

Fine-grained debris flows and extraordinary vertebrate burials in the Late Cretaceous of Madagascar

Raymond R. Rogers* Geology Department, Macalester College, Saint Paul, Minnesota 55105, USA

ABSTRACT

Vertebrate fossils are remarkably abundant and exceptionally well preserved within the Upper Cretaceous Maevarano Formation of northwestern Madagascar. The vast majority of these fossils, including all of the currently known bone beds, are entombed within deposits of fine-grained cohesive debris flows. These deposits are typically massive and are characterized by very poor sorting and a significant montmorillonite-dominated silt-clay (mud) fraction ranging from 17% to 46% by weight. Deposition is attributed to recurrent exceptional rainfall events that prompted erosion and flooded ancient channel belts with sediment-laden flows. These extraordinary burial events shielded vertebrate remains from destructive surface processes and also afforded protection for soft tissues. Taphonomic attributes of associated bone concentrations suggest that debris flows had limited transport potential and generally entombed subaerially exposed bone assemblages. The remarkable and recurrent association of bone beds and debris-flow deposits likely reflects marked seasonality in this Late Cretaceous terrestrial ecosystem, with prolonged dry spells prompting mortality and subsequent rains setting debris flows in motion.

Keywords: debris flows, vertebrate paleontology, Upper Cretaceous, Madagascar, bone beds.

INTRODUCTION

Upper Cretaceous terrestrial deposits in the central part of the Mahajanga Basin in northwestern Madagascar (Fig. 1) have been known to yield vertebrate fossils for more than a century (Depéret, 1896). Fossils are most abun-

dant in the Campanian(?)–Maastrichtian Maevarano Formation (Rogers et al., 2000; Abramovich et al., 2002), which is the uppermost terrestrial unit of Cretaceous age in the basin. Spectacularly fossiliferous beds of the Maevarano Formation crop out in the vicinity of the village of Berivotra (Fig. 1A), where National Route 4 cuts across rolling grass-

lands with patchy exposures. From a taphonomic perspective, the rather limited outcrops in Berivotra are extraordinary, both in respect to the abundance of vertebrate fossils and the quality of preservation (e.g., Forster et al., 1998; Sampson et al., 1998; Schweitzer et al., 1999; Buckley et al., 2000; Curry Rogers and Forster, 2001). It is virtually impossible to traverse the Berivotra field area without encountering fossil bones and/or teeth, and to date 15 multi-individual bone beds have been identified in an area that encompasses ~10 km². All of the bone beds and most isolated fossil occurrences are intercalated in a distinctive package of alluvial facies that Rogers et al. (2000) formalized as the Anembalemba Member of the Maevarano Formation (Fig. 1B). I present evidence that links the exceptional preservation of fossils in the Anembalemba Member to recurrent burial by fine-grained debris flows.

GEOLOGIC AND TAPHONOMIC BACKGROUND

Anembalemba Member

Two distinctive sandstone-dominated lithologies designated facies 1 and facies 2 by Rog-

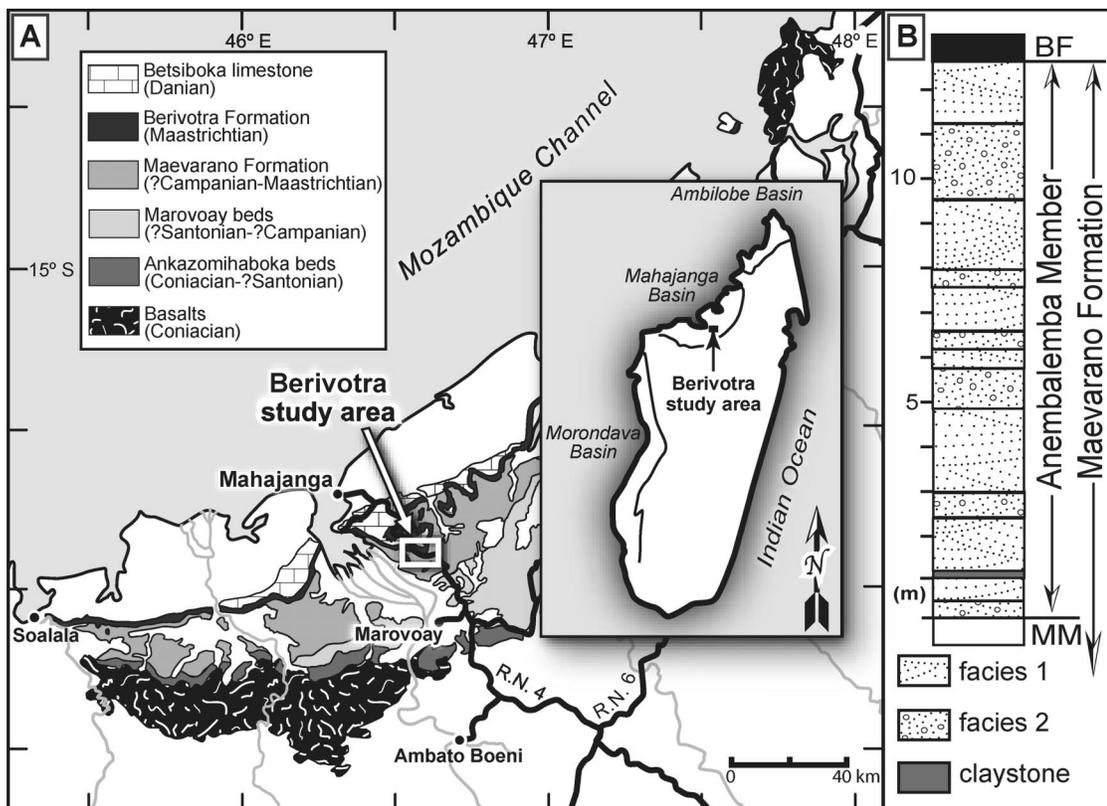
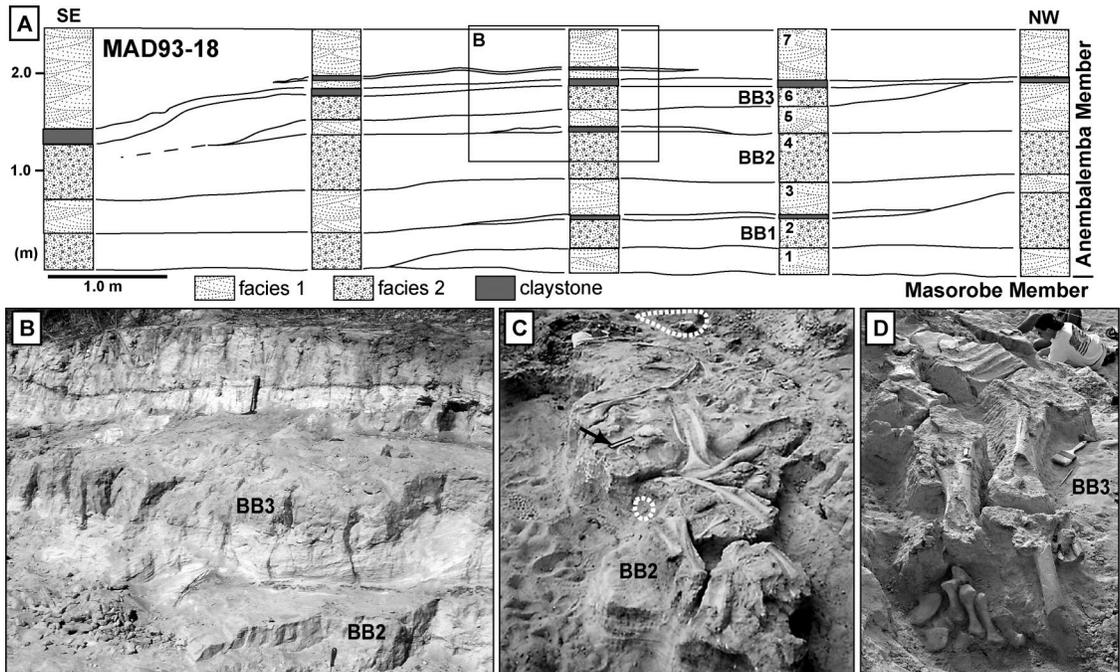


Figure 1. A: Outcrop map of Upper Cretaceous and Tertiary strata in Mahajanga Basin of northwestern Madagascar, with location of Berivotra study area. **B:** Schematic profile of Anembalemba Member stratotype. See text for descriptions of facies 1 and 2. In Berivotra study area, richly fossiliferous Anembalemba Member is underlain by Masorobe Member (MM) of Maevarano Formation and overlain by marine strata of Berivotra Formation (BF).

Figure 2. A: Cross section through quarry MAD93-18, which includes three discrete bone beds (BB1, BB2, BB3). Grain-size data for beds 1–7 are presented in Figure 3. B: Excavated back wall showing recurrent interbedding of facies 1 and facies 2 (see inset in A for approximate position in quarry). Hammer = 30 cm. C: Disarticulated skeletal elements of sauropod dinosaur *Rapetosaurus krausei* in BB2 (Curry Rogers and Forster, 2001). White dashed lines indicate areas where bird fossils were recovered. Scale bar (arrow) = 16 cm. D: Articulated and/or closely associated limb elements and ribs of large sauropod dinosaur in BB3. Brush = 20 cm.



ers et al. (2000) characterize the Anembalemba Member of the Maevarano Formation (Figs. 1, 2, and 3). In outcrop they are readily differentiated on the basis of color and sedimentary structures. Facies 1 is light greenish gray (10GY 8/1) to white (N 8/) and typically exhibits small- to medium-scale trough and tabular cross-bedding. Sandstones of facies 1 are typically fine to medium grained and moderately sorted, with a mud (silt + clay) content

averaging <10% by weight. Scattered beds of facies 1 are characterized by coarser-grained fractions. Facies 2 is characteristically a light olive gray (5Y 6/2) and is typically massive. Sandstones of facies 2 range from fine to very coarse grained and are typically very poorly sorted. Silt-clay content varies from 17% to 46% by weight. The characteristic green hue of facies 2 reflects its considerable clay content. In most exposures, facies 1 and 2 are

recurrently interstratified with sharp and relatively flat contacts. Some contacts show evidence of erosion in the form of local relief and rip-ups. Soft-sediment deformation structures are relatively common and are most often developed between facies 1 and underlying beds of facies 2 (see Fig. 8 in Rogers et al., 2000).

Thin beds of silty green claystone are also intercalated in the Anembalemba Member, and X-ray diffraction of the unit's abundant clay fraction indicates that montmorillonite is the predominant clay mineral. The abundance of montmorillonite presumably reflects, at least in part, the weathering of Coniacian basalts that were emplaced in updip reaches of the drainage basin (see Fig. 1) when the Indian subcontinent–Seychelles rifted from Madagascar ca. 88 Ma (Storey et al., 1997).

Vertebrate fossils are abundant in the Anembalemba Member, especially within the muddy sandstones of facies 2. Bone beds that yield diverse assemblages of fish, frogs, lizards, turtles, snakes, crocodiles, dinosaurs, birds, and mammals are common, and the quality of preservation is spectacular (Krause, 2003a). Sandstones of facies 1 also preserve vertebrate remains but tend to yield mostly isolated elements, commonly in pristine quality. Small gastropods, bivalves, and chonchotracs are also preserved in the Anembalemba Member, but they are rare (Krause and Hartman, 1996; Rogers et al., 2000).

Quarry MAD93-18

Quarry MAD93-18 exemplifies preservation in the Anembalemba Member because fossils are preserved most abundantly, but not exclusively, in facies 2. The site is remarkable

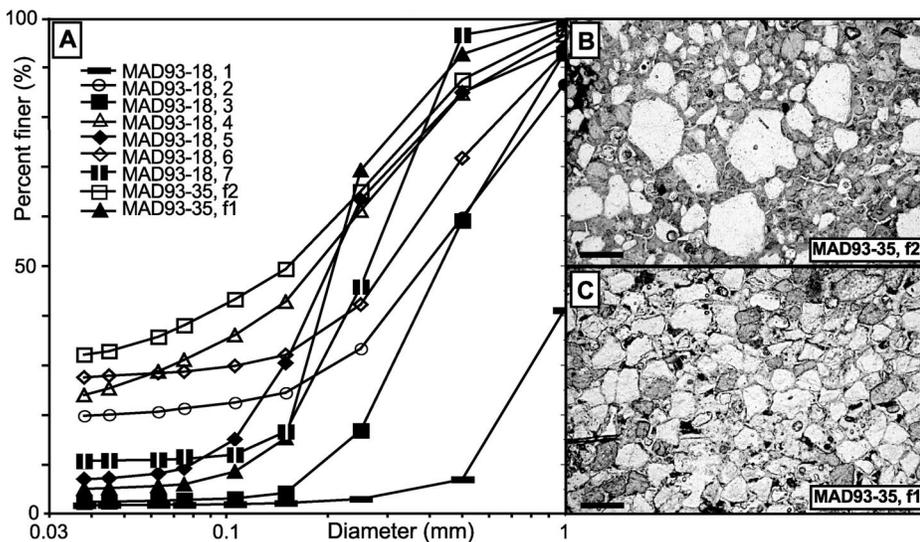


Figure 3. A: Particle-size distributions of selected beds of facies 1 (f1) and facies 2 (f2) from quarries MAD93-18 (1–7 in Fig. 2A) and MAD93-35 as determined by centrifuge-based separation of clays and sieve analysis. Beds of facies 2 deposited by debris flows (open symbols) are readily distinguished from better sorted beds of facies 1 (closed symbols). B: Photomicrograph of bone-bearing cohesive debris-flow deposit (site MAD93-35), exhibiting matrix support and very poor sorting. C: Bed intercalated directly above bone-producing layer in B (above) exhibits sorting and cross-bedding consistent with deposition via “normal” streamflow. Scale bars = 0.5 mm in B and C. Thin sections in B and C are stained for K-feldspar.

because in <2 m of section it includes three discrete fossil-bearing levels of facies 2 (BB1, BB2, BB3; Fig. 2) separated by intervening beds of typical cross-stratified facies 1. Collections from BB1, BB2, and BB3 include animals that range from fragile sparrow-sized birds to massive titanosaurian sauropods, and many individuals are represented in each layer. Fossils recovered from the two lower bone beds (BB1 and BB2) were typically disarticulated (Fig. 2C), although in many cases elements from individual animals were found in close association, or, more rarely, articulated (Forster et al., 1998; Curry Rogers and Forster, 2001). BB3 is the most recent fossiliferous level to be worked at quarry MAD93-18, and this bone bed preserves articulated components of at least one large sauropod dinosaur in association with disarticulated sauropod, theropod, and turtle elements (Fig. 2D).

Taphonomic attributes of the MAD93-18 bone assemblages, including the high degree of association and the extremely wide range in body size, are inconsistent with a long-distance transport-related accumulation scenario and suggest instead repetitive episodes of localized mortality. Animals represented in the fossiliferous beds of MAD93-18 exhibit variable degrees of disarticulation and indication of differential weathering (e.g., pristine bird elements preserved alongside more weathered dinosaur bones), and thus it seems evident that animals perished over a period of time, as opposed to dying en masse during instantaneous death events. Several bone beds in the Anembalemba Member, including those of MAD93-18, also show evidence of carcass utilization in the form of feeding traces, which indicates a time lag between death and permanent burial.

ENTOMBMENT BY RECURRENT FINE-GRAINED DEBRIS FLOWS

Facies of the Anembalemba Member (Figs. 1 and 2) are indicative of at least three distinct flow conditions in an overall fluvial setting. The relatively rare beds of silty claystone intercalated in the unit are interpreted to reflect the settling of fines under low-energy conditions with essentially negligible flow rates. These fine-grained deposits presumably accumulated in local depressions that served to pond water in the channel belt complex. The characteristically cross-bedded sandstones of facies 1 are interpreted to represent normal streamflow. Stratification in this facies reflects bed-load transport and the migration of bedforms in Anembalemba channels. The richly fossiliferous mud-rich sandstones of facies 2 are herein interpreted to record a third distinct mode of sedimentation associated with debris flows.

Deposits of facies 2 exhibit bimodality in grain size and very poor sorting, with a sizable montmorillonite-dominated silt-clay fraction admixed with a substantial medium to coarse sand fraction. Some of the more clay-rich beds are matrix supported (Fig. 3). Beds of facies 2 typically lack any indication of stratification, which is interpreted as an original depositional feature because there is minimal indication of pedogenic alteration and/or bioturbation, and the facies is intercalated with numerous beds that exhibit pervasive stratification. The relatively abundant indication of soft-sediment deformation is interpreted to reflect the metastable, water-saturated nature of beds of facies 2 after deposition.

These sedimentary characteristics are consistent with the emplacement of fine-grained cohesive debris flows (Hampton, 1975; Pierson and Costa, 1987; Costa, 1988; Scott et al., 1992; Iverson, 1997; Iverson et al., 1997; Vallance and Scott, 1997). Sediment-charged slurries rich with sand and clay apparently surged through the fluvial system multiple times, with a minimum of seven distinct debris flow deposits intercalated in sections that span the Anembalemba Member. Nonuniform flow conditions evidently prevailed in the drainage basin for the duration of Anembalemba deposition, with recurrent episodes of heightened erosion and sediment yield alternating with periods of dilute streamflow.

DISCUSSION Origin of Debris Flows

The recurrent debris-flow deposits of the Anembalemba Member are arguably too widespread and too regular in their stratigraphic occurrence to represent localized collapse of unstable banks or bars within the relatively shallow Anembalemba channels (Martin and Turner, 1998; Rogers et al., 2000). Moreover, their sedimentology suggests that sediment was derived from clay-rich source areas outside the local channel belt. With regard to potential external sources, there is no record of contemporaneous volcanism on the island of Madagascar, and thus volcanic scenarios of flow mobilization (e.g., Cronin et al., 1997; Vallance and Scott, 1997) are unlikely. A glacial link to debris-flow generation (e.g., Scott et al., 1992; Maizels, 1997) can also be dismissed because northern Madagascar was situated at ~25–30°S near the end of the Cretaceous (Royer et al., 1992; Scotese, 1998), which would have placed the Mahajanga Basin within the influence of the subtropical desert belt.

Exceptional rainfall events are herein deemed the most plausible explanation for the recurrent debris-flow deposits of the Anembalemba Member. Heavy rains are proposed as agents of both intense erosion and flooding on

the Maevarano alluvial plain. The Late Cretaceous paleogeography of the Mahajanga Basin is arguably consistent with the premise of a semiarid alluvial plain susceptible to sudden intense downpours and intensified erosion, perhaps on a seasonal basis. Associated paleosols of the underlying Masorobe Member also show features consistent with pedogenesis on semiarid, well-drained floodplains (Miller et al., 2000; Rogers et al., 2000).

Extraordinary Burial Events

Extraordinary burial events make for an extraordinary fossil record (Seilacher et al., 1985; Loope et al., 1998), and it is now apparent that the amazing fossils of the Anembalemba Member were largely entombed by recurrent fine-grained debris flows. Sediment was delivered rapidly and repeatedly to Anembalemba channels and accumulated in sufficient quantity to permanently bury bioclasts ranging from millimeter-scale fish and mammal teeth to meter-scale sauropod elements. These burial events shielded vertebrate remains from destructive surface processes and also afforded some protection for soft tissues in the postburial environment. Keratin was identified on the claw of the bird *Rahonavis ostromi* from layer BB2 in MAD93-18 (Schweitzer et al., 1999), skin impressions of a sauropod dinosaur are preserved in layer BB3 of the same quarry (Figs. 2C, 2D), and costal cartilages are preserved on a mammalian skeleton recovered from a separate locality, MAD99-15 (D. Krause, 2003b, and 2003, personal commun.).

Entombed fossils also afford unique insights into flow processes. Taphonomic data suggest that these fine-grained debris flows had somewhat limited transport potential, at least with regard to vertebrate remains. Disarticulated skeletal elements from single individuals (large and small) are often recovered in close association, and the representation of skeletal elements in most bone beds is inconsistent with significant hydraulic sorting related to element size, shape, or density (e.g., Behrensmeier, 1975). The presence of vertebrate and invertebrate feeding traces and insect puparial chambers (Roberts and Rogers, 1997; Rogers et al., 2003) also suggests that many Anembalemba bone assemblages were at least partially exposed to subaerial conditions prior to final burial. Clay-rich slurries apparently coursed through inactive (and perhaps dry) channel reaches, at least on occasion.

SUMMARY AND CONCLUSIONS

This study explores the alluvial record of the Upper Cretaceous Maevarano Formation of northwestern Madagascar and documents the presence of abundant fine-grained debris-flow deposits in the richly fossiliferous Anem-

balemba Member. Debris flows are attributed to recurrent exceptional rainfall events that prompted erosion and flooded ancient channel belts with sediment-laden slurries rich with clay and sand. Debris-flow deposits were repeatedly intercalated with cross-bedded facies that accumulated via traction currents in dilute flows. The variable and distinct flow conditions that characterized the alluvial system are attributed to strong seasonality in the hydrologic cycle of this Late Cretaceous ecosystem.

The abundance of bone beds preserved within debris-flow deposits, as exemplified by the multiple bone-bearing layers of quarry MAD93-18 (Fig. 2), is truly remarkable and affords novel insights into the nature of sedimentation events. Taphonomic attributes of bone concentrations suggest that associated debris flows had limited transport capability in relation to vertebrate bioclasts and that they generally entombed subaerially exposed assemblages of skeletal debris (and perhaps even the occasional live individual). The recurring association of bone beds and debris-flow deposits prompts the question, Why did diverse assemblages of dead animals accumulate again and again in and around the channel belt prior to the initiation of debris flows? Arguably the best answer hinges upon a single overarching theme—seasonality, with prolonged dry spells and their attendant hardships prompting mortality, and subsequent rains setting debris flows in motion to capture accumulated death records.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grants EAR-9418816 and EAR-9706302, and grants from the National Geographic Society and Macalester College. I thank the people of Berivotra for their hospitality, members of the Mahajanga Basin Project for their hard work, and the University of Antananarivo and the Institute for the Conservation of Tropical Ecosystems for logistical support. I also thank M. Brady, K. Curry Rogers, E. Hajek, P. Heller, T. Hickson, S. Kidwell, D. Krause, D. Loope, B. Sheets, J. Thole, and an anonymous reviewer for comments and suggestions, A. Jerve for her efforts to isolate the clay fraction, and L. Betti-Nash, D. Randrianarisata, and S. Sampson for artwork and/or photographs.

REFERENCES CITED

Abramovich, S., Keller, G., Adatte, T., Stinnesbeck, W., Hottinger, L., Stueben, D., Berner, Z., Ramanivosoa, B., and Randriamanantsoa, A., 2002, Age and paleoenvironment of the Maastrichtian–Paleocene of the Mahajanga Basin, Madagascar: A multidisciplinary approach: *Marine Micropaleontology*, v. 47, p. 17–70, doi: 10.1016/S0377-8398(02)00094-4.

Behrensmeier, A.K., 1975, The taphonomy and paleoecology of the Plio-Pleistocene vertebrate assemblages east of Lake Rudolf, Kenya: *Museum of Comparative Zoology Bulletin*, v. 146, p. 473–578.

Buckley, G.A., Brochu, C.A., Krause, D.W., and

Pol, D., 2000, A pug-nosed crocodyliform from the Late Cretaceous of Madagascar: *Nature*, v. 405, p. 941–944.

Costa, J.E., 1988, Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows, in Baker, V.R., et al., eds., *Flood geomorphology*: New York, John Wiley and Sons, p. 113–122.

Cronin, S.J., Neall, V.E., Lecointre, J.A., and Palmer, A.S., 1997, Changes in Whangaehu River lahar characteristics during the 1995 eruption sequence, Ruapehu volcano, New Zealand: *Journal of Volcanology and Geothermal Research*, v. 76, p. 47–61, doi: 10.1016/S0377-0273(96)00064-9.

Curry Rogers, K.A., and Forster, C.A., 2001, The last of the dinosaur titans: A new sauropod from Madagascar: *Nature*, v. 412, p. 530–534, doi: 10.1038/35087566.

Depéret, C., 1896, Note sur les Dinosauriens Saurpodes et Théropodes du Crétacé supérieur de Madagascar: *Bulletin de la Société Géologique de France*, v. 21, p. 176–194.

Forster, C.A., Sampson, S.D., Chiappe, L.M., and Krause, D.W., 1998, The theropod ancestry of birds: New evidence from the Late Cretaceous of Madagascar: *Science*, v. 279, p. 1915–1919, doi: 10.1126/science.279.5358.1915.

Hampton, M.A., 1975, Competence of fine-grained debris flows: *Journal of Sedimentary Petrology*, v. 45, p. 834–844.

Iverson, R.M., 1997, The physics of debris flows: *Reviews of Geophysics*, v. 35, p. 245–296.

Iverson, R.M., Reid, M.E., and LaHusen, R.G., 1997, Debris-flow mobilization from landslides: *Annual Reviews of Earth and Planetary Science*, v. 25, p. 85–138.

Krause, D.W., 2003a, Late Cretaceous vertebrates of Madagascar: A window into Gondwanan biogeography at the end of the age of dinosaurs, in Goodman, S.M., and Benstead, J.P., eds., *The natural history of Madagascar*: Chicago, Illinois, University of Chicago Press, p. 40–47.

Krause, D.W., 2003b, Discovery of a relatively complete mammalian specimen from the Late Cretaceous of Madagascar [abs.]: *Journal of Vertebrate Paleontology*, v. 23, no. 3, supplement, p. 69A.

Krause, D.W., and Hartman, J.H., 1996, Late Cretaceous fossils from Madagascar and their implications for biogeographic relationships with the Indian subcontinent, in Sahni, A., ed., *Cretaceous stratigraphy and palaeoenvironments*: Geological Society of India Memoir 37, p. 135–154.

Loope, D.B., Dingus, L., Swisher, C.C., III, and Minjin, C., 1998, Life and death in a Late Cretaceous dune field, Nemegt basin, Mongolia: *Geology*, v. 26, p. 27–30, doi: 10.1130/0091-7613(1998)026<23.CO>2.

Maizels, J., 1997, Jökulhlaup deposits in proglacial areas: *Quaternary Science Reviews*, v. 16, p. 793–819, doi: 10.1016/S0277-3791(97)00023-1.

Martin, C.A.L., and Turner, B.R., 1998, Origins of massive-type sandstones in braided river systems: *Earth-Science Reviews*, v. 44, p. 15–38.

Miller, J.H., Rogers, R.R., Wirth, K.R., and Dunn, R.K., 2000, Preliminary analyses of paleosols in the Upper Cretaceous Maevarano Formation (Mahajanga Basin), northwestern Madagascar: Paleoclimatic implications: *Geological Society of America Abstracts with Programs*, v. 32, no. 7, p. A305.

Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, in Costa, J.E., and Wieczorek, G.F., eds., *Debris flows/avalanches: Process, recognition, and mitigation*: Geological Society of America Reviews in Engineering Geology, v. 7, p. 1–12.

Roberts, E.M., and Rogers, R.R., 1997, Insect modification of dinosaur bones from the Upper Cretaceous of Madagascar [abs.]: *Journal of Vertebrate Paleontology*, v. 17, no. 3, supplement, p. 71A.

Rogers, R.R., Hartman, J.H., and Krause, D.W., 2000, Stratigraphic analysis of Upper Cretaceous rocks in the Mahajanga Basin, Madagascar: Implications for ancient and modern faunas: *Journal of Geology*, v. 108, p. 275–301, doi: 10.1086/314403.

Rogers, R.R., Krause, D.W., and Curry Rogers, K., 2003, Cannibalism in the Madagascar dinosaur *Majungatholus atopus*: *Nature*, v. 422, p. 515–518, doi: 10.1038/nature01532.

Royer, J.Y., Schlater, J.G., Sandwell, D.T., Cande, S.C., Schlich, R., Munsch, M., Dymant, J., Fisher, R.L., Muller, R.D., Coffin, M.F., Patriat, P., and Berg, H.W., 1992, Appendix 1—Indian Ocean plate reconstructions since the Late Jurassic, in Duncan, R.A., et al., eds., *Synthesis of results from scientific drilling in the Indian Ocean*: American Geophysical Union Geophysical Monograph 70, p. 471–475.

Sampson, S.D., Witmer, L.M., Forster, C.A., Krause, D.W., O'Connor, P.M., Dodson, P., and Raivoavy, F., 1998, Predatory dinosaur remains from Madagascar: Implications for the Cretaceous biogeography of Gondwana: *Science*, v. 280, p. 1048–1051, doi: 10.1126/science.280.5366.1048.

Schweitzer, M.H., Watt, J.A., Avci, R., Forster, C.A., Krause, D.W., Knapp, L., Rogers, R.R., Beech, I., and Marshall, M., 1999, Keratin immunoreactivity in the Late Cretaceous bird *Rahonavis ostromi*: *Journal of Vertebrate Paleontology*, v. 19, p. 712–722.

Scotese, C.R., 1998, Continental drift (0–750 million years), a Quicktime computer animation: Arlington, University of Texas, PALEOMAP Project.

Scott, K.M., Pringle, P.T., and Vallance, J.W., 1992, Sedimentology, behavior and hazards of debris flows at Mount Rainier, Washington: U.S. Geological Survey Open-File Report 90-385, 106 p.

Seilacher, A., Reif, W.E., and Westphal, F., 1985, Sedimentological, ecological, and temporal patterns of fossil Lagerstätten: *Royal Society of London Philosophical Transactions*, ser. B, v. 311, p. 5–23.

Storey, M., Mahoney, J.J., and Saunders, A.D., 1997, Cretaceous basalts in Madagascar and the transition between plume and continental lithosphere mantle sources, in Mahoney, J.J., and Coffin, M.F., eds., *Large igneous provinces. Continental, oceanic, and planetary flood volcanism*: American Geophysical Union Geophysical Monograph 100, p. 95–122.

Vallance, J.W., and Scott, K.M., 1997, The Osceola Mudflow from Mount Rainier: Sedimentology and hazard implications of a huge clay-rich debris flow: *Geological Society of America Bulletin*, v. 109, p. 143–163.

Manuscript received 31 August 2004

Revised manuscript received 21 December 2004

Manuscript accepted 22 December 2004

Printed in USA