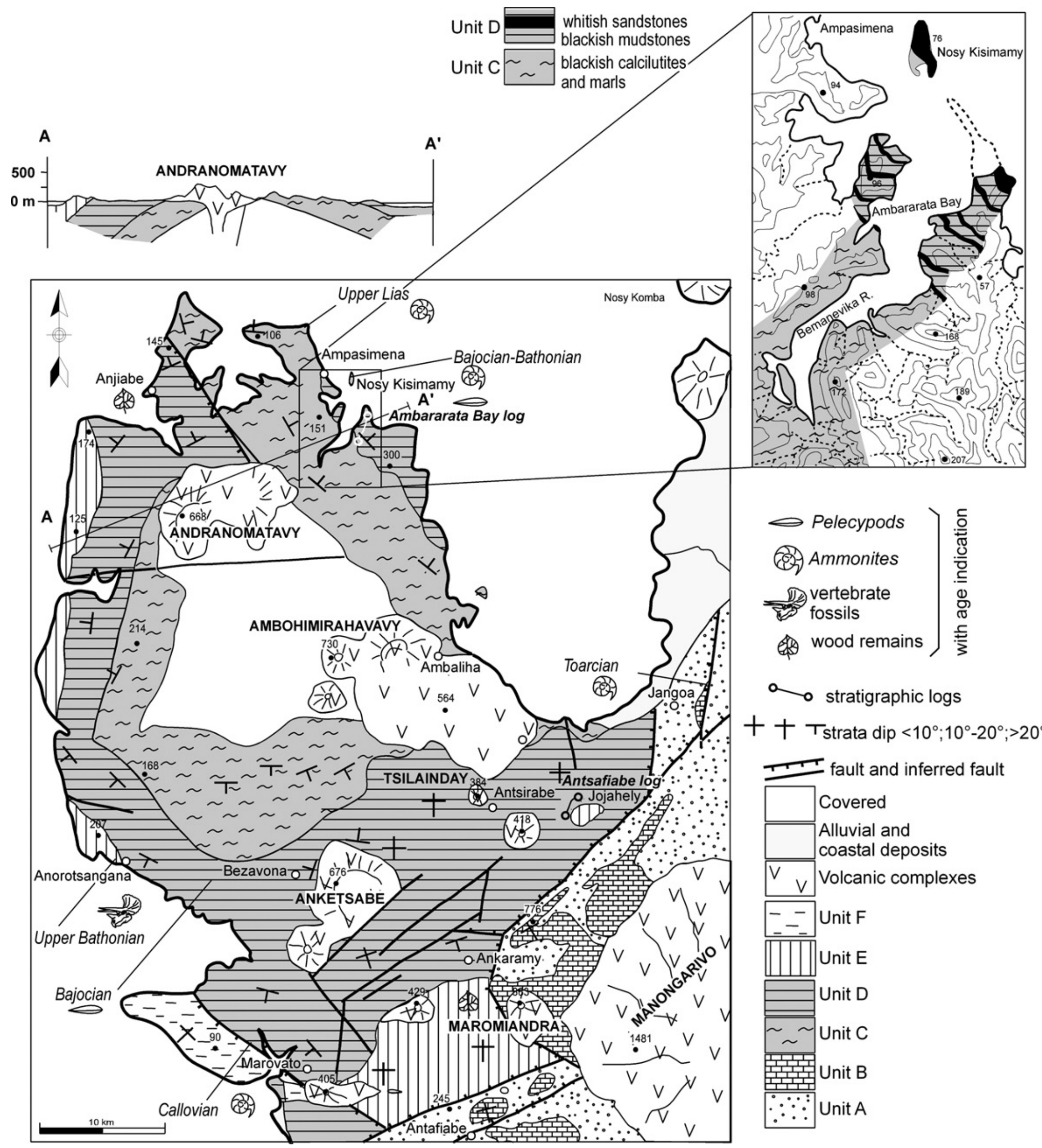

Fig. 3. Geological map of the Ampasindava Peninsula; inset with distribution of units C and D in the Ambarata Bay–Bemanevika estuary area.

The fine-grained deposits observed in the Antsafiabe outcrops document a fluvial low-energy, depositional environment under a different hydrological regime compared to the muddy deposits within unit D in the Ambarata Bay. Diffuse mottling points to fluctuating water table which hampered the accumulation of organic matter, which are abundant on the contrary in the claystones exposed in the Ambarata Bay. This depositional contrast can be explained as a change of the depositional environment both in space and in time. This variation could have resulted from a gradient in the fluvial-coastal plain recorded by unit D in which the Antsafiabe and Ambarata outcrops are located in a proximal, well-drained, and distal, poorly-drained, position. In contrast, these changes of the depositional setting could also have formed at different stages during the deposition of unit D.

2.4.1. Unit E

At the top of the Antsafiabe section (Fig. 4b) two sandstone layers are considered to mark the base of unit E which rests erosively on unit D (Fig. 6a). Sandstones are medium-fine grained and horizontal laminated. They comprise lenticular beds up to 2.5 m thick with a erosive base. The sandstone bodies occur in black laminated claystones. The upper sandstone body is characterized by a fining-upward trend and on top by a weathered horizon. Neither macro- nor microfossils have been found in this section. Near Ankarami village an outcrop shows a further, limited,

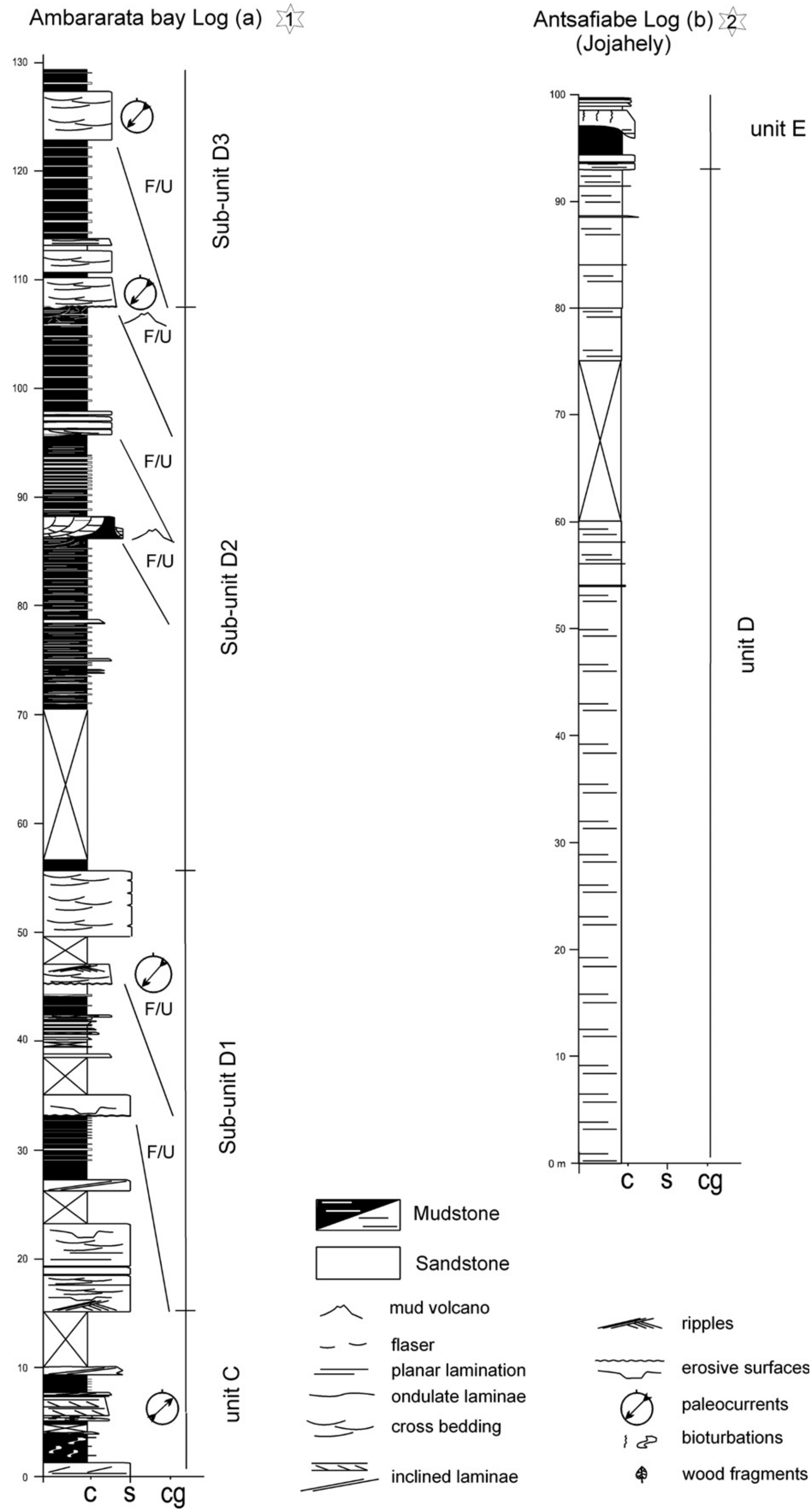

Fig. 4. (a) Ambarata Bay section: This succession is referred to a fluvial–floodplain setting characterized by cyclic change of the depositional environment such as channels, floodplain and ponds. (b) Antsafiabe section: The fine-grained deposits observed in this section document a fluvial low-energy, depositional environment under a different hydrological regime compared to the muddy deposits within unit D in the Ambarata Bay.

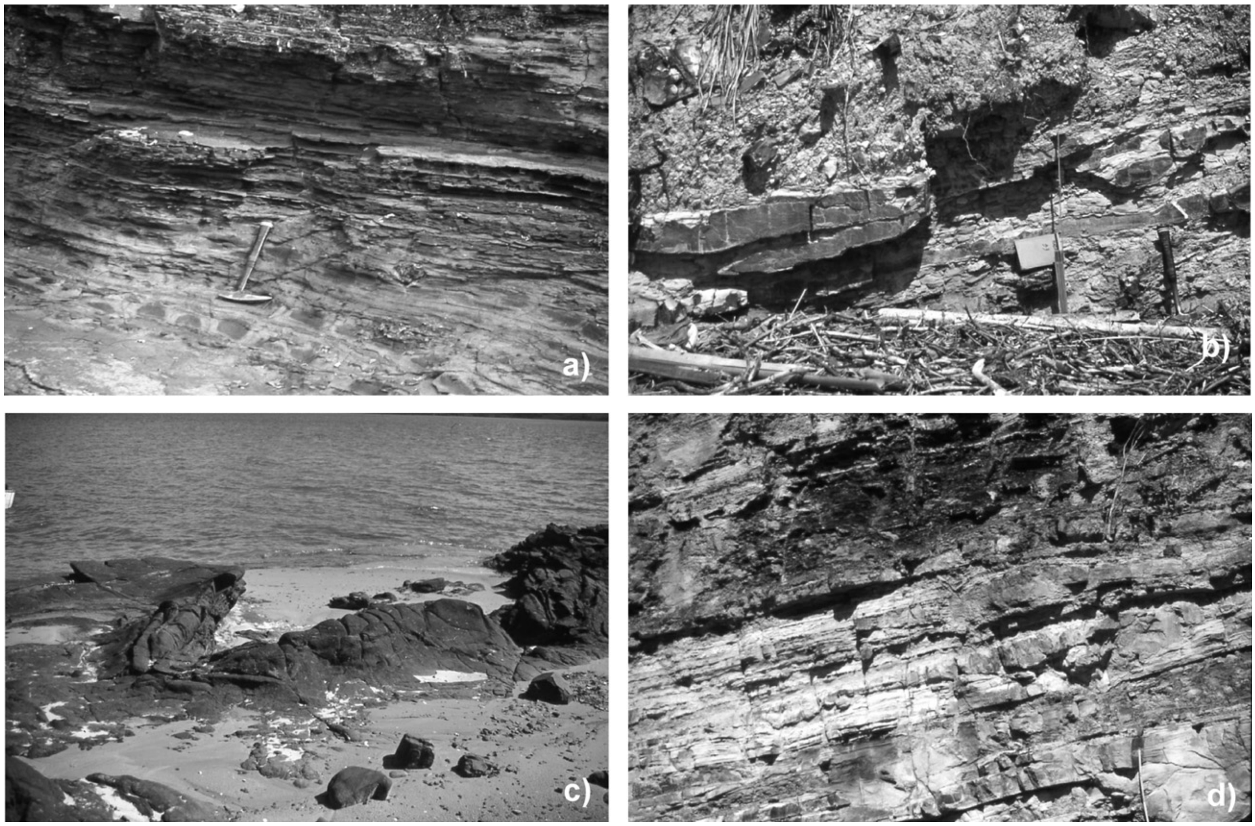

Fig. 5. (a) Thinly stratified black calcilutites of unit C exposed on the bank of the Bemanevika estuary, hammer for scale (see Table 1); (b) channellized sandstones and interbedded mudstone of sub-unit D1 in the Ambarata Bay area, hammer for scale (see also Fig. 5a); (c) large-scale mud volcano affects a 1.5 m thick calcarenite bed which is overlain by undisturbed laminated mudstones, sub-unit D2, Ambarata Bay; (d) sheet sandstone and interbedded mudstone in sub-unit D3, Ambarata Bay, the rod is 1 m long.

portion of unit E (Fig. 6b). The section is characterized by alternations of medium-fine yellow sandstones in lenticular beds 10–15 cm thick and black laminated claystones locally bearing plant remains. These deposits pass upwards into medium-fine grained white sandstones, arranged in a 1 m thick lenticular bed with an erosive base and occasional planar inclined sets of laminae. These are overlain by sandstones in decimetre-thick tabular beds with interbedded black mudstones.

The sandstone units are interpreted as fluvial channels incised in the floodplain and crevasse splays basing on beds geometry and sedimentary structures. Channels are particularly evident in the Antsafiabe outcrop and indicate fluvial incision at the transition between unit D to E as the consequence of fluvial rejuvenation. At Ankarami a channelized sandstone shows evidence of lateral accretion and thus of the development of a sinuous channel oriented more or less E–W. At the top of the section the sandstone sheets indicate unconfined overbank deposits of crevasse splays.

2.5. The Ankarana–Analamera sub-basin: tectonic setting and revised litostratigraphy (Fig. 7)

The Ankarana–Analamera plateau outlines a very gentle NW–SE oriented syncline which is characterized by NE–SW and NW–SE trending sets of normal faults, locally determining vertical offset up to some tens of meters (Papini, 1995).

Six sedimentary units have been distinguished basing on field and photogeological analysis (Fig. 7) within lithostratigraphic units defined in previous studies (Rerat, 1964; Besairie and Collignon, 1972, Fig. 2, Table 2). Units 3, 4 and 5 have been observed in more detail and will be specifically discussed for their facies development.

2.6. Facies analysis of units 3, 4 and 5

2.6.1. Unit 3

Unit 3 exposed in the Ambilomagodro area (Fig. 7) has been divided into five sub-units (Fig. 8a) which are shortly described by their main lithologic and sedimentologic features.

Sub-unit 3.1 is about 8 m thick and characterized in the basal part by light grey marlstones in tabular beds, 10 cm thick, with subordinate thin calcarenite beds. A micropalaeontological analysis done in this study, revealed a poorly-preserved association of nannofossils including *Carinolithus magharensis* pointing to an Aalenian age (cf. Bown et al., 1988; Reale et al., 1992). Sub-unit 3.2 is about 27 m thick and characterized at the base by massive calcarenites in

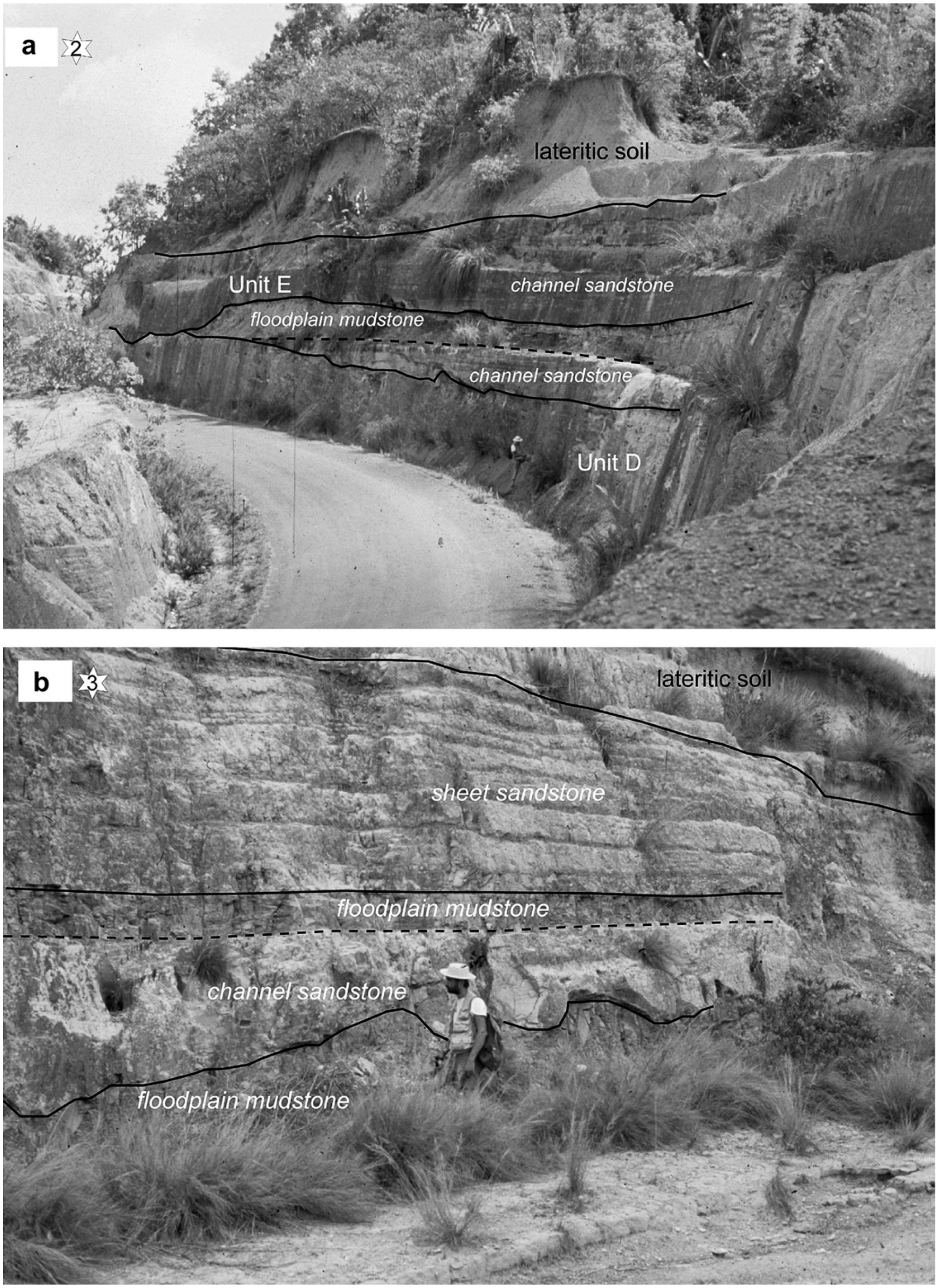

Fig. 6. (a) The upper portion of Antsafiabe section shows the transition from unit D to unit E, person for scale; (b) unit E at Ankarami characterized by channellized sandstone passing upward into sheet sandstones, person for scale.

beds up to 20 cm thick. Upward dark grey massive marlstone is present and capped by a 1 m thick oncolitic grainstone bed. The oncoids, more than 2 mm in diameter and elongated in shape, are characterized by concentric carbonate coatings produced by algal mats around fragments of bivalves, gastropods, echinoids and agglutinated foraminifera. The uppermost part of sub-unit 3.2 is characterized by an alternation of massive and laminated dark grey mudstone arranged in wavy beds few cm thick (Fig. 9b). Sub-unit 3.3 is about 35 m thick and composed of dark grey massive marlstones with interbedded thin (3–5 cm thick) levels of massive calcarenites. No macro- or microfossils have been found. Sub-unit 3.4 is 15 m thick and consists of white calcarenites interbedded with light grey mudstones.

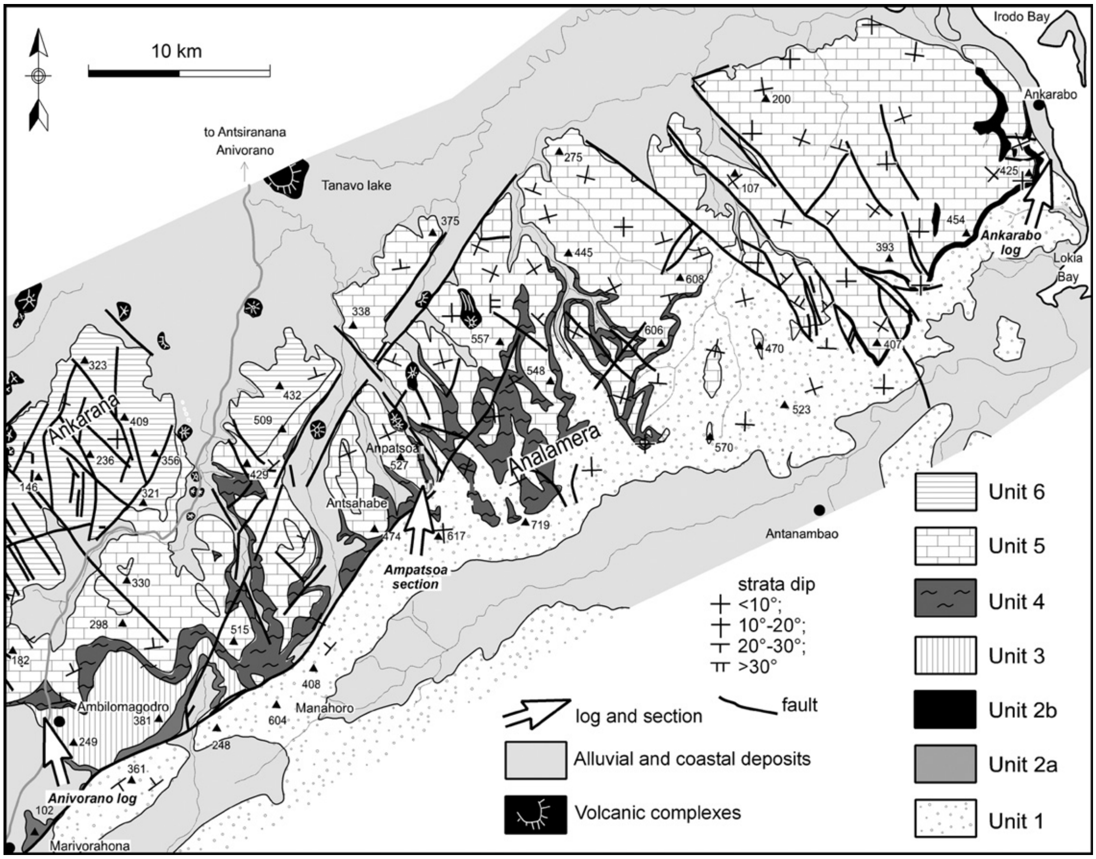

Fig. 7. Geological map of the Ankarana–Analamera region showing the relations among the Lower–Middle Jurassic units defined in this study.

Calcarenites, including also quartz and mica grains, are characterized by horizontal as well as trough and planar lamination indicating palaeoflow towards WSW (Fig. 8a). In places laminae of carbonized organic matter are abundant. Some beds show an erosive base. Mudstones are massive and lack of fossil remains. Sub-unit 3.5 is 15 m thick and consists of grey mudstones and light grey marlstones. Limestones are arranged in tabular beds, separated by thin marly wavy interbeds, forming thickening upward bedsets of 1.5–2 m thickness. Dispersed bioclasts consisting mainly of pelecypods and gastropods, are common especially in the lower part of these bedsets where mudstones are generally dark grey.

2.6.2. Unit 4

This unit, at least 35 m thick on top of the Anivorano log (Fig. 8a), is formed of massive dark grey limestones passing upward to marlstones with intervening thin calcarenite beds. Samples for micropalaentological analysis yielded a nannofossil association including *Carinolithus magharensis.*

2.7. Facies interpretation of units 3 and 4

On the whole units 3 and 4 show a cyclic facies development which is interpreted in terms of relative sea level fluctuations affecting a mixed carbonate–siliciclastic ramp during part of the Aalenian. Sub-unit 3.1, interpreted to be deposited in the outer portion of a mixed siliciclastic–carbonate ramp setting, documents the transgressive portion of a first, incomplete, cycle whereas the overlying sub-units 3.2 and 3.3 attest to a subtle lowering of sea-level followed by deepening of the depositional environment. At the base sub-unit 3.2 records a basin-ward shift of continent-derived coarse-grained siliciclastic deposits due to a possible fall of sea level. Low-energy conditions are evidenced further up in the section. The peculiar oncolitic limestone on top of sub-unit 3.2 may indicate condition of sediment starving on the outer ramp (Tucker and Wright, 1990). In ancient ramp settings oncolites have been referred to low-energy depositional areas on both the landward and seaward side of carbonate shoals (Legarreta, 1991). Jurassic oncolite-bearing limestone have been reported to have frequently formed in relatively deep water during phases of starved or condensed deposition (Bernoulli and Jenkyns, 1974; Eliuk, 1978) coinciding with high sea level. Further up the marly sub-unit 3.3 would be deposited on the ramp throughout the sea level highstand. The following sub-units 3.4, 3.5 and unit 4 depict a further cycle of relative sea-level fluctuation in large part similar to the previous one. Nevertheless a significant difference relies on the basal coarse-grained deposits in sub-unit 3.4 which attest to a more pronounced sea-level lowering in respect to that recorded by the basal portion of sub-unit 3.2. Calcarenites, bearing siliciclastic

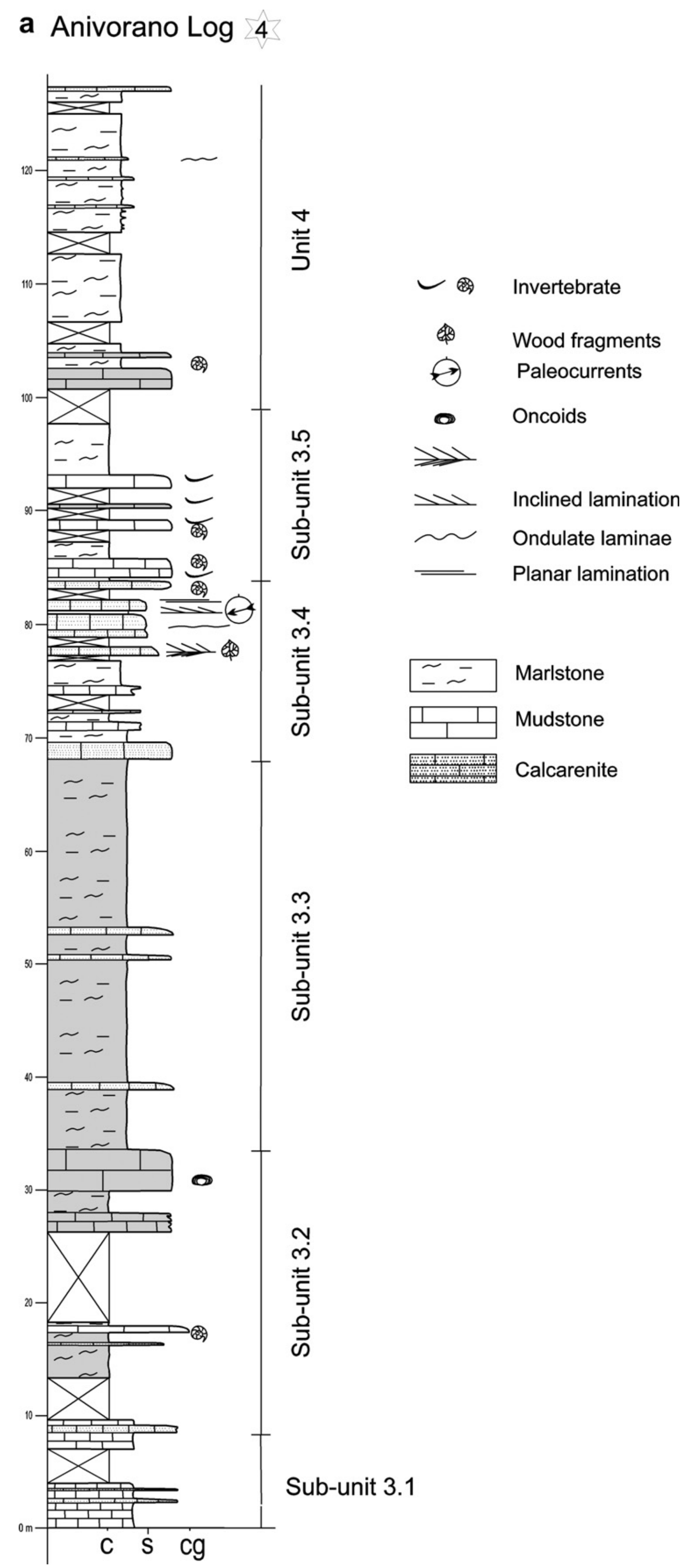

Fig. 8. (a) Anivorano section; (b) panoramic view of the Ampatsoa ridge and interpretative line-drawing showing the stratigraphic transition between units 4 and 5 and the internal stacking of exposed intervals within unit 5 discussed in the text; (c) Ankarabo section. The units 3 and 4 show a cyclic facies development which is interpreted in terms of relative sea level fluctuations affecting a mixed carbonate–siliciclastic ramp during part of the Aalenian. The unit 5 is interpreted as a carbonate platform with the deposition of carbonate mud in a lagoonal environment and the deposition of ooid shoals and in barriers at the platform rim.

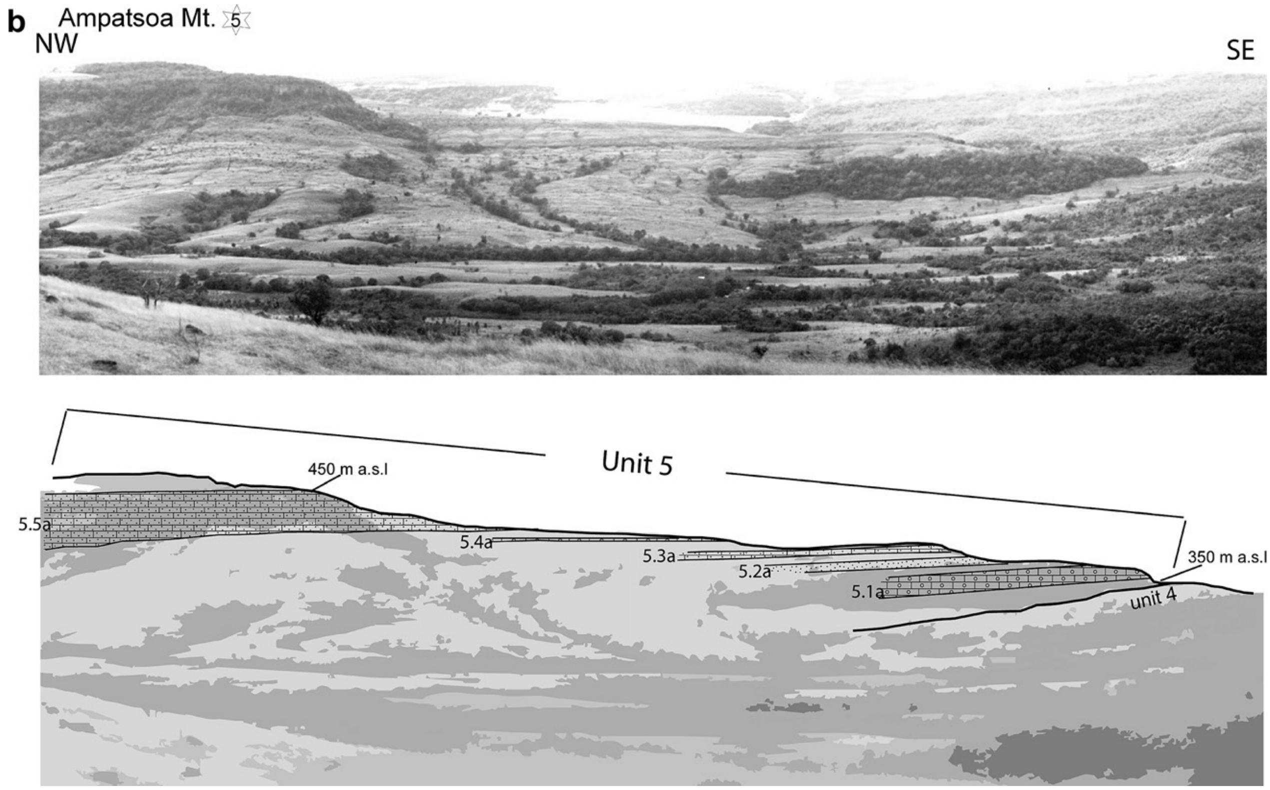

Fig. 8 (*continued*)

grains, and current structures indicate a mixed sediment supply in which the terrigenous component reflects denudation of sources located towards ENE (the Madagascar mainland). These deposits are referred to a river-dominated deltaic system pointing to a significant variation of base level and sediment supply to the sub-basin.

Limestones in sub-unit 3.5 document a relatively low terrigenous input to the ramp. This is a result of a maximum sea-level rise. The thickening-upward trend of the bedsets in this sub-unit could be indicative for autocyclic processes on the shelf (Wilson, 1975; Goodwin and Anderson, 1985). Similarly to sub-unit 3.3, marlstones in unit 4 document increasing terrigenous input to the ramp throughout the highstand.

2.7.1. Unit 5

This unit is characterized by predominantly limestones interbedded with sandstones and shales. This unit corresponds to the lower part of the Ankarana–Analamera Formation (Rerat, 1964) and it has been investigated in two distinct sections along a SW–NE transect (Fig. 7). Five exposed intervals (5.1–5.5) can be correlated across the two sections along what is here considered as the original depositional profile. Letters "a" and "b" refer to distal and proximal locations within the same interval, respectively.

To the SW (Ampatsoa section Fig. 8b) the basal interval 5.1a, resting on marlstones of unit 4, is composed of grey oncolitic limestones up to 20 m thick. The oncoids, up to 4 mm in diameter, develop around both bioclastic and siliciclastic (quartz) grains. The following interval 5.2a, about 15 m thick, consists of light grey siliciclastic fine-grained sandstones with planar cross-lamination arranged in lenticular beds. Interval 5.3a, exposed for a partial thickness of 10 m, is made of pinkish, planar cross-laminated, oolithic limestones locally rich in pelecypods.

The overlying interval 5.4a is represented by a thin bed (5 m max.) of oncolitic limestones. Oncoids, up to 1 cm in diameter, are enclosed in a reddish matrix and show concentric growth around both bioclastic grains, including large fragments of pelecypods and quartz grains (Fig. 9c). The uppermost interval 5.5a, up to 30–35 m thick, is represented by grey oolithic limestones, in places characterized by hummocky cross stratification (Fig. 9d).

To the NE (Ankarabo section Fig. 8c), the basal exposed interval 5.1b, which rests on sub-unit 2b, is composed of greyish oolithic limestones 5 m thick. Oolithes are strongly recrystallised and occur in beds up to 1 m thick within the greyish mudstones on the whole characterized by wavy stratification. The overlying interval 5.2b is composed of planar cross-laminated coarse-medium sandstones with carbonate cement in tabular beds about 1 m thick. Palaeocurrent, measured from cross bedding, indicates sediment transport from ESE. The following interval 5.3b is represented by coarse-medium sandstones which are planar cross-laminated in tabular beds 1 m thick arranged in a 10 m thick bedset. Paleocurrent is again from ESE. Further up in the section, interval 5.4b consists of tangential cross-laminated medium-fine sandstones with carbonate cement

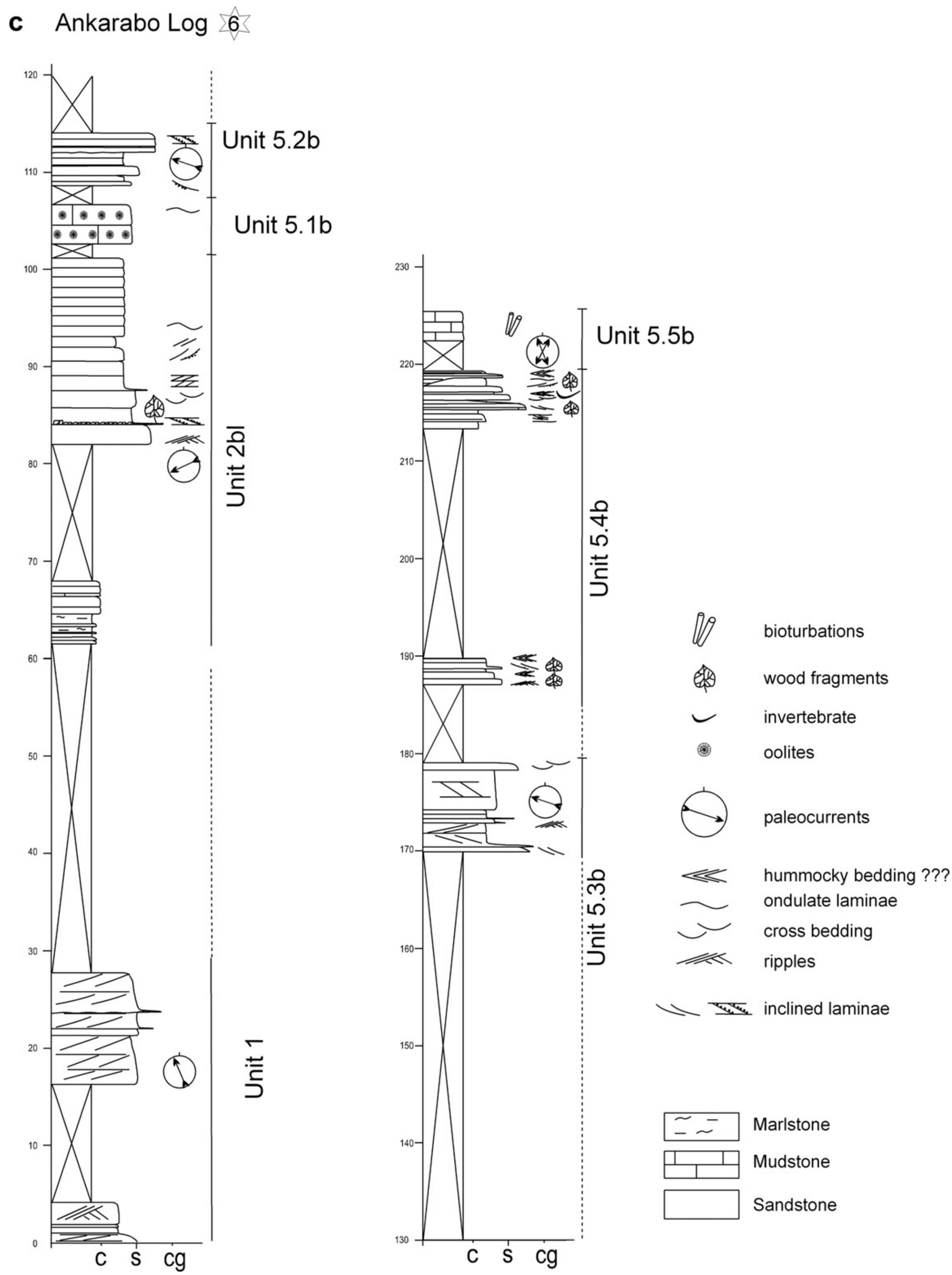

Fig. 8 (*continued*)

in beds 0.5 m thick. Beds, stacked in a 70 m thick sandstone body, have erosive bases. Individual beds frequently show abundant pebble-sized quartz clasts, mud clasts and clasts of wood fragments resting above the base. Disarticulated and abraded pelecypod shells are abundant in the upper part of these deposits. Laminasets show a sigmoidal geometry and in some case bipolar current directions (NE–SW and NW–SE). The uppermost exposed interval 5.5b is composed of whitish mudstones at least 5 m thick. Sub-vertical cylindrical burrows 1–2 cm in diameter occur at the top of this sub-unit. Neither micro- nor macro-fossils have been found in this part of unit 5.

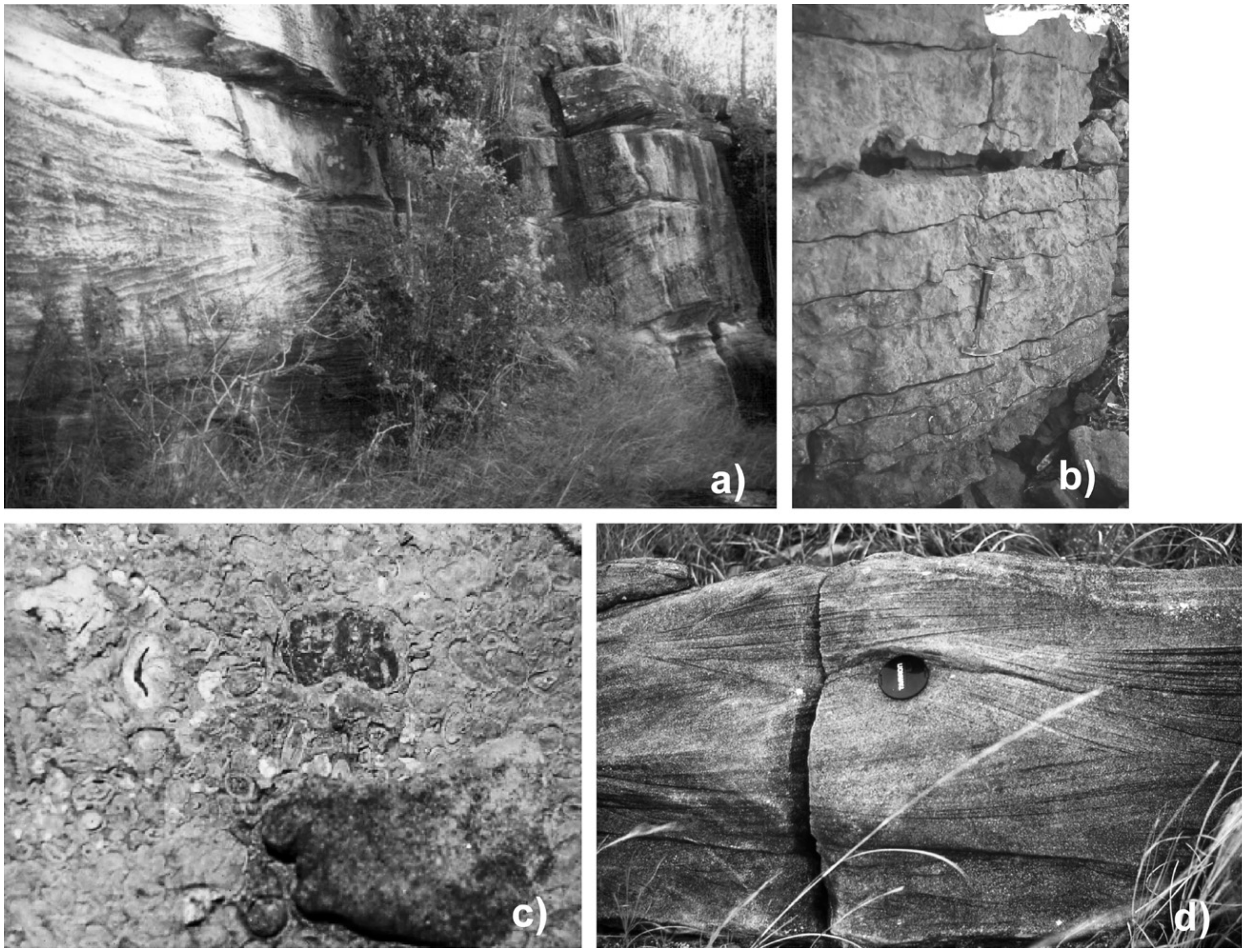

Fig. 9. (a) Planar cross-stratified sandstone of sub-unit 2a exposed in the Ankarabo area (see Table 2); (b) Anivorano section: detail on the mudstones on top of sub-unit 3.2 showing a thickening-upward trend, hammer for scale; (c) oncolitic limestone of interval 5.4a exposed in the Ampatsoa Ridge (Fig. 7b); (d) hummocky cross stratification in the oolithic grainstone of the interval 5.5a exposed in the Ampatsoa Ridge, cap lens for scale.

2.8. Facies interpretation of unit 5

Three recurring facies types have been recognized in the exposed intervals of unit 5: (a) oncolites; (b) oolithic limestone; (c) arenites with a mixed carbonate–terrigenous composition. The lateral and vertical transitions among these basic facies along the considered SW–NE transect, outline a distal-proximal gradient of depositional processes and environments controlled by relative fluctuations of sea level.

Oncolitic (5.1a) and oolithic (5.1b) limestones in the basal part of unit 5 record a gradient along the ramp. Similarly to unit 3, oncolites are considered to have formed in relatively quiet water in the distal and deeper portion of the ramp meanwhile oolithic shoals were developing in shallower water landward. This early stage of the development of unit 5 is considered to record a subtle relative sea-level fluctuation following the highstand documented by unit 4. Intervals 5.1a and 5.1b point to renewed high sea level determining a far inland transgression which caused the transgressive onlap of unit 5 on sub-unit 2b.

The following intervals 5.2a and 5.2b document a more significant change in sediment supply and base sea-level. In both locations cross-stratified sandstones point to an abrupt basin-ward shift of the terrigenous supply transported by a fluvio–deltaic system fed from the Madagascar mainland. This interval is, thus, interpreted as the evidence of a relative sea-level fall.

Intervals 5.3a and 5.3b mark a renewed relative rise of sea level. Oolithic shoals developed in the mid ramp whereas river-dominated estuarine dominated to the NE.

The upwards following intervals 5.4a and 5.4b point again to a subtle sea-level fluctuation. The thin oncolitic bed (5.4a) in this case is interpreted as re-sedimented from an original landward location. A subaqueous origin of the reddish matrix in which the oncolites are dispersed, in fact, seems highly improbable. A mechanical reworking of oncolites and sediments deposited and weathered in subaerial environments appears a more suitable explanation for these deposits. Landward, interval 5.4b, which is characterized by shallow marine fossils and current structures pointing to tidal influence, records sub-tidal conditions within estuarine channels. Similarly to interval 5.1 also in this case the SW–NE facies tract reflects condition of rising sea-level along the ramp profile, following a low-amplitude lowstand.

Finally, intervals 5.5a and 5.5b document a further depositional shift forced by relative sea-level variation. Oolithic shoals, again, developed in a mid ramp setting to SW meanwhile intertidal condition prevailed to NE as documented by interval 5.5b whose lithological and sedimentological features suggest a tidal flat depositional environment (see Tucker and Wright, 1990).

From a depositional point of view unit 5 shows many analogies with the Bemaraha–Sakaraha formations described in the Morondava Basin (Geiger et al., 2004; Geiger and Schweigert, 2006). The Bajocian Bemaraha Formation in the northern Morondava Basin is interpreted as a carbonate platform with the deposition of carbonate mud in a lagoonal environment and the deposition of ooid shoals and in barriers at the platform rim (Clark and Ramanampisoa, 2002). This formation is considered to pass southward into the correlative Sakaraha Formation characterized by mixing of siliciclastic and carbonate deposits (Geiger and Schweigert, 2006). The latter represents a supra-intertidal coastal setting within the coastal carbonate platform characterized by significant fluvial influx.

Analogous carbonate–terrigenous ramps characterized by a cyclic facies development due to relative sea-level fluctuations, have been reported from other Gondwana margins. Legarreta (1991) described four vertically stacked depositional sequences in the late Middle–Upper Jurassic evolution of a carbonate ramp system in the Nequén Basin (Argentina). Each sequence is composed of the following systems tracts: (a) inner ramp environments with fluvial, lagoonal and shoal systems, (b) mid ramp environment with shoals and carbonate build-up, (c) outer ramp to basin environment with dominated by fine-grained and skeletal deposits. Oolithic limestone and oncolites are present in systems tracts (a) and (b). Oncolites developed both seaward and landward of the oolithic shoals.

3. Discussion

This paper presented new aspect for the interpretation of the Early–Middle Jurassic tectono-depositional evolution of the Antsiranana Basin. Stratigraphical transects running from the Ampasindava Peninsula through Nosy Be Island to the Ankarana–Analamera Plateau explain this evolution starting from the Early–Middle Toarcian (Fig. 10a).

- Early Toarcian is characterized by a widespread marine transgression over the fluvial environments of the Isalo Sandstones. This transgression affected a wide part of the basin, probably excluding the Nosy Be-Ambilobe area, with deposition of units B and 2 which, respectively, indicate a mixed carbonate–siliciclastic ramp in which terrigenous sediments were supplied from ENE (see paleocurrent in sub-unit 2b, Table 2).
- During the late Toarcian–early Aalenian (Fig. 10b) the basin underwent significant depositional differentiation with activation of asymmetric sub-basins bounded by steep faults. At this time a major structural high was located just NE of Ambilobe separating a strongly subsiding zone with dominantly non-marine deposition to SW from a slowly subsiding zone to NE with a coastal shallow marine depositional environment. Paleocurrent data indicate a sediment supply from SW for unit C (Ampasimena Formation) in the Ampasindava sub-basin and from ENE in the Ankarana–Analamera sub-basin. In both cases the provenance area consequently is the Madagascar mainland.
- During the Aalenian the tectono-sedimentary evolution was not much different except for a more pronounced subsidence and block tilting in the central-southwestern part of the Ankarana–Analamera (Fig. 10c) where shelfal carbonates and marls of units 3 and 4 deposited. The stratigraphic architecture of these units reflects the deposition in a mixed carbonate–terrigenous ramp controlled by relative sea-level fluctuations. In the Ampasindava area the upper part of unit C was forming in a coastal setting dominated by terrigenoud deposition and accumulation of organic material. At the Aalenian/Bajocian transition a widespread marine flooding in the Ankarana–Analamera area caused the north-eastward onlap of unit 5 directly onto sub-unit 2b. A coeval rise of the base-level in the Ampasindava area is speculated on the thick claystone of sub-unit D2. In unit D paleocurrent data point to sediment supply from NNE. This suggests that at that time the area around Nosy Be was an uplifted block with exposure and erosion of pre-Toarcian rocks. Photogeologic and field studies in Nosy Be (Papini, 1995) revised the local stratigraphy reported by Rerat (1964) and Besairie and Collignon (1972). More than 800 m thick cross-bedded quartzitic sandstones cropping out in the eastern part of the island, previously classified as "Upper Liassic" deposits, have been interpreted as Isalo Sandstones (Papini, 1995). This conclusion is supported also by the occurrence of non-marine claystone with an Upper Liassic flora (Besairie and Collignon, 1972) above the sandstones, which may represent an equivalent of unit C in this area. The denudation of the Nosy Be Isalo sandstones, exposed by progressive block tilting, could have therefore fed the fluvial systems of unit D in the Ampasindava sub-basin.
- During the Bajocian–Bathonian (Fig. 10d–e) the Nosy Be high was a major structural element in the basin separating differently subsiding zones. To the SW non-marine deposition of unit D and E frequently dominate in the rapidly subsiding Ampasindava sub-basin. To the NE shelfal mixed carbonate–siliciclastic deposition of units 5 and 6 occurred in the slowly subsiding Ankarana–Analamera sub-basin. Similarly to units 3 and 4, the unit 5 indicates relative sea-level fluctuations.

The striking depositional and paleogeographic features of the Antsiranana Basin are further emphasized when compared with those of the northern Kenyan-southern Somali coastal areas (Luger et al., 1994) and the Seychelles

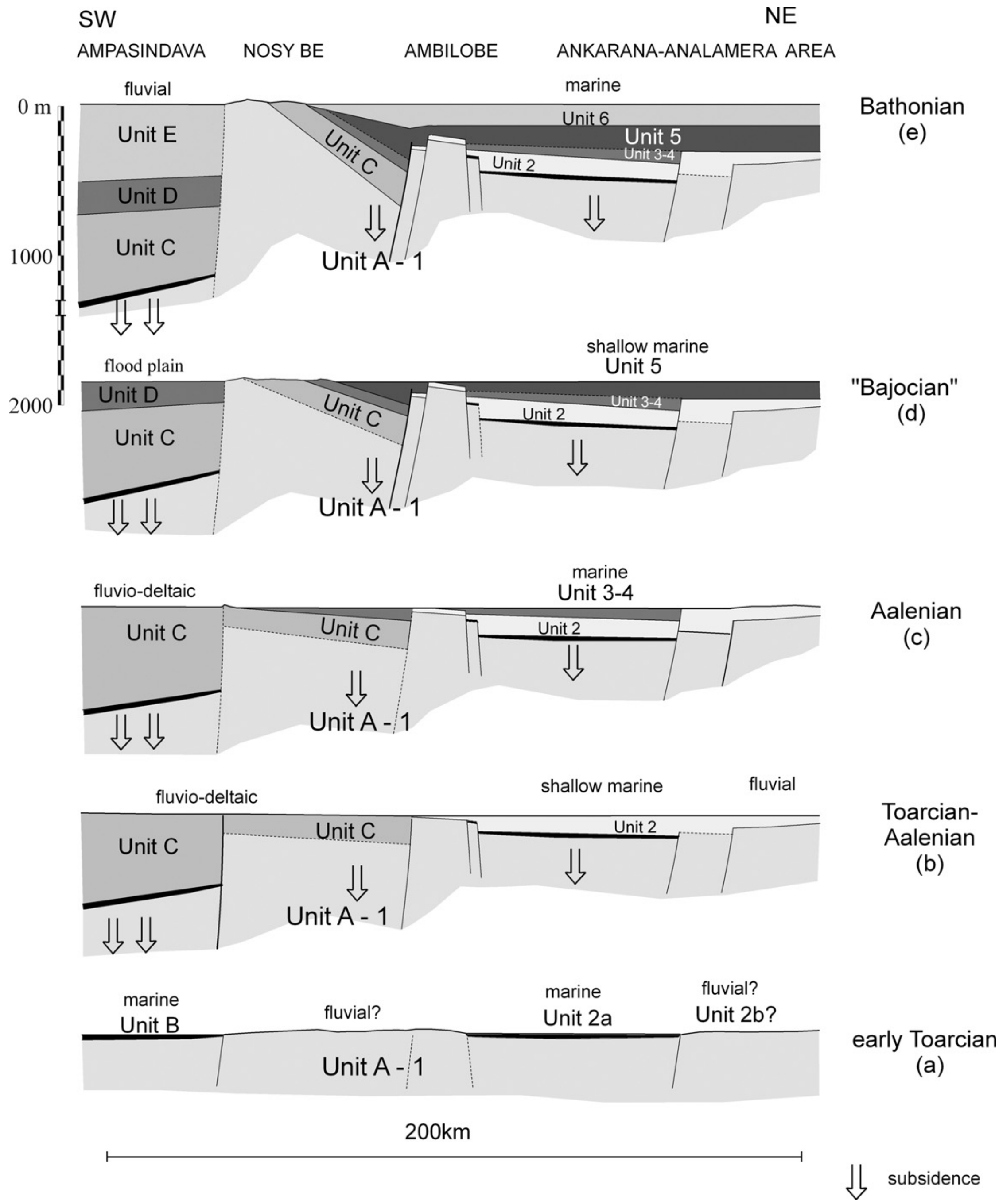

Fig. 10. Tectono-sedimentary cross-sections of the Antsiranana Basin from the Toarcian to Bathonian illustrate Early Toarcian: widespread marine transgression over the Isalo Sandstones. Late Toarcian–early Aalenian: the basin underwent significant depositional differentiation with activation of asymmetric sub-basins bounded by steep faults. Aalenian: more pronounced subsidence and block tilting in the central-southwestern part of the Ankarana–Analamera. Bajocian–Bathonian: the Nosy Be high was a major structural element in the basin separating differently subsiding zones.

archipelago (Plummer and Belle, 1995; Plummer et al., 1998) (Fig. 11a). During the latest Early–Middle Jurassic the Madagascar–Seychelles block were facing the Kenyan-Somali coast (Luger et al., 1994), through a narrow sea resulting from the ongoing East Africa-Madagascar rifting. The continental rifting, initiated since the Early Triassic, affected the coastal areas of East Africa with the development of basins in northern Kenya (Lamu Basin, Fig. 10b, Bosellini, 1989; Abbate et al., 1994), and in southern Somalia (Mogadishu and Lugh-Mandera Basins, Fig. 11b; Bosellini, 1989; Abbate et al., 1994; Ali Kassim et al., 2002). Following to the regional Triassic–Early Jurassic mostly fluvial deposition (Fig. 11b), the Toarcian (Fig. 11c) is represented all over the considered region by coastal carbonates with the exception of the Lamu Basin characterized by evaporite deposition. This evidence suggests that in this period a narrow sea flooded a wide region between East Africa and the north-western Madagascar–Seychelles. The

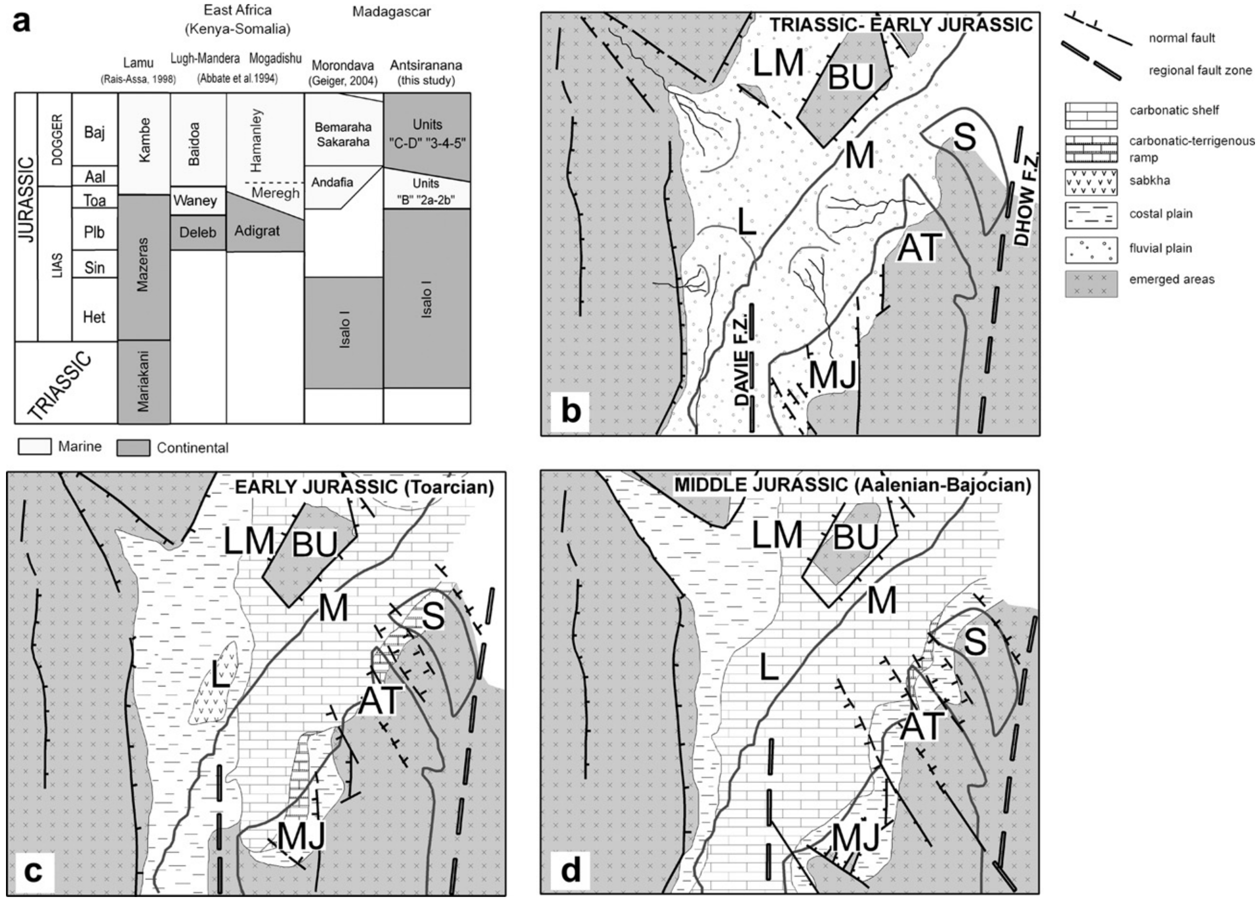

Fig. 11. (a) comparative stratigraphy of the Triassic–Middle Jurassic successions of East Africa and NW Madagascar–Seichelles (see text for references); (b–d) regional paleogeographic maps discussed in the text. Codes for the basins (see text for details): LM, Lugh-Mandera; M, Mogadischu; L; Lamu; S; Seichelles; AT; Antsiranana; MJ; Mahajanga.

Aalenian–Bajocian (Fig. 11d) regional evolution is marked by progressively deepening of the marine basin with the deposition of shelfal mixed terrigenous–carbonates in the East Africa basins as well as in the Ankarana–Analamera sub-basin and in the Seychelles microcontinent. This overall depositional pattern contrasts the predominantly non-marine clastics of units C and D in the Ampasindava sub-basin suggesting that the marine flooding advanced from NE and that tectonic subsidence in the south-western Antsiranana Basin was balanced by high sediment flux. The NW-trending structural high of Ambilobe which was active during this period confined the siliciclastic coastal–deltaic depositional setting of the Ampasindava from the shelf areas occurring to NE. Similarly, to the SW an uplifting high between the Mahujanga and the Antsiranana Basins played a major role in determining long living deltaic and coastal settings. In the north-eastern Mahujanga Basin, adjacent to the Ampasindava sub-basin, the Toarcian–Bathonian interval is represented by fluvio–deltaic clastics, the Isalo II and III sandstone sensu Besairie and Collignon (1972), while the south-western Mahujanga Basin is characterized by shallow marine mixed carbonate–siliciclastic deposition. This depositional transition, thus, is similar to that in the adjacent Ampasindava sub-basin suggesting the occurrence of a NW-trending divide which provided high sediment supply to fluvio–deltaic systems developing in the two basins.

4. Conclusions

The structural articulation of the Antsiranana Basin during the latest Early and Middle Jurassic was crucial in differentiating depositional patterns in the Ampasindava and Ankarana–Analamera sub-basins. NW–SE oriented structural highs (North Ambilobe, Nosy Be) acted as structural thresholds which inhibited massive sea flooding in subsiding areas. Non-marine (coastal plain) conditions with possibly short-lived marine incursions, in fact dominated in the Ampasindava sub-basin while shelfal conditions were prevailing in the Ankarana–Analamera sub-basin. Facies analysis in the Aalenian–Bajocian portion of the successions exposed in these sub-basins suggests that the depositional dynamic was controlled by multiple fluctuations of relative sea level regulated by the combined effect of eustacy and active tectonism.

NNW–SSE structural lines with evidence of sinistral strike-slip motion presently visible in Madagascar (Fig. 1), may represent the relics of tectonic lines which controlled subsidence and sedimentary patterns in the Madagascan

Basins during the Mid-Late Jurassic transition from rifting to drifting. In agreement with the tectono-sedimentary evolution proposed for the Morondava Basin (Geiger et al., 2004; Geiger and Schweigert, 2006), the data collected in this study, compared with the regional stratigraphic and paleogeographic setting, support an effective separation of East Africa from Madagascar only from the Toarcian (syn-Gondwana breakup stage *sensu* Geiger et al., 2004). This stage occurred after a Permo-Triassic pre-Gondwana breakup rifting (Geiger et al., 2004) and was followed by a subsequent drifting stage active from the Bajocian (post-Gondwana breakup stage).

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