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

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Introduction

Papini and Benvenuti (2001) provide a lengthy critique of our recent stratigraphic analysis of the Upper Cretaceous section of the central Mahajanga Basin, northwestern Madagascar, near the village of Berivotra. Their commentary hinges upon the predication that a marine interval (their unit 3) is intercalated within the Maevarano Formation (Papini and Benvenuti 1998) and is not instead the structurally down-dropped top of the local Cretaceous section (Rogers et al. 2000). We welcome this opportunity to again compare our findings with those of Papini and Benvenuti (1998), although we maintain that our interpretation of the data is the most reasonable. In this reply, we concisely review the stratigraphic interpretations of Papini and Benvenuti (1998, 2001) and address the significant points of contention.

The Papini and Benvenuti Stratigraphic Model

Papini and Benvenuti (1998) surveyed the stratigraphy of the Berivotra region during a single field season in 1992 and pieced together a single composite section. They distinguished eight distinct lithologic units in their section, and they related all eight units to fluctuations of relative sea level within a sequence stratigraphic framework. Four depositional sequences were recognized in their study.

Unit 1 of the Papini and Benvenuti (1998) composite section was assigned to the top of the "série de Marovoay" (Besairie 1972). A paleosol characterized as weathered silty sandstone with diffuse color mottling caps unit 1, and this paleosol was interpreted to mark the top of a highstand systems tract. Thickness data were not reported for unit 1 in the text, but a schematic log indicates that it is approximately 1 m thick (Papini and Benvenuti 1998, their fig. 5). Unit 2 was interpreted to crop out at the base of the Maevarano Formation and consists of 15 m of alternating beds of medium- to coarse-grained sandstone and clayey siltstone with intercalated paleosols. Deposition of unit 2 was inferred to have occurred in fluvial and floodplain settings as part of a late lowstand systems tract. According to Papini and Benvenuti (1998, p. 234), unit 2 passes upsection via a "gradual shifting from continental to marine conditions" to unit 3. Unit 3, which is 3 m thick in their schematic composite section, consists of clayey siltstones capped by a bed of white limestone that yields marine molluscs. This unit was interpreted as a transgressive systems tract. The contact separating unit 3 from unit 4 was described in their text as sharp, but, unfortunately, there is no documentation as to where this critical contact can be observed. Unit 4 was described as a poorly exposed sandy deposit with an estimated thickness of 20 m. Locally exposed trough cross-beds in this unit were interpreted as an "aeolian-modified fluvial deposit" of another late lowstand systems tract. Unit 5, also 20 m thick, was reported to consist of intercalated beds of green normally graded sandstone and pink mottled siltstone. The sandstone beds were interpreted to have accumulated in a "lacustrine palaeoenvironment by hyperpycnal flow generated by fluvial floods" (Papini and Benvenuti 1998, p. 237). Deltaic deposits are purportedly present at the top of unit 5, which overall was relegated to a transgressive systems tract. Unit 6 is the uppermost unit

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of the Maevarano Formation described by Papini and Benvenuti (1998). This unit was estimated to be 50 m thick and includes three alternating lithofacies: (1) white trough cross-bedded sandstones, (2) white massive sandstones with color mottling and root traces, and (3) purple massive siltstones with intense color mottling and local calcareous nodules. Papini and Benvenuti (1998, p. 240) interpreted unit 6 as deposits of either a fluvial and floodplain setting or "a distributary channel, a delta-front and a delta-plain of a shoaling-type river delta system." Unit 6 was described as a late lowstand systems tract.

Papini and Benvenuti (1998) described two additional units above the Maevarano Formation, and included both in a transgressive systems tract. Their unit 7, which spans 25 m, consists of massive gray siltstones and marls that preserve a paralic molluscan fauna (no diagnostic taxa were specified). Unit 7 was interpreted to reflect deposition in a "restricted coastal/lagoonal palaeoenvironment." Unit 8 caps their composite section and was described as 10 m of "whitish mudstones and calcarenites" that preserve a marine fauna (Papini and Benvenuti 1998, p. 240). This final unit was interpreted as an inner shelf deposit.

Comparison of Stratigraphic Models

Comparing our work (Rogers et al. 2000) with the interpretations of Papini and Benvenuti (1998) is difficult for at least a few reasons. First, Papini and Benvenuti (1998, 2001) do not reveal the location of their composite section—we simply do not know where they made their observations and therefore cannot precisely compare them with our own. Second, their sedimentological descriptions are vague and afford little insight into the actual lithologic character of their section. Third, Papini and Benvenuti (1998) present their data within the context of a poorly supported sequence stratigraphic framework that does not readily relate to the predominantly nonmarine interval under consideration. Nevertheless, in the brief commentary that follows, we will attempt to address the major elements of disagreement.

Faults in the Vicinity of the Anembalemba Escarpment. In their commentary, Papini and Benvenuti (2001) first focus on the multiple faults that occur in the vicinity of the Anembalemba escarpment (mapped at the 1 : 100,000 scale by the Service Géologique de Madagascar 1960). In their original manuscript, Papini and Benvenuti (1998) did not acknowledge the presence of these faults. In their comment, Papini and Benvenuti (2001) question the validity of the faults because they are not indicated on a much larger scale map (the 1 : 500,000 Carte Géologique du Madagascar, Feuille n. 3 Majunga: Service Géologique de Madagascar 1969). Papini and Benvenuti (2001) also question the proposed kinematics on the basis of one fault trace placed erroneously by the Service Géologique de Madagascar (curiously, this is the only fault reproduced from the original map in fig. 2 of Papini and Benvenuti 2001).

In figure 2 of Rogers et al. (2000) we faithfully reproduced all of the faults as mapped by the Service Géologique de Madagascar (1960) and added one of our own, based on our own mapping. We have carefully explored the region surrounding Anembalemba during the course of five 6-wk field seasons, and there is no evidence of older strata uplifted along the flanks of the Anembalemba escarpment. There is, however, ample indication of faulting in the form of steeply tilted beds in the valley to the east of Anembalemba (lat. 15°56′2.7″ S, long. 46°36′46″ E).

Correlation of the Contentious Marine Interval. According to Papini and Benvenuti (1998, 2001), units 2 and 3 in their composite section can be projected with a very low northwesterly dip (2°–3°) to the base of the Anembalemba escarpment, where they presumably intercalate exactly at the base of the Maevarano Formation. On the basis of their composite section, units 2 and 3 span approximately 18 m. Papini and Benvenuti (1998) estimated that 90 additional meters of the Maevarano Formation overlie unit 3.

Papini and Benvenuti (1998, 2001) did not specify how or where they determined their regional dip estimate, but high resolution (Leica System 300) GPS-based three-point solutions indicate that the top of the Maevarano Formation dips north-northwesterly at less than 1°. They also did not indicate where they described units 2 and 3, but careful inspection of figure 6 in Papini and Benvenuti (1998) indicates that they too worked in the vicinity of kilometer marker 508 along national route A.P. 4 (in fact, their photograph matches exactly with our A.P. 4-508.4 locality). At this locality, they underestimated the thickness of both units 2 and 3. Strata they relegated to unit 2 (our Miadana Member) span at least 20 m at A.P. 4-508.4; and overlying beds of clayshale and limestone (their unit 3, our Berivotra Formation and Betsiboka limestone) comprise at least an additional 15 m (in our published log of this locality [Rogers et al. 2000, their fig. 7*B*], we did not include several meters of an overlying slope covered with limestone debris). Lastly, we identified strata referable to the Anembalemba Member beneath their unit 2 at the nearby Miadana Hills. The section we published from this locality (Rogers et al. 2000, their fig. 7*B*) is not a composite section and thus less than 1 m of the Anembalemba Member is illustrated. However, several additional meters of typical Anembalemba Member facies, replete with vertebrate fossils, can be accessed between the two Miadana Hills (lat. 15°56′16.2 S and long. 46°38′0.1 E).

Regardless of the regional dip, the thickness of units 2 and 3, or the fact that beds referable to the Anembalemba Member crop out beneath unit 2 (=Miadana Member), Papini and Benvenuti's hypothesis can be validated if strata comparable to units 2 and 3 crop out on the flanks of Anembalemba or surrounding hills. We have hiked to and around the base of Anembalemba with the express purpose of testing this hypothesis and found no trace of marine shales or limestones that can be correlated to unit 3. Instead, we encountered the characteristic mottled red sandstone facies of the Masorobe Member (Rogers et al. 2000). We have also measured a continuous section on a nearby ridge (Masorobe) that spans 88.5 m of the Maevarano Formation (Rogers et al. 2000, their figs. 2, 4), and this section also shows no trace of either unit 2 or unit 3.

Age of the Contentious Marine Interval. Finally, we can provide new biostratigraphic data for the thin marine clayshale and the superjacent marine limestone (=unit 3) that crop out at the A.P. 4-508.4 locality, although the work is ongoing. To date, molluscs (*Agerostrea ungulata*, *Exogyra* sp., and a fragmentary small pycnodonte), brachiopods (*Crania* [*Isocrania*] *larva*, *Argyrotheca* sp.), echinoderms, bryozoans, and a benthic foraminiferan have been identified. The oyster *A. ungulata* and the two brachiopod taxa are consistent with a Maastrichtian age designation. Overall, the invertebrate assemblage is comparable to that of the upper Berivotra Formation in the main Berivotra field area, where numerous invertebrate and vertebrate taxa, most recently elasmobranchs (Gottfried et al., 2001), indicate that the Berivotra Formation is Maastrichtian in age. Thus, even if unit 3 were to intercalate at the base of the Maevarano Formation, and there is no indication that it does, overlying beds would be Maastrichtian in age or younger, not Campanian as suggested by Papini and Benvenuti (1998, 2001).

Conclusions

We appreciate the comments of Papini and Benvenuti (2001) and recognize their contribution with regard to the stratigraphy of the central Mahajanga Basin. However, we presently find no reason to modify our lithostratigraphic or chronostratigraphic framework to accommodate their arguments.

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