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The Pan-Amazonian Ucayali Peneplain, late Neogene sedimentation in Amazonia, and the birth of the modern Amazon River system

Kenneth E. Campbell Jr. [a,*], Carl David Frailey [b,c], Lidia Romero-Pittman [d]

[a] *Vertebrate Zoology, Natural History Museum of Los Angeles County, 900 Exposition Boulevard, Los Angeles, CA 90007, USA*
[b] *Johnson County Community College, Overland Park, KS 66210 and Museum of Natural History, University of Kansas, Lawrence, KS 66045, USA*
[c] *Vertebrate Paleontology, Natural History Museum of Los Angeles County, 900 Exposition Boulevard, Los Angeles, CA 90007, USA*
[d] *Instituto Geológico, Minéro y Metalúrgico (INGEMMET), Av. Canadá 1470, San Borja, Apartado 889, Lima 41, Peru*

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Abstract

We review the Neogene geologic history of lowland Amazonia in an attempt to focus attention on areas of agreement, as well as areas in dispute, in this research arena. We reinterpret pre-existing hypotheses, present new data, and discuss new insights intended to support a unified synthesis of the Amazon Basin as a single sedimentary basin, albeit on a vast scale, during the late Miocene to middle late Pliocene. We document the Ucayali Peneplain as an isochronous, Pan-Amazonian geologic feature that formed following the early to mid-Miocene Quechua I orogenic phase of Andean tectonism. Peneplanation began possibly as early as ∼15 Ma and terminated abruptly near the beginning of the late Miocene Quechua II orogenic event at ∼9.5–9.0 Ma. Subsequently, a thin cover of sediments comprising the Madre de Dios Formation began blanketing most of lowland Amazonia, excepting only the eastern Subandean Fold-and-Thrust Belt and isolated highlands within the basin. The buried peneplain is readily observed in river cutbanks throughout Amazonia as the marked, often angular Ucayali Unconformity that separates eroded, older, often folded, faulted, and weathered, moderately to well consolidated Tertiary formations from unconsolidated, near horizontal, upper Neogene deposits. The dates of formation of major unconformities and subsequent depositional events at widely separated areas within the Andes of Bolivia, Ecuador, and Peru are coincident with that of the Ucayali Unconformity and deposition of the Madre de Dios Formation and suggest that the events are linked to a common cause, which is interpreted to be the still on-going collision between the South American and Nazca tectonic plates.

The Madre de Dios Formation has three members, the oldest of which documents a short-lived, high energy depositional environment followed by a moderate-energy depositional environment, both occurring at a time when drainage from the basin was unobstructed. The upper two members record fluctuations between moderate and low energy continental depositional environments during a period when drainage from the basin was obstructed, disorganized, and took place over long distances with extremely low gradients. The sedimentology of the Madre de Dios Formation, particularly the thick, massive beds of clay, and the widespread presence of paleodeltas and associated geomorphic features on the Amazonian *planato* are consistent with the hypothesis that much of the upper two members formed as lacustrine and deltaic deposits within a gigantic lake, Lago Amazonas, or, more probably, within a complex series of interconnected mega-lakes that occasionally united to cover most or all of lowland Amazonia to a shallow depth from the latest Miocene until ∼2.5 Ma. The presence of the Ucayali Unconformity and the relatively uniform lithostratigraphy basin-wide of the fluvial, fluviolacustrine, and lacustrine sediments of the upper Neogene Madre de Dios Formation are consistent with the hypothesis that the Amazon Basin acted as a single, undivided sedimentary basin in the late Neogene. The biostratigraphic correlation across important modern drainage divides of both micro- and macro-sized, late Miocene

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* Corresponding author. Fax: +1 213 765 8179.
E-mail addresses: kcampbell@nhm.org (K.E. Campbell), cfrailey@jccc.net (C.D. Frailey), lromero@ingemmet.gob.pe (L. Romero-P.).

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fossil vertebrates recovered from basal conglomerates of the Madre de Dios Formation, and the absence therefrom of fossil vertebrates of any other age, is also consistent with this hypothesis. Two $^{40}Ar/^{39}Ar$ dates on ash deposits within the Madre de Dios Formation corroborate the upper Miocene age of the basal horizons of that formation indicated by fossil vertebrates and support an upper Pliocene age for the youngest sediments of the formation.

The modern Amazon River drainage system was established in the late Pliocene, at ~2.5 Ma, by the breaching of the eastern rim of the sedimentary basin as a result of the basin being overfilled, or by headward erosion of the lower Amazon River, or both. Data on Cenozoic mass accumulation rates and the chemistry of terrigenous sediments in the Atlantic Ocean obtained by Ocean Drilling Project Leg 154, Ceara Rise support the postulated timing of the establishment of the modern Amazon River drainage system at ~2.5 Ma, rather than the long-held view that this event occurred in the late Miocene. We discuss the important role of ocean currents and sea level fluctuations on terrigenous mass accumulation rates on the Ceara Rise. The postulated time of formation of the modern Amazon River is nearly coincident with the onset of the Plio-Pleistocene glacial climatic regime and the lowest sea level stands since the latest middle Miocene. This analysis indicates that modern Amazonia is a product of terrain development within an erosional regime since ~2.5 Ma.

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1. Introduction

For anyone seeking an introduction to the late Neogene geologic history of Amazonia, the task can be quite daunting because, at first glance, the geology of this region can appear very complex. This apparent complexity can be attributed, in large part, to the confusing picture of Amazonian geology present in the modern literature and the lack of a clear synthesis as to where research in this area currently stands. Contributing to the problem is the observation that hypotheses, or models, of the geologic history of Amazonia are often presented based entirely on local or regional, rather than basin-wide, data, and few attempts have been made to relate new hypotheses to those that have been presented before. Attempts to correlate geologic events of Amazonia to continental- or global-scale geologic activity are even rarer. All hypotheses that have attempted to resolve some large-scale aspect of the basin's geologic history have been subject to controversy, which has given rise to a currently contentious debate, and none have achieved the consensus status of what might be called a "working model."

Perhaps surprising, given the level of contentiousness of the current debate, is the fact that there are actually many aspects of Amazonian geology, or data sets pertaining thereto, that can be agreed upon, or recognized as valid, by many researchers. The difficulties arise in the interpretation of these data and their implications for the overall history of the basin. Nonetheless, significant progress in understanding the Neogene of Amazonia has been achieved in recent years (e.g., Schobbenhaus et al., 1984; Hoorn, 1993, 1994a,b; Hoorn et al., 1995; Campbell et al., 2000, 2001; Wesselingh et al., 2002; Vonhof et al., 2003). And it is necessary that progress continue because until we understand the geologic evolution of modern Amazonia, which is fascinating and important in its own right, all hypotheses attempting to explain the great biological diversity of the Amazon Basin's extensive and complex ecosystems are without a solid physical foundation.

Much of the apparent, or perceived, complexity of the geology of lowland Amazonia can also be attributed to non-geologic factors. Foremost among these is the fact that Amazonia is a vast physiographic region, comprising approximately 40% of the South American continent, inaccessible in large part, and with portions found in several countries. Historically, these factors have made it difficult for individual researchers to view and appreciate the basin as a whole. Another complication is the almost unbroken cover of the world's largest tropical forests, which limits natural rock outcrops to the banks and channels of rivers where they lie under water for much of the year. Outcrops produced by humans (e.g., road cuts) are even rarer, usually very superficial, and ephemeral in the tropical environment.

This paper addresses what we consider to be two of the major unresolved questions regarding the late Cenozoic evolution of South America: What was the late Neogene geologic history of lowland Amazonia? And, How was the geologic evolution of lowland Amazonia influenced by geologic events outside of the Amazon Basin? Central to these issues is the question of whether or not the region that now comprises lowland Amazonia functioned as a single sedimentary basin during the late Neogene/Quaternary, or was this region one of a series of independent sub-basins, each with their own geologic history? In the former case, basin-wide, isochronous or nearly isochronous signatures of major geologic events would be evident, whereas, in the latter, major geologic events in one sub-basin would be isolated from those occurring in other sub-basins, not only in space but possibly also in time. In the former case, the uppermost deposits underlying the Amazonian *planalto*, or Amazonian high plain, and the modern ecosystems covering them, would be of approximately equal age everywhere, whereas in the latter case the sequence-capping deposits of some regions could be millions of years older than those of adjacent or neighboring regions. Resolution of this single- vs. multiple-basin question is necessary to establish the basic framework for a detailed refinement of the geologic history of lowland Amazonia.

Previously, we have argued for the single sedimentary basin hypothesis (Campbell et al., 2000; Frailey, 2002), and we think recent advances in the field further support this hypothesis. Herein we review the evidence for a basin-wide, isochronous (late Miocene) Ucayali Peneplain, which became the basis for the Ucayali Unconformity, and discuss the possible reasons for its development. We discuss the geologic and paleontological data available for the Madre de Dios Formation, the youngest Neogene formation of Amazonia. We then review the various hypotheses presented to explain the late Neogene/Pleistocene geologic history of lowland Amazonia following the formation of the Ucayali Peneplain, suggest what we regard as points in common among the various disparate hypotheses, and discuss some of the reasons for the controversies surrounding them. We conclude by re-evaluating hypotheses and data pertaining to the cause(s) and timing of the establishment of the modern Amazon River drainage system, and we present a new interpretation of the timing of this event, which brought to an end the penultimate phase in the physical evolution of the Amazon Basin and ushered in modern Amazonia.

Although our own field efforts in Amazonia extend over three decades and thousands of kilometers of rivers, we have seen only a relatively small part of Amazonia in three countries. To put the area in perspective, the Amazon River drainage area comprises ~90% of the area of the contiguous United States, or ~90% of the area of the continent of Australia. Only a small percentage of this drainage area falls outside what is known as “lowland Amazonia.” We are, therefore, dependent upon the published works of other researchers for observations and data pertaining to areas we have yet to visit, both within and outside the Amazon Basin proper. We do not question the accuracy of these data, but we often suggest different interpretations of those data pertaining to lowland Amazonia based on our understanding of the late Neogene geologic history of the region. Our view of Amazonian geology has changed slightly over the years, primarily in regard to the timing of certain signature events and the dating of sediments, and it will continue to evolve and be refined as new data become available. It must be recognized that much work remains to be done before a consensus can be reached on a unified synthesis of the Neogene geologic evolution of Amazonia. We hope this review and the presentation of new insights contained therein will further this process and perhaps challenge others to pursue new lines of geologic research in this little known and relatively neglected physiographic region.

2. The Ucayali Unconformity

The first step in establishing a unified synthesis for the geologic history of Amazonia is to determine if the Amazon Basin functioned as a single sedimentary basin in the late Neogene, or whether it was a series of independent sedimentary basins. To resolve this question in favor of the former, it is necessary to document a signature, isochronous geologic feature common throughout the basin, that is, a feature that ties the several recognized sub-regions of the basin together as one in the late Neogene. We think the Ucayali Unconformity is just such a feature (Campbell et al., 2000), and we postulate that its development was intimately tied to Andean tectonic events. Thus, it is important to document this unconformity in detail and present a logical explanation for its formation. We do not present every reference to the Ucayali Unconformity and Andean tectonism known to us, but we do provide a number that should be sufficient to portray, first, a convincing picture of a basin-wide unconformity in lowland Amazonia and, second, a linkage between the unconformity and Andean tectonics.

2.1. Documenting the Unconformity

The Ucayali Peneplain was first identified by Kummel (1948) in the Contamana region of the Ucayali River valley of north central Amazonian Peru (Fig. 1). He described the peneplain as having formed on the rock formations of the Contamana Group, which comprise the older Tertiary “red bed” sequence in Peru. He postulated that a period of erosion followed an orogenic episode of strong folding and faulting near the end of the Miocene, which he suggested produced the Subandean Fold-and-Thrust Belt and the high anticlinal hills and ridges that extend from the Contamana region

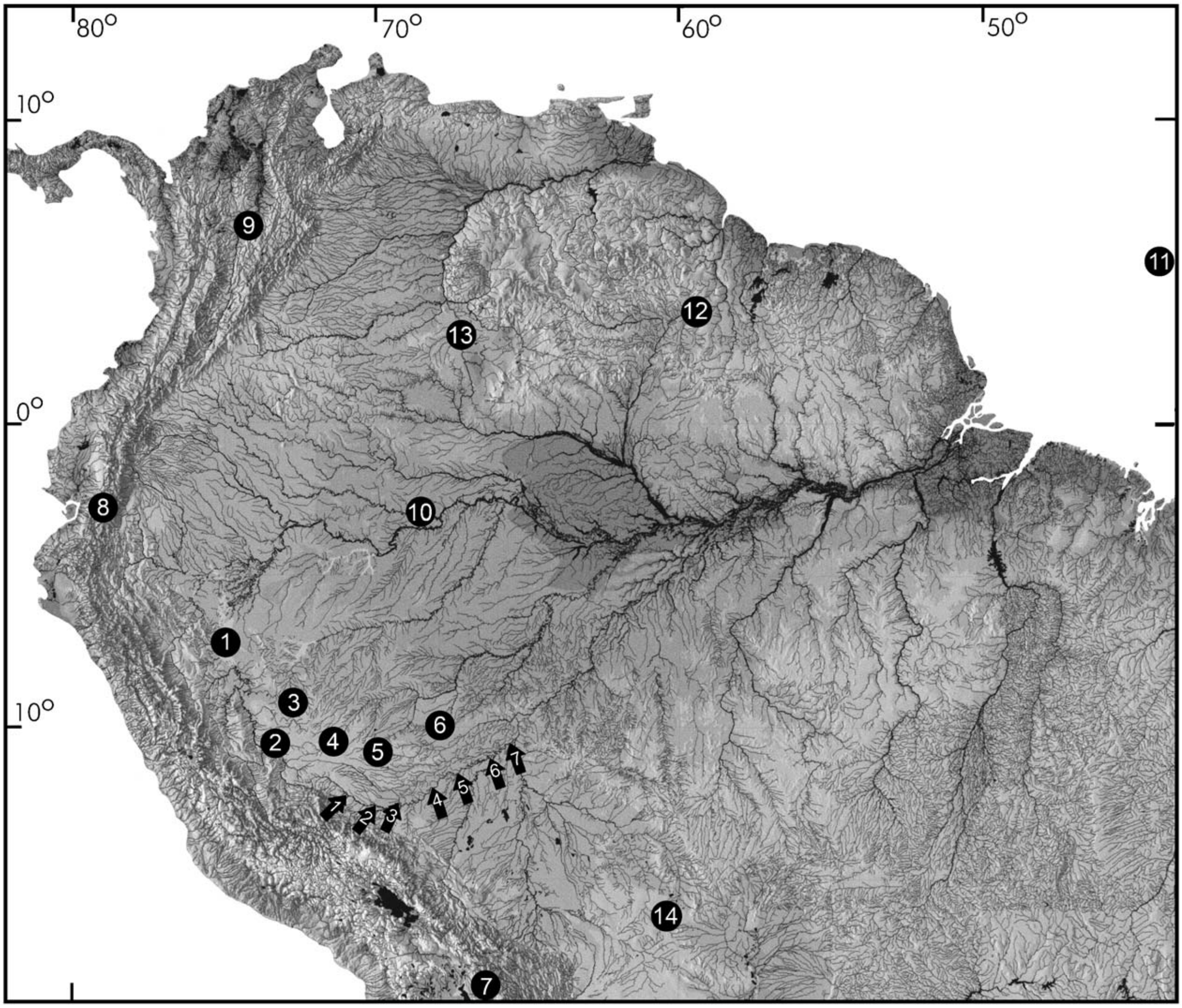


Fig. 1. Map of northern South America showing the location of the: (1) Contamana region of Peru, where Kummel (1948) first described the Ucayali Peneplain and where we have recovered late Miocene (Chasicoan-Huayquerian SALMA) vertebrates from basal conglomerates of the Madre de Dios Formation exposed along the Cachiyacu River; (2) Locality Inuya-03-III, on the Inuya River, Peru; (3) Locality RJ-95-2, on the Juruá River, Brazil; (4) Locality RP-94-2 and RP-94-4, on the Purus River, Peru; (5) Locality Acre VI, on the Acre River, Peru; (6) Locality Niteroi, on the Acre River, Brazil; (7) San Juan del Oro surface, Bolivia; (8) area of unconformity in Andes of southern Ecuador (Hungerbühler et al., 2002); (9) Magdalena Valley of Colombia; (10) type locality for the Içá Formation (Maia et al., 1977); (11) Ceara Rise; (12) divide between the Amazon Basin and Essequibo River valley; (13) area of lowest elevation divide between the Amazon Basin and the Orinoco River valley; and (14) area of lowest elevation divide between the Amazon Basin and the Paraná River valley. Arrows indicate locations of measured sections (Figs. 7 and 8) along the Madre de Dios River and its tributaries in a sequence across the southern edge of the Amazon Basin. From west to east, (1) Manu River; (2) Cerro Colorado; (3) Las Piedras River; (4) Humaita; (5) Sena; (6) Candelaria; and (7) Perserverancia. See text for details. Base map: U.S. Geological Survey Digital Data Series DDS-62-A.

southward into the Sierra de Divisor (Serra do Môa in Brazil). He referred to the denudation that followed this uplift as "extremely rapid" and substantial, removing "in places almost 3 miles [4.83 km] of sediments" (Kummel, 1948, 1260). Kummel (1948, 1262) referred to "the broad flat topographic area" extending east of the Cordillera Oriental and surrounding the Contamana and Contaya Mountains under the heading "Ucayali Peneplane." He further stated that flat-lying alluvial deposits unconformably overlie the Contamana Group close to the Ucayali River and its larger tributaries. These alluvial deposits comprise what he referred to as the Ucayali Formation, which he tentatively considered to be Pliocene to Recent in age. We correlate these alluvial deposits with those named the Madre de Dios Formation in southeastern Peru by Oppenheim (1946), and we use the latter name because it has priority over the plethora of names proposed for this formation since its original

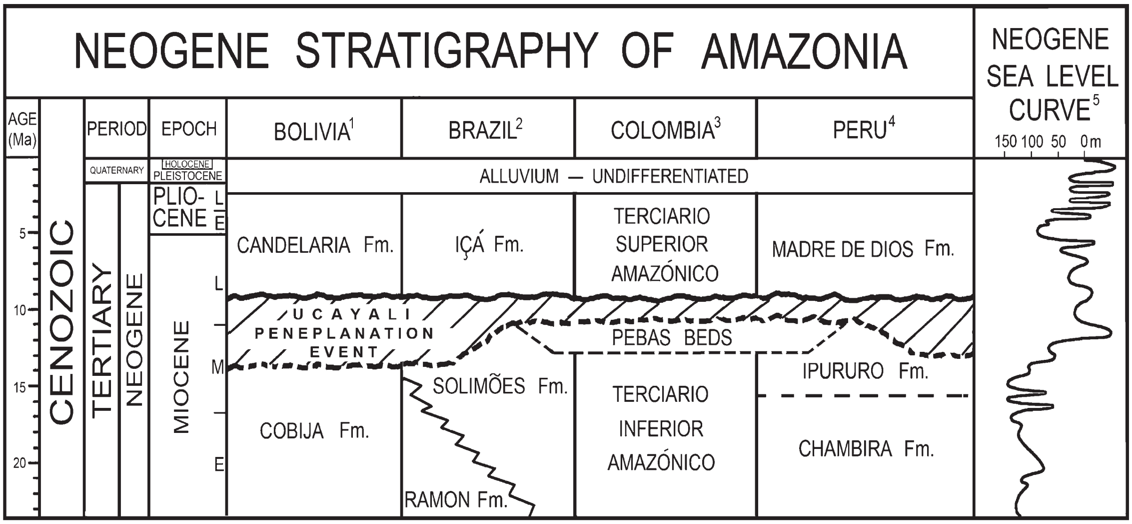


Fig. 2. Correlation chart for the Neogene stratigraphy of Amazonia. The end of the Ucayali peneplanation event is estimated to lie between 9.5 and 9.0 Ma, whereas the initiation of this erosional phase is less securely dated and probably varied somewhat around the basin. Note that the peneplanation event occurred during a time of falling sea level. The end of deposition of the Madre de Dios Formation is estimated to have occurred by 2.5 Ma, which corresponds to the second low sea level stand of the Plio-Pleistocene. We interpret the post-unconformity deposits as comprising a single formation, the Madre de Dios Formation. Formational terminology after [1]Leytón and Pacheco (1989); [2]Maia et al. (1977); [3]Galvis et al. (1979); and [4]Campbell et al. (2000). Sea level curve after [5]Hardenbol et al. (1998).

description, both in Peru and in neighboring countries. Thus, in the Ucayali River drainage basin the Ucayali Peneplain can be observed in the high sides of tributary valleys, whereas in the lowlands the Ucayali Peneplain is covered by the Madre de Dios Formation.

As an erosional surface, the Ucayali Peneplain is also an erosional unconformity, the Ucayali Unconformity, where younger deposits overlie it. The often angular Ucayali Unconformity separates the eroded, steeply to slightly tilted, often weathered, moderately to well consolidated, older Tertiary formations of the Contamana Group in Peru [= Ramon Formation and Solimões Formation in Brazil (Schobbenhaus et al., 1984)] from the overlying, unconsolidated, nearly horizontal beds of the Madre de Dios Formation [= Içá Formation in Brazil (Schobbenhaus et al., 1984)] (Campbell et al., 2000) (Figs. 2–4).

Rüegg and Rosenzweig (1949) and Rüegg (1952, 1956) also recognized in Peru the presence of a marked unconformity between the older, folded Tertiary

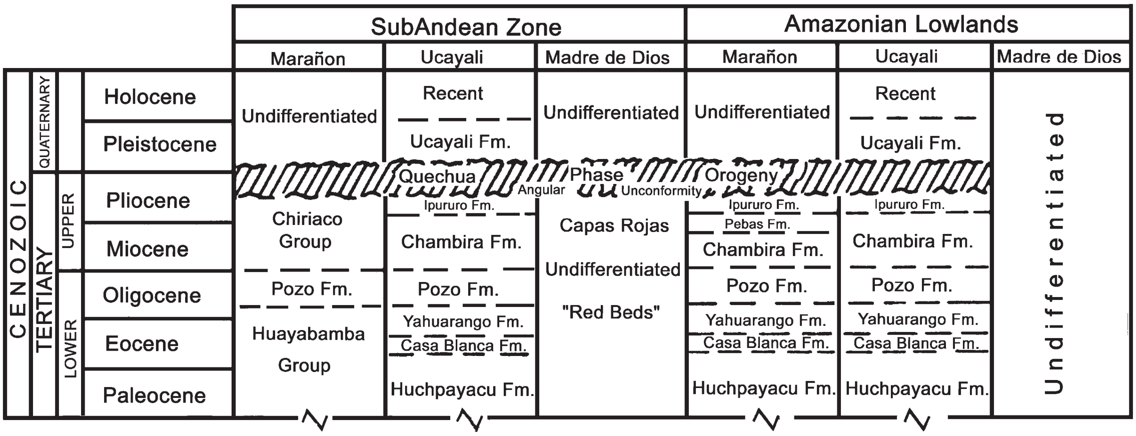


Fig. 3. Stratigraphic chart for eastern Peru showing early recognition of the Ucayali peneplanation event throughout eastern Peru, except for southeastern Peru, an area for which there were almost no data in the mid-1970s. Note that the peneplanation event is placed in the late Pliocene–earliest Pleistocene, as opposed to the late Miocene. Adapted from Pardo and Zuñiga (1976); translated from Spanish.

formations and the overlying horizontal to sub-horizontal beds. These authors related the origin of the unconformity to peneplanation that followed the "Quechua-Andino" phase of Andean tectonism, which they thought dated to the early to middle Pliocene. They suggested that this peneplain was the result of a single, prolonged tectonic event that affected all of the older, or, in their view, pre-lower Pliocene, "red bed" deposits of eastern Peru.

Koch (1959a,b) described the Ucayali Peneplain in Peru in some detail, indicating that the youngest formation of the older Tertiary "red beds" subjected to peneplanation pertained to the Miocene. He concluded that the age of the Ucayali Peneplain must be Pliocene, and he noted that unfolded beds of probable Pliocene age were frequently found where the peneplain was well preserved. He did not seem to recognize a distinction between the Ucayali Peneplain, that is, areas where eroded, older Tertiary deposits occur at the surface, and the Amazonian *planalto* represented by the top of the Madre de Dios Formation (= Ucayali Formation of Kummel, 1948).

In southeastern Peru, Douglas (1933) might have been the first geologist ever to note the Ucayali Unconformity, but his description is tantalizingly brief. ONERN (1972, 1977) described the horizontal to sub-horizontal beds of the Madre de Dios Formation exposed along the Inambari River, Acre River, and Madre de Dios River as resting with notable angularity on older Tertiary beds. Campbell and Frailey (1984, 1985), Frailey (1986), and Campbell and Romero (1989) also described the unconformity in this area, assigning a late Quaternary age to the overlying Madre de Dios Formation. Räsänen et al. (1987, 1400) recognized a regional unconformity in southeastern Peru, but suggested "The discordance is probably of highly varying age in different areas." More recently, Hovikoski et al. (2005, 177) noted the Madre de Dios Formation overlying "a regional unconformity" in the same area.

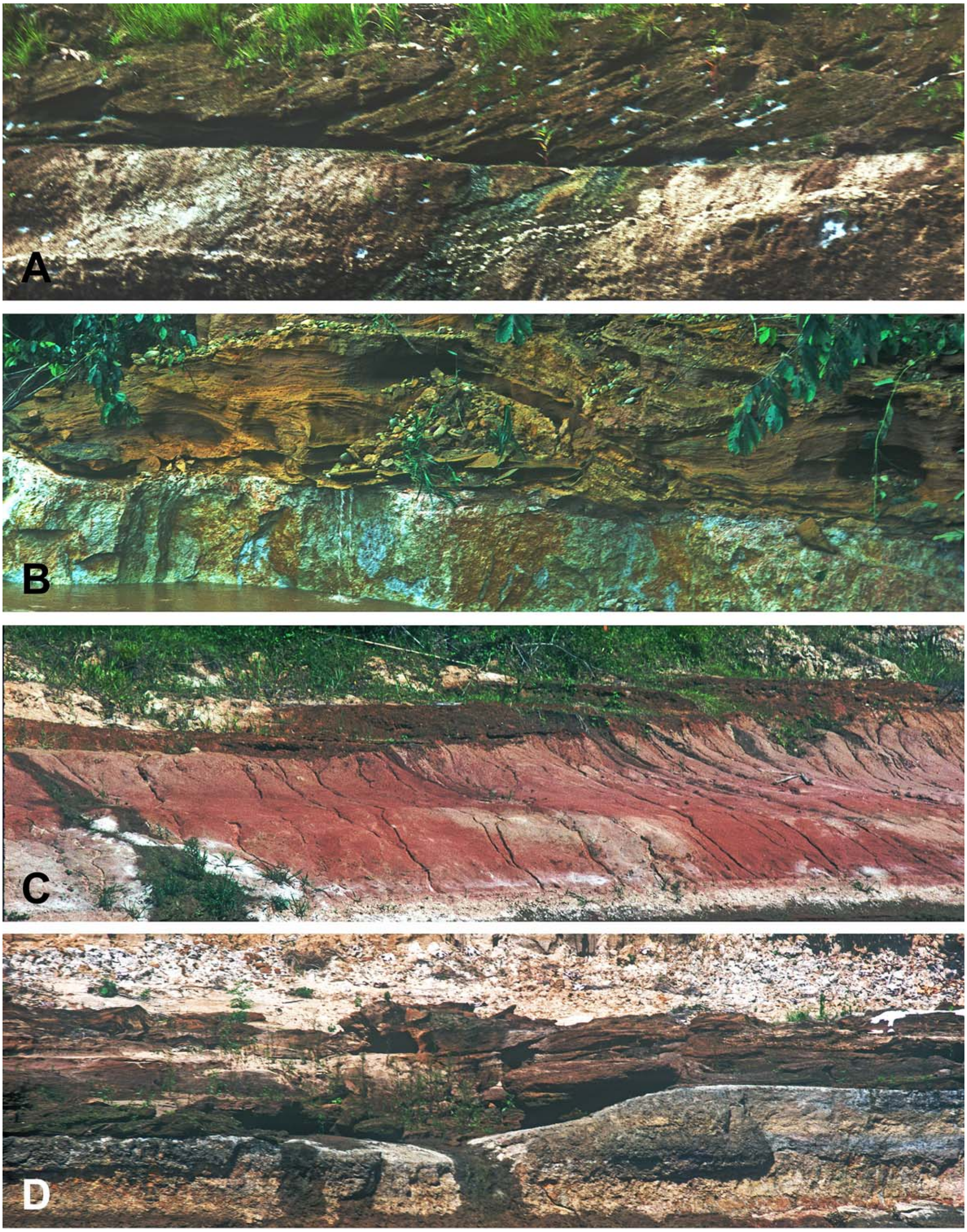
In northeastern Peru, Guizado (1975) described thick molasse deposits overlying the "Pebas Formation" via an angular unconformity west of Iquitos, but he correlated these deposits with the Ipururo Formation of Kummel (1948). The Ipururo Formation, however, underlies the Ucayali Unconformity and is often considered a lateral equivalent of the "Pebas Formation" (e.g., Mathalone and Montoya, 1995). Räsänen et al. (1998) and Roddaz et al. (2005) illustrated and described sections showing older Tertiary deposits unconformably overlain by younger deposits in the Iquitos area, but they did not correlate the unconformity with the Ucayali Unconformity.

Pardo and Zuñiga (1976) (Fig. 3) and Mathalone and Montoya (1995) emphasized the importance of the Ucayali Unconformity as a stratigraphic marker throughout Subandean and Amazonian Peru. It is also recognized in many recent bulletins published by the Peruvian Instituto Geológico, Minéro y Metalúrgico (INGEMMET) in support of the geologic map of Peru (e.g., Asociación LAGESA-CFGS, 1997). Räsänen et al. (1992) also suggested that an unconformity separating younger from older Tertiary deposits was present throughout the major part of the Peruvian Amazonian lowlands.

In eastern Ecuador, Tschopp (1953) described the "Quaternary" Mesa Formation overlying the older Rotuno Formation via an angular unconformity. In southeastern Colombia, Galvis et al. (1979) identified the Tertiary deposits as Terciario Inferior Amazonico and Terciario Superior Amazonico. They did not discuss an unconformity between these two units, but they did indicate that there were dramatic differences between them and that, in general, the base of the Terciario Superior Amazonico is an iron-rich conglomerate that is similar virtually everywhere. Khobzi et al. (1980) described horizontal, upper Tertiary deposits with basal conglomerates overlying the lightly folded beds of the "Pebas Formation." They suggested a tentative correlation with the Corrientes (= Madre de Dios) Formation of Peru and the Sanozama (= Içá) Formation of Brazil. Hoorn et al. (1995, 239) described the unconformity in southeastern Colombia thusly: "The base of the upper Miocene–Pleistocene molasse sequence is a regional unconformity in the Llanos basin…."

In northern Bolivia, Campbell et al. (1985) and Leytón and Pacheco (1989) described and illustrated the Ucayali Unconformity along the Beni River and Madre de Dios River, respectively, without referring to it by name.

The Ucayali Unconformity is also quite well known in Brazil, although, again, not by name. Simpson (1961) described and illustrated the unconformity along the Juruá River, although Maia et al. (1977) credit Gold (1967) with being the first in Brazil to recognize the unconformity that separates older from younger Tertiary deposits. Maia et al. (1977) described the Içá Formation (= Madre de Dios Formation) of Brazil, demonstrated its separation from the underlying Solimões Formation via an unconformity over a vast area in central Amazonia, and also demonstrated that it was mapable both in the subsurface (i.e., via well cores) and in outcrops. They concluded that the Içá Formation was the same geologic unit as the Sanozama Formation of Almeida (1974), but they rejected the latter name because it was not properly established. Simpson and Paula Couto (1981) demonstrated the great extent of the unconformity where it crops out along the Juruá River in western Brazil. Gingras et al. (2002) described the unconformity at a section along the Acre River in southern Brazil, on the border with Bolivia. More recently, Rossetti et al. (2005) also described the Içá Formation as overlying the Solimões Formation via an unconformity, although they did not think the Içá Formation had as wide an areal extent as did Maia et al. (1977).



Campbell et al. (2000) reviewed the subject of the Ucayali Peneplain and the overlying deposits comprising the Madre de Dios Formation. They were the first authors to place the many descriptions of a late Neogene unconformity into a Pan-Amazonian context, and they tentatively dated the period of formation of the Ucayali Peneplain to between the end of the middle Miocene Quechua I tectonic phase of the Andes at ~15 Ma and the beginning of the Quechua II tectonic phase at ~10–9 Ma. The probable end phase of peneplanation was narrowed to ~9.5–9.0 Ma by the discovery and dating of a volcanic ash just overlying the Ucayali Unconformity in southeastern Peru (Campbell et al., 2001).

However, the hypothesis that a single geologic event resulted in a Pan-Amazonian peneplain is not universally accepted. Santos (1974), Santos and Silva (1976), and Silva (1988), in discussing the geology of the Brazilian Amazon, argued against the presence of a widespread unconformity separating older Tertiary deposits from the surficial beds in Amazonia. Santos (1974) dated the uppermost deposits to the Pleistocene, saying their deposition was strongly controlled by a balance between rates of subsidence and sedimentation indirectly controlled by glacioeustatic oscillations in sea level. Santos and Silva (1976) recognized that wherever the contact between the older and younger beds in Amazonia could be seen, it was abrupt, but they attributed this to “cut and fill” river actions. Silva (1988) argued that the Madre de Dios Formation (= the Içá Formation of Maia et al., 1977) was not separable from the Solimões Formation. Cozzuol and Silva (2003) and Cozzuol (in press) argued that the Ucayali Unconformity probably represents localized features of fluvial systems.

The works of Räsänen et al. (1987, 1990, 1992) are also at variance with the concept of a Pan-Amazonian peneplain covered by a single formation throughout lowland Amazonia. In the views of these authors, even though they recognized the presence of an erosional unconformity between the older Tertiary formations of Amazonia and overlying beds, the Ucayali Peneplain as a unifying, isochronous feature did not exist and the uppermost sedimentary deposits do not comprise a single formation.

In summary, we see that a marked, late Neogene unconformity has been noted throughout lowland Amazonia independently by numerous authors in several countries. Most of the authors point out the angular nature of the unconformity and the marked differences in the lithology found above and below the unconformity, and they assign a late Miocene or early Pliocene age to the unconformity and a Pliocene to Pleistocene age to the overlying deposits comprising the Madre de Dios Formation. Even most of those authors dissenting from the hypothesis that the Ucayali Unconformity is an isochronous Pan-Amazonian feature, recognize an unconformity on a local, if not regional, basis. So the question is not whether or not there is an unconformity that could be, or could be mistaken for, a basin-wide, isochronous unconformity. The question lies in how one interprets the significance of the observed unconformity(-ies). To support the argument that the Ucayali Unconformity is an isochronous Pan-Amazonian event, we now turn to more firmly bracket its possible age and suggest an explanation for its formation.

2.2. Formation of the Ucayali Unconformity

We have proposed elsewhere (Campbell et al., 2000) that formation of the Ucayali Peneplain was initiated following the early to mid-Miocene Quechua I compressive tectonic event of the Andes. A more precise dating of the initiation of peneplanation cannot be given at this time because there are numerous questions regarding the precise timing of the Quechua I event, as there are for most tectonic events in the Andes (see Marshall and Sempere, 1993, app. B; Jaillard et al.,

Fig. 4. The Ucayali Unconformity between the older Tertiary “red beds” and the Madre de Dios Formation is identifiable by an abrupt change in lithology. (A) Bench of Tertiary “red beds” with overlying clay-pebble conglomerates that show steeply inclined (right to left) bedding (Purus River, Peru; 70°20′22″W, 9°47′13″S); (B) complex channel sand deposits with thin hematitic layers overlying clay of older Tertiary “red beds” (Carama River, Peru; 69°31′12″W, 12°54′36″S); (C) a high bank of older Tertiary “red beds” is capped by a series of low angle conglomeratic deposits (sloping left to right) that grade upslope into coarse sand deposits (Yurúa River, Peru, near junction with Huacapistea River; 72°42′21″W, 09°45′23″S); (D) hematitic channel deposits of clay-pebble conglomerates level the undulating peneplain surface of the Tertiary “red beds,” then grade upward into coarse sands with high hematite content, which, in turn, transition to loose, unconsolidated, light buff sands (Las Piedras River, Peru; 69°15′00″W, 12°27′36″S). Springs emanating from the unconformity are visible at each site [center in A and D, left of center in B (two streams of water); and far left in C]. Note the low angle, inclined bedding of the “red beds” in A, with a fault plane in center of image. Note also in A the diminution and then disappearance of calcitic bands upward toward the unconformity (best noted right of center), which is interpreted as an indicator of weathering (i.e., a paleosol). Rounded rock clasts sourced from paleochannel deposits upslope are noted as slump debris in B (just above spring and near top left). The basal sediments of the Madre de Dios Formation in A and C are best interpreted as the leading edge deposits of foreset beds, whereas in B and D the basal sediments represent channel deposits.

2000). Nonetheless, there is some agreement on approximate timing [e.g., Mégard, 1984, 1987 bracketed the Quechua I to between 20 and 12.5 Ma, whereas Noble et al., 1990 placed it at 25–17 Ma; Sébrier et al., 1988 placed it at 17–15 Ma; and Steinmann et al., 1999 cite a period of compressional deformation in Ecuador at 18 Ma, followed by extensional tectonism beginning at ~15 Ma (see also, Hungerbühler et al., 2002)]. Thus, if formation of the Ucayali Peneplain followed the Quechua 1 compression event, peneplanation could have begun as early as ~15 Ma.

As a counterpoint, however, it should be mentioned that some authors (e.g., Noblet et al., 1996) have argued that Andean uplift was more of a continuous process, rather than a series of compressive events of short duration with intervening periods of stasis as is often presented (e.g., Mégard, 1984, 1987; Ellison et al., 1989; Sébrier and Soler, 1991). There might be some merit to this proposal for certain extended periods in the life of the Andean chain, but based on the Andean events that we review here we think that at least during the time of formation of the Ucayali Peneplain a period of relative stability, rather than continual compression and uplift, persisted. Some uplift, or exhumation, resulting from rapid erosion during the period of relative stability following the Quechua 1 orogenic event (e.g., the removal of almost 5 km of sediments cited by Kummel, 1948) would have occurred, but it was probably minor in comparison to what followed during the Quechua II orogenic event.

If a late mid-Miocene period of relative tectonic stasis prevailed in the Andes, it should be possible to identify geologic features within the Andes comparable in nature and timing to the Ucayali Unconformity of Amazonia. We cite two candidates as just such features. The first is the San Juan del Oro surface and related surfaces in the Andes of Bolivia south of Amazonia (Fig. 1), which are widely recognized, regionally extensive, geomorphic surfaces (Servant et al., 1989; Gubbels et al., 1993; Kennen et al., 1997). The San Juan del Oro surface is best characterized as a composite landform, with low-relief uplands, coalesced pediments, and a prominent unconformity beneath shallow, undeformed, but now deeply incised, Tertiary clastic deposits, a description not unlike that applicable to western lowland Amazonia. Furthermore, the age of the unconformity of the San Juan del Oro surface is bracketed between 18–8 Ma near 18°S and 13–9 Ma at 21°S, or age ranges that overlap the estimated age of the Ucayali Unconformity (Campbell et al., 2000). Ignimbrites that overlie the unconformity date to 8.0–5.0 Ma (Gubbels et al., 1993).

Of further interest is the estimation that surface uplift of the San Juan del Oro surface, and others that are comparable, approached between 2 and 3.5 km since ~10 Ma (Kennen et al., 1997; Gregory-Wodzicki, 2000). This would place the Andean foreland basin, including the Subandean Fold-and-Thrust Belt, at near sea level in the early late Miocene (Gregory-Wodzicki, 2000). It would also suggest that uplift of the Subandean Fold-and-Thrust Belt probably began during the Quechua II tectonic event at 9.5–8.5 Ma, rather than the Quechua III event at ~6 Ma, as was suggested by Mégard (1987).

The second Andean event is recorded in the rocks of southern Ecuador, west of central Amazonia (Fig. 1). Hungerbühler et al. (2002) described in detail a well-dated model for the Neogene sedimentary and tectonic history of the southern Ecuadorian Andes. In their model, subsidence resulting from extensional tectonics west of the Cordillera Real in the middle Miocene led to the formation of depositional basins at or near sea level that filled with sediment derived primarily from the east. Hungerbühler et al. (2002) referred to this depositional series as the "Pacific Coastal Sequence," and their chronostratigraphic zircon fission-track data indicated that this depositional period lasted from ~15 to 9.5 Ma. Their preferred explanation for this period of extensional tectonics is that it was prompted by the collision of the South American continent with the Carnegie Ridge, which Spikings et al. (2001) estimated began at ~15 to 9 Ma. The data of Hungerbühler et al. (2002) suggested to them that the older date within this range was probably the most accurate.

Hungerbühler et al. (2002) described as the "Intermontane Sequence" a series of continental (i.e., alluvial fan and proximal fluvial facies elements) and pyroclastic deposits that overlie the "Pacific Coastal Sequence." A major, partly angular unconformity separates the older Miocene deposits from the overlying, younger Neogene deposits. Hungerbühler et al. (2002) attributed this unconformity to the initiation of compression and tectonic inversion in the southern Ecuadorian Andes that began between 10 and 9 Ma, a timing that is well constrained by facies development and zircon fission-track dating. They correlate the events they recorded in southern Ecuador to those reported for the northern Ecuadorian Andes by Spikings et al. (2000, 2001). They could not say with certainty what brought about the end of extensional tectonics and initiated the period of compression and tectonic inversion that led to the deposition of the "Intermontane Sequence," but they suggested that it was related to the degree to which the

South American continent had overridden the buoyant Carnegie Ridge.

Steinmann et al. (1999) calculated that surface uplift of the "Pacific Coastal Stage" rock series of the Cuenca Basin of Ecuador, which were deposited at or near sea level, has been approximately 2700 m since ~9.5 Ma. This degree of elevation is in the middle of the estimated range of surface elevation for the San Juan del Oro surface (Kennen et al., 1997; Gregory-Wodzicki, 2000). The timing of the uplift of these two widely separated areas in the Andean chain is consistent with the hypothesis of major Andean tectonic events bordering Amazonia being nearly isochronous.

One might reason that once initiated, possibly as early as ~15 Ma, the peneplanation event in lowland Amazonia was facilitated by the gradual drop in sea level from a high of ~145 m amsl (above modern sea level) at ~14.5 Ma to a low of ~50 m bmsl (below modern sea level) at ~11.3 Ma (Hardenbol et al., 1998). If there were no restrictions on outlets to the sea, this nearly 200 m drop in ultimate base level would have ensured that erosion, not deposition, was the dominant force at work in lowland Amazonia at this time. However, this period also corresponds to the time of existence of the younger portion of Lago Pebas (Wesselingh et al., 2002), a long-lived, freshwater mega-lake in western Amazonia. Hungerbühler et al. (2002) suggested that local extension in the middle Miocene might have stepped back across the Cordillera Real, providing a connection between their Pacific Coastal depositional realm and the Amazonian region. If this were the case, then it is reasonable to assume that during the period of low sea level centered at ~11.3 Ma (Hardenbol et al., 1998) this connection might have been the primary portal for drainage of the Amazon Basin, and it suggests that the Andes were serving as a local base level, maintaining Lago Pebas at an elevation above sea level. However, marine incursions into Lago Pebas have been documented between 12 and 10 Ma (Wesselingh et al., 2002). Although Vonhof et al. (1998) and Wesselingh et al. (2002) proposed that these marine incursions came from the north, it might be more parsimonious to consider the possibility that continued extension and subsidence in southern Ecuador provided a shorter incursion pathway by the time sea level rose to ~22 m amsl at ~10 Ma (Hardenbol et al., 1998), just prior to the beginning of the Quechua II orogenic event. Following compression and tectonic inversion, which began at 10–9 Ma, this portal to the Pacific closed and the drainage system within lowland Amazonia experienced reorganization. Given the long-term existence of Lago Pebas in west-central Amazonia, it is to be expected that peneplanation was restricted to those parts of the basin not covered by the mega-lake, whereas deposition was occurring within the core area of Lago Pebas. Therefore, it is conceivable that the youngest Pebasian sediments are overlain conformably by the Madre de Dios Formation. If this is the case, however, the youngest Pebasian sediments must be in undescribed areas to the west of Iquitos because paleosols cap the Pebas beds in the Iquitos area (e.g., Räsänen et al., 1990; Roddaz et al., 2005), and in nearby southeastern Colombia the Pebas beds are slightly tilted (Khobzi et al., 1980).

Renewed, strong compression and uplift in the Andes [Quechua II event; 9.5–8.5 Ma (Mégard, 1984, 1987); 12–8 Ma (Noble et al., 1990); ~10 Ma (Sébrier et al., 1988; Sébrier and Soler, 1991); ~9 Ma (Steinmann et al., 1999); ~10–9 Ma (Hungerbühler et al., 2002)] brought to an end the Ucayali peneplanation event and initiated deposition of the Madre de Dios Formation.

The sequence and timing of tectonic events in the Colombian Andes were more complex than those to the south because of the influence of impacting allochthonous terranes and the movement of the Caribbean Plate (Aleman and Ramos, 2000). Of note to this discussion, uplift of the Eastern Cordillera of Colombia began at ~12.9 Ma, and by ~11.8 Ma the Eastern Cordillera might have been established as a continuous range separating the Magdalena River valley (Fig. 1) from the Amazon Basin (Guerrero, 1997). Although Hoorn et al. (1995) refer to deposition over an unconformity within the Magdalena River valley beginning at ~10.1 Ma, there are no data to indicate how or when the presence of the Eastern Cordillera began to impact deposition within lowland Amazonia. Given the more complicated history of tectonism in the Colombian Andes, it would not be surprising if initiation of deposition of the Madre de Dios Formation in the llanos of Colombia began slightly earlier, or even later, than farther to the south.

In summary, two large-scale unconformities separated by nearly 2500 km are found within the Andes that correspond closely in age to each other and to the postulated basin-wide, isochronous Ucayali Unconformity of lowland Amazonia. Although the occurrence of these three unconformities of similar ages could be a coincidence, we think it more likely that they reflect an interrelated response to Andean tectonism, the ultimate cause of which was the convergence of the Nazca and South American tectonic plates (see, e.g., Pilger, 1984; Pardo-Casas and Molnar, 1987, and Sébrier and Soler, 1991). There are undoubtedly other large-scale peneplanation surfaces in the Andes [e.g., the Pampa Lagunas Apron Pediment, also known as the Puna surface (Garver et al., 2005), which is bracketed by dated ignimbrites of 14.2 Ma and 11.2 Ma (Tosdal et al., 1984)], but it is not considered necessary to produce a finite list and description of all known peneplanation surfaces in order to convey the probable teleconnection between Andean tectonic events and peneplanation in lowland Amazonia.

3. The Neogene formations of Amazonia

3.1. Pre-Ucayali Unconformity formations

The older Tertiary continental deposits of Amazonia underlying the Ucayali Unconformity comprise a series of formations that are often difficult to distinguish in the field. As a result, for many decades of the last century these strata were simply referred to as the Tertiary "red beds" of Amazonia. In Peru, these formations are now placed within the Contamana Group (Kummel, 1948), whereas in Brazil they are referred to as the lower Tertiary Ramon Formation and the younger Solimões Formation (Schobbenhaus et al., 1984) (Fig. 2). Although ages for these formations have been postulated based on scarce and scattered paleontological data, there are no numerical age dates to corroborate these ages. The youngest of these strata correspond to the Ipururo Formation in Peru and its lateral equivalent in Brazil, the upper part of the Solimões Formation. For detailed lithologic descriptions of the older Tertiary formations, see Kummel (1948), Rüegg (1956), Maia et al. (1977), Khobzi et al. (1980), Schobbenhaus et al. (1984), Hoorn (1993, 1994), and Wesselingh et al. (2002).

As mentioned above, the "Pebas Formation" is often considered a lateral equivalent of the Ipururo Formation, and it would, therefore, also be a lateral equivalent of the upper part of the Solimões Formation. Although the term "Pebas Formation" is often used (e.g., Wesselingh et al., 2002; Vonhof et al., 2003), this stratum has never been formally named, and these fossiliferous deposits are probably best referred to as simply the "Pebas beds." These beds have been dated by pollen (Hoorn, 1993, 1994; Wesselingh et al., 2002), and their age range appears to extend from the early Miocene to early late Miocene (~20 Ma to ~10 Ma). If these dates are accurate, deposition of the younger of the Pebas beds took place at the same time peneplanation was occurring in other parts of the basin.

Three features seem to characterize the top of the older "red bed" sequence. First, these older, moderately to well consolidated "red beds" with their high clay content are relatively impervious to ground water compared to the unconsolidated, overlying sediments, thus ground water migrates laterally at the Ucayali Unconformity and appears as springs in riverbank sections where the unconformity is above the water level (Fig. 4). The springs serve as excellent field markers for the unconformity because they do not occur within the unconsolidated sediments of the overlying Madre de Dios Formation, although "wet" zones associated with pervious horizons bounded by impervious clays do occur in that formation. Slumping of the overlying strata at the Ucayali Unconformity is very common because of the lubricating effect of abundant ground water, and this slumping often makes it difficult to view complete stratigraphic sections. The widespread occurrence of very high concentrations of hematite just above the Ucayali Unconformity is also attributable to the impervious nature of the older, consolidated strata, which leads to high concentrations of iron in ground water above the unconformity. That is, downward percolation of ground water carrying iron compounds is stopped at the unconformity, and the iron concentration at that level is then increased to high levels by evapotranspiration during extended dry seasons, which leads to the deposition of iron deposits. Hematitic zones attributable to ground water flow are also found scattered throughout the upper horizons of the Madre de Dios Formation, but they never approach the magnitude seen just above the Ucayali Unconformity.

Second, paleosols commonly occur at the top of the older Tertiary sequence (Figs. 4A and 5A). Simpson and Paula Couto (1981, 16) noted that the oldest exposed Tertiary beds along the Juruá River in Brazil had "a clear weathered and erosional disconformity" at their top. Campbell and Frailey (1984) noted the presence of a paleosol at the top of the older "red beds" in southeastern Peru. Along the Acre River in southeastern Peru, Frailey (1986) described visible bedding planes and calcitic stringers of the older "red beds" disappearing upward into a weathered zone underlying an unconformity (Figs. 4A and 5A). Räsänen et al. (1990, 1992) noted the "weathered" condition of the top of the older "red bed" sequence throughout the major part of the Peruvian Amazon, and Räsänen et al. (1998) and Roddaz et al. (2005) described paleosols marking the top of the Pebas beds in the Iquitos area of Peru. These observations of weathering and paleosol development are important because they demonstrate that the Ipururo/Solimões Formation experienced sub-aerial weathering for some time before deposition of the overlying Madre de Dios/Içá Formation. The common, widespread presence of a strong weathering zone marking the top of the "red beds" would appear to falsify hypotheses of

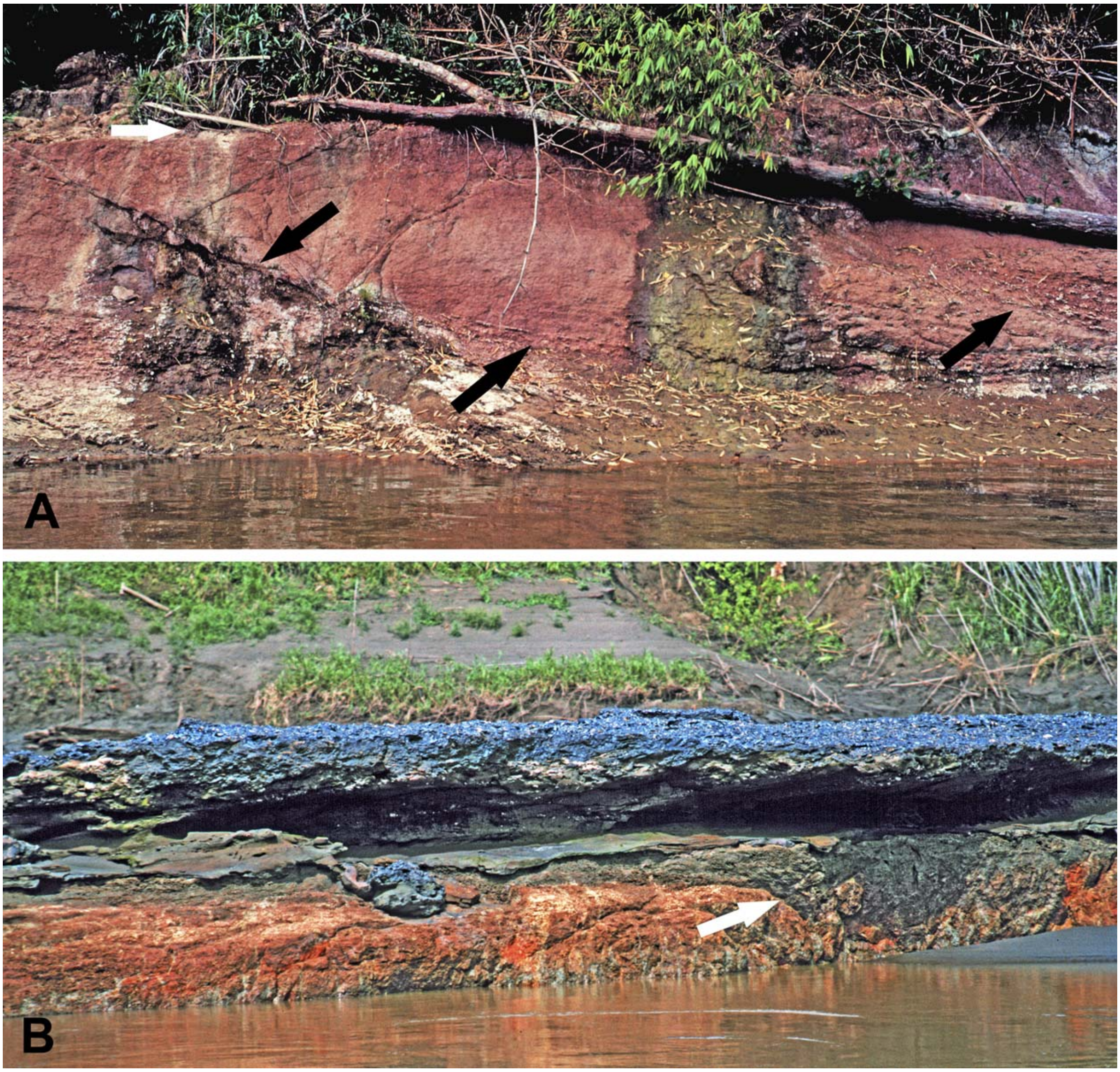


Fig. 5. (A) The presence of paleosols on the consolidated older Tertiary "red beds" is illustrated by calcitic bands (sloping left to right, center and right arrow) disappearing upward toward the Ucayali Unconformity (white arrow). A fault plane is indicated by arrow on the left, and this arrow lies between two other fault planes that are almost in parallel with it. This combination of fault planes is a demonstration of a classic strain ellipsoid. Fault planes, other than those resulting from large scale slump blocks, are absent from the overlying Madre de Dios Formation. (Acre River, Peru; approximately 69°47′22″W, 10°55′20″S). (B) The basal conglomerates of the Madre de Dios Formation can be iron-cemented and form highly resistant shelves overlying the "red beds." At this site there is a layer of iron-cemented, coarse sand directly underlying the basal conglomerate and overlying the Ucayali Unconformity. The cemented conglomerate transitions rapidly upward into loose sands of Member "A" of the Madre de Dios Formation. Where the basal conglomerate is cemented in this fashion, it will form rapids when the water level reaches certain depths. The arrow indicates the edge of a paleochannel within the "red beds" that predates deposition of the Madre de Dios Formation (Madre de Dios River, near mouth of Las Piedras River, Peru; 69°27′30″W, 12°29′10″S).

continuous deposition within Amazonia throughout the Neogene, as well as arguments for fluvial cut-and-fill processes creating local unconformities. In a dynamic fluvial system, the latter type of unconformity presumably would experience only short-lived exposure insufficient for the formation of deep paleosols. Complete paleosol profiles have not been reported under the Ucayali Unconformity, nor is a weathering zone present at every outcrop, but this is to be expected given the high energy erosional environment that must have immediately preceded deposition of the Madre de Dios Formation (see below).

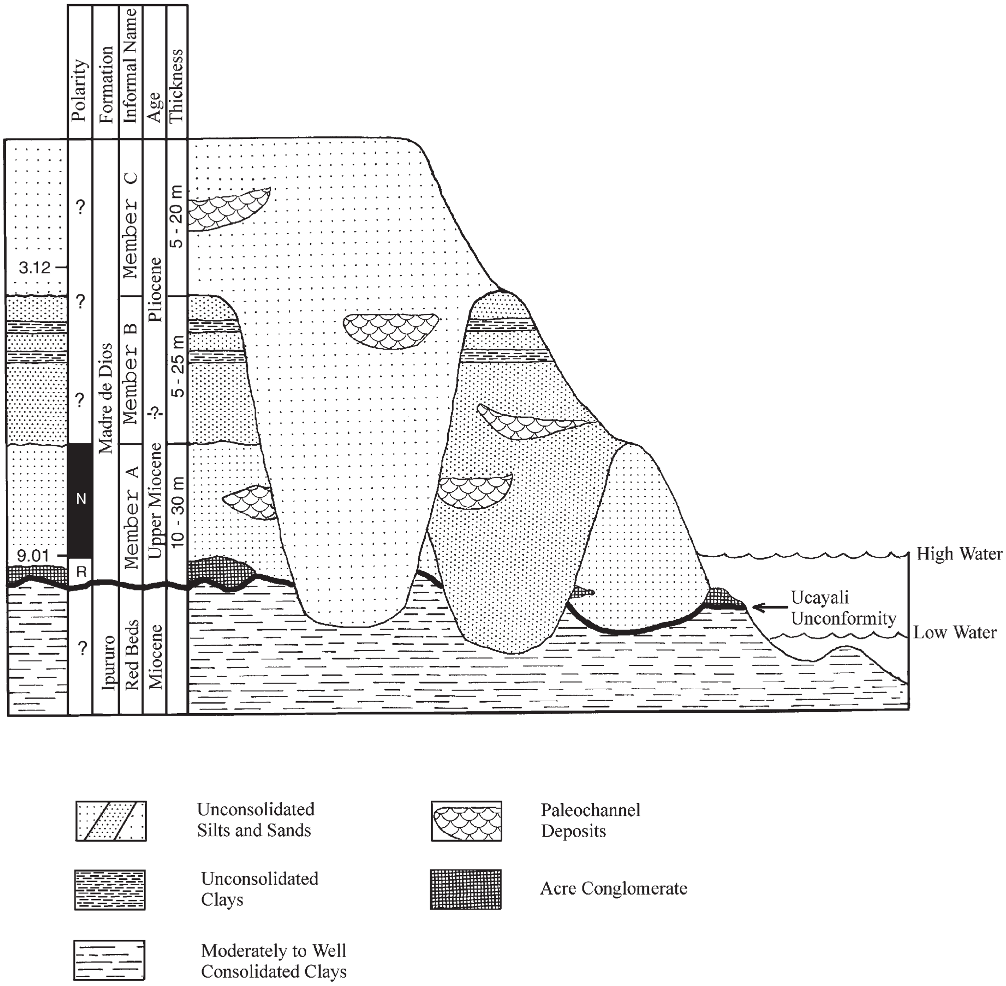


Fig. 6. Generalized geologic section seen along rivers in western, southern, and central Amazonia. The oldest strata exposed during the dry season low water period belong to the Contamana Group, usually the Ipururo Formation (shown here) or Chambira Formation in Peru (both included in the Solimões Formation in Brazil). The Ucayali Peneplain appears as a marked unconformity, shown here as the dark line separating the Ipururo Formation from the overlying Madre de Dios Formation (=Içá Formation in Brazil). The Madre de Dios Formation is divisible into three horizons, the oldest being Member "A," which dates to the upper Miocene (Chasicoan/Huayquerian SALMA) based on contained fossils and the ^{40}Ar/^{39}Ar date on the Cocama ash. The age of Member "B" is unknown, but the lower portion of Member "C" has been ^{40}Ar/^{39}Ar dated to 3.12 ± 0.02 Ma. Theoretically, Member "B" and Member "C" could extend downward as far as the Contamana Group, a consequence of deposition following riverine erosion of the underlying unit(s), but the extreme downcutting illustrated here has not been observed in the field. The three members of the Madre de Dios Formation are primarily composed of horizontal beds of unconsolidated sands and silts, and the upper two members often have high clay content. Member "A" consistently has a much coarser clast size than the other two members of the formation. Fairly thick clay horizons might occur in all three units, but they are most common in Unit B (where they are depicted here). Isolated paleochannel deposits occur in all three units of the Madre de Dios Formation. Modified from Campbell et al. (2001).

Third, the Ucayali Unconformity most often occurs in outcrops very near the dry season low water mark. This is because Amazonian rivers are entrenched into the unconsolidated deposits of the Madre de Dios Formation, a process that began with the establishment of the modern Amazonian drainage system, and it is the resistant, consolidated "red beds" that usually form local base levels. Indeed, rapids formed by differential erosion of well consolidated horizons of the "red beds" are common in smaller tributary streams during dry seasons, and they also occur in some of the major rivers (e.g., the Madre de Dios River in Bolivia). This is not to say that all rapids occur because of resistant "red beds," however. Where the basal conglomerates are well cemented by iron deposits, they can form very resistant horizons that result in the formation of rapids (Fig. 5B).

It should also be noted that low angle faulting is commonly observed within the "red beds" (Figs. 4A and

5A). This faulting probably resulted from compressive forces exerted on the “red beds” during the Quechua I tectonic event. Similar faulting has not been observed in the Madre de Dios Formation.

3.2. The Madre de Dios Formation

We interpret the youngest sedimentary sequence in lowland Amazonia, excluding Quaternary floodplain and terrace deposits, as comprising a single formation (Figs. 2 and 6). This formation is mapable from northern Bolivia in the south to southeastern Colombia in the north and from eastern Peru and Ecuador in the west to east-central Brazil in the east. This formation is known by many names that have been applied locally, or regionally, the most well known of which are: Madre de Dios Formation, Ucayali Formation, and Içá Formation. We prefer the first of these names because

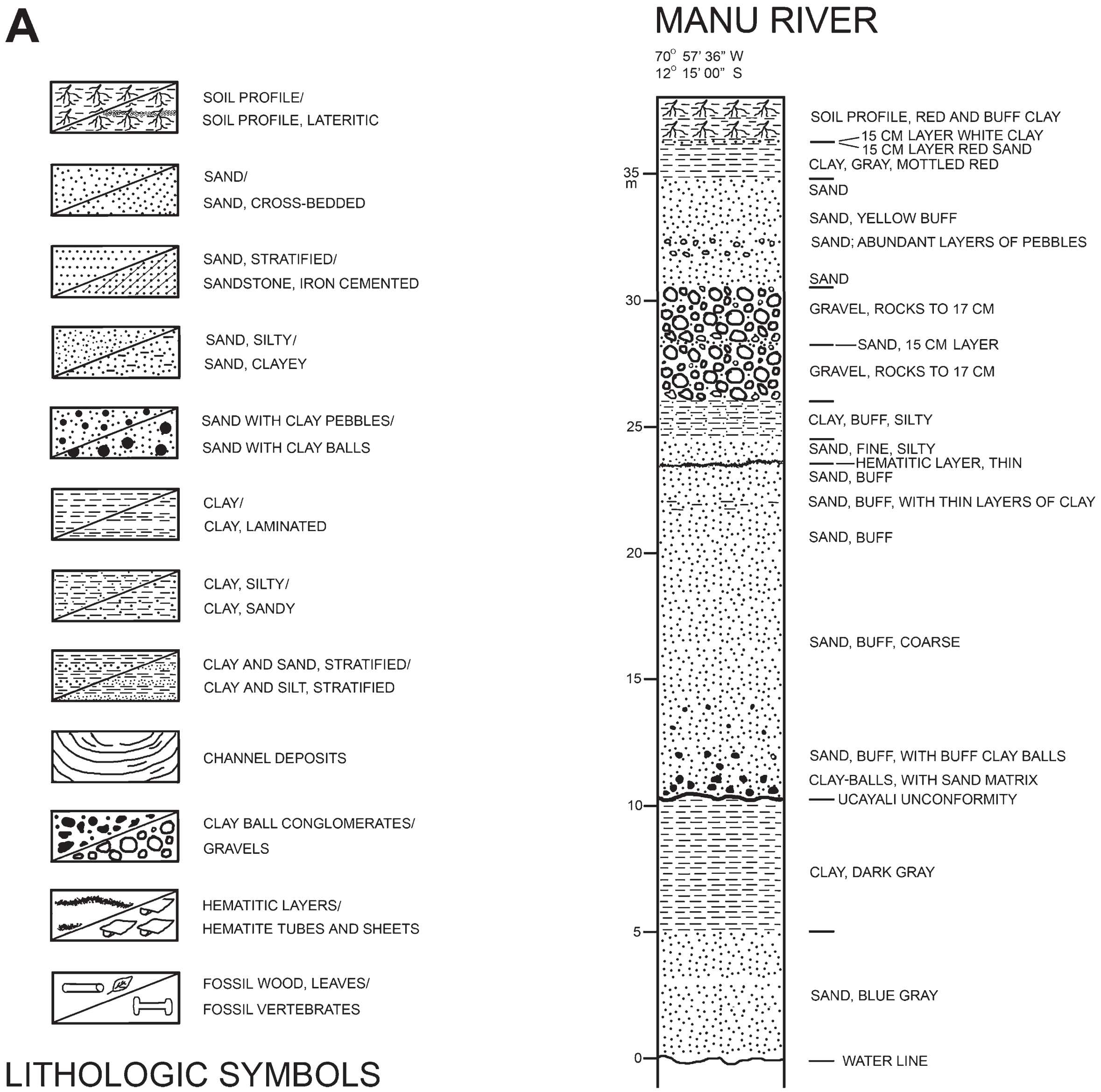


Fig. 7. A series of sections along the Madre de Dios River across the southern rim of the Amazon Basin demonstrate the complexity of the lithostratigraphy of the Madre de Dios Formation. Sections were measured and examined at 1 m intervals by rope descent of vertical cliffs, except in one instance. Sediment samples were collected at each interval, but they have not yet been analyzed. Fine structural details were not recorded, but major lithologic changes between sampled intervals were.

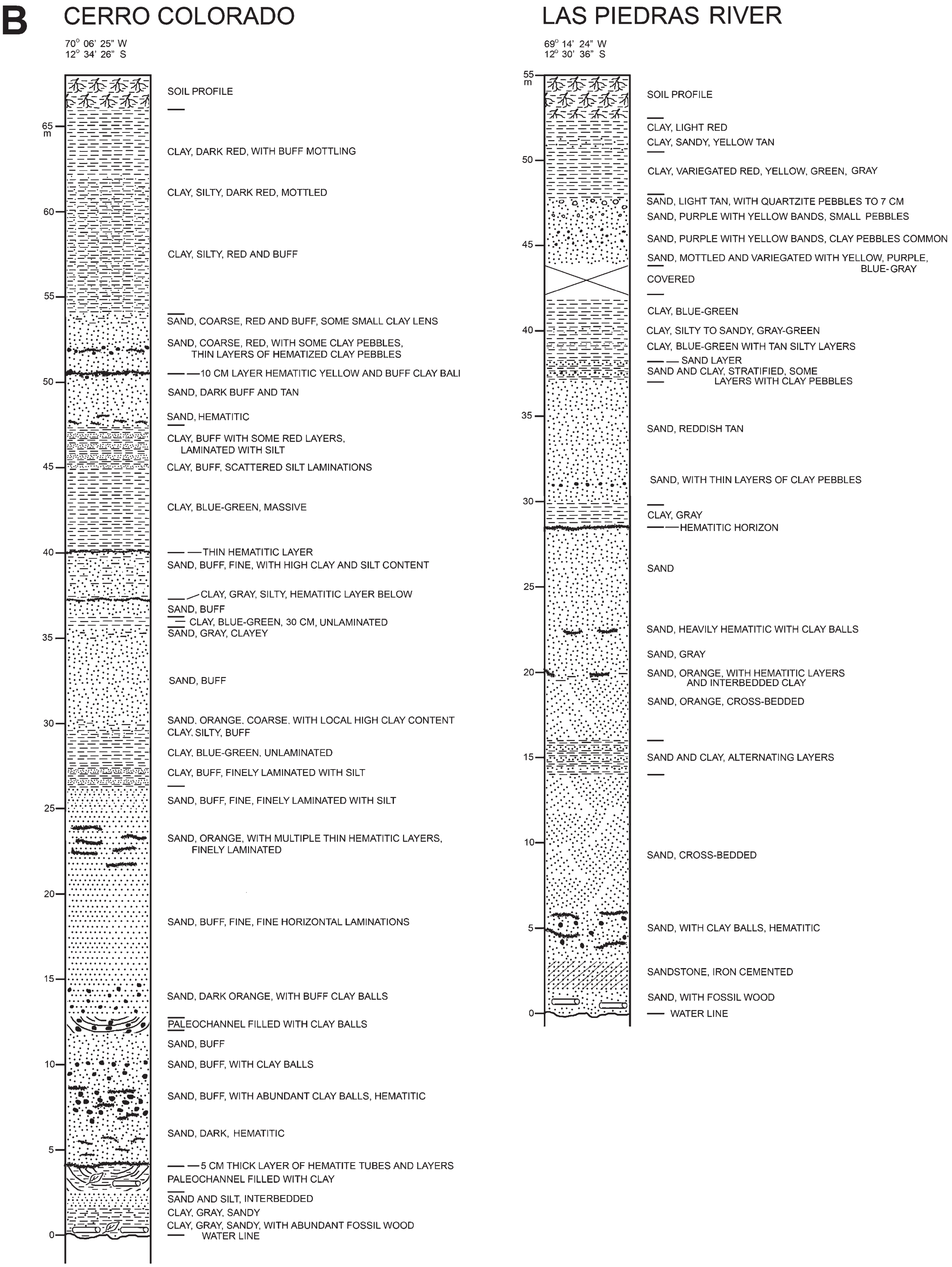
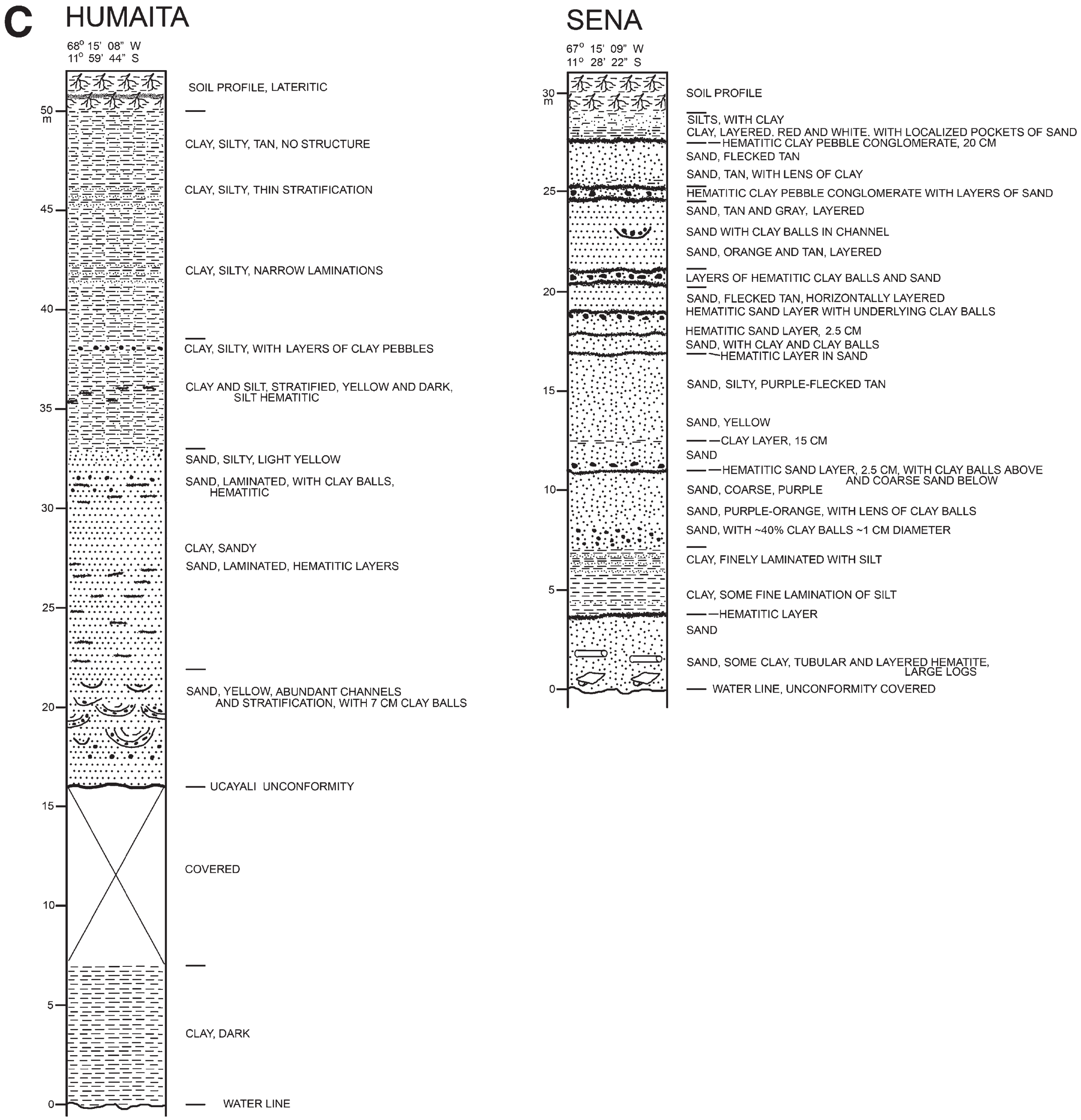


Fig. 7 (*continued*).

it has priority over all others and suggest that it be adapted throughout the basin. The Madre de Dios Formation has been described by numerous authors based on independent local or regional studies, and there are many points in common among these descriptions, as we shall discuss. Because of its importance, we will look at four aspects of this formation (i.e., lithology, age, paleontological data, and environments of deposition) separately.

All authors have described the uppermost Neogene deposits of lowland Amazonia as comprising horizontal or sub-horizontal beds. In outcrops, these beds do appear horizontal, but even the longest outcrops are much too short and too widely spaced to permit tracing elevations over long distances. We have noted possible broad, slight uplift of these beds south of the Sierra de Divisor, which might reflect minor uplift along a southern extension of that fold and thrust belt. Dumont



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et al. (1991) also suggested that the surface of these beds is tilted away from the structural highs in the lowlands of eastern Peru. The possible slight tilt away from the axis of the Sierra de Divisor might be related to compressive forces acting on that zone, or it might be related to igneous activity there (Campbell et al., 2000). The differences in elevation observed, however, are so small that ascertaining the magnitude of any broad scale tilt of these beds is impossible without highly sophisticated devices unavailable to us. Still, from the essentially horizontal structure of these beds throughout lowland Amazonia, and in the absence of bedding plane offsets resulting from faulting, it can be assumed that no compressive phase of tectonism has affected the basin since deposition of the Madre de Dios Formation began ~9.5–9.0 Ma.

The thickness of the Madre de Dios Formation is highly variable. In northern Bolivia, the formation is in places < 10 m thick (Campbell et al., 1985), whereas, at the other end of the basin, Galvis et al. (1979) illustrate a section 52 m thick in Colombia. Maia et al. (1977) measured the thickness of the formation as 79 m at the reference locality of their Içá Formation (well 1AS-41-AM), and they give an estimated maximum thickness for the formation of 140 m. A notable thinning of the formation from west to east has been noted by several authors (e.g., Maia et al., 1977; Galvis et al., 1979; Figs. 7 and 8). The base of the formation, covering as it does a peneplain, is undulating and irregular. The thickest section we have measured is 70 m (locality MP-5 of Campbell and Romero, 1989), which is found at Cerro Colorado (also known as Aurinsa) on the Madre de Dios River in southeastern Peru (12°34′26″S; 70°06′25″W) (Figs. 1, 7–9). (Note: Hovikoski et al., 2005 describe this section and give its thickness as only 40 m.)

The top of the Madre de Dios Formation comprises the Amazonian *planalto*, which is equivalent to and also known as the Amazonian *terra firme* in those regions of Amazonia where the *planalto* has not yet been eroded. Almeida (1974), Khobzi et al. (1980), and Campbell (1990) observed that the top of this formation comprises a surface of accumulation, not a peneplain. Rapid, basin-wide entrenchment of the rivers and streams of

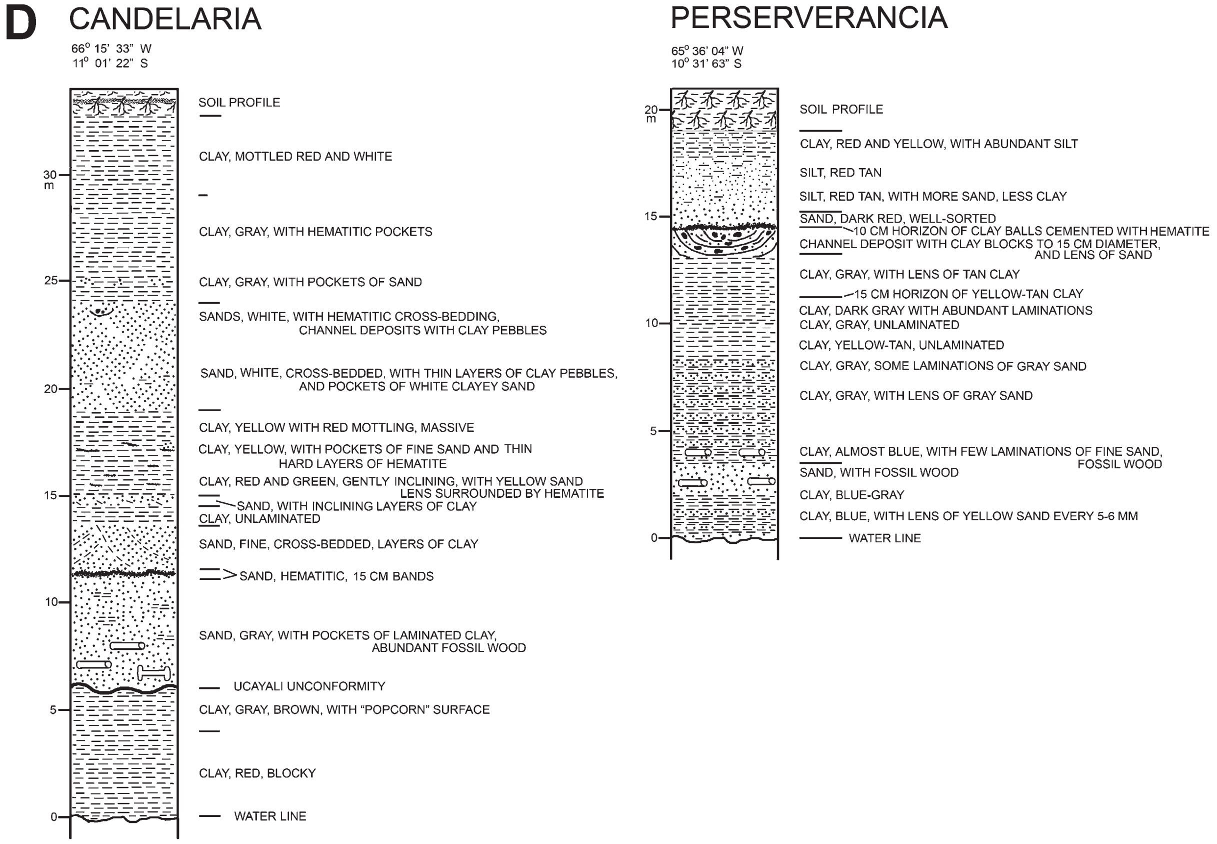


Fig. 7 (*continued*).

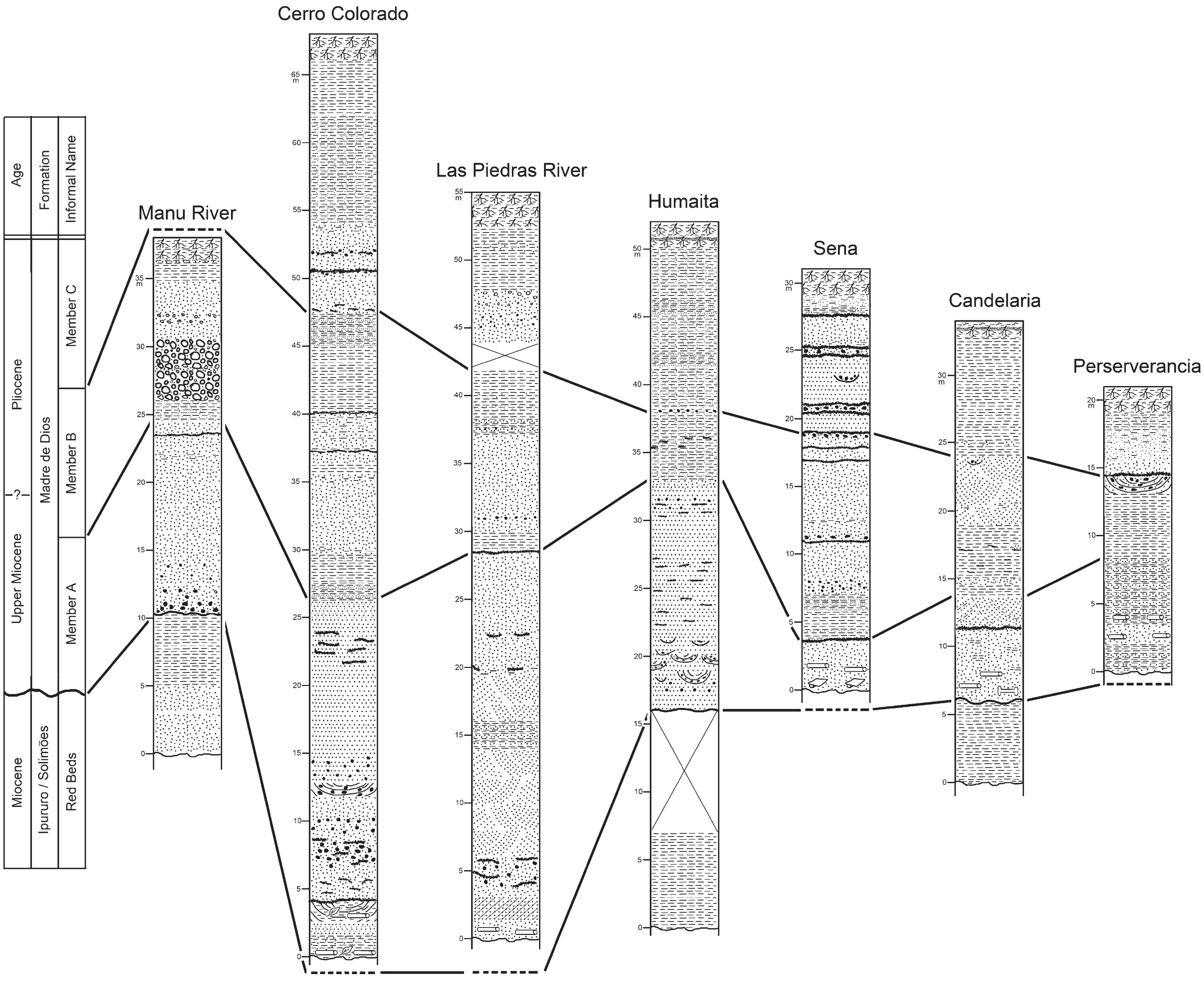


Fig. 8. Tentative correlation chart of sections shown in greater detail in Fig. 7.

Amazonia has resulted in the geomorphology of uneroded portions of the *planalto* being much as it was at the time accumulation of the formation ceased. That is, the *planalto* represents a “snap shot” of the depositional environment at the time deposition in lowland Amazonia ceased. Within the confines of the flood plains of all large Amazonian rivers, fluvial erosion has substantially, if not entirely, removed both the Madre de Dios Formation and all traces of the Ucayali Peneplain. Nonetheless, wherever Amazonian rivers and streams erode their valley walls, the Madre de Dios Formation is exposed in the resulting cutbank.

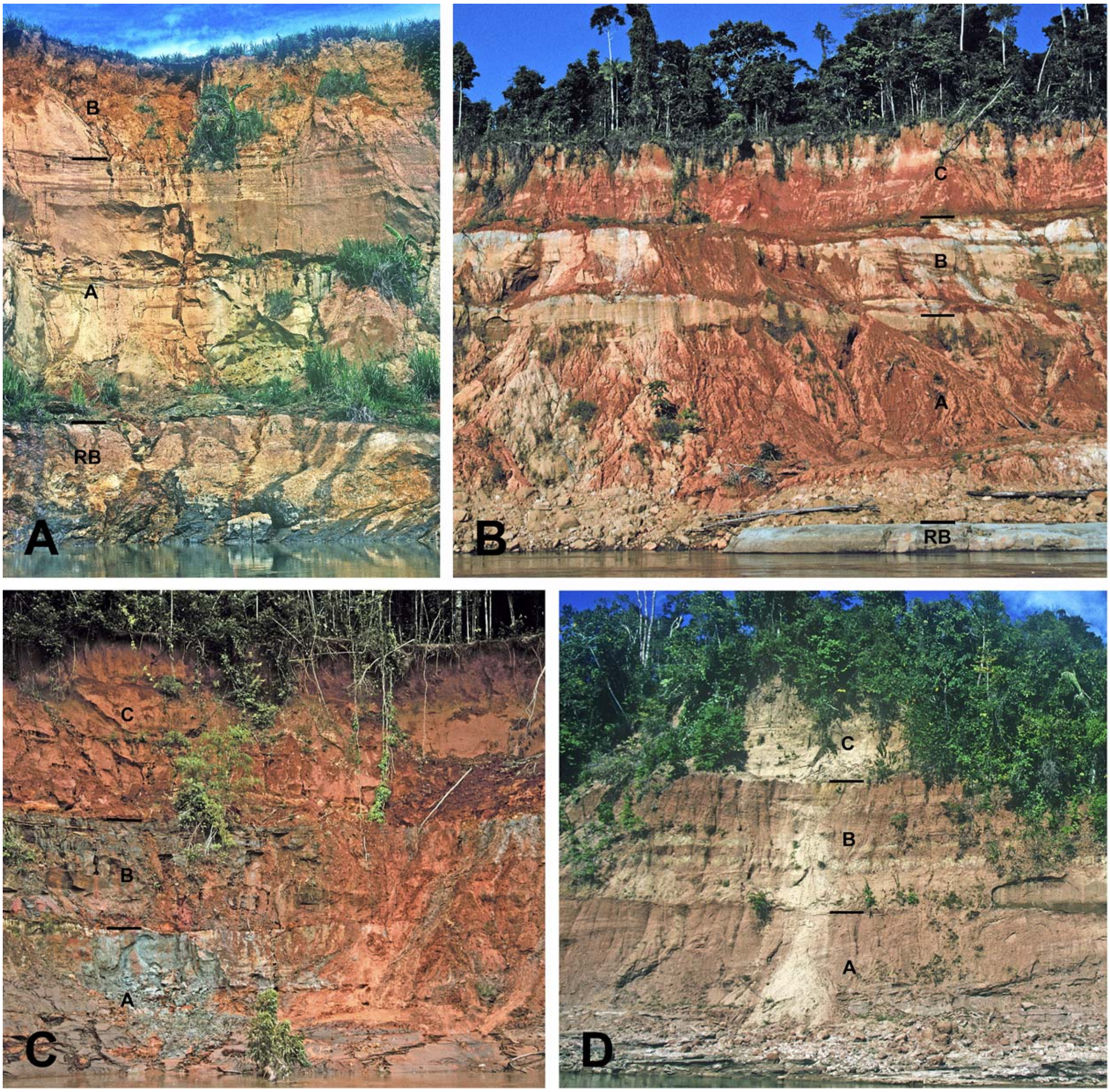


Fig. 9. The Madre de Dios Formation comprises three members, which are often clearly visible in fresh outcrops, as seen in these four photographs. (A) Madre de Dios River, just upriver from Puerto Maldonado, Peru (69°11′21″W, 12°35′ 07″S); (B) Madre de Dios River, Cerro Colorado, Peru (70°06′25″W, 12°34′26″S); (C) Tambopata River, Peru, just downriver from mouth of Carama River (69°30′59″W, 12°54′24″S); and (D) Upper Purus River, Peru (71°20′47″W, 10°32′41″S). Horizontal bars indicate boundaries between members; RB = older Tertiary “red beds.” Member “C” and part of Member “B” of the Madre de Dios Formation are missing from the section shown in A, and the lowermost stratum comprises the Ipururo Formation (RB). In A and B, the Ucayali Unconformity is above the water line, whereas in C and D it occurs below the water line. In A, note the springs at the Ucayali Unconformity, which are indicted by dark bands across the exposed older Tertiary “red beds.” In D, note the inclined (right to left) bedding in Member “A,” whereas in Member “B” and Member “C” the bedding is horizontal.

3.2.1. Lithology

In their initial work on the Acre River in Peru, Campbell and Frailey (1984, 1985) recognized three distinct horizons of the Madre de Dios Formation, which they informally designated Member "A," Member "B," and Member "C," from bottom to top (Figs. 6 and 9). Earlier, Simpson and Paula Couto (1981) had divided the Madre de Dios Formation into two primary sequences along the upper Juruá River, with a basal conglomerate considered as a separate horizon. We interpret their "Pleistocene Phase 1" as correlating with Member "A" and their "Pleistocene Phase 2" to include both Member "B" and Member "C." Hovikoski et al. (2005) divided the Madre de Dios Formation in southeastern Peru into three horizons, although they place the contact between the horizons at slightly different positions within the stratigraphic column than we do.

The three members of the Madre de Dios Formation are normally distinguishable wherever a complete stratigraphic section is exposed (Fig. 9), but complete sections tend to be relatively far apart because of slumping and terracing during river downcutting, especially in larger rivers (Fig. 1). Usually, it is only the lowermost horizons, which are swept clean during periods of high water, or the uppermost horizons exposed at fresh slump scarps, that are clearly visible. In exposures whose faces have been open to the elements for a long period, debris wash can cover intraformational contacts and facies transitions that are readily seen in fresh exposures. The intraformational contacts might represent erosional surfaces or brief interludes of non-deposition, or they might represent points in time of dramatic shifts in the depositional environment within the basin. At this time, there is no clear explanation for the observed intraformational contacts, although the lack of paleosols suggests an absence of long-term, sub-aerial exposure. For stratigraphic profiles of representative sections at sites from west to east, from near the Andes to near the Brazilian Shield, across southern Amazonia, see Figs. 7 and 8.

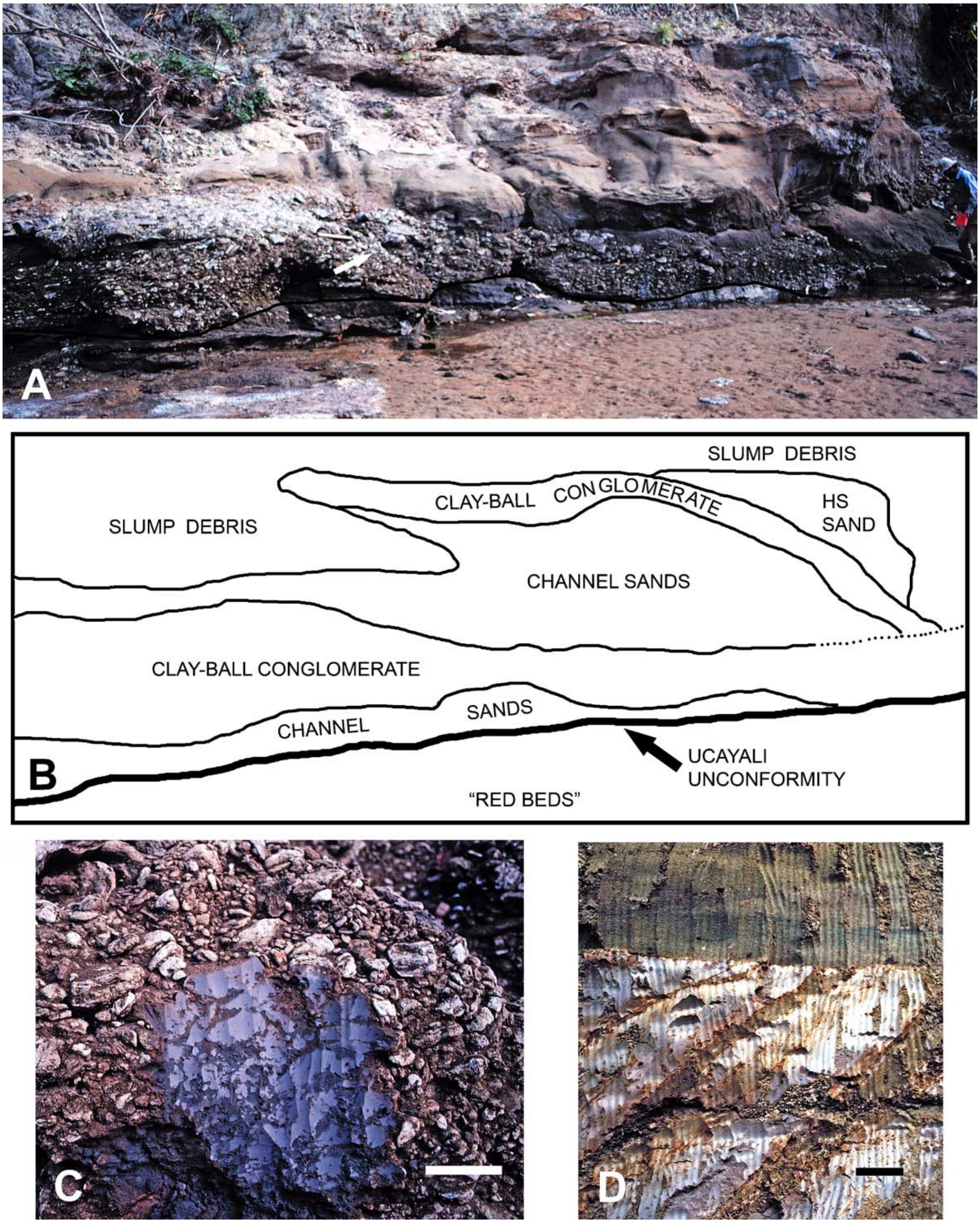
Member "A" of the Madre de Dios Formation is "… very complex sedimentologically and structurally, with considerable lateral and vertical facies changes" (Campbell and Frailey, 1984, 193). The basal portion of Member "A" is the most complex of the unit, with numerous different facies present ((Figs. 4, 5B, 7, 10 11 12). An important, regularly occurring basal facies is a clay-pebble, or clay-ball, conglomerate, commonly including vertebrate fossils and fossilized wood (Figs. 10C and 11). Fossiliferous conglomerates also occur slightly higher in the section in Member "A," but this is rare. The conglomerates have a coarse clast size that ranges from < 1 cm to > 1 m, with a background matrix that ranges from clayey silts to coarse sands. The conglomerates often have high iron content, and complex deposits of hematite (Fig. 12B), including sheet deposits, are common. The fossilized wood can either be silicified, carbonaceous, or carbonaceous undergoing silicification, and it can range in size from twigs to large tree trunks. The carbonaceous forms usually have significant sulfur content that is easily noted by smell when the fossil wood is broken open. Unlike fossil wood from Quaternary terrace deposits, when pieces of wood from the basal conglomerates are left to dry in the laboratory they gradually disintegrate completely. Local deposits of clay often preserve fossil leaves as well as wood.

Near the foot of the Andes, the basal conglomerates of the Madre de Dios Formation comprise a thick wedge of rock clasts that rapidly thins eastward. The clasts quickly decrease in size away from the foothills and are replaced by gravel and then coarse sand deposits that begin to include clay pebbles and clay balls. This transition can occur in only a few tens of kilometers. A classic example of this transition can be seen in the valley of the Inuya River, southeastern Peru (Fig. 1), which heads in the lowlands and flows westward for some distance nearly perpendicular to the trend of the Andean front range. Cross-bedded channel deposits of coarse sands are often found lateral to the conglomerates (Fig. 10A), as are less common deposits of silts and clays (Fig. 12A).

The Ucayali Unconformity is an undulating surface, and the basal deposits of Member "A," particularly the conglomerates, tend to fill the topographic lows and provide a more level plain upon which the upper sand deposits accumulated (Fig. 4D). In areas too high for the conglomerates to cover, sand deposits of the upper portion of Member "A" are often seen to follow the topography (Fig. 12C).

Campbell et al. (1985) named the basal conglomerates of the Madre de Dios Formation the Acre Conglomerate Member of that formation. However, more than a decade of additional work led us (Campbell et al., 2000) to recognize that the Acre Conglomerate is not so much a single horizontal stratum as it is a very large-scale collection of individual channel deposits (Figs. 4B, D, 10, 11) and multiple, leading edge deposits of aggrading series. The latter are perhaps best characterized as deltaic foreset beds developed in shallow-water environments (see Miall, 1984) (Fig. 4A, C).

The basal conglomerates of the Madre de Dios Formation have been recognized and described throughout lowland Amazonia independently by many authors. Galvis et al. (1979) and Khobzi et al. (1980) described the base of the Madre de Dios Formation in southeastern Colombia as a conglomerate with high iron content. Maia et al. (1977), in describing the Içá Formation of central Amazonia, stated that conglomerates occurred in the basal part of the section, generally in lenticular form, poorly consolidated, and diminishing in thickness and clast size toward the center of the basin. They described the conglomerates as comprising rounded pebbles of quartz, flintstone and other rocks, as well as clay-ball conglomerates with clasts ranging in



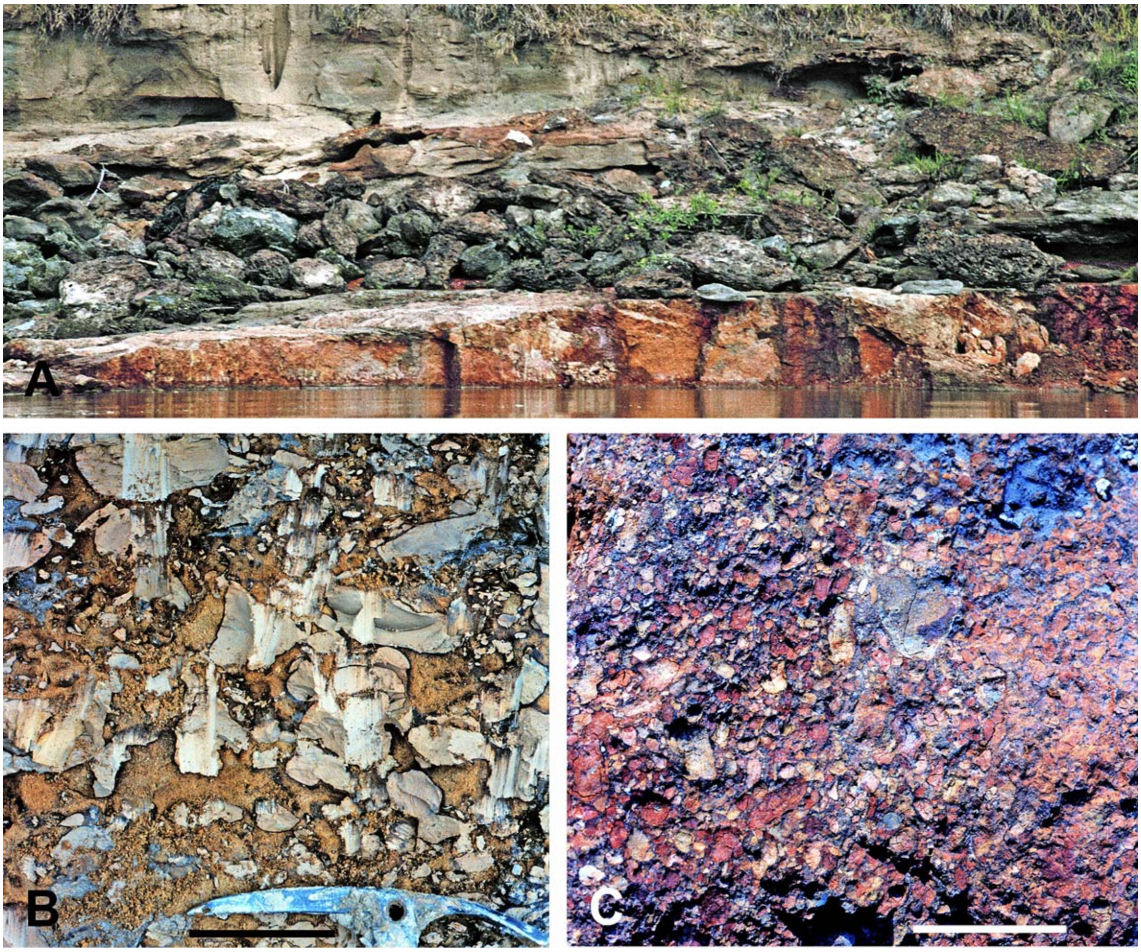


Fig. 11. Three examples of clay-ball conglomerates of Member “A” illustrate the variety of these deposits. (A) Channel deposit of clay-boulders overlying the Ucayali Unconformity, with the “red beds” exposed above the water line. Some of the clay-boulders at this site exceed 1 m diameter. The clay-boulders transition abruptly upward into channel sands. (Las Piedras River, Peru, 69°15′36″W, 12°27′39″S). (B) Poorly sorted and rather angular clay balls with a sand matrix (Madre de Dios River, Bolivia, 67°59′27″W, 11°50′48″S; scale bar = 10 cm). (C) An iron-cemented clay-pebble conglomerate (Madre de Dios River, Esperanza, Bolivia, 68°29′26″, 12°25′24″; scale bar = 5 cm).

size from millimeters to 40–60 cm. Rossetti et al. (2005) illustrate the base of the Içá Formation in central Amazonia as an iron cemented “mud pebble” (= clay-ball) conglomerate. In the Iquitos area of Peru, Räsänen et al. (1998) and Roddaz et al. (2005) describe and illustrate basal conglomerates of the Madre de Dios Formation (in our interpretation) overlying the weathered erosional surface of the Pebas beds. Simpson (1961, 623) noted a “basal conglomerate” along the upper Juruá River in Brazil, and Simpson and Paula Couto (1981, 16) described the basal part of what they considered to be Pleistocene deposits in the same river

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Fig. 10. Member “A” of the Madre de Dios Formation is very complex lithologically, with considerable vertical and lateral facies changes. This complexity is well illustrated at the Acre VI locality on the Acre River, Peru, which is the source for the abundant and diverse Acre VI local fauna (Frailey, 1986), as it appeared at the time of its discovery in 1979. (A, B) The river channel bottom, which is here mostly covered by modern sand (except in lower left), comprises older Tertiary “red beds.” Overlying the Ucayali Unconformity is a sand horizon, which is covered by a clay-ball conglomerate that extends across the face of the outcrop, being nearly twice as thick on the left as on the right. The conglomerate transitions upward abruptly to channel sands. A second horizon of clay-ball conglomerate covers the channel sands, and is steeply inclined (into the outcrop, left to right). Overlying this conglomerate is another horizon of horizontally bedded (HS) channel sands, which, at the far right, extend below the top of the clay-ball conglomerate on the left. (C) Close-up of clay-ball conglomerate seen at point indicated by arrow in A, illustrating uniformity in composition of clay balls and sand matrix. (D) Close-up of portion of outcrop just to right of that seen in A, showing inclined heterolithic stratification (thin bands of sand; thick bands of clay) covered by horizontally stratified sand. Scale bars = 10 cm.

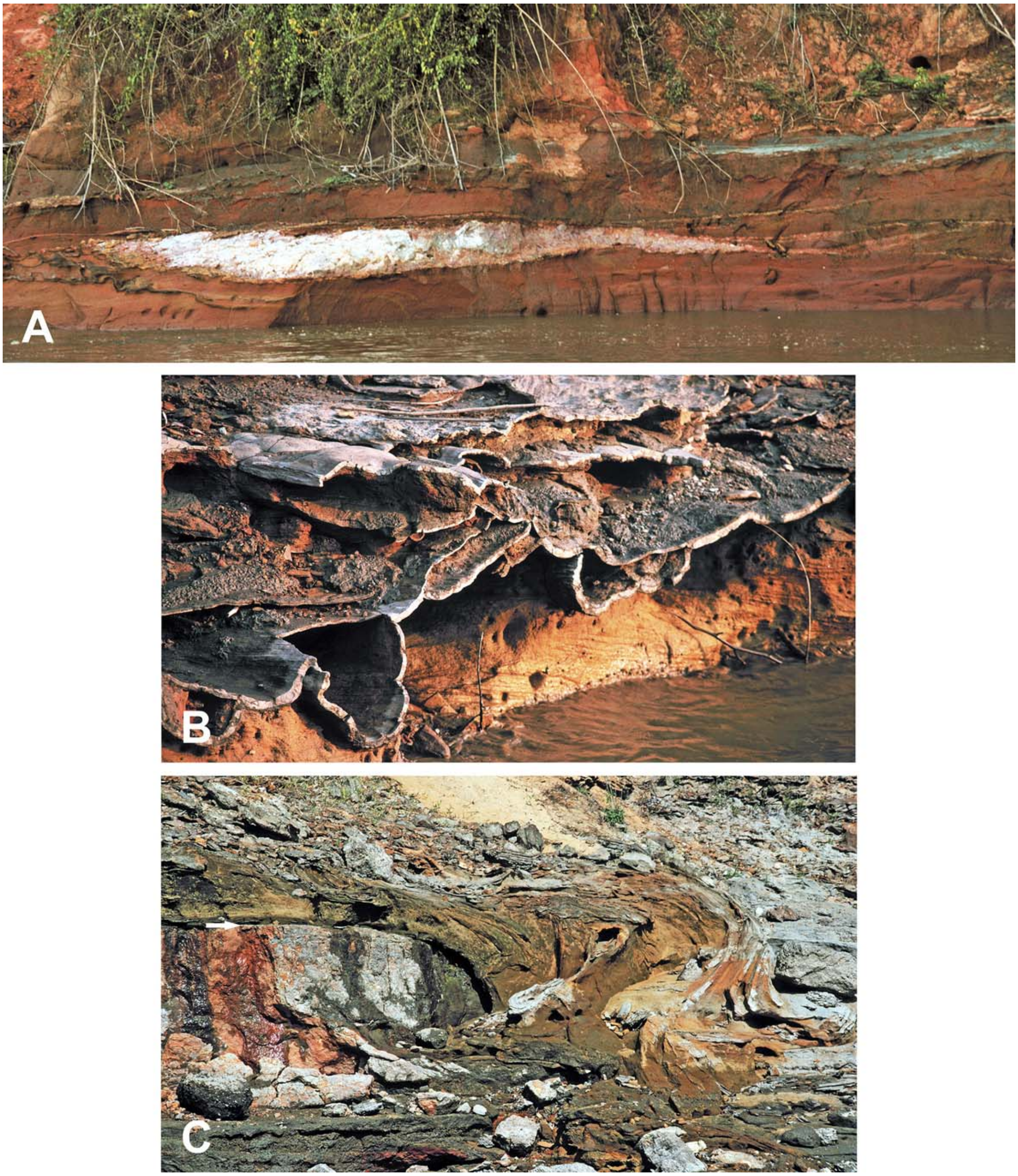

Fig. 12. Complex structures are common in Member “A” of the Madre de Dios Formation. (A) A paleochannel of white clay is surrounded by sand deposits (Madre de Dios River, near Laberintho, Peru, 69°35′24″W, 12°43′50″S). Note how the clay deposit trails off to the right, crossing under inclined (right to left) bedding of the sand deposits. (B) Very irregular deposits of hematite are common in Member “A,” especially in basal sands of the horizon (Madre de Dios River, Sena, Bolivia, 65°15′09″W, 11°28′22″S). (C) Where the undulating surface of the Ucayali peneplain was elevated above the depositional level of basal conglomerates, sand deposits of the upper portion of Member “A” can be found that conform to its irregular surface. (Madre de Dios River, near Puerto Maldonado, Peru, 69°10′18″W, 12°31′07″S). Note springs issuing forth at Ucayali Unconformity (arrow).

valley as comprising a “heavy conglomerate with rolled concretions, clay pebbles and plates” that also contained vertebrate fossils. Gingras et al. (2002) describe a “pebble lag” overlying a paleosol along the Acre River in Brazil, and Hovikoski et al. (2005) describe and illustrate “mud clasts” (= clay balls) overlying an erosional contact (= Ucayali Unconformity) in south-eastern Peru. Other authors, too many to continue listing, also describe the base of the Madre de Dios Formation in a similar fashion. Even some authors who disagree with the hypothesis of a basin-wide unconformity have described the basal conglomerates. For example, Santos and Silva (1976) describe abrupt contacts, or what they refer to as local unconformities, as being overlain by clay balls, wood fragments, and hematitic lens.

The only well-consolidated portions of the Madre de Dios Formation are those where the basal conglomerates, or laterally equivalent sands, are cemented by hematite (Fig. 5B). Their vertical extent is usually less than 1 m, or < 10 cm in the case of iron-cemented sand layers. Highly irregular hematite deposits of varying thickness are common in the sands of Member “A” (Fig. 12B). These deposits often follow bedding planes (Campbell et al., 1985), but they also often form tubular structures. These structures might have formed by deposition of hematite as a “rind” around fossil tree trunks, which has been observed.

Silva (1988) criticized the description for the basal horizon of the Madre de Dios Formation provided by Campbell and Frailey (1984) (see quote above), claiming that the extreme lateral variation cited for the basal conglomerates makes it impossible to locate and characterize a contact between the Madre de Dios Formation and the Solimões Formation because of a lack of lithologic continuity of the basal conglomerates. In fact, it is precisely the laterally continuous, complex lithostratigraphy of Member “A” of the Madre de Dios Formation, and particularly the basal portion of that member, that is one of its most defining characteristics and one that makes it very easy to distinguish this horizon from the relatively extreme monotony of the clays of the underlying “red beds,” which are devoid of comparable lithostratigraphy.

Accumulations of clay-pebble and clay-ball conglomerates are common in Amazonia today, where they occur alongside slump blocks that extend into river channels, on point bars, and as the leading edge, basal sediments of channel bed form deposits (e.g., dune fields). All of these modern conglomeratic deposits are particularly noticeable during low water periods. Analogs of these modern deposits are seen in the Madre de Dios Formation above the basal conglomeratic layer, but they differ from the basal layer by (1) not resting on a weathered, erosional surface; (2) not occupying a common stratigraphic position, and (3) by being deposits only a tiny fraction of the volume of the basal conglomerates.

The upper portion of Member “A” usually consists of massive sequences of cross-bedded and horizontally bedded, coarse sands. The basal conglomerates sometimes fine upward into the sands, and at other sites the contact between the upper coarse sand facies and the lower facies complex of Member “A” is abrupt. In sections where the conglomerates are absent, Member “A” can consist entirely of sand, which can be many meters thick (Fig. 7), and bedding can follow the undulating surface of the underlying “red beds” (Fig. 12C). Small clay and silt lens can be found within the thick sand sequences, and they become more common toward the top of Member “A” (Fig. 12A). In some sections, inclined clay beds are common within the sands (see Gingras et al., 2002) (Fig. 10D). Tree trunks are common within the sand deposits, and they can be found encased in hematite. Hovikoski et al. (2005) refer to the massive sand deposits of Member “A” as dune foreset beds. The modern sand deposits of large rivers in Amazonia, which can reach tens of meters in thickness, can be considered analogous to those of Member “A.” In an exception, along the lower Beni River, in northern Bolivia, far from the Andean front range, the sediments overlying the conglomerates are mostly clays (Campbell et al., 1985).

We place the contact between Member “A” and Member “B” at the top of the coarse sand sequence in southern Amazonia. This intraformational contact usually corresponds to the base of what is often a massive, meters thick, finely laminated or unlaminated clay horizon that we interpret to mark the base of Member “B” (Fig. 8). Hovikoski et al. (2005), in accordance with their interpretation that each of the three members represents a cyclic, fining upward sequence, place this contact at the top of the lowest massive clay horizon at Cerro Colorado in southeastern Peru.

The complex lithostratigraphy seen in Member “A” is considerably reduced in Member “B” and Member “C” of the Madre de Dios Formation. These two members are similar in many ways, but usually they can be easily separated visually in fresh outcrops (Fig. 9), and they appear to be distinct lithologically. Still, Campbell and Romero (1989) noted that it is possible that they represent distinct end members of a single depositional series. More detailed studies are needed to determine if there really are sufficient differences to warrant recognition of two individual members, although we follow that practice here.

The contact between these two members is often found at the top of a massive clay layer, and where the clay layer is absent the contact is often marked by paleochannels cut into clayey silts or silty sands at the top of Member “B.” The sediments of Member “B” tend to be better sorted than those of Member “C.” That is, there are more thick horizons within Member "B" that consist of well-sorted sands or pure clays, whereas Member "C" tends to have higher silt content. Both members often display distinct mini-horizons, or small-scale bedding (Fig. 13A) that record individual depositional events. Paleochannels, often with clay-pebble conglomerates usually of rather small clast size, are common throughout Member "B" (Fig. 13B) and Member "C." Near the Andes, gravels are found in some paleochannel deposits. There are also many layers, usually only a few cm thick, with high iron content, often associated with paleochannels, or abrupt changes

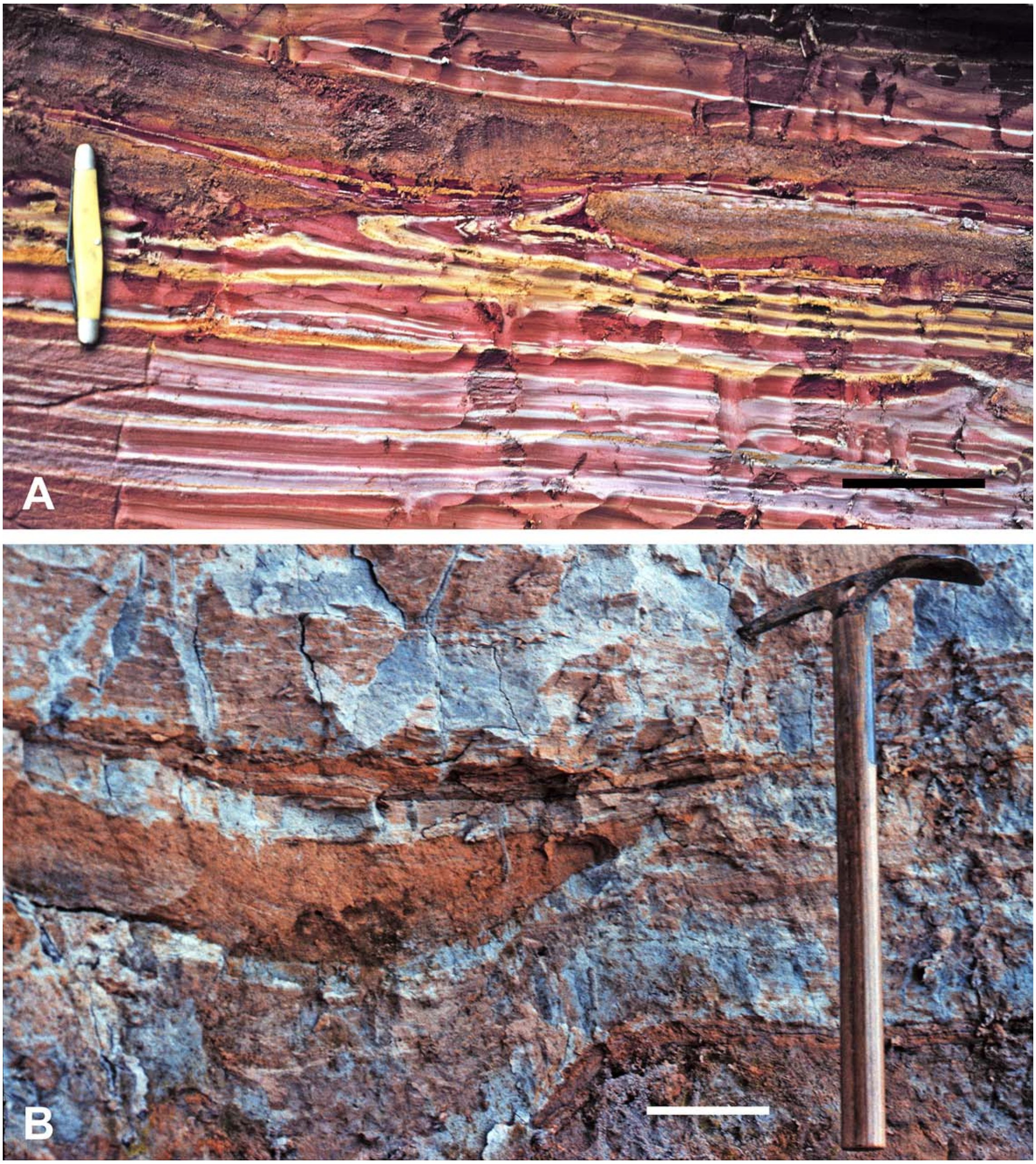

Fig. 13. (A) A close-up view of finely banded clay deposits of Member "C" of the Madre de Dios Formation showing occurrences of ripped-up and overturned bedding that record multiple flooding events, some of sufficiently high energy for sand transport at this locality. Plastic deformation of clay deposits can also be seen. View at road cut near Senador Guiomard, Acre State, Brazil (67°42′12″W; 10°8′4″S). Scale bar = 5 cm. (B) Blocky, silty clays are common in Member "B" of the Madre de Dios Formation, as are paleochannels of sand (shown here) and clay-ball conglomerates. Scale bar = 10 cm (Madre de Dios River, Villa Verde, Bolivia, 68°07′16″W, 12°01′06″S).

in lithology. Despite the fact that the overall sedimentary pattern of Member "B" and Member "C" is similar, the detailed sedimentary fabric through a vertical profile at each exposure is unique. Indeed, any two vertical profiles taken, say 10–15 m apart, in long outcrops such as Cerro Colorado on the Madre de Dios River are likely to show many lithologic differences.

A horizon unique to Member "C" that is often seen in southern and southwestern Amazonia is a hematitic concretionary zone, which can be up to 1 m or more thick. This zone is included within the soil profile at the top of the section and consists of small (usually < 1 cm diameter) concretions that are often grown together. Similar hematitic concretionary zones have not been noted elsewhere in the section profile, which suggests that they are a result of pedogenesis since the end of deposition of the Madre de Dios Formation.

All other authors have presented essentially the same basic description of the Madre de Dios Formation. That is, it is an extremely heterolithic formation, subdivisions of which, if recognized, are difficult to correlate between outcrops that are usually far apart. For example, Maia et al. (1977) summarized the Içá Formation as being a sedimentary sequence of primarily sands and, to a lesser degree, silts, clays, and conglomerates. Galvis et al. (1979) and Khobzi et al. (1980) described the formation in Colombia as very heterogeneous and variable, with clays of various colors and poorly consolidated sands. Gingras et al. (2002) and Hovikoski et al. (2005) illustrated the variability of this formation at sites in southwestern Amazonia, and Rossetti et al. (2005) illustrated complex sections in central Amazonia. The numerous volumes published by the Instituto Geológico, Minéro y Metalúrgico (INGEMMET) of Peru on the geology of the Peruvian Amazon are a wealth of information on the Madre de Dios Formation. (For a list of publications, see http://www.ingemmet.gob.pe/publicaciones/index.htm.) The heterogeneity of the sediments, the variety of facies present, and the structural fabric of the Madre de Dios Formation suggest an extremely complicated depositional environment.

In summary, the Madre de Dios Formation is characterized throughout lowland Amazonia by basal conglomerates of varying thicknesses that often rest upon paleosols capping older Tertiary formations. The basal conglomerates often contain vertebrate fossils, fossil wood, and layers of hematite. Thick horizons of well-sorted sands and thinner horizons of pure, but often finely laminated, clays are common in the formation. Paleochannels, often with a fill of clay-pebble or clay-ball conglomerates, are found throughout the section. At least in the southern half of the basin, the formation can be subdivided into three distinct members based on lithology and visible physical contacts, which might represent unconformities or abrupt transitions in the depositional environment. Soil profiles, other than the modern soil profile at the top of the section, appear absent from the formation. The modern soil profile contains a prominent hematitic concretion zone, at least in the southern part of the basin.

3.2.2. Age

The youngest deposits in western and central Amazonia have traditionally been considered Pliocene to Recent in age, with the postulated age being inferred by hypotheses of formation (e.g., Santos, 1974; Räsänen et al., 1987), incorrect interpretations of the stratigraphic significance of ^{14}C and thermoluminescence dates (e.g., Campbell and Frailey, 1984; Campbell and Romero, 1989; Räsänen et al., 1990; Dumont et al., 1991; Rossetti et al., 2005), or simply the youthful appearance of the beds (e.g., Koch, 1959a,b; Simpson and Paula Couto, 1981). However, such a young age for the deposits we refer to the Madre de Dios Formation was recognized by many as inconsistent with the upper Miocene [Chasicoan to Huayquerian SALMA (= South American Land Mammal Age)] age indicated by the fossil vertebrates derived from the basal conglomerates that comprise the lowest horizon of these strata. Rather than accepting the paleontological data as indicating the true age of the deposits, authors were overly influenced by other factors as noted above, and for many years most of the fossils in question were considered to be reworked from older deposits (e.g., Simpson and Paula Couto, 1981; Frailey, 1986).

Fortunately, two ^{40}Ar/^{39}Ar dates from localized ash deposits within the Madre de Dios Formation have delimited the age range of this formation in southwestern Amazonia (Campbell et al., 2001). Both of the ash deposits occur in the Departamento de Madre de Dios, southeastern Peru (Fig. 14). The oldest of these dates, 9.01 ± 0.28 Ma, is from the Cocama ash, which occurs ~4 m above the Ucayali Unconformity and the fossiliferous basal conglomeratic horizons of the Madre de Dios Formation in an outcrop on the Cocama River just upriver from its confluence with the Purus River. This ash date is consistent with, and would appear to corroborate, the late Miocene age assignment for the vertebrate fossils from the basal conglomerates of that formation. Given the stratigraphic position of the Cocama ash, an age of ~9.5–9.0 Ma is considered reasonable for the initiation of the deposition of the basal conglomerates and their contained late Miocene fossils in this region. We accept this ash date, and the paleontological data reviewed below, as corroboration of the hypothesis that deposition of the Madre de Dios Formation began in the late Miocene rather than the Plio-Pleistocene.

The second numerical age date came from the Piedras ash, which occurs in the highest of the three horizons of the Madre de Dios Formation, or Member "C," in an outcrop on the Las Piedras River about 221 km south of the Cocama ash. This date, 3.12 ±0.02 Ma, and the stratigraphic position of the ash led Campbell et al. (2001) to estimate that the end of deposition of the Madre de Dios Formation occurred at ~2.5 Ma, or in the middle late Pliocene. It was only following this date that widespread deposition within lowland Amazonia ceased, the modern Amazonian drainage system formed, and incision of the Madre de Dios Formation by the entrenching rivers began, as outlined below.

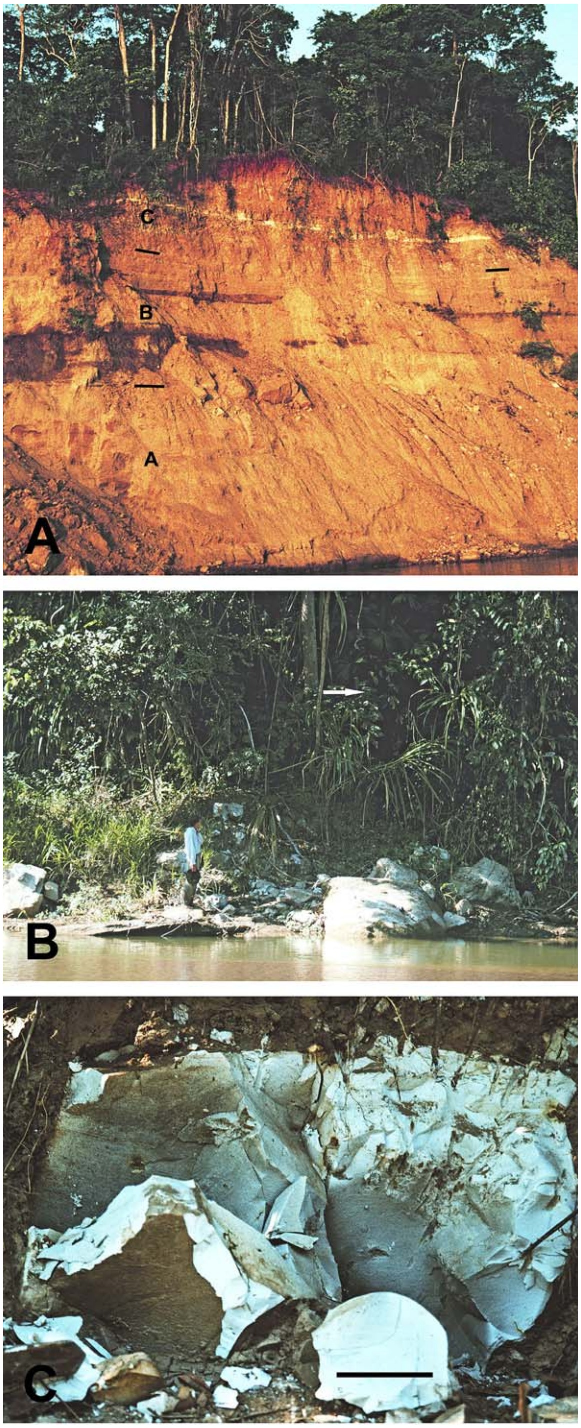

Fig. 14. Two localized ash deposits have provided a source for ^{40}A/^{39}Ar radiometric dates, the only numerical age dates available for deposits of the Amazon Basin. (A) The Piedras Ash, from an outcrop along the Las Piedras River (69°54′06.5″W; 12°03′11.5″S). The ash appears as the thin white band in Member "C" of the Madre de Dios Formation near the top of the outcrop. The boundaries between the members of the Madre de Dios Formation are indicated. (B) The Cocama Ash, from an outcrop along the Cocama River (71°10′22″W; 10°24′55″S), a tributary of the Purus River. The ash crops out at the level of the arrow and falls as slump blocks to the river bed below. (C) The Cocama Ash in close-up. This block appears just above and to the right of the person in B, and it displays the typical conchoidal fracture pattern of consolidated ash. Scale bar in C = 10 cm.

3.2.3. The paleontological data

To our knowledge, the basal conglomerates are the only horizons of the Madre de Dios Formation that consistently preserve vertebrate fossils, and we have recovered fossil vertebrates from outcrops of the basal conglomerates in every drainage system we have surveyed. We have never found Plio-Pleistocene fossil vertebrates in situ at any locality in the Madre de Dios Formation (= Içá Formation in Brazil), but we have encountered fossils of this age as float in river channels. Latrubesse et al. (1997) report a fossil locality in a road cut near the town of Sena Madereira in Acre State, Brazil, which is located in the upper levels of the Madre de Dios Formation (= Solimões Formation in their interpretation). This fauna has not been described, but one of us (CDF) who visited the site found the fossils to be fragmentary and with a preservation unlike that of Miocene fossils. Their stratigraphic position suggests a Pliocene age for these fossils, but no age indicative fossils were reported by Latrubesse et al. (1997) or elsewhere. Cozzuol (in press) comments on reports of a Brazilian late Pleistocene fauna from the "Jari-Paraná Formation" (recognized by him to be laterally equivalent to the Madre de Dios Formation of Peru and Bolivia). We presume the Pleistocene fossils are derived from channel or terrace deposits formed as the modern rivers incised into the Madre de Dios Formation because deposition of the Madre de Dios Formation ceased by at least ~2.5 Ma, as noted above.

All of the vertebrate taxa represented by fossils from the basal conglomerates that are also found in other regions of South America pertain to recognized late Miocene [Chasicoan SALMA, 12–9 Ma; or Huayquerian SALMA, 9–6 Ma (Marshall and Sempere, 1993)] species (Campbell et al., 2000). Although some vertebrate fossils from the basal conglomerates were initially described as being Pleistocene in age (Simpson and Paula Couto, 1981; Frailey, 1986), these instances reflected misinterpretations of the fossil data based on preliminary identifications of fossil taxa and early stratigraphic interpretations. The ranges of all identified species include the Huayquerian SALMA, but the ranges of some species extend back into the Chasicoan SALMA and those of others extend forward into the early Montehermosan SALMA (6.0–2.5 Ma; Marshall and Sempere, 1993). The strongest argument against the hypothesis that the basal conglomerates of the Madre de Dios Formation are diachronic, then, is the total absence from these beds, which are very commonly fossiliferous, of fossils definitively younger than the late Miocene.

We recognize, however, that certain factors might appear to lend weight to arguments that the paleontological data are not persuasive in documenting an isochronous Pan-Amazonian geologic event giving rise to the fossiliferous basal conglomerates of the Madre de Dios Formation. We highlight a few of these points here. First, too few fossil localities have been studied in sufficient detail to accurately define the late Miocene paleofauna of Amazonia. Other than the works of Paula Couto (1956, 1978, 1981, 1982, 1983a, b), Simpson and Paula Couto (1981), and Frailey (1986), there have been no studies of faunas as complete entities, and even the works cited omitted important taxonomic groups of the faunas studied. Most papers have reported on individual species or specific taxonomic groups (e.g., Mones and Toledo, 1989; Kay and Frailey, 1993; Campbell, 1996; Czaplewski, 1996; Gaffney et al., 1998; Negri and Ferigolo, 1999; Alvarenga and Guilherme, 2003).

Second, an age for the fossils from the basal conglomerates is commonly inferred by reference to the same or similar species in other parts of South America, for example, Argentina and Venezuela. Although the presence of species in common among these sites is suggestive of age equivalency, this cannot be taken for granted. This is because the ages of the most important of the latter deposits, for example, the “Mesopotamian” (Ituzaingo Formation) of Argentina (Cione et al., 2001) and the Urumaco Formation of Venezuela (Linares, 2004), are not defined by numerical age dates, so these long-distance correlations must remain suspect as far as dating is concerned. Further, these correlations have as a basic assumption a synchronicity in paleoecology in these disparate regions. It might well be that the paleoecology was similar in each of the localities at the time the fossils of species in common to the respective sites were deposited, but perhaps the comparable ecosystems were separated in time by millions of years, which is quite conceivable for deposits separated geographically by many thousands of kilometers and many tens of degrees of latitude. Until numerical age dates and more intervening fossil discoveries are available, age correlations among these regions at opposite ends of the continent remain unsecured. This is not to suggest that biostratigraphy is not a valid means of correlation, but only that caution must be exercised when data points are separated by extreme distances that range from tropical to temperate latitudes. In fact, we think the conglomerates of the Madre de Dios Formation and those of the Ituzaingo Formation are probably age equivalent, in part, and their deposition might very well have resulted from the same triggering geologic event.

Third, there is considerable confusion in the literature regarding the stratigraphic relationships of Amazonian fossil localities. This problem, of course, is inextricably tied to the recognition and acceptance of the Ucayali Unconformity as a stratigraphic marker. Certain sites that are clearly below the Ucayali Unconformity have been referred correctly to the Solimões Formation, or to the Ipururo Formation, the Peruvian equivalent of the upper part of the Solimões Formation. Examples of these include Acre I on the Acre River [LACM (= Natural History Museum of Los Angeles County locality) 4418; Frailey, 1986], which extends across the international border between Peru and Brazil, and Niteroi (LACM 5954) on the Acre River in Brazil (Mones and Toledo, 1989; Latrubesse et al., 1997), both sites at which we have had considerable excavation experience. However, the latter authors and others (e.g., Bergqvist et al., 1998; Cozzuol, in press) combined the differently aged paleofaunas by lumping the fossil localities found above the Ucayali Unconformity with those found below the unconformity. The former include such important localities as Acre VI (LACM 4611; Frailey, 1986), on the upper Acre River in Peru [inexplicably and erroneously referred to by the name “Patos” by Latrubesse et al., 1997 and Cozzuol, in press, presumably after a Brazilian creek 0.5 km away from the Peruvian site, but otherwise unrelated to it], and various sites described by Simpson and Paula Couto (1981) on the Upper Juruá River. Repetition of these errors (e.g., Alvarenga and Guilherme, 2003) has undoubtedly created confusion among readers not familiar with the actual lithostratigraphic context of these fossil localities, particularly when faunal lists are created that do not make a distinction between paleofaunas above and below the unconformity (e.g., Latrubesse et al., 1997; Cozzuol, in press). Cozzuol (in press) explicitly took the action of combining faunas above and below the Ucayali Unconformity when he argued against the validity of the Ucayali Unconformity as a key stratigraphic marker, an action that significantly reduced the value of his otherwise interesting comparative faunal analyses. Further confusing the issue, Alvarenga and Guilherme (2003, 614) even referred the Niteroi locality to the "Acre Conglomerate member of the Solimões Formation," apparently confusing that below-unconformity locality with the basal conglomeratic horizon of the Madre de Dios Formation named by Campbell et al. (1985). The Niteroi locality actually comprises beds of moderately consolidated clays that accumulated in a low energy depositional environment. This is quite the opposite of the high energy depositional environment in which the unconsolidated basal conglomerates of the Madre de Dios Formation above the Ucayali Unconformity were deposited.

In our experience, the nature of preservation of the fossils above and below the Ucayali Unconformity is fundamentally different. Below the unconformity the most fossiliferous localities, for example, Acre I and Niteroi on the Acre River, are bone beds with a matrix of clay with some silts and rarely fine sands. Within these bone beds occur numerous articulated or partially articulated specimens, a prime indicator that the fossils are in their original, or in situ, positions. Of course, isolated specimens or small aggregates of specimens also are found apart from bone beds in the "red beds." In contrast, articulated or partially disarticulated fossils are extremely rare in the high energy deposits comprising the basal conglomerates of the Madre de Dios Formation. The matrix of these conglomerates most often consists of clay pebbles and clay balls of various sizes, or sand, usually with abundant hematitic concretions (Figs. 4, 10, 11). At fossiliferous localities, the fossils are usually mixed throughout the conglomerate and can be considered to be one component of the matrix. Many of the fossils show wear that might be attributable to fluvial transport, or perhaps digestion by gastric acids of predators before burial, but many other specimens, such as dentigerous skulls and mandibles, extremely fragile, thin fossils, and many fossils with fine, delicate protuberances show no wear at all. It is possible that some of the fossils showing considerable wear were reworked from deposits below the unconformity, rather than being eroded by transport, but we are of the opinion that most, if not all, of the fossils in the conglomerates are in situ and actually represent animals that lived post-unconformity. Further, many of the most productive fossil localities in the basal conglomerates also preserve carbonaceous fossil wood, often as tree trunks or limbs of considerable size. Water-logged fossil wood does not usually float and these pieces of wood are often far in excess of the clast size of the enclosing matrix, which suggests that they were probably floated into position after entering the water and becoming part of the water-borne debris in the late Miocene, rather than having been eroded from older deposits and then transported as bed load.

Fourth, most of the Amazonian fossil species studied to date have been large bodied vertebrates, which generally tend to have a larger spatial and a longer temporal distribution than microvertebrates. Indeed, a number of taxa, such as the giant crocodilian *Purussaurus brasiliensis* Barbosa Rodrigues (1892) and the large rodent *Potamarchus murinus* Burmeister (1885) are found both above and below the Ucayali Unconformity (Campbell et al., 2000). This is consistent with an interpretation that the fossil deposits found above and below the Ucayali Unconformity in some areas are nearly the same age, but it does not imply that the unconformity does not exist. One possible explanation for some instances of close relationships between fossils found above and below the unconformity is that some fossil deposits below the unconformity might have formed in stream channels that were eroding, and hence incised into, older "red beds" shortly before deposition of the Madre de Dios Formation began. If this were the case, it would mean that these fossil deposits could date from the actual time of formation of the Ucayali Unconformity, that is, near the Chasicoan-Huayquerian SALMA boundary, but the surrounding "red beds" in which they are found would actually be much older. This possibility was suggested by Frailey (1986) for the large deposit at Acre I on the Acre River that produced the Acre I local fauna and by Campbell et al. (2000) for the preservation of the oldest proboscidean known for South America, the late Miocene *Amahuacatherium peruvium* Romero-Pittman (1996). A channel deposit that might illustrate this type of occurrence is illustrated in Fig. 5.

The presence of certain large vertebrates in deposits both above and below the unconformity does not serve to distinguish them in age, but it is important for purposes of correlation. For example, the consistent presence in the fossiliferous basal conglomerates of the Madre de Dios Formation of the late Miocene *Potamarchus murinus* and other vertebrates is significant because it is a strong argument against the hypothesis that these conglomerates were formed during the Plio-Pleistocene by "cut-and-fill" fluvial processes or laterally migrating river channels. To accept a Plio-Pleistocene age for basal conglomerates of the Madre de Dios Formation requires invoking reworking of late Miocene fossils from older "red beds" as an explanation for their presence in Plio-Pleistocene deposits. To accept this hypothesis, however, also requires ignoring the absence of Plio-Pleistocene fossil vertebrates from the basal conglomerates. This is, in our opinion, an unsatisfactory explanation.

However, the micromammals are of even greater significance for the purpose of correlating the basal conglomerates of the Madre de Dios Formation. Nearly four hundred small rodents, which are currently being described, have been collected at various localities in the basal conglomerates, and representatives of different species in common to several of the localities have been identified. For example, one small porcupine (Fig. 15A–C), family Erethizontidae, occurs in localities in three river systems: Acre VI (LACM 4611), on the upper Acre River; RJ-95-2 (LACM 6288), on the Upper Juruá River; and RP-94-2 (LACM 6218), on the Upper Purus River (Fig. 1). A second, smaller erethizontid (Fig. 15D–E) is found at the Acre VI and RJ-95-2 localities. The teeth of these two species are similar to each other, and of known taxa they are most like those of an erethizontid from the Miocene La Venta fauna of the Magdalena Valley of Colombia (Walton, 1997).

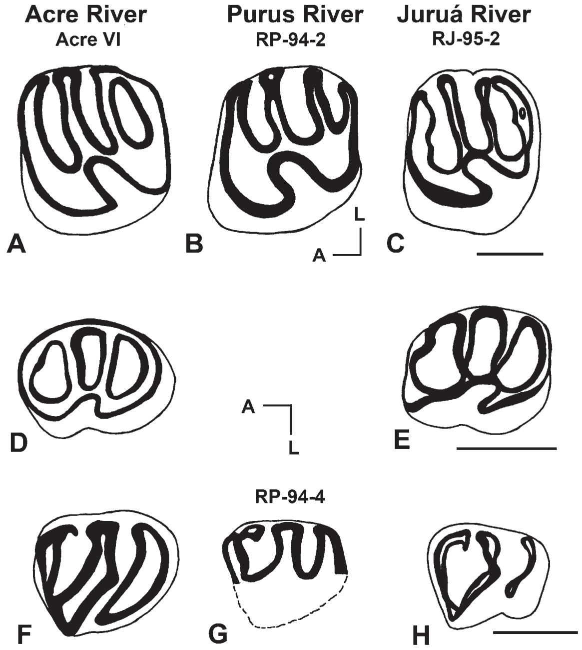

Fig. 15. Cheek teeth of three new, undescribed late Miocene rodents from the basal conglomerates of the Madre de Dios Formation. The four localities represent three separate drainage basins: Acre VI, Acre River, Peru; RP-94-2 and RP-94-4, Upper Purus River, Peru; RJ-95-2, Upper Juruá River, Brazil (Fig. 1). (A–C) A large species of erethizontid, upper teeth; (D–E) a small species of erethizontid, lower teeth; (F) a species of echimyid, lower tooth; (G–H) lower molars of the same species as in F, or of a closely related species. Other specimens exist for these species. See text for significance of these microvertebrates. For directional indicators, A = anterior, L = labial. Scale bar = 1 mm; each group is scaled differently.

A species of small dasyproctid, family Agoutidae, has been identified from both the Acre VI locality (Frailey, 1986:13) and Inuya-03-III (LACM 7522) locality, on the Inuya River in Peru. Dental features of the lower teeth are most like those of "*Neoreomys*" *huilensis* Fields (1957) of La Venta, Colombia, as seen in the expanded sample of this species that was studied by Walton (1997).

A small echimyid (Fig. 15G–H), probably a species of *Acarechimys* Patterson (in J.L. Kraglievich, 1965) (family Echimyidae) is found in deposits along both the Upper Juruá River and the Upper Purus River in Peru. A closely related species, if not, in fact, the same species, is present in the Acre VI local fauna (Fig. 15F). The characteristic trilophodont lower molars permit a quick identification of these specimens. A distinctive feature of these two(?) species is a remnant of the metaconid/metalophid that appears as a short hook on the labial terminus of the anterolophid. An apparently atavistic feature, the size of this conid and abbreviated lophid are variable, but nonetheless they are present in the majority of specimens identified as belonging to these two(?) species.

The significance of these microvertebrates lies in the fact that vertebrates of this size range tend to evolve at a much faster rate than mega-vertebrates because they are more influenced by local environmental conditions that can drive speciation events. Thus, the life span of any given microvertebrate species is relatively short compared to those of mega-vertebrate species. If conditions are suitable, microvertebrates can have a wide aerial and elevational distribution, but they tend to be more restricted to a given ecotone. So, there is not much significance in the fact that any given species of microrodents can be found within different sub-basins of Amazonia, even if these sub-basins were separated by low-elevation arches as some suggest. Their importance lies in the fact that the presence of any given species of microvertebrate in the basal conglomerates of disparate regions would be nearly impossible if those basal conglomerates were deposited at different times. The widespread occurrence of these species of microrodents is a powerful argument against both the "shifting depocenter" hypothesis of Räsänen et al. (1987, 1990, 1992) and the local "cut-and-fill" hypothesis of Santos and Silva (1976), Cozzuol and Silva (2003), and Cozzuol (in press), wherein the basal conglomerates are considered to be localized and of widely differing ages.

The similarities of the new, small species of rodents mentioned above to those from La Venta (Walton, 1997) might be a consequence of sample size bias in that most of these species represent the smallest members of their families known for this period of the Miocene. That is, they are recovered only by screen-washing techniques used in these areas, but not in most others. Another possible factor is the geographic proximity between the Magdalena Valley of Colombia and the western Amazon Basin, and the fact that in the late middle Miocene the La Venta fauna could be considered an extension of the Amazonian fauna (Hoorn et al., 1995; Lundberg et al., 1998). Although the La Venta fauna is older (13.5–11.8 Ma; middle Miocene) than that from the basal conglomerates of the Madre de Dios Formation (~9.5–9.0 Ma), a greater faunal similarity, at least among the micromammals, exists between these two tropical regions than between the latter and the late Miocene, temperate faunas of Argentina.

There is also good negative evidence against a diachronous origin of the basal conglomerates of the Madre de Dios Formation. The majority of the nearly four hundred small rodent teeth that were collected from the basal conglomerates come from one site, but numerous specimens have been found in all river basins in which we have collected. Notably, there is a complete absence of cricetid rodent teeth in this large sample. Cricetid rodents (family Cricetidae) are extremely speciose, with hundreds of species in South America. The absence of cricetid rodents in this large sample of micromammals from the Madre de Dios Formation strongly suggests that these deposits predate the arrival of this family of rodents in South America, an event that has been variously placed to "sometime in the Miocene" (Reig, 1980, 1986), to between 7.0 and 5.0 Ma (Marshall, 1979), to the base of the Montehermosan SALMA (~6 Ma) (Marshall and Cifelli, 1990), and to 2.5 Ma (e.g., Marshall and Sempere, 1993; Webb and Rancy, 1996). The oldest South American cricetids actually known are from Pliocene deposits (Simpson, 1980; Marshall and Sempere, 1993; Vrba, 1993). If any of the basal conglomerates of the Madre de Dios Formation bearing rodent teeth were deposited in the Plio-Pleistocene, as proposed by some, then one would expect to find cricetid teeth in the extensive samples of microvertebrates from these deposits. We consider their absence significant and indicative of an age for the basal conglomerates that predates the arrival of cricetids in South America.

Thus, the hypothesis of an isochronous origin for the basal conglomerates of the Madre de Dios Formation is not only supported by the fact that all of the fossils present in these deposits pertain to the late Miocene (Chasicoan or Huayquerian SALMAs), but also by the fact that the taxa found in the conglomerates, both mega-vertebrates and microvertebrates, are often in common among widely dispersed sites, sites that some authors would place into distinct sub-basins with unique depositional histories. Were the latter true, unique paleofaunas of different ages would be expected in the basal conglomerates of different sub-basins. In fact, acceptance of the "cut-and-fill" fluvial hypothesis for formation of the basal conglomerates would lead to unique, localized paleofaunas of different ages within the basal conglomerates of the same sub-basin. Instead, what is found is just one late Miocene paleofauna in common to all sites.

3.2.4. *Environments of deposition*

A high energy, seasonal, and relatively shallow water environment was required for the deposition of the basal conglomerates of Member "A," as indicated by the following features. The size of the clasts [up to > 1 m in some instances in southeastern Peru (pers. obs.) (Fig. 11A); 40–60 cm in central Amazonia (Maia et al., 1977)] dictates a powerful flow of water. The presence of extensive paleochannel deposits of clay balls requires a source clay deposit from which they could be derived, but within a high energy fluvial environment clay deposits can only form during times when the energy level is reduced to minimal levels and clay particles can settle out in the calm waters of isolated pools or abandoned channels. This occurs during dry seasons. Upon renewed flooding, the clays can be ripped up and become bed load clasts as clay balls or clay pebbles. In situ basal clay deposits occur in Member "A" (Fig. 12A) but they are localized, and when they occur they often contain fossil plants. This is suggestive of temporary ponds or abandoned channels, or the accumulation of floating plant material in backwash channels. The lack of large scale, undisturbed clay deposits in Member "A," in contrast to their abundance in the two younger members, suggests an absence of long-standing, deep water.

A shallow water environment is indicated by the fact that most facies are of limited lateral and vertical extent. Where multiple leading edge, or foreset type, deposits of an aggrading series are exposed, their height is indicative of shallow water (Fig. 4A, C). Although high energy deposits can certainly occur in deep water channels, they would normally be on a scale much larger than what is observed in the basal conglomerates. Thus, we view the basal conglomerates as different types of aggradational basin fill deposits that moved as a rapidly passing front away from the Andes over the Ucayali Peneplain, probably carried by large scale, high energy, braided rivers with marked seasonality. Deposits of this depositional phase would have leveled the landscape, filling first the topographic lows formed during formation of the Ucayali Peneplain, but not necessarily covering topographic highs. This initial depositional phase of Member "A" was probably of relatively short duration.

The second depositional phase formed the upper sand facies of Member "A." These fine- to coarse-grained, cross-bedded or horizontally bedded sands are often several meters thick (Figs. 7–9). Channel deposits are commonly encountered in these sands, and inclined beds of clay alternating with beds of sand are occasionally seen (e.g., Gingras et al., 2002) (Fig. 10D). The low clay content and high size sorting of the sand at any given locality is indicative of extensive transport and reworking. The water depth is not readily interpretable at this time, but based on the length of some of the inclined beds it can be estimated at several to a few tens of meters (see, e.g., Gingras et al., 2002). As mentioned earlier, analogs of these sand deposits are common in large river systems in Amazonia today, and they can be examined when exposed during the dry season. These modern analogs can include deep, localized mud deposits, especially at the downstream and near shore sides of large sand bars, and these instances are very similar to the inclined heterolithic stratification described by Gingras et al. (2002). We interpret the transition from the basal conglomerates to the sands as indicating a reduction in flow velocity of the transporting rivers, but the lack of massive clay beds is still indicative of the absence of widespread deep, or still, water. The presence of the alternating, inclined horizons of clay and sand (inclined heterolithic stratification), the paleochannels deposits, and occasional horizontal clay deposits suggests seasonality, much as is seen in Amazonia today.

The sedimentary fabric and lithology of Member "B" and Member "C" are similar to each other. Massive beds of meters-thick clay indicate a shift in the depositional environment to one in which large bodies of deep, standing water became prominent. The presence of numerous paleochannels, alternating horizons of clay and sand, both inclined and horizontal, and the added presence of significant quantities of silt, especially toward the top of the section, indicate a highly fluctuating, but relatively low-energy, environment. Still, bursts of high-energy water flow, presumably resulting from flood events, are indicated by ripped up bedding planes (Fig. 13A) and clay-ball conglomerates. The fluvial (cross-bedded sands, channel deposits), fluviolacustrine (silty sands, clayey silts), and lacustrine (thick beds of clay) deposits that comprise Member "B" and Member "C" are all typical of sediments deposited in deltaic environments (Bates, 1953; Coleman, 1981; Tye and Coleman, 1989a, b), as pointed out by Frailey et al. (1988). The coarsening-upward sequences seen in sections in southwestern Amazonia, another feature of deltaic deposition, were pointed out by Räsänen et al. (1995), although they attributed a tidal origin to them. Modern analogs of these deltaic deposits can be seen in the floodplains of large rivers throughout Amazonia where seasonal lakes exist, and they are particularly noticeable in ria lakes.

Important indicators of the environments of deposition of the uppermost deposits of Member "C" are found in the uneroded parts of Amazonia where the *planalto* preserves the geomorphic features in place at the time deposition within the basin ceased. The most obvious evidence is the basin-wide occurrence of paleodeltas visible in aerial photos and radar and satellite imagery (Schobbenhaus et al., 1984; Campbell et al., 1989; Campbell, 1990) (Fig. 16). Deltas are geomorphic features limited to formation in standing bodies of water, and their form and structure cannot be confused with any other geomorphic feature. The Amazonian paleodeltas stand out today for several reasons. They are of higher elevation, although usually of only a few meters, relative to the paleolake beds into which they were deposited, and pedogenic differences between the tops of the paleodeltas and the paleolake beds create different physical environments that support different types of vegetation (Figs. 16 and 17). The areas covered by paleolake beds, particularly when isolated from modern rivers, often flood and remain flooded for portions of the year because they are lower in elevation than the paleodeltas that surround them, they lack external drainage, and their predominantly clay soils prevent rapid ground absorption of surface water. Long-duration flooding also contributes to vegetation differences between the paleolake beds and the more elevated paleodeltaic deposits because many plants cannot survive flooded conditions for long periods.

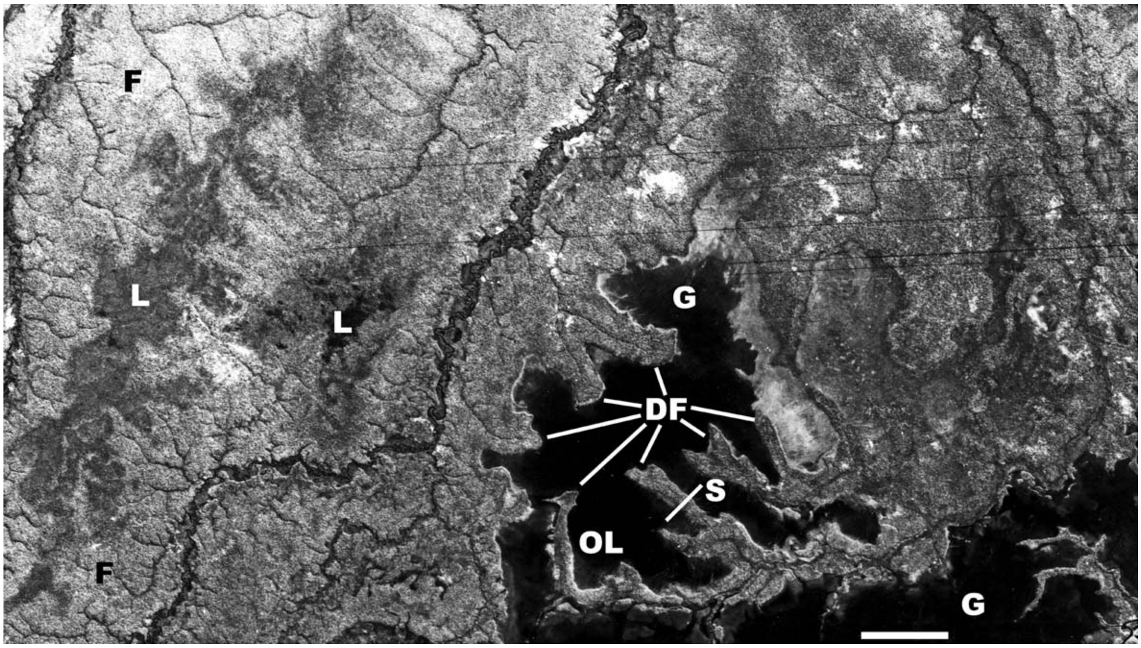

Fig. 16. Representative view of paleodeltas that comprise portions of the *planalto* of lowland Amazonia. Light gray areas denote tall canopy forests (F) on highest elevation terrain, whereas darkest areas denote seasonally inundated grasslands (G) on lowest elevation terrain. Intervening shades of gray represent varying degrees of vegetation cover. Paleolakes completely surrounded by infilling delta fingers are identified as L, whereas OL denotes an area that was a large, open lake at the time of establishment of the modern drainage system. Various types and sizes of delta fingers infilling OL are identified as DF. Note that deltaic sediments are infilling the paleolakes from all sides, not just from the west. A representative cross-section through a delta finger along line S is illustrated in Fig. 17. Note high angle, crevasse splay branching of tributaries of large channels, which is in contrast to the lower angle branching of distributary channels of delta fingers. Channels visible in delta fingers are far larger than that expected given the area being drained, resulting in underfit streams. Area illustrated lies in northern Bolivia, centered near 12°33′S, 67°36′W. Photograph taken from satellite imagery. Scale bar = 5 km.

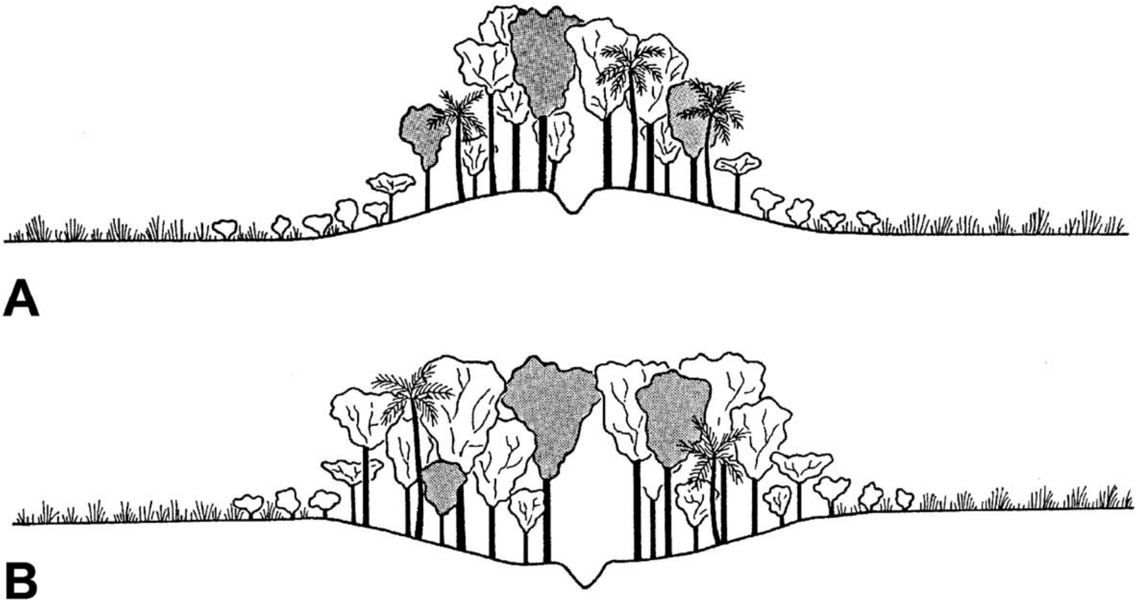

Fig. 17. (A) Diagrammatic cross-section through a typical paleodelta finger with an elevated canopy forest in lowland Amazonia, as illustrated in Fig. 16 (S), in contrast to (B) a diagrammatic cross-section through a stream channel eroding a flat plain and its associated riparian forest.

Secondly, many of the streams and rivers of lowland Amazonia are underfit, i.e., the channels within which modern streams flow are much larger than warranted by the amount of water actually carried in the channel (Dury, 1964; Campbell, 1990). This is to be expected given that the amount of water flowing outward to create a distributary channel within a paleolake system would be significantly greater than that currently being drained from the immediate area that was formerly covered by a given lobe of a paleodelta.

A third line of evidence comes from the nature of modern Amazonian stream and river courses. As has been noted by various authors (Sternberg, 1950; Howard, 1965; illustrated as well in Almeida, 1974), tributaries entering larger rivers do so predominately at an angle of 90°. This is also often true for even the smallest of tributaries in lowland Amazonia. This has been attributed primarily to subsurface tectonic lineaments and neotectonics (e.g., Sternberg, 1950; Bemerguy and Costa, 1991). However, the unconsolidated nature of the Madre de Dios Formation makes it unlikely that subsurface tectonic lineaments could manifest themselves at the surface in a way that would affect stream drainage patterns in such fine detail. Further, bedding displacement resulting from faulting is rarely seen in the Madre de Dios Formation, and, when present, displacement can be attributed to large-scale slump block movement. The high angle branching within Amazonian drainage systems is best explained as a function of crevasse splaying from deltaic distributary channels (Bates, 1953; Coleman, 1981).

Analogs of the environments of deposition within which accumulated the sediments of the Madre de Dios Formation, including deltaic deposition, can be found throughout the modern Amazon River system. The only exceptional depositional environment that might not occur today was that which prevailed at the time of deposition of the basal conglomerates of Member "A." It is not necessary to invoke any explanation beyond normal, continental fluvial, fluviolacustrine, or lacustrine environments of deposition to explain the sedimentogenesis of the Madre de Dios Formation.

3.2.5. Hypotheses of origin

Many hypotheses have been presented to explain the origin, or environment(s) of deposition, of the Madre de Dios Formation (sensu lato). We review some of the prior and more current of the hypotheses of origin, and in the following section we present a refined model for the depositional environment(s) of the Madre de Dios Formation.

Regardless of the age or formational assignment of any given author(s) for the deposits we refer to as the Madre de Dios Formation, the consensus is that they comprise primarily fluvial, fluviolacustrine (including deltaic), or lacustrine continental deposits. For example, Kummel (1948, 1260) described the deposits of the Madre de Dios Formation as "flat-lying alluvial deposits." Almeida (1974, 183) noted the widespread distribution of fluvial deposits typical of a "plain of accumulation" covering the surface of Amazonia, and suggested that the clay beds of these deposits were deposited in a low energy environment, "probably lacustrine and of great extension." Santos and Silva (1976) regarded the "upper zone" of the Solimões Formation (i.e., the Içá Formation) to represent part of a fluvial cycle characteristic of a floodplain. Maia et al. (1977) described the Içá Formation of central Amazonia as being deposited in a typical continental, fluvial environment, possibly a fluvial system grossly similar to that of today. Writing of the dominant sands comprising the formation in Colombia, Khobzi et al. (1980) stated that they indicated an environment of deposition that was, more than anything, fluvial. After obtaining the first ^{14}C dates on samples of fossil wood from Amazonia, which were consistent with the then prevailing interpretation that the age of the deposits was Pleistocene (e.g., ONERN, 1972, 1977; Simpson and Paula Couto, 1981), Campbell and Frailey (1984) postulated that massive floods caused by end-Pleistocene melting of the Andean glaciers scoured the Amazonian plains and deposited the basal conglomerates of the Madre de Dios Formation. They suggested that seasonal flooding was probably the cause for the heterolithic deposition in the upper part of the stratigraphic column.

Further field work by those authors, and the discovery that (1) there were massive clay deposits that could only be deposited in deep, calm water, and (2) there was much evidence of deltaic deposition, led Campbell et al. (1985), Frailey et al. (1988), and Campbell (1990) to modify the proposal of Campbell and Frailey (1984) to include deposition within a mega-lake, Lago Amazonas. In the absence of evidence to the contrary, they continued to regard the deposits as Pleistocene. Indeed, late Pleistocene ages for Amazonian deposits comparable to those first reported by Campbell and Frailey (1984) were also reported by Dumont et al. (1988), Dumont (1989), Räsänen et al. (1990, 1992), and, most recently, by Rossetti et al. (2005).

Räsänen et al. (1987, 1990, 1992) proposed an alternative model, arguing instead that the young deposits overlying and separated from older Tertiary deposits by an unconformity were the result of long term lateral shifting of depocenters, or aggrading fluvial systems in flood basins or restricted flood plains. Räsänen et al. (1987, 1400) stated that "…, we interpret the uppermost fluvial beds as having been formed when laterally migrating Pleistocene–Holocene rivers, similar to present ones, have eroded the Tertiary sediments and aggraded their channel and flood plain deposits." Räsänen et al. (1990, 320) stated that "Little attention has been paid to the possible diachronism of the [topmost sedimentary] deposits..." of lowland Amazonia, and they concluded that these beds are considerably more heterogeneous in origin and age than previously assumed. Räsänen et al. (1992) suggested that the basal conglomerates of the Madre de Dios Formation formed during major periods of incision, which they interpreted to have occurred during interglacials.

Crucial to their hypothesis was the suggestion by Räsänen et al. (1987, 1990), followed by others (e.g., Dumont et al., 1991), that in the Plio/Pleistocene the Amazon Basin was divided into several independent regional sub-basins by structural arches (e.g., the Iquitos Arch, the Fitzcarrald Arch, etc.). But, as Campbell et al. (2000) pointed out, and Rossetti et al. (2005) agreed, although there might be structural highs and sub-basins in the basement rocks in the regions indicated, there are no data to support the hypothesis that these structural highs, or arches, had any effect on late Neogene deposition in lowland Amazonia. The several papers cited by Lundberg et al. (1998) as sources for data documenting the influence of the structural arches are all secondary sources or theoretical papers lacking primary data on the purported arches. Indeed, the only detailed studies of subsurface sections across these arches known to us (e.g., Miura, 1972; Caputo, 1991) demonstrate quite clearly that these structural arches, where they exist, are well below the surface and did not affect late Neogene/Quaternary deposition within lowland Amazonia. For details on ancient arches and basins in South America, see Jacques (2003a,b). In the absence of data to the contrary, we regard the postulated influence of these arches and sub-basins on late Neogene/Pleistocene sedimentation in Amazonia as non-existent.

Later, Räsänen et al. (1995) interpreted the presence of coarsening-upward sediments within the Madre de Dios Formation (Solimões Formation, their usage) as tidal deposits and cited them, along with the presence of fossil sharks in the basal conglomerates in southeastern Peru (Acre VI local fauna), as evidence for a late Miocene interior seaway reaching southwestern Amazonia from the south. Hoorn (1996) and Paxton et al. (1996) argued that the data of Räsänen et al. (1995) documented fluvial deposits, not tidal deposits, but fluvial deposits outside of deltas do not exhibit coarsening-upward sequences. They are, however, a classic feature of deltaic deposition (Bates, 1953; Coleman, 1981). In fact, fining-upward fluvial deposits are found in the Madre de Dios Formation lateral to coarsening-upward deposits, indicating a combination of fluvial and deltaic deposition. Campbell et al. (2000) pointed out that the fossil sharks belonged to the genus *Carcharhinus*, a group well known in the Amazonian river systems of today (Thorson, 1972). The fossil sharks were also found in association with amphibians and strictly freshwater mollusks, which could not have lived in even a partially saline environment.

To provide an alternative explanation for the "tidal deposits" observed by Räsänen et al. (1995), Marshall and Lundberg (1996) and Lundberg et al. (1998) proposed that late Neogene foreland basin depression east of the Andes created a deep trench parallel to the Andes that was "at least at times and in places, tens of meters below sea level (Marshall and Lundberg, 1996, 124)" and which filled with marine waters from the north. The foreland depression was suggested to have lasted from ~11 Ma to 5 Ma. There are, however, no data to support a tectosedimentary event as outlined by these authors. And if foreland basin depression had occurred as proposed in these models, it would not be possible to observe the Ucayali Unconformity throughout western Amazonia in essentially the same position relative to modern river channels, and especially not in areas close to the Andean front range. Were this model of foreland depression valid, one would expect the unconformity to be deeply buried in the hypothetical depressed areas, rather than being exposed in the sides of river channels, as it is. The only exception that might actually be a modern foreland depression appears to be the Ucamara depression in the Marañón River valley of Peru (Dumont et al., 1991; Dumont and Garcia, 1991).

Gingras et al. (2002) and Hovikoski et al. (2005) revived the model of marine or brackish-water deposition in western Amazonia. They based their conclusions on what they interpreted to be bioturbated inclined stratification, cyclic rhythmites displaying semidiurnal cyclicity, and an array of ichnological features that they claimed originated from marine organisms. However, all of the sedimentary features they describe as representing tidal deposits (e.g., soft sediment deformation, inclined stratification) are just as easily or more readily interpreted as indicating deltaic or fluvial deposits, although with a seasonal rather than daily cyclicity. Among the many complex sedimentary features seen in the Madre de Dios Formation (Figs. 10–13), there are none that are best explained as tidal deposits. Although the ichnological features they described can provide significant information about paleoenvironmental conditions and paleoecology, given the total absence of any fossil of any strictly marine or estuarine organism whatsoever in the Madre de Dios Formation, the attribution of the ichnological features to marine organisms is questionable. Further, it is not possible to differentiate between late Neogene marine invertebrate traces and the traces of late Neogene freshwater Amazonian invertebrates because the latter are virtually unknown.

Although both Gingras et al. (2002) and Hovikoski et al. (2005) suggested that their postulated marine influence came from the Paranan Sea to the south via an embayment through eastern Bolivia, they fail to explain how this could have occurred given the fluctuating sea levels of the late Neogene as revealed in the sea level curves of Hardenbol et al. (1998) (Fig. 2). Hovikoski et al. (2005) state "The age of the deposits [at Cerro Colorado] is estimated as ca. 9 Ma on the basis of ^{40}Ar/^{39}Ar dates (Campbell et al., 2001)," but this corresponds to a time when sea level was below modern levels. Another difficulty with this hypothesis, of course, is the observation that the divides separating the Amazon Basin from encroaching seas are now, and probably were in the latest Miocene, nearly twice as high in eastern Bolivia as they are in the northern and northeastern parts of the basin. Additionally, Campbell et al. (2001) suggested that deposition at the site studied by Hovikoski et al. (2005) continued until ~2.5 Ma, a factor they did not mention. Application of a ~6.5 myr time span to their cyclicity analyses eliminates any possibility of semidiurnal deposition, although it does present interesting possibilities for research into longer term cyclic depositional patterns within Amazonia.

Latrubesse et al. (1997) proposed a model for the late Cenozoic of southwestern Amazonia that postulated deposition of the youngest Tertiary deposits through a complex megafan system. They suggested that deposition of these beds began ~10±2 Ma and ended in the late Pliocene with "...the formation of a watershed that separated the basin of Ucayali from the basins of southwestern Brazilian Amazonia rivers" (Latrubesse et al., 1997, 114). Presumably the watershed in question is the Sierra de Divisor, but as noted by Kummel (1948), this watershed developed during the Quechua I orogenic event, or prior to 15 Ma. These authors did not mention the Ucayali Unconformity, and they considered the uppermost deposits of southwestern Amazonia to be part of the Solimões Formation. This contrasts with the long recognized assignment of these deposits to the Içá Formation in Brazil (e.g., Maia et al., 1977; Rossetti et al., 2005) and their earlier assignment to the Sanozama Formation (Almeida, 1974). Therefore, the paleontological data they present are confusing because they lump together pre- and post-unconformity faunas. Their conclusions that their facies analyses indicated the presence of lacustrine and swamp deposits are similar to, and reinforce, those reached by Frailey et al. (1988) on deposits in the same study area. Although they postulated deposition of these sediments from a megafan, no source river for the proposed megafan was identified, even though the gross morphology, other than elevation, of the Andean chain has not changed significantly since the late Pliocene, and no fan-shaped sediment lobe was identified. Ultimately, their proposed megafan meets none of the criteria of a megafan as described by Horton and DeCelles (2001) and Leier et al. (2005).

Recently, Rossetti et al. (2005) proposed another model for the geologic framework of western Amazonia. They postulated that western Amazonia behaved as a subsiding basin in the late Neogene, with a depocenter migrating northeast, within which accumulated the Içá Formation. They recognized a "Plio-Pleistocene" Içá Formation with intraformational erosional surfaces and conglomerates unconformably overlying the Solimões Formation. They proposed that after deposition of the Içá Formation, and following a period of stability, a series of Pleistocene depositional phases occurred in which sediments accumulated over a wide area in fluvial, deltaic, or fluvial crevasse splay environments on top of the Içá Formation. They suggested deposition within the basin ended at ~27 ka, which is when they postulated that the modern Amazon River formed and began flowing into the Atlantic. With one major exception (i.e., western Amazonia as a subsiding basin, which is refuted by the data of Caputo, 1991), this model resembles aspects of that of Campbell et al. (1985), Frailey et al. (1988), and Campbell (1990), including accumulation of deposits within a large scale lake system and the misinterpretation of similar-aged ^{14}C dates as representing widespread depositional sequences instead of localized river terrace deposits. The migrating depocenter aspect is reminiscent of early models of Räsänen et al. (1987, 1990).

As this review might suggest, it would seem that we have just about come full circle in interpreting late Neogene deposition in Amazonia. As stated earlier, there is agreement among many researchers on a number of points having to do with directly observable geologic features in lowland Amazonia. The difficulty continues to lie in obtaining a consensus as to the meaning of the data.

3.2.6. Refining the model

In our view, any model that attempts to explain late Neogene deposition within Amazonia must accommodate and explain the following features: (1) a basin-wide, but not continuous, basal conglomeratic sequence with clasts occasionally reaching >1 m diameter that overlies a weathered erosional surface, often via an angular unconformity; (2) vertebrate faunas in basal conglomerates exclusively of Chasicoan or Huayquerian age; (3) vast regions covered by up to tens of meters of well-sorted, cross-bedded or horizontally bedded sands that can locally include inclined heterolithic stratification, abundant fossil logs, and paleochannels; (4) massive, meters thick clay deposits; (5) finely laminated sand and clay beds; (6) paleochannels throughout the stratigraphic sequence; (7) a *planalto*, or upper surface of accumulation, with dominant landforms being paleodeltas, within which flow modern, underfit streams in directions opposite to those in place at the time of formation of the paleodelta; (8) modern stream branching patterns that mimic patterns of crevasse splay channels in modern deltas, as opposed to branching patterns formed by headward erosion in unconsolidated sediment; and (9) a period of deposition estimated at ~9.5 Ma to ~2.5 Ma. The following model achieves all of those goals, and it also provides a synthesis that treats the Amazon Basin as a unified sedimentary basin. The latter is perhaps the most difficult point to grasp because of the basin's enormous size.

We propose that deposition of the Madre de Dios Formation began at ~9.5–9.0 Ma, directly after the beginning of the late Miocene Quechua II orogenic event in the Andes. The period between the Quechua II event and the Quechua I orogenic event was a period of erosion within lowland Amazonia, as recorded in the weathered erosion surfaces and paleosols noted by so many throughout Amazonia. The reach of the late early Miocene Quechua I compressive event extended far into lowland Amazonia, elevating the Paleogene and early to middle Neogene strata and imparting a dip to these strata that is evident at the angular Ucayali Unconformity. This event apparently was also responsible for much of the uplift of the Sierra de Divisor because Kummel (1948, 1262) described the Ucayali Peneplain as surrounding the Contamana and Contaya Mountains that comprise its northern end, and the Madre de Dios Formation covers the lower elevation reaches of this uplifted belt (Kummel, 1948; personal observation). Uplift resulting from the removal of up to ~5 km of sediment during the formation of the Ucayali Peneplain also must have played a role in the structural history of the strata along the western rim of the basin. The peneplanation phase between the Quechua I and Quechua II orogenic events is also recorded in disparate regions of the Andes.

The Quechua II compressive event initiated the great Neogene uplift phase of the Andes, but it apparently did not significantly influence lowland Amazonia east of the Subandean Fold-and-Thrust Belt. That is, formation of a deep foreland basin, or a prominent forebulge, did not occur, as evidenced by (1) the consistent appearance of the Ucayali Unconformity in outcrops along rivers crossing the areas where such tectonic features would be predicted; and (2) the horizontal to sub-horizontal position of the beds of the Madre de Dios Formation noted throughout the basin. This includes covering the numerous anticlines and synclines of the Contamana and Contaya mountains that were formed during the Quechua I orogenic event. Minor uplift associated with the Sierra de Divisor appears to have occurred, but it might have resulted more from igneous activity (Stewart, 1971; Campbell et al., 2000) than to compression and uplift in the Andes.

A swift and dramatic change, geologically speaking, from an environment of peneplanation to one in which deposition of conglomerates, often of large clast size, occurred throughout the basin beginning at ~9.5–9.0 Ma. This event was cataclysmic. Huge quantities of high energy water flowing over vast regions were required for the sudden, rapid deposition of these conglomerates, which filled existing river valleys and leveled a surface upon the Ucayali Peneplain. The source for this water and the reason for the dramatic change to a high energy depositional environment must be complex and involve several factors, especially in that the deposits suggest seasonal deposition in shallow water. First among these factors would be the rapid uplift of the Andes at the beginning of the Quechua II orogenic event, which provided an elevated sediment source area. A change in atmospheric circulation brought about by the Andes when they reached a critical threshold elevation would have ended the passage of moisture-laden winds into the Pacific, trapping precipitation within the Amazon Basin and markedly increasing precipitation. The increase in precipitation, especially if coupled with an increase in seasonality, would lead to extreme flooding events. But could this have occurred over a short enough period of time to cause the abrupt transition observed?

An extra-continental, global-scale climatic event might also have dramatically increased precipitation within the Amazon Basin. Interestingly, the limited oxygen isotope data for the late Miocene from the Ceara Rise hint at a possible cooling of ocean surface waters of ~3 °C centered on ~9.5 Ma (Shackleton and Hall, 1997). Although those authors cautioned reading too much into these data, Keller and Barron (1983) described the period from 10 to 9 Ma as having the coolest temperatures of the Miocene, which led to deep sea hiatus NH 5. A cooling of the atmosphere would have led to precipitation forming at lower atmospheric elevations. If the cooling were rapid enough, and if the Andes were high enough, the conditions necessary for trapping Amazonian moisture within the basin could have developed over a relatively short time period with dramatic effect.

As mentioned earlier, the vertical extent of the conglomerates is not great, which indicates that they were deposited as a rapidly advancing, aggradational sedimentary series in high energy, relatively shallow water. This suggests to us that the western drainage portal of the Amazon Basin (i.e., through southern Ecuador) was still open, thereby allowing rapid draining of the water flooding into the basin. Rapid drainage was facilitated at this time by a sea level stand below modern levels (Hardenbol et al., 1998). When uplift of the Cordillera Real began to close this portal, and sea level began to rise, drainage from the basin was slowed and reduced. The reduced stream gradients and long distance transport of sediment set the stage for deposition of the massive, well-sorted sand deposits of the upper part of Member "A." These sand deposits have their modern analogs in the major, low gradient rivers of Amazonia today. Gradually, drainage was shifted to a long passage to the north via the paleo-Orinoco River system (Hoorn et al., 1995) and possibly to the northeast through the Essequibo valley and to the south via eastern Bolivia (Figs. 1 and 18).

At a later point in time, possibly marked by the beginning of deposition of Member "B" of the Madre de Dios Formation, a further rise in the base level of the rivers draining lowland Amazonia occurred, causing water to begin accumulating within the basin. In time, a vast mega-lake complex evolved, forming what we refer to as the Lago Amazonas complex (see following). For most of its life, this mega-lake complex is envisioned as an interconnected system of large, shifting bodies of water and inter-distributary bays whose positions changed as sediment influx filled first one area, then another, and whose extent fluctuated widely seasonally. Distributary channels were abandoned and created numerous times over the presumed long period of existence of the lake system, as indicated by the

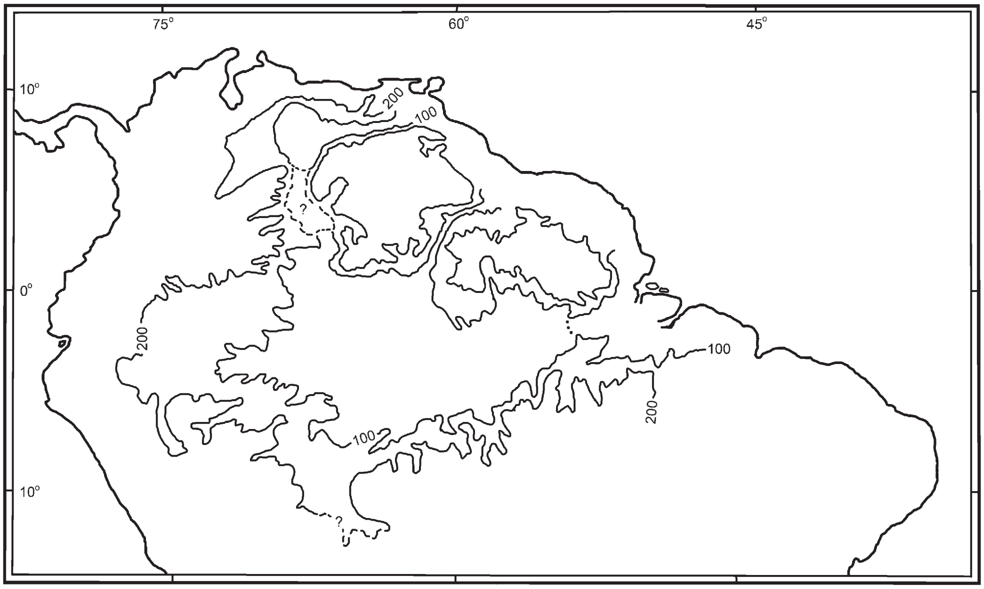

Fig. 18. The 100 m and 200 m contour intervals within lowland Amazonia illustrate the minimum extent of Lago Amazonas. The possible drainage route northward into the Orinoco River valley is currently slightly over 100 m, whereas that to the south via eastern Bolivia exceeds 200 m. Only the possible drainage route northeastward via the Essequibo River is below 100 m. Paleodeltas and associated features occur at elevations higher than 200 m in southern Amazonia, which indicates that the size of Lago Amazonas exceeded the area enclosed within the 200 m contour. This situation could occur because of the minimal drainage gradient existing within the basin (see text for details). The dotted line across the modern Amazon River valley represents the estimated position of the divide that prevented drainage of lowland Amazonia eastward until the late Pliocene, or the time when the modern Amazon River system was established.

complexity of the lithostratigraphy of the Madre de Dios Formation. The striking uniformity of the variability of the sedimentary fabric of the complex lithostratigraphy of the Madre de Dios Formation across lowland Amazonia is explained by the constantly shifting fluvial, fluviolacustrine/deltaic, and lacustrine depositional environments. For detailed descriptions and illustrations of the complex sedimentology of fluvially dominated deltaic sedimentation in large scale lacustrine environments, such as those expected to have dominated in Lago Amazonas, see Tye and Coleman (1989a,b).

The Lago Amazonas mega-lake complex persisted until the modern Amazon River system developed, as indicated by the widespread occurrence of paleodeltas capping the Madre de Dios Formation (Fig. 16). The height of these paleodeltas relative to the paleolakes they surround is only a few meters, suggesting relatively shallow water in the lakes they were infilling at the time deposition of the Madre de Dios Formation ceased. In many areas the paleodeltas retain their original form because erosion and weathering have not yet significantly impacted them. Subsequent to the establishment of the modern Amazon River, the water flow in the paleodeltas reversed course. In headwater regions in many parts of Amazonia, underfit streams continue to flow in what were originally large distributary channels of paleodeltas. In some areas, when major rivers reach high flood stages, the current in the underfit streams of the paleodeltas reverses course and they regain their original function as distributary channels (e.g., flooding of the Madre de Dios River in northern Bolivia reversing the course of the Sena River, leading to floodwaters reaching the grasslands of the llanos to the south).

Campbell et al. (2001) estimated that deposition of the Madre de Dios Formation in southwestern Amazonia continued until ~2.5 Ma, based on the $^{40}Ar/^{39}Ar$ date of 3.122±0.019 Ma on the Piedras ash from Member "C." At that time, the Lago Amazonas complex drained as the modern Amazon River drainage system was established and western Amazonian water began flowing eastward to the Atlantic rather than north to the Caribbean, or south through eastern Bolivia. Deposition of the Madre de Dios Formation probably ended earlier in some parts of the basin and later in others because formation of the modern Amazon River system across the basin was unlikely to have been isochronous, although it was probably nearly so.

3.2.7. Lago Amazonas

As noted above, many authors have recognized the lacustrine and deltaic nature of the sediments of the Madre de Dios Formation. When paleodeltaic geomorphic features are also considered, it appears there is little alternative but to recognize that the upper members of the Madre de Dios Formation were deposited in a long-term "Lago Amazonas mega-lake complex." This hypothesis is highly controversial, however, and earlier attempts (Frailey et al., 1988; Campbell, 1989, 1990; Frailey, 2002) to describe Lago Amazonas and suggest a mechanism for its formation were imprecise. With new data and insights on Andean tectonism and Amazonian sedimentation in hand, we propose the following.

The lack of lacustrine deposits in Member "A" of the Madre de Dios Formation suggests that during the time of deposition of this member a mega-lake did not exist in Amazonia. The exception to this is in the northern llanos of Bolivia where clay deposits form a large part of Member "A." Drainage from the Amazon Basin at this time was probably well organized and exited to the Pacific via a western portal through southern Ecuador. As this portal began to close and sea level to rise, drainage within the basin slowed and became disorganized, and water began to pool within the lower parts of the basin. If the surface uplift rates for the Cuenca region of Ecuador (Steinmann et al., 1999) can be applied as an approximation of the rate of closing of the western portal, after the beginning of the Quechua II orogenic event, less than 500,000 years would have been required to raise the base level ~100 m. Assuming a minimum elevation divide of ~100 m over the Guiana Shield to exit via the proto-Orinoco to the Caribbean, a similar elevation divide through the Essequibo River valley, and a higher divide (>200 m) to the south through eastern Bolivia, a sizable lake could have existed in central Amazonia by 8.5 Ma (Fig. 18). The rising Andes became an impassable barrier to westward drainage, but it is reasonable to conclude that at most any lake would have been maintained at a level no higher than ~100 m because of water flow out of the basin to the north and northeast. However, a lake of this elevation would not suffice to accommodate lacustrine deposition at 250–300 m amsl in southwestern Amazonia. An additional mechanism is required to explain those deposits.

That mechanism is probably best described as simply an extremely low, essentially non-existent drainage gradient. For example, airports at Iquitos, Peru (~125 m amsl), Pucallpa, Peru (~150 m amsl), and Puerto Maldonado, Peru (~265 m amsl) are about 1100 km, 1625 km, and 2150 km, respectively, from the ~100 m elevation divide leading into the proto-Orinoco River to the north. A straight line gradient from Iquitos to the divide is ~2.3 cm/km, from Pucallpa to the divide is ~3.1 cm/km, and from Puerto Maldonado to the divide

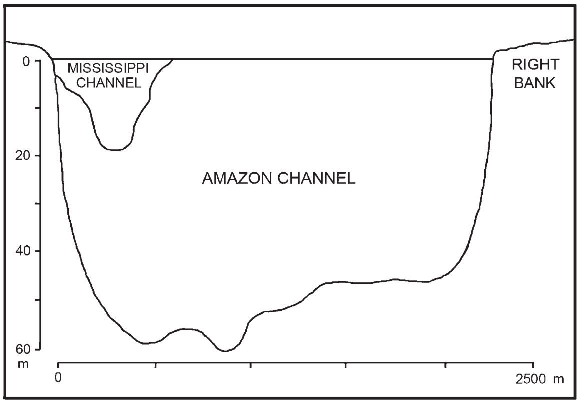

Fig. 19. The depth of the Amazon River channel at its narrowest point near Santarém, Brazil, dwarfs that of the Mississippi River at Vicksburg, Mississippi, and illustrates the great size of the channel required to drain modern Amazonia. The depth as illustrated is greater than the relief above 100 m of Pucallpa, Peru (elevation at airport, 150 m amsl) and twice that at Iquitos, Peru (elevation at airport, 125 m amsl). See text for discussion of gradients. After Davis (1964) and Sioli (1984).

is ~7.6 cm/km. No river flows in a straight line, however, so a doubling of the distance resulting from river meandering (a conservative approach) halves the gradient to ~1.1 cm/km, ~1.5 cm/km, and ~3.8 cm/km. For all intents and purposes, gradients of this magnitude amount to flow over a flat surface. No normal river drainage system can exist on a flat surface, especially when such a surface is required to handle the ever-increasing amounts of water flowing into the basin that must have come from the rising Andes. For example, the channel depth of the modern Amazon River reaches ~60 m (Fig. 19). This is deeper than the relief of the region of Pucallpa, Peru, above an ~100 m elevation base level (divide) to the north. At the present we have no way of knowing if freshwater outflow from lowland Amazonia in the Pliocene was equivalent to today, but even if it was much less, without a gradient sufficient to support an organized drainage system the basin regularly must have had the appearance of a vast shallow lake.

Once the basin had filled with sediment to a certain level, even with minimal rainfall one might expect lowland Amazonia to appear as a series of giant, shallow lakes, surrounding swamps, and intervening rivers held in place by natural levees (Fig. 20). The shallow lakes were subject to infill of sediments from crevasse splays and overbank deposits, which eventually led to their

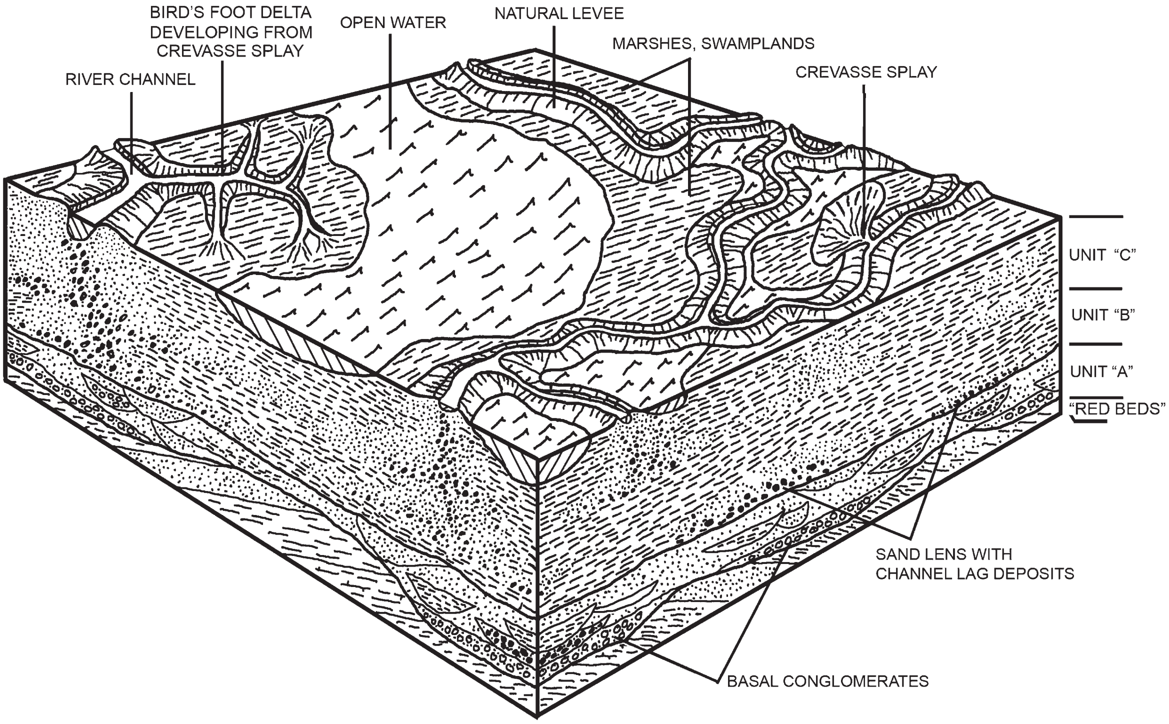

Fig. 20. Block diagram illustrating the depositional environments associated with the Madre de Dios Formation. The surface depicted is what would be expected during the dry season, whereas during the wet season, or during decadal-long wet periods, the entire surface could be expected to have been under water. With a return to the drier conditions depicted, it is unlikely that all of the channels present before a major flooding event would regain their original role, especially if it were a multi-year flood event. Not to scale; vertical exaggeration.

conversion from lakes to swamps. During wet seasons, however, all rivers might well have surpassed flood stage and sheet flow would have prevailed as the dominant form of water movement. During these periods of flooding, all of lowland Amazonia might have been a shallow lake. As the dry season took effect, receding water would once again expose the natural levee system, but the basin might well have had river channels in different places than before.

Although we have suggested that the closing of the western portal led to the initial formation of Lago Amazonas, it is also reasonable that uplift of the Andes contributed significantly to its origin by dramatically increasing rainfall amounts and seasonality within the basin. No extraordinary mechanism is required to produce the Lago Amazonas mega-lake complex. A flat-bottomed basin thousands of kilometers across subjected to abundant tropical, monsoonal precipitation is sufficient.

In many ways, Lago Amazonas was probably comparable to Lago Pebas (Wesselingh et al., 2002), although it was much younger, perhaps more seasonal, and, at its extreme, much larger. It differed in one major aspect, however, which is that it rarely preserved fossils, plant or animal. This is explained most readily by two factors. The first is that deposition occurred in a highly oxidizing, shallow water environment, which resulted in the rapid decomposition of most organic debris. Second, unlike Lago Pebas, which had an abundant vegetation complex in and around it, Lago Amazonas probably had as its modern analog the llanos of eastern Bolivia. There, long-term, seasonal flooding effectively curtails much vegetation growth, including on the banks of numerous lakes that fill the region. Compared to the Amazonian forests that cover the modern landscape, lowland Amazonia in the late Neogene was probably a vast complex of shallow mega-lakes surrounded by swampy, grassland savanna that endured months-long periods of seasonal inundation. It is also reasonable to expect that climatic cycles leading to extended periods of exceptional precipitation could have produced years-long periods of inundation.

4. Establishment of the modern Amazon River

The hypothesis that the modern drainage system comprising the Amazon River and its many large tributaries was established in the late Miocene is widely accepted. However, although previously available data and interpretations of these data reasonably supported this hypothesis, we find that it is no longer adequate to explain crucial aspects of late Neogene Amazonian geology. First and foremost of these is the fact that it would have been physically impossible to deposit the Pliocene portion of the Madre de Dios Formation, with its complex of paleodeltaic deposits and surficial distributary systems, if the modern Amazonian drainage system had been in place in the late Miocene. Here we briefly review the history and supporting arguments for the hypothesis of a late Miocene origin of the Amazon River system and present new arguments in favor of a late Pliocene origin of the modern Amazonian drainage.

In one of the most cited recent works regarding the postulated late Miocene formation of the modern Amazon River, Hoorn et al. (1995) drew upon their extensive experience in northwestern South America to establish a very persuasive hypothesis. In summary, they postulated that Andean tectonics in the late middle Miocene formed a unified Amazonian drainage, that is, uplift of the Andean chain west of Amazonia combined the northern and southern drainage of west central Amazonia into one drainage system by blocking the westward flow of Amazonian water into the Pacific Ocean. A paleo-Amazon River then began flowing northward to join a paleo-Orinoco River in central Colombia, which at that time drained into the Caribbean via Lake Maracaibo. At this time there was no drainage eastward out of the Amazon Basin. Substantial, rapid uplift of the northern Andes of Colombia in the late Miocene then re-routed the paleo-Orinoco River eastward, toward its current position, although the modern course in eastern Venezuela developed only in the Plio-Pleistocene. The model of Hoorn et al. (1995) also called for this late Miocene phase of Andean uplift to re-route the Amazon River eastward, establishing both its connection to the Atlantic Ocean and its current configuration. They did not give a more specific timing for this postulated event. Lundberg et al. (1998) presented a model patterned after that of Hoorn et al. (1995), and they narrowed the time of establishment of the modern Amazonian drainage system to ~8.5–8.0 Ma based on the finding of Shipboard Scientific Party (1995) of a significant change in the chemistry of terrigenous sediments on the Ceara Rise at that time. Räsänen et al. (1998) and Wesselingh et al. (2002) subsequently followed this date. Rossetti et al. (2005), however, proposed that the Amazon River system developed at ~27 ka. These models all embody the essence of that proposed over a century ago by Katzer (1903), although with numerous refinements.

We find many aspects of these models acceptable. We are not convinced, however, by the arguments offered to support the proposal that the Amazon River connected to the Atlantic during the late Miocene. We propose instead that this event occurred in the middle late Pliocene, or ~2.5 Ma. We outline the sequence of events leading to the establishment of the modern Amazon River drainage as follows. Based on the work of Hungerbühler et al. (2002), the western drainage portal through Ecuador, through which Amazonian drainage passed to the Pacific, began closing ~9.5–9.0 Ma when the initial uplift of the Quechua II orogenic event of the Andes brought to an end the extensional tectonic phase that had originally created this drainage portal. This is much later than proposed by Hoorn et al. (1995). By this time, the Eastern Cordillera of Colombia was well established (Guerrero, 1997) and its continued uplift gradually forced a shifting of the paleo-Orinoco River toward the modern Orinoco River valley. Thus, at the same time the western portal to the Pacific was closing, the rising Eastern Cordillera was effectively partially damming, but not completely blocking, the flow of Amazonian water northward, a condition that persisted until the late Pliocene. From the beginning of the Quechua II orogenic event until the late Pliocene, a flow of Amazonian water southward through eastern Bolivia and into the South Atlantic via the Paraná River might also have occurred, as well as a flow northeastward through the valley of what is now known as the Essequibo River (based on the low divide separating the Amazon Basin from the Atlantic coast) (Fig. 1). The slowed drainage from Amazonia after initiation of the Quechua II orogenic event resulted first in the shallow water, probably seasonally flooded, but still relatively well-drained depositional environments into which Member "A" of the Madre de Dios Formation was deposited and, later, in the shifting, deep water environments of the disorganized Lago Amazonas mega-lake complex in which the thick horizons of clay of the upper two members of this formation accumulated and into which deltaic distributary systems dumped huge amounts of sediments. In this model, it would be expected that deposition of the basal horizons of the Madre de Dios Formation would have occurred first around the perimeters of the basin close to the Andes and in topographic lows. For this reason, deposition of the basal conglomerates of the Madre de Dios Formation was not exactly isochronous across the entire basin, but nearly so.

However, for the hypothesis of Campbell et al. (2001) to be correct, that is, that deposition of the Madre de Dios Formation continued until ~2.5 Ma, the modern Amazonian drainage system could not have been established before ~2.5 Ma. By that time the basin had filled with sediment to what is now referred to as the *planalto* level, and a breach was cut through the eastern lip of the basin. Many authors place the eastern edge of the basin at the Purus Arch (e.g., Rossetti et al., 2005), but we think it was located farther east (Fig. 18). This breach might have occurred because of an overflow of the eastern basin edge by Amazonian waters, or it might have come about by headward erosion of the proto-Amazon River, which is now the lower Amazon River, or a combination of these two factors. It must also be kept in mind that the entire Lago Amazonas complex probably did not all drain at once. That is, the Madeira River, which drains southwestern Amazonia (including the region wherein lies the Piedras ash) and the Bolivian llanos, enters the Amazon River far to the east of the Purus River, the Juruá River, and the major tributaries draining the northern and western parts of the basin (Fig. 1). It is conceivable that the Madeira River might have joined the proto-Amazon River some time before the complete establishment of the modern drainage system. Ultimately though, the entire upper Amazon Basin, which previously drained northward, northeastward, and possibly southward, was connected to the lower Amazon Basin, draining eastward, and the modern Amazon River system was formed. The connection between the modern Orinoco River and the Amazon River is not yet broken, however, because these two great river systems remain connected by the Casiquiare Canal.

The primary support for the model we present here comes from the database created by the Ocean Drilling Project Leg 14, Ceara Rise, an aseismic ridge located in the Atlantic Ocean about 800 km northeast of the mouth of the Amazon River (Fig. 21) (Shipboard Scientific Party, 1995; Shackleton et al., 1997) and later discussions of this database (e.g., Dobson et al., 2001; Harris and Mix, 2002). Cores taken from five sites drilled on the Ceara Rise record a precisely dated series of deposits extending from the Recent back to the late Paleocene. The sediments comprising the core material are a combination of biogenic and terrigenous debris; the primary source of the latter is assumed to be sediment carried into the Atlantic by the Amazon River. Thus, the mass accumulation rates of terrigenous material (TMAR) on the Ceara Rise are assumed to reflect the volume of sediment supplied to the Atlantic via the Amazon River, which is taken as one indicator of the size of this river. Different authors (e.g., Shipboard Scientific Party, 1995; Dobson et al., 1997, 2001; various authors in Shackleton et al., 1997) related changes in TMAR on the Ceara Rise to establishment of a transcontinental Amazon River in the late Miocene, and suggested that TMAR on the Ceara Rise increased steadily since the late Miocene. However, we interpret the available data

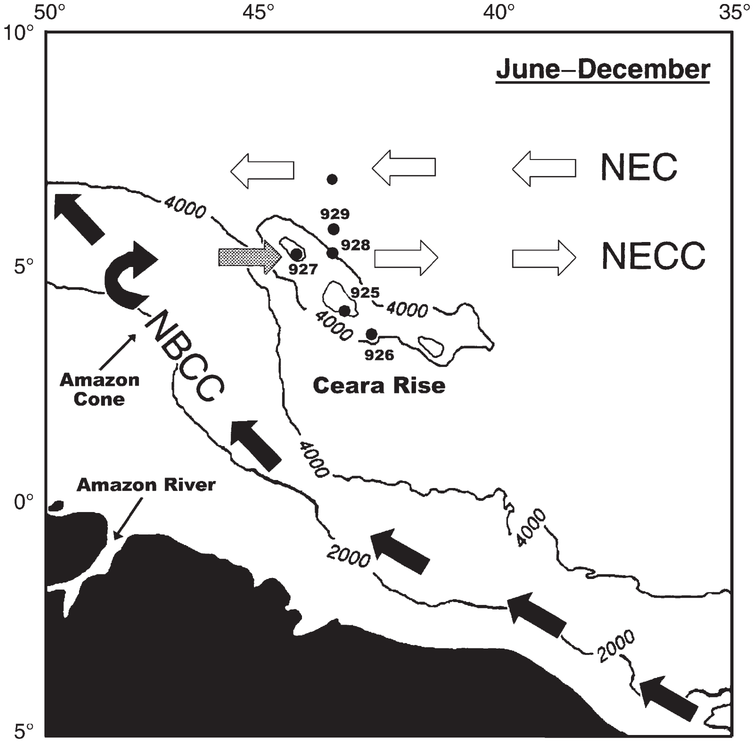

Fig. 21. Map showing the location of the Ceara Rise relative to the mouth of the Amazon River and the Amazon Cone, as well as the location of ODP sites 925–929. Also indicated are the positions of the North Brazilian Coastal Current (NBCC), the North Equatorial Current (NEC), and the North Equatorial Countercurrent (NECC) during the months June–December. Modified from Tiedemann and Franz (1997).

as demonstrating that the modern Amazon River drainage system was established in the late Pliocene, as reported by the astute observation of Dobson et al. (2001, 227): "Importantly, the extraordinary discharge from the Amazon is probably a relatively recent phenomenon since the Pliocene."

The records of TMAR at the five drill sites on the Ceara Rise show a similar pattern, although they are not equal at each site. Using the data presented by King et al. (1997), which covers the period from 14.0 Ma to Recent (Fig. 22), we can make the following general observations. First, from 14.0 Ma until ~4.5 Ma, ODP Sites 925 and 926 received slightly more terrigenous sediment than ODP Sites 927 and 928. After ~4.5 Ma, following a marked increase in TMAR at all sites, the reverse was true. Second, at ~2.5 Ma there was a major increase in TMAR, especially at ODP Sites 927–929, which are closest to the Amazon Cone. Subsequently, the overall TMAR was higher at all sites and the amplitude of cyclic variation, which was in tune with orbital frequencies, was greater. Third, the overall TMAR during that portion of the middle Miocene depicted in Fig. 22 was greater than, or nearly equal to, that seen throughout the late Miocene, the opposite of what would be expected if a transcontinental Amazon River were emplaced in the late Miocene. In fact, a marked decline in TMAR occurs after the beginning of the late Miocene (11.2 Ma; Berggren et al., 1995) (Fig. 22), and it is not until after ~8.0 Ma that this trend is reversed, although only temporarily. After ~8.0 Ma and until the end of the late Miocene (5.32 Ma; Berggren et al., 1995), the TMAR appears to be slightly higher at times than in the middle Miocene, but the differences are not as dramatic as seen in later changes and they are not convincing as representing a flood of sediments being carried into the Atlantic by a newly established transcontinental Amazon River. Unfortunately, there are no graphs available in Shackleton et al. (1997), or otherwise known to us, comparable to Fig. 22 that illustrate TMAR prior to 14.0 Ma. However, Dobson et al. (1997, 2001) present figures illustrating TMAR at discontinuous time periods at ODP 925 extending back to the Paleocene. Although those authors discussed a general increase in TMAR in the late Miocene, it can be seen in their figures that it is not until ~4.5 Ma that the TMAR consistently exceeds that of the early Miocene. The most dramatic increase, as they point out in their later paper, does not occur until the late Pliocene.

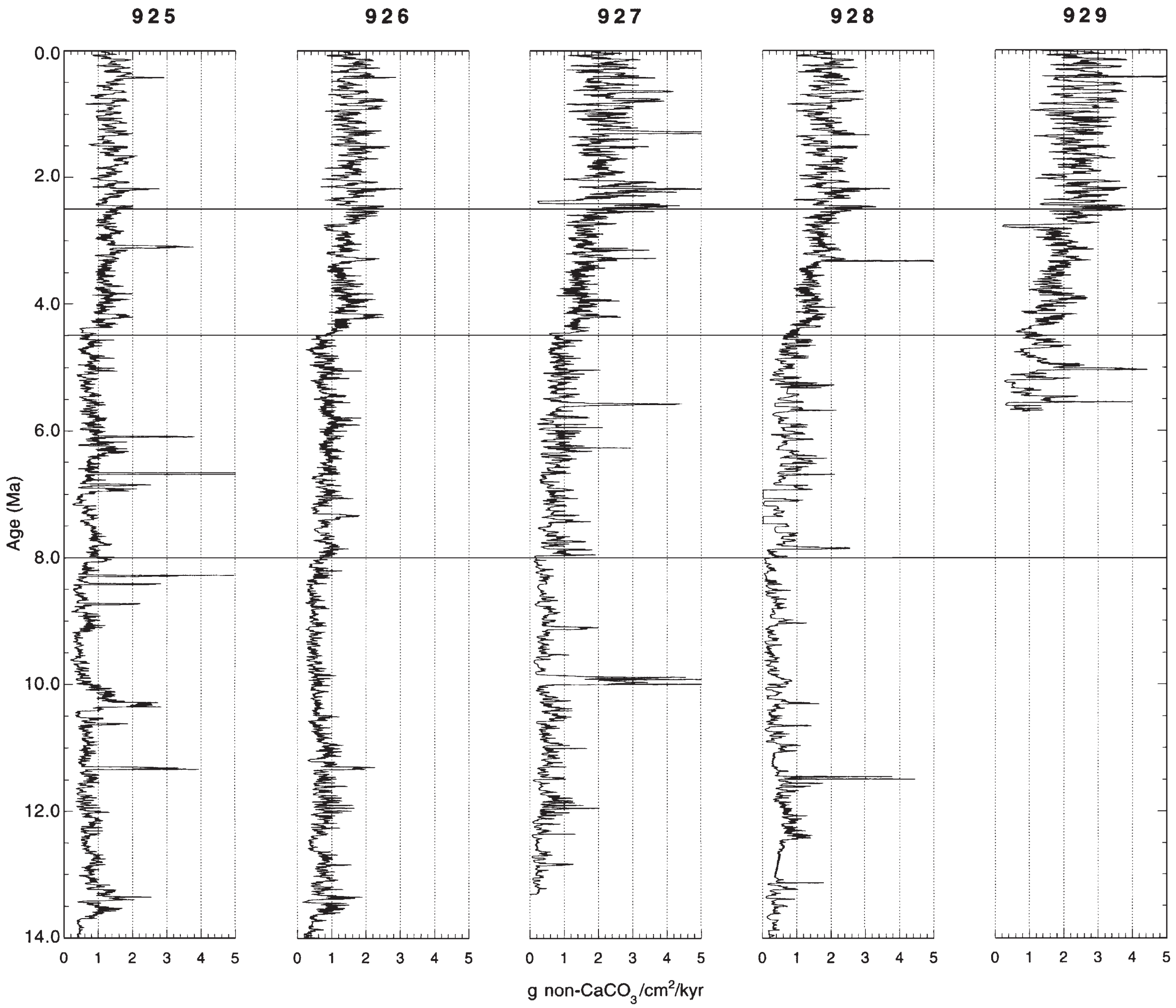

Fig. 22. Illustration of the estimates of terrigenous (non-CaCO$_3$) sediment mass accumulation rates at ODP sites 925–929, 0–14 Ma. Modified from King et al. (1997). See text for details.

However, interpreting the TMAR data from the Ceara Rise as reflecting solely the sediment input to the Atlantic by the Amazon River, and extrapolating from there the size or date of origin of the Amazon River, can be deceptive. At least two other major factors seriously affect TMAR on the Ceara Rise: ocean currents and sea level fluctuations.

Ocean currents and sea levels affect TMAR on the Ceara Rise in different ways. The mouth of the Amazon River is currently some distance (~300 km) from the edge of the continental shelf and the head of the Amazon Cone. During periods of sea level comparable to today, sediment laden waters from the Amazon River are carried northwestward along the South American coast by the North Brazilian Counter Current (NBCC), which is also known as the Guiana Current (Fig. 21). Most Amazonian sediment is deposited on the continental shelf or carried farther northwestward. At these times, low TMARs predominate on the Amazon Cone and Ceara Rise (Damuth and Kumar, 1975). During periods of low sea level, Amazon River discharge is much closer to the Amazon Cone and TMAR on the Ceara Rise increases. This is reflected in the observations that sedimentation in the Amazon Cone is currently minimal (Damuth and Kumar, 1975) and that TMAR on the Ceara Rise was greater during lower sea level stands of glacial episodes than at other times (Harris et al., 1997; Schneider et al., 1997).

Further, as Tiedemann and Franz (1997) discuss, the North Equatorial Counter Current (NECC) is reflected eastward from the NBCC and carries sediment-laden water from it toward the Ceara Rise during the second half of the year (Fig. 21). During the first half of the year, when the Intertropical Convergence Zone (ITCZ) is in its southernmost position, the NECC does not exist. The combination of lower sea levels and glacial climates, which must have affected seasonal movements of the ITCZ, certainly played an important role in determining TMAR on the Ceara Rise in the Plio-Pleistocene. The affects of the interplay of fluctuating sea levels and position of ITCZ at earlier times are still unclear.

One of the often cited, early arguments for a late Miocene origin of the Amazon River was the observation that the carbonate platform on the continental shelf at the mouth of the Amazon River was covered by siliciclastic sediments in the late Miocene (see, e.g., Damuth and Kumar, 1975; Castro et al., 1978). However, this observation is not as straightforward as it might appear. Prior to the postulated late Miocene origin of the Amazon River, sea level was much higher than today (~145 m amsl in early middle Miocene; Hardenbol et al., 1998) and, presumably, the original proto-Amazon River was quite small compared to now. The mouth of the proto-Amazon River was also much farther west, both because of the higher sea level and because sediment deposition has extended the course of the river eastward since then. Given the presumed existence at that time of the NBCC, it could be expected that minimal amounts of proto-Amazon River sediment reached the continental shelf, and even less reached the Ceara Rise (reflected in the TMAR graphs in Dobson et al., 1997, 2001). However, even with the mouth of the rudimentary proto-Amazon River located farther west, Castro et al. (1978, 1844) described the shelf platform east of the mouth of the Amazon in the Oligo-Miocene as “discontinuous in the central basin, with carbonate ‘islands’ adjacent to topographic lows containing shales.” They also illustrate about one-half, i.e., the landward side of the continental shelf, as being formed of, or covered by, fluvio-deltaic sediments. It is clear from this that the proto-Amazon River delivered sediment to the near continental shelf area in the early to middle Miocene and that the carbonate platform on the shelf was less than pristine at that time. The argument that suddenly in the late Miocene terrigenous sediment began burying a previously pure carbonate platform is not sustainable.

Further, sea level fluctuations played a major role in terrigenous sedimentation on the continental shelf in the Miocene. Two major changes in sea level in the late early Miocene and early middle Miocene, followed by a dramatic drop to ~50 m bmsl by the end of the middle Miocene, increased the gradient of the proto-Amazon River and moved its mouth much farther east. The immediate effect of this was to increase rates of erosion in eastern continental regions, thereby bringing abundant quantities of sediment onto the continental shelf and thoroughly covering the carbonate platform. An additional effect was to increase TMAR on the Ceara Rise. The latter is reflected in the TMAR data of Dobson et al. (1997, 2001), wherein increases in TMAR occur at ~16.5 Ma, ~15.0 Ma, and following ~14.0 Ma, all periods approximating times when sea level experienced major drops (Hardenbol et al., 1998).

Another argument for a late Miocene origin of the modern Amazon River system was the estimated late Miocene date of origin of the Amazon Cone. Damuth and Kumar (1975), on the basis of inferred sedimentation rates, hypothesized that the Amazon Cone began forming between 15 and 8 Ma, or middle to late Miocene, although earlier postulated dates of formation appeared subsequently (see Damuth and Flood, 1984). However, Schneider et al. (1997) suggested that a sea level threshold value of ~40–50 m bmsl enabled sediment delivery directly to the Amazon Cone. They reported that during glacial lowstands, terrigenous sediment from the Amazon River was discharged directly into the Amazon Cone, as opposed to the current situation where sediments are distributed northwestward by the NBCC. Assuming that the continental shelf and ocean currents have not changed dramatically since the middle Miocene, it would seem reasonable that the timing of sediment delivery initiating growth of the Amazon Cone in the Miocene would also be limited to a comparable period of low sea level. Hardenbol et al. (1998) placed the first recorded sea level drop to ~50 m bmsl at ~11.5 Ma, near the time when there is also a dramatic spike in TMAR on the Ceara Rise (Fig. 22). From this we conclude that the covering of the carbonate shelf off the mouth of the Amazon River and the birth of the Amazon Cone were both the result of middle Miocene reductions in sea level that brought about a redistribution of sediment-laden waters from the proto-Amazon River of the middle Miocene, not the establishment of the modern Amazon River drainage system in the late Miocene.

Dobson et al. (1997, 2001) also reported changes in the chemistry of the terrigenous sediments at distinct periods in the history of the Ceara Rise. Pertinent here is their observation that the period from ~16.5 to 13.0 Ma is characterized by deposition of sediments derived from highly weathered source rocks and similar in chemistry to the Barreiras Formation near the mouth of the Amazon. Also, Harris and Mix (2002) reported a significant change in sediment chemistry at ~8.0 Ma based on the ratios of chlorite/kaolinite (C/K) and goethite/(goethite+hematite) (G/(G+K) of terrigenous sediments of ODP 926 covering the period from 13 Ma to Present. They interpreted low C/K and high G/(G+K) ratios from 13 Ma to ~8.0 Ma as suggesting a source comprising weathered lowland soils. This is consistent with the source material continuing to be located in the eastern reaches of the continent. Thus, both the timing of changes in TMAR and the chemistry of the sediments are consistent with changes in sea level being responsible for the origination of the siliciclastic deposits covering the carbonate platform of the continental shelf off the mouth of the Amazon River.

King et al. (1997), Dobson et al. (1997, 2001), and Harris and Mix (2002) all report a drop in TMAR on the Ceara Rise at ~10.5 Ma (Fig. 22), which corresponds to a time when sea level returned to above modern levels from the late middle Miocene lowstand (Hardenbol et al., 1998). Shortly thereafter, there was another significant change in the chemistry of Ceara Rise terrigenous sediments. Shipboard Scientific Party (1995) and Harris and Mix (2002) timed this change as occurring at ~8.0 Ma, but Dobson et al. (2001) placed it at ~10.0 Ma. This change in chemistry was interpreted as indicating a change to a less weathered source area and it was thought that it probably indicated an influx of sediments from the Andes. However, Harris and Mix (2002) also suggested, on the basis of G/(G+K) ratios, that there was a shift toward drier than average conditions on the continent at this time. The critical question is, do these observations support the establishment of a transcontinental Amazon River at this time, that is, at ~8.0 Ma, or were other factors at work? We suggest the latter.

Shipboard Scientific Party (1995) identified the change in sediment composition at ~8.0 Ma as an increase in illite (and quartz) relative to kaolinite and smectite, that is, to less weathered from more weathered, clay minerals. The indicator used by Harris and Mix (2002) for an Andean sediment source was an increase in the C/K ratios, also indicating an influx of less weathered sediments. However, rather than increasing steadily as the Amazon River grew in size, as might be expected, the latter ratios declined significantly after ~7.0 Ma, before increasing dramatically again at ~4.5 Ma, only to decrease once again (Harris and Mix, 2002; Fig. 2). Significantly, the ratios of the <2 μm fraction do not reach the levels seen at ~4.5 Ma again until the Pleistocene, whereas the 2–20 μm fraction never again reached the high levels of ~8.0 Ma and ~4.5 Ma. These fluctuations do not seem consistent with an establishment of a transcontinental Amazon River in the late Miocene, or even in the early Pliocene. In order for these fluctuations to occur, there would had to have been major changes in the proportions of quantities of sediment provided to the Amazon River from weathered vs. unweathered sources once the modern Amazon River was established. This is possible, but we regard it as unlikely.

It is at ~8.0 Ma or slightly thereafter that the TMAR on the Ceara Rise begins to return to the levels seen in the late middle Miocene, albeit only temporarily (Fig. 22). Unlike prior increases in TMAR, however, this instance does not correspond to a sea level fall, but, instead, to a sea level rise (Hardenbol et al., 1998). At the same time there appears to be a temporary increase in carbonate mass accumulation rates (CMAR), especially at ODP 925 and 927 (Fig. 23) (King et al., 1997). All of these factors, especially the reversion in the chemistry of the sediments on the Ceara Rise and the increase in TMAR only to levels seen much earlier in the Miocene, suggest to us that something other than the establishment of a transcontinental Amazon River is responsible for the change in C/K ratios. Shipboard Scientific Party (1995) suggest that the observed shift in mineralogy might reflect the onset or intensification of granitic weathering associated with Andean uplift, but perhaps it was instead a result of aridity and changing erosional processes in eastern continental regions, as might be implied from the results of Harris and Mix (2002).

However, what might be of even greater importance is the impact of salinity values on the settling properties of the clay minerals examined. Patchineelam and Figueiredo (2000) reported significant differences in settling rates of clay minerals on the Amazon continental shelf and described the effect of salinity values on these rates. They found, for example, that kaolinite flocculates and settles in less saline waters than does smectite, whereas illite did not show a preference. Preferential settling of clay minerals resulting from changing salinity values would certainly affect the ratios of different clay minerals arriving at the Ceara Rise. High sea level at ~8.0 Ma, combined with increasing aridity and reduced water flow from the proto-Amazon River, might have combined to cause more kaolinite to settle on the near continental shelf, effecting the change in kaolinite/illite ratio on the Ceara Rise observed by Shipboard Scientific Party (1995).

Of course, these explanations for the changes in the chemistry of the sediments on the Ceara Rise do not negate the fact that there was an overall increase in TMAR beginning at ~8.0 Ma. The fact that this increase is only temporary argues against it resulting from establishment of the modern Amazon River drainage system, but an

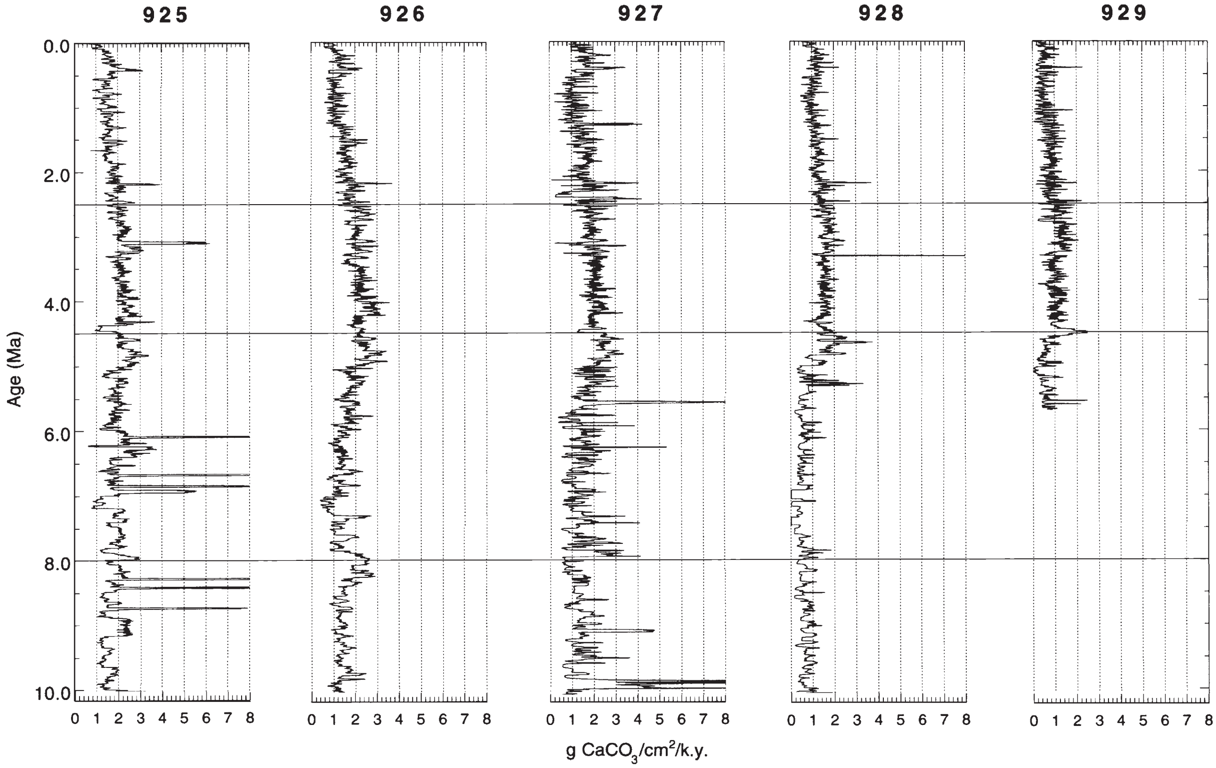

Fig. 23. Illustration of the estimates of carbonate ($CaCO_3$) sediment mass accumulation rates at ODP sites 925–929, 0–10 Ma. Modified from King et al. (1997). See text for details.

explanation for this increase is not yet clear. A clue to the cause might lie with the corresponding increases in CMAR at the different sites (Fig. 10), which were also only temporary, but additional research is required before this question can be answered.

There is a marked increase in TMAR in all ODP cores (Fig. 22) from the Ceara Rise at ~4.5 Ma, but this also might not be related to an increase in sediment supply from the Amazon River. Dobson et al. (2001) referred to this as the beginning of an order of magnitude increase from ~5.0 Ma to Present (in ODP Site 925) and said it corresponded closely in time to the period of maximum Andean uplift. Harris and Mix (2002) also related this increase in TMAR to Andean tectonics, specifically the Quechua III tectonic event. It also corresponds in time to a spike in the G/(G+K) ratios reported by Harris and Mix (2002), which suggests, as for the change at ~8.0 Ma, increasing aridity. The latter authors also report a spike in the C/K ratios at ~4.5 Ma, but as noted above, this drops off rapidly to near levels seen earlier. Interesting as well is the fact that, as at ~8.0 Ma, the increase in TMAR at ~4.5 Ma coincides with a high sea level stand, in this case the highest since the middle Miocene, which seemingly would have acted to reduce TMAR on the Ceara Rise by keeping the proto-Amazon River sediment plume farther toward the west. Thus, all the arguments against establishment of the modern Amazon River system at ~8.0 Ma apply as well at ~4.5 Ma.

However, as noted by Tiedemann and Franz (1997) and King et al. (1997), at about the same time as the increase in TMAR at ~4.5 Ma there is an increase in the CMAR on the Ceara Rise (Fig. 23), as at ~8.0 Ma. Although the latter authors seemed to regard this as a coincidence, the former suggest that the increase in CMAR might be related to changes in ocean currents brought about by the arrival of the Panamanian isthmus at the critical threshold level that blocked the Pacific to Caribbean flow of ocean waters (Kiegwin, 1982; Haug et al., 2001). Thus, in this instance, there would seem to be a clear alternative explanation for the increase in TMAR that is unrelated to Andean tectonics.

The next significant increase in TMAR, which is also seen in all cores, occurred at ~3.0–2.5 Ma. This increase is greatest in ODP Sites 927–929, or those closest to the Amazon Cone. We interpret this increase, which occurred at about the same time that deposition of the Madre de Dios Formation is postulated to have ceased (Campbell et al., 2001), as marking the establishment of the modern Amazon River drainage system. The timing of this increase also coincided with the onset of northern hemisphere glaciation (Haug and Tiedemann, 1998) and the first low sea level stand of the late Pliocene (Hardenbol et al., 1998). This increase in TMAR is not matched by an increase in CMAR, as the latter began a steady decline at ~3.0 Ma to the rates seen today, which are the lowest since the late Miocene (Fig. 23).

The interpretations of the TMAR data from the Ceara Rise presented above are a departure from those presented earlier by other authors. However, the earlier interpretations were framed by attempts to accommodate the data to a postulated late Miocene establishment of the modern Amazon River. By postponing that event until the late Pliocene, and looking more at the role of fluctuating sea levels, ocean currents, and differential settling of clay minerals in saline waters, a different picture of sedimentation on the Ceara Rise emerges. We think this picture more accurately reflects the late Neogene history of Amazonia.

5. Conclusions

An angular unconformity underlying the youngest Neogene formation of the Amazon Basin has been extensively documented by numerous authors working in different countries throughout lowland Amazonia. This, as well as extensive personal observations in many parts of Amazonia, is accepted as strong evidence that this unconformity, the Ucayali Unconformity, resulted from a single peneplanation event that began following the end of the Quechua I orogenic event, or possibly as early as ~15 Ma, and which ended at ~9.5–9.0 Ma. Similarly aged peneplanation events are reported within the Andes of Bolivia, Ecuador, and Peru, which suggests that they are the result of a similar underlying causal mechanism. This causal mechanism is considered to be directly related to the collision between the South American and the Nazca tectonic plates.

Räsänen et al. (1990) wrote: "The **extensive documentation** of the surficial **lithostratigraphic uniformity** of the *terra firme* has created **an illusion** of the presence of a widespread 'surficial mantle' in the Amazon [emphases ours]." However, the fact that so many workers in so many countries (of which only a partial listing was included in this paper) report the same litho- and biostratigraphy within lowland Amazonia must be of some significance. We argue that it is precisely the extensive documentation of the lithostratigraphic uniformity of the Madre de Dios Formation (including the Içá Formation of Brazil) that has created, not an illusion, but rather a solid demonstration of the fact that a single widespread 'surficial mantle' **does** cloak all of lowland Amazonia. If it were otherwise, there could be no observable uniformity.

We find that the surficial mantle comprising the Madre de Dios Formation was deposited following the extended period of peneplanation that formed the Ucayali Unconformity. At ~9.5–9.0 Ma, or near the beginning of the Andean Quechua II orogenic event, the environment of lowland Amazonia changed from one of erosion to one of extremely turbulent, high energy deposition of the basal conglomerates of Member "A" of the Madre de Dios Formation that covered the Ucayali Peneplain. Following that cataclysmic event, the basal conglomerates were covered by various thicknesses of sands, usually well-sorted and often cross-bedded, that comprise the upper portion of Member "A." An $^{40}Ar/^{39}Ar$ ash date and the vertebrate paleofauna from the basal conglomerates corroborate a late Miocene age for initiation of deposition of the Madre de Dios Formation. Drainage from Amazonia during the initial phase of deposition of the Madre de Dios Formation was probably to the west through Ecuador via a portal through the Cordillera Real.

As a result of the base level of Amazonian drainage being raised as the western portal closed early in the Quechua II orogenic phase, drainage was rerouted to a northern, and possibly a northeastern and southern, outlet. The rising Eastern Cordillera of the northern Andes in Colombia routed the northern drainage via the proto-Orinoco eastward, onto the Guiana Shield, raising its base level as it did so. At an as yet unspecified time, but following the closure of the western drainage portal, a mega-lake complex, Lago Amazonas, formed in lowland Amazonia because of the higher base levels of the new exits from the basin and because of the minimal, almost non-existent drainage gradient across the basin. The Lago Amazonas mega-lake complex lasted until ~2.5 Ma, and within it massive beds of clays, clayey silts, and silty sands were deposited as Member "B" and Member "C" of the Madre de Dios Formation. These sediments comprise fluvial, fluvio-deltaic, deltaic, and lacustrine deposits, and these deposits and the geomorphic expressions of widespread paleodeltas on the *planalto* of lowland Amazonia remain as documentation of this mega-lake complex. The *planalto* of Amazonia represents the uppermost surface of accumulation of Member "C" of the Madre de Dios Formation, and in many areas it remains essentially undisturbed. It would have been physically impossible to form paleodeltas on the *planalto* of lowland Amazonia in the late Pliocene if the modern Amazonian drainage system had been in place in the late Miocene.

The drainage of the Amazon Basin began flowing eastward at ~2.5 Ma, either because the eastern rim of the basin was breached, or because of headward erosion of the proto-Amazon River, or a combination of both. This time estimate is based on an ^{40}Ar/^{39}Ar ash date for Member "C" of the Madre de Dios Formation. The establishment of the modern Amazon River drainage system is marked by a major increase in terrigenous sedimentation on the Ceara Rise, an aseismic ridge in the Atlantic located ~800 km northeast of the mouth of the Amazon River. Terrigenous sedimentation events on the Ceara Rise, earlier interpretations of which were framed to accommodate a late Miocene origin of the Amazon River, are found to be better explained by changes in sea level and ocean currents and by differential settling of clay minerals in saline environments. The spacing of the major tributaries of the modern Amazon River suggests that the draining of Lake Amazonas was spread over a period of time.

In summary, we find that the middle to late Miocene period of peneplanation that led to the formation of the Ucayali Peneplain affected the Amazon Basin relatively uniformly. The Amazon Basin behaved as a single, unified sedimentary basin during the subsequent deposition of the upper Miocene to middle upper Pliocene Madre de Dios Formation. The lithostratigraphy of the Madre de Dios Formation is consistent with the upper horizons of this formation being deposited in the fluvial, deltaic, fluviolacustrine, and lacustrine environments of a mega-lake complex. Deposition within lowland Amazonia ceased and establishment of the modern Amazon Basin drainage system began at ~2.5 Ma. Paleontological data, numerical age dates, and the lithostratigraphy of the Madre de Dios Formation support these conclusions, as do large scale unconformities and depositional events within the Andes of comparable conformation and age and the mass accumulation rates and chemistry of terrigenous sediments on the Ceara Rise. Thus, we suggest the physiography of modern Amazonia is a result of terrain development within an erosional regime that began in the middle late Pliocene, or ~2.5 Ma.

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References

Aleman, A., Ramos, V.A., 2000. Northern Andes. In: Cordani, U.G., Milani, E.J., Filho, A.T., Campos, D.A. de (Eds.), Tectonic Evolution of South America. 31st International Geological Congress, Rio de Janeiro, Brazil, pp. 453–480.

Almeida, L.F.G. de, 1974. A drenagem festonada e seu significado fotogeológico. Sociedade Brasileira de Geologia Anais do 38E Congresso, Porto Alegre 7, 175–197.

Alvarenga, H.M.F., Guilherme, E., 2003. The anhingas (Aves: Anhingidae) from the Upper Tertiary (Miocene–Pliocene) of southwestern Amazonia. Journal of Vertebrate Paleontology 23 (3), 614–621.

Asociación LAGESA-CFGS, 1997. Geología de los cuadrángulos de Obenteni y Atalaya. Boletín-Instituto Geológico Minero y Metalúrgico. Serie A, Carta Geológica Nacional 95, 1–163.

Barbosa Rodrigues, J., 1892. Les reptiles fossiles de la Vallée de l'Amazone. Vellosia—Contribuicões do Museu Botanico do Amazonas 2, 41–56.

Bates, C.C., 1953. Rational theory of delta formation. Bulletin of the American Association of Petroleum Geologists 41, 359–382.

Bemerguy, R.L., Costa, J.B.S., 1991. Considerações sobre a evolução do sistema de drenagem da Amazônia e sua relação com o arcabouço tectônico-estrutural. Boletim do Museu Paraense Emílio Goeldi. Série Ciências da Terra 3, 75–97.

Berggren, W.A., Kent, D.V., Swisher, C.C., Aubry, M.P., 1995. A revised Cenozoic geochronology and chronostratigraphy. SEPM Special Publication 54, 129–212.

Bergqvist, L.P., Ribero, A.M., Bocquentin, J., 1998. Primata, Roedores e Litopternas do Mio/Pliocene da Amazonia Sul-Ocidental (Formação Solimões, Bacia do Acre), Brasil. Geología Colombiana 23, 19–29.

Burmeister, H., 1885. Exámen crítico de los mamíferous y reptiles fósiles denominados for D. Augusto BRAVARD y mencionados en su obra precedente. Anales del Museo Nacional de Buenos Aires 3 (14), 95–174.

Campbell Jr., K.E., 1989. The late Pleistocene of South America: a new approach. Brazilian Association of Quaternary Studies (ABEQUA), Special Publication (1), 118–124.

Campbell Jr., K.E., 1990. The geologic basis of biogeographic patterns in Amazonia. In: Peters, G., Hutterer, R. (Eds.), Vertebrates in the Tropics. Proceeding of the International Symposium on Vertebrate Biogeography and Systematics in the Tropics, Bonn, June 5–8, 1989, pp. 33–43.

Campbell Jr., K.E., 1996. A new species of giant anhinga (Aves: Pelecaniformes: Anhingidae) from the Upper Miocene (Huayquerian) of Amazonian Peru. Contributions in Science, Natural History Museum of Los Angeles County 460, 1–9.

Campbell Jr., K.E., Frailey, C.D., 1984. Holocene flooding and species diversity in southwestern Amazonia. Quaternary Research 21, 369–375.

Campbell Jr., K.E., Frailey, C.D., 1985. Paleontological investigation in southeastern Peru. Research Reports-National Geographic Society 18, 189–199.

Campbell Jr., K.E., Romero-P., L., 1989. Geología del cuaternario del Departamento de Madre de Dios [Perú]. Boletín de la Sociedad Geológica del Perú 79, 53–61.

Campbell Jr., K.E., Frailey, C.D., Arellano-L., J., 1985. The geology of the Rio Beni: further evidence for Holocene flooding in Amazonia. Contributions in Science, Natural History Museum of Los Angeles County 364, 1–18.

Campbell Jr., K.E., Grieve, R.A.F., Pacheco-Z., J., Garvin, J.B., 1989. A newly discovered possible impact structure in Amazonian Bolivia. National Geographic Research 5, 495–499.

Campbell Jr., K.E., Frailey, C.D., Romero-P., L., 2000. The Late Miocene gomphothere *Amahuacatherium peruvium* (Proboscidea: Gomphotheriidae) from Amazonian Peru: implications for the Great American Faunal Interchange. Boletín-Instituto Geológico Minero y Metalúrgico. Serie D: Estudios Regionales 23, 1–152.

Campbell Jr., K.E., Heizler, M., Frailey, C.D., Romero-P., L., Prothero, D.R., 2001. Upper Cenozoic chronostratigraphy of the southwestern Amazon Basin. Geology 29 (7), 595–598.

Caputo, M.V., 1991. Solimões megashear: intraplate tectonics in northwestern Brazil. Geology 19, 246–249.

Castro, J.C. de, Miura, K., Braga, J.A.E., 1978. Stratigraphic and structural framework of the Foz do Amazonas Basin. Tenth Annual Offshore Technology Conference, vol. 3, pp. 1843–1847.

Cione, A.L., Azpelicueta, M., Bond, M., Carlini, A.A., Casciotta, J.R., Cozzuol, M.A., Fuente, M., Gasparini, Z., Goin, F.J., Noriega, J., Scillato-Yané, G.J., Soibelzon, L., Tonni, E.P., Verzi, D., Vucetich, M.G., 2001. Miocene vertebrates from Paraná, eastern Argentina. In: Aceñolaza, F.G., Herbst, R. (Eds.), El Neógeno de Argentina. INSUGEO, Serie Correlación Geológica, vol. 14. Tucumán, Argentina, pp. 191–237.

Coleman, J.M., 1981. Deltas. Processes of Deposition and Models for Exploration. Burgess Publishing Company, Minneapolis. 124 pp.

Cozzuol, M.A., in press. The Acre vertebrate fauna: age, diversity and geography. Journal of South America Earth Science.

Cozzuol, M.A., Silva, S.A.F., 2003. The Biotic Diversity of the Neogene Solimões Formation, Problems and Data. 3rd Latinamerican Congress of Sedimentology, Belém, Brazil.

Czaplewski, N.J., 1996. Opossums (Didelphidae) and bats (Noctilionidae and Molossidae) from the Late Miocene of the Amazon Basin. Journal of Mammalogy 77 (1), 84–94.

Damuth, J.E., Flood, R.D., 1984. Morphology, sedimentation processes, and growth pattern of the Amazon Deep-Sea Fan. Geo-Marine Letters 3, 109–117.

Damuth, J.E., Kumar, N., 1975. Amazon Cone: morphology, sediments, age, and growth pattern. Geological Society of America Bulletin 86, 863–878.

Davis Jr., L.C., 1964. The Amazon's rate of flow. Natural History 73, 14–19.

Dobson, D.M., Dickens, G.R., Rea, D.K., 1997. Terrigenous sediment at Ceara Rise. In: Shackleton, N.J., Curry, W.B., Richter, C., Bralower, T.J. (Eds.), Proceeding of the Ocean Drilling Program, Scientific Results, vol. 154. Ocean Drilling Program, College Station, TX, pp. 465–473.

Dobson, D.M., Dickens, G.R., Rea, D.K., 2001. Terrigenous sediment on Ceara Rise: a Cenozoic record of South American orogeny and erosion. Palaeogeography, Palaeoclimatology, Palaeoecology 165, 215–229.

Douglas, J.A., 1933. The geology of the Marcapata Valley in eastern Perú. Quarterly Journal of the Geological Society of London 89, 308–354.

Dumont, J.F., 1989. Neotectonica y dinamica fluvial de la Baja Amazonia Peruana. Boletín de la Sociedad Geológica del Perú 80, 51–64.

Dumont, J.F., Garcia, F., 1991. Active subsidence controlled by basement structures in the Marañón Basin of northeastern Peru. Land Subsidence (Proceeding of the Fourth International Symposium on Land Subsidence, May 1991). IAHS Publication, vol. 200, pp. 343–350.

Dumont, J.F., Lamotte, S., Fournier, M., 1988. Neotectónica del Arco de Iquitos (Jenaro Herrera, Perú). Boletín de la Sociedad Geológica del Perú 77, 7–17.

Dumont, J.F., Deza, E., Garcia, F., 1991. Morphostructural provinces and neotectonics in the Amazonian lowlands of Perú. Journal of South American Earth Sciences 4 (4), 373–381.

Dury, G.H., 1964. Principles of underfit streams. U.S. Geological Survey Professional Paper 452-A, A1–A67.

Ellison, R.A., Klinck, B.A., Hawkins, M.P., 1989. Deformation events in the Andean orogenic cycle in the Altiplano and Western Cordillera, southern Peru. Journal of South American Earth Sciences 2 (3), 263–276.

Fields, R.W., 1957. Hystricomorph rodents from the late Miocene of Colombia, South America. University of California Publications in Geological Sciences 32, 273–403.

Frailey, C.D., 1986. Late Miocene and Holocene mammals, exclusive of the Notoungulata, of the Rio Acre region, western Amazonia. Contributions in Science, Natural History Museum of Los Angeles County 374, 1–46.

Frailey, C.D., 2002. Neogene paleogeography of the Amazon Basin. TER-QUA Symposium Series 3, 71–97.

Frailey, C.D., Lavina, E., Rancy, A., Souza Filho, J. de, 1988. A proposed Pleistocene/Holocene lake in the Amazon Basin and its significance to Amazonian geology and biogeography. Acta Amazonica 18 (3–4), 119–143.

Gaffney, E.S., Campbell, K.E., Wood, R.C., 1998. Pelomedusoid side-necked turtles from late Miocene sediments in southwestern Amazonia. American Museum of Natural History, Novitates 3245, 1–11.

Galvis, J., Huguett, A., Ruge, P., 1979. Geología de la Amazonia Colombiana. Boletín Geológico, Bogotá 22, 1–86.

Garver, J.I., Reiners, P.W., Walker, L.J., Ramage, J.M., Perry, S.E., 2005. Implications for timing of Andean uplift from thermal resetting of radiation-damaged zircon in the Cordillera Huayhuash, northern Peru. The Journal of Geology 113, 117–138.

Gingras, M.K., Räsänen, M., Ranzi, A., 2002. The significance of bioturbated inclined heterolithic stratification in the southern part of the Miocene Solimoes Formation, Rio Acre, Amazonia Brazil. Palaios 17, 591–601.

Gold, O., 1967. Pesquisa preliminary de carvão ou linhito na Bacia Terciária do Alto Amazonas, Alemanha. Relatório Final. 152 pp. (not seen).

Gregory-Wodzicki, K.M., 2000. Uplift history of the Central and Northern Andes: a review. Geological Society of America Bulletin 112, 1091–1105.

Gubbels, T.L., Isacks, B.L., Farrar, E., 1993. High-level surfaces, plateau uplift, and foreland development, Bolivian central Andes. Geology 21, 695–698.

Guerrero, J., 1997. Stratigraphy, sedimentary environments, and the Miocene uplift of the Colombian Andes. In: Kay, R.F., Madden, R. H., Cifelli, R.L., Flynn, J.J. (Eds.), Vertebrate Paleontology in the

Neotropics. The Miocene Fauna of La Venta, Colombia. Smithsonian Institution Press, Washington, pp. 15–43.

Guizado, J., 1975. Las molasas del pliocenico-cuaternarios del Oriente Peruano. Boletín de la Sociedad Geológica del Peru 45, 25–44.

Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., de Graciansky, P.-C., Vail, P.R., 1998. Mesozoic and Cenozoic sequence chronostratigraphic chart: Chart 1. In: de Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. SEPM Special Publication, vol. 60.

Harris, S.E., Mix, A.C., 2002. Climate and tectonic influences on continental erosion of tropical South America, 0–13 Ma. Geology 30, 447–450.

Harris, S.E., Mix, A.C., King, T., 1997. Biogenic and terrigenous sedimentation at Ceara Rise, western tropical Atlantic, supports Pliocene–Pleistocene deep-water linkage between hemispheres. In: Shackleton, N.J., Curry, W.B., Richter, C., Bralower, T.J. (Eds.), Proceeding of the Ocean Drilling Program, Scientific Results, vol. 154. Ocean Drilling Program, College Station, TX, pp. 331–345.

Haug, G.H., Tiedemann, R., 1998. Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation. Nature 393, 673–676.

Haug, G.H., Tiedemann, R., Zahn, R., Ravelo, A.C., 2001. Role of Panama uplift on oceanic freshwater balance. Geology 29, 207–210.

Hoorn, C., 1993. Marine incursions and the influence of Andean tectonics on the Miocene depositional history of northwestern Amazonia: results of a palynostratigraphic study. Palaeogeography, Palaeoclimatology, Palaeoecology 105, 267–309.

Hoorn, C., 1994a. Fluvial palaeoenvironments in the intracratonic Amazonian Basin (Early Miocene–early Middle Miocene, Colombia). Palaeogeography, Palaeoclimatology, Palaeoecology 109, 1–54.

Hoorn, C., 1994b. An environmental reconstruction of the palaeo-Amazon River system (Middle-Late Miocene, NW Amazonia). Palaeogeography, Palaeoclimatology, Palaeoecology 112, 187–238.

Hoorn, C., 1996. Miocene deposits in the Amazonian foreland basin: technical comment. Science 273, 122–123.

Hoorn, C., Guerrero, J., Sarmiento, G.A., Lorente, M.A., 1995. Andean tectonics as a cause for changing drainage patterns in Miocene northern South America. Geology 23, 237–240.

Horton, B.K., DeCelles, P.G., 2001. Modern and ancient fluvial megafans in the foreland basin system of the central Andes, southern Bolivia: implications for drainage network evolution in fold-thrust belts. Basin Research 13, 43–61.

Hovikoski, J., Räsänen, M., Gingras, M., Roddaz, M., Brusset, S., Hermoza, W., Romero Pittman, L., 2005. Miocene semidiurnal tidal rhythmites in Madre de Dios, Peru. Geology 33, 177–180.

Howard, A.D., 1965. Photogeologic interpretation of structure in the Amazon Basin: a test study. Geological Society of America Bulletin 76, 395–406.

Hungerbühler, D., Steinmann, J., Winkler, W., Seward, D., Egüez, A., Peterson, D.E., Helg, U., Hammer, C., 2002. Neogene stratigraphy and Andean geodynamics of southern Ecuador. Earth-Science Reviews 57, 75–124.

Jacques, J.M., 2003a. A tectonostratigraphic synthesis of the Sub-Andean basins: implications for the geotectonic segmentation of the Andean Belt. Journal of the Geological Society (London) 160, 687–701.

Jacques, J.M., 2003b. A tectonostratigraphic synthesis of the Sub-Andean basins: inferences on the position of South American intraplate accommodation zones and their control on South Atlantic opening. Journal of the Geological Society (London) 160, 703–717.

Jaillard, E., Hérail, G., Monfret, T., Díaz-Martínez, E., Baby, P., Lavenu, A., Dumont, J.F., 2000. Tectonic evolution of the Andes of Ecuador, Peru, Bolivia and northernmost Chile. In: Cordani, U.G., Milani, E.J., Filho, A.T., Campos, D.A. (Eds.), Tectonic Evolution of South America. 31st International Geological Congress, Rio de Janeiro, pp. 481–559.

Katzer, F., 1903. Grundzüge der Geologie de unteren Amazonasgebietes. Verlag von Max Weg, Leipzig. 296 pp.

Kay, R.F., Frailey, C.D., 1993. Large fossil platyrrhines from the Rio Acre local fauna, late Miocene, western Amazonia. Journal of Human Evolution 25, 319–327.

Keller, G., Barron, J.A., 1983. Paleoceanographic implication of Miocene deep-sea hiatuses. Geological Society of America Bulletin 94, 590–613.

Kennen, L., Lamb, S.H., Hoke, L., 1997. High-altitude palaeosurfaces in the Bolivian Andes: evidence for late Cenozoic surface uplift. In: Widdowson, M. (Ed.), Palaeosurfaces: Recognition, Reconstruction and Palaeoenvironmental Interpretation. Geological Society Special Publication, vol. 120, pp. 307–323.

Khobzi, J., Kroonenberg, S., Faivre, P., Weeda, A., 1980. Aspectos Geomorfológicos de la Amazonia y Orinoquia. Revista CIAF (Bogotá) 5 (1), 97–126.

Kiegwin, L., 1982. Isotopic paleoceanography of the Caribbean and East Pacific: role of Panama uplift in late Neogene time. Science 217, 350–353.

King, T.A., Ellis Jr., W.G., Murray, D.W., Shackleton, N.J., Harris, S.E., 1997. Miocene evolution of carbonate sedimentation at the Ceara Rise: a multivariate data/proxy approach. In: Shackleton, N.J., Curry, W.B., Richter, C., Bralower, T.J. (Eds.), Proceeding of the Ocean Drilling Program, Scientific Results, vol. 154. Ocean Drilling Program, College Station, TX, pp. 349–365.

Koch, E., 1959a. Unas apuntes sobre la geomorphología del Río Ucayali (Oriente Peruana). Boletín de la Sociedad Geológica del Peru 34, 32–41.

Koch, E., 1959b. Geología del campo petrolifero Maquia en el oriente del Peru y su ubicación regional. Boletín de la Sociedad Geológica del Peru 34, 42–58.

Kraglievich, J.L., 1965. Spéciation phylétique dans les rongeurs fossiles du genre *Eumysops* Amegh. (Echimyidae, Heteropsomyinae). Mammalia 29, 258–267.

Kummel, B., 1948. Geological Reconnaissance of the Contamana Region, Peru. Geological Society of America Bulletin 69, 1217–1266.

Latrubesse, E.M., Bocquentin, J., Santos, J.C.R., Romonell, C.G., 1997. Paleoenvironmental model for the late Cenozoic of southwestern Amazonia: paleontology and geology. Acta Amazonica 27 (2), 103–118.

Leier, A.L., DeCelles, P.G., Pelletier, J.D., 2005. Mountains, monsoons, and megafans. Geology 33, 289–292.

Leytón-D., F., Pacheco-Z., J., 1989. Geología del cuaternario-terciario aflorante en el Río Madre de Dios (Deptos.: Pando-La Paz-Beni). Sociedad Geológica Boliviana, Memorias, Publicación Especial, Tomo I, pp. 328–352.

Linares, O.J., 2004. Bioestratigrafia de la fauna de mamiferos de las formaciones Socorro, Urumaco y Codore (mioceno medioplioceno temparano) de la region de Urumaco, Falcon, Venezuela. Paleobiologia Neotropical 1, 1–26.

Lundberg, J.G., Marshall, L.G., Guerrero, J., Horton, B., Malabarba, M.S.L., Wesselingh, F., 1998. The stage for Neotropical fish diversification: a history of tropical South American rivers. In: Malabarba, L.R., Reis, R.E., Vari, R.P., Lucena, Z.M., Lucena, C. A.S. (Eds.), Phylogeny and Classification of Neotropical Fishes. Edipucrs, Porto Alegre, pp. 13–48.

Maia, R.G., Godoy, H.K., Yamaguti, H.S., Moura, P.A.F. de, Costa, S. da, Holanda, M.A. de, Costa, J., 1977. Projeto Carvão no Alto Solimões. Relatorio Final. Companhia de Pesquisa de Recursos Minerais-Departamento Nacional da Produçáo Mineral. 142 pp.

Marshall, L.G., 1979. A model for paleobiogeography of South America cricetine rodents. Paleobiology 5, 126–132.

Marshall, L.G., Cifelli, R.L., 1990. Analysis of changing diversity patterns in Cenozoic land mammal age faunas, South America. Palaeovertebrata 19, 169–210.

Marshall, L.G., Lundberg, J., 1996. Miocene deposits in the Amazonian foreland basin: technical comment. Science 273, 123–124.

Marshall, L.G., Sempere, T., 1993. Evolution of the Neotropical Cenozoic land mammal fauna in its geochronologic, stratigraphic and tectonic context. In: Goldblatt, P. (Ed.), Biological Relationships Between Africa and South America. Yale University Press, New Haven, pp. 329–392.

Mathalone, J.M.P., Montoya-R., M., 1995. Petroleum Geology of the Sub-Andean Basins of Peru. In: Tankard, A.J., Suárez-S., R., Welsink, H.J. (Eds.), Petroleum Basins of South America. American Association Petroleum Geologists Memoir, vol. 62, pp. 423–444.

Mégard, F., 1984. The Andean orogenic period and its major structures in central and northern Peru. Journal of the Geological Society (London) 141, 893–900.

Mégard, F., 1987. Structure and evolution of the Peruvian Andes. In: Schaer, J.P., Rodgers, J. (Eds.), The Anatomy of Mountain Ranges. Princeton University Press, Princeton, pp. 179–210.

Miall, A.D., 1984. Principles of Sedimentary Basin Analysis. Springer-Verlag, New York. 490 pp.

Miura, K., 1972. Possibilidades petrolíferas da Bacia do Acre. Anais do XXVI Congresso Brasileiro de Geologia, Belém 3, 15–20.

Mones, A., Toledo, P.M., 1989. Primer hallazgo *Euphilus* Ameghino, 1889 (Mammalia: Rodentia: Neoepiblemidae) en el Neogeno del Estado de Acre, Brasil. Comunicaciones Paleontológicas del Museo de Historia Natural de Montevideo 2 (21), 1–15.

Negri, F.R., Ferigolo, J., 1999. Anatomia craniana de *Neoepiblema ambrosettianus* (Ameghino, 1889) (Rodentia, Caviomorpha, Neoepiblemidae) do Mioceno Superior-Plioceno, Estado do Acre, Brasil, e revisão das espécies do gênero. Boletim do Museu Paraense Emílio Goeldi 2, 3–80.

Noble, D.C., McKee, E.H., Mourier, T., Mégard, F., 1990. Cenozoic stratigraphy, magmatic activity, compressive deformation, and uplift in northern Peru. Geological Society of America Bulletin 102, 1105–1113.

Noblet, C., Lavenu, A., Marocco, R., 1996. Concept of continuum as opposed to periodic tectonism in the Andes. Tectonophysics 255, 65–78.

ONERN, 1972. Inventário, evaluación e integración de los recursos naturales de la zona de los ríos Inambari y Madre de Dios. Oficina Nacional de Evaluación de Recursos Naturales (ONERN), República del Perú, Lima, Perú. 296 pp.

ONERN, 1977. Inventário, evaluación e integración de los recursos naturales de la Zona Iberia-Iñapari. Oficina Nacional de Evaluación de Recursos Naturales (ONERN), República del Perú, Lima, Perú. 334 pp.

Oppenheim, V., 1946. Geological reconnaissance in southeastern Peru. Bulletin of the American Association of Petroleum Geologists 30, 254–264.

Pardo, A.A., Zuñiga, F., 1976. Estratigrafía y evolución tectónica de la region de la selva del Perú: Parte II. Mesozoico y Cenozoico. Segundo Congreso Latinoamericano de Geología, Memorias. Boletín Geológico, Caracas, Publicación Especial 7, 588–608.

Pardo-Casas, F., Molnar, P., 1987. Relative motion of the Nazca (Farallon) and South American plates since late Cretaceous time. Tectonics 6, 233–248.

Patchineelam, S.M., Figueiredo, A.G. de, 2000. Preferential settling of smectite on the Amazon continental shelf. Geo-Marine Letters 20, 37–42.

Paula Couto, C. de, 1956. Mamíferos fósseis do Cenozóico da Amazônia. Boletin, Conselho Nacional de Pesquisas, Rio de Janeiro 3, 1–121.

Paula Couto, C. de, 1978. Fossil mammals from the Cenozoic of Acre, Brazil. 2. Rodentia Caviomorpha Dinomyidae. Iheringia. Série Geologia 5, 3–17.

Paula Couto, C. de, 1981. Fossil mammals from the Cenozoic of Acre, Brazil: IV. Notoungulata Notohippidae, and Toxodontidae Nesodontinae. Congresso Latino-Americano de Paleontologia, Porto Alegre, Anais 1, 461–477.

Paula Couto, C. de, 1982. Fossil mammals from the Cenozoic of Acre, Brazil: V. Notoungulata Nesodontinae (II) Toxodontinae and Haplodontheriinae, and Litopterna, Pyrotheria and Astrapotheria (II). Iheringia. Série Geologia 7, 5–43.

Paula Couto, C. de, 1983a. Fossil mammals from the Cenozoic of Acre, Brazil: VI. Edentata Cingulata. Iheringia. Série Geologia 8, 33–49.

Paula Couto, C. de, 1983b. Fossil mammals from the Cenozoic of Acre, Brazil. VII. Miscellanea. Iheringia. Série Geologia 8, 101–120.

Paxton, C.G.M., Crampteon, W.G.R., Burgess, P., 1996. Miocene deposits in the Amazonian foreland basin: technical comment. Science 273, 123.

Pilger Jr., R.H., 1984. Cenozoic plate kinematics, subduction and magmatism: South American Andes. Journal of the Geological Society (London) 141, 793–802.

Räsänen, M.E., Salo, J.S., Kalliola, R.J., 1987. Fluvial perturbance in the western Amazon Basin: regulation by long-term sub-Andean tectonics. Science 238, 1398–1401.

Räsänen, M.E., Salo, J.S., Jungner, H., Romero-Pittman, L., 1990. Evolution of the Western Amazon lowland relief: impact of Andean foreland dynamics. Terra Nova 2, 320–332.

Räsänen, M.E., Neller, R., Salo, J., Jungner, H., 1992. Recent and ancient fluvial deposition systems in the Amazonian foreland basin, Perú. Geological Magazine 129 (3), 293–306.

Räsänen, M.E., Linna, A.M., Santos, J.C.R., Negri, F.R., 1995. Late Miocene tidal deposits in the Amazonian Foreland Basin. Science 269, 386–390.

Räsänen, M.E., Linna, A.M., Irion, G., Rebata, L.-H., Vargas, R.-H., Wesselingh, F., 1998. Geología y geoformas de la zona de Iquitos. In: Kalliola, R., Flores, S.-P. (Eds.), Geoecología y desarrollo Amazónico: estudio integrado en la zona de Iquitos, Perú. Annales Universitatis Turkuensis Ser A II, vol. 114, pp. 59–137.

Reig, O., 1980. A new fossil genus of South American cricetid rodents allied to *Wiedomys*, with an assessment of the Sigmodontinae. Journal of Zoology, London 192, 257–281.

Reig, O., 1986. Diversity patterns and differentiation of high Andean rodents. In: Vuilleumier, F., Monasterios, M. (Eds.), High Altitude Tropical Biogeography. Oxford University Press, Oxford, pp. 404–439.

Roddaz, M., Baby, P., Brusset, S., Hermoza, W., Darrozes, J.M., 2005. Forebulge dynamics and environmental control in Western Amazonia: the case study of the Arch of Iquitos (Peru). Tectonophysics 399, 87–108.

Romero-Pittman, L., 1996. Paleontologia de Vertebrados. In: Palacios-M., O., Molina-G., O., Galloso-C., A., Reyna-L., C. (Eds.), Geología de los cuadrangulos de Puerto Luz, Colorado, Laberinto, Puerto Maldonado, Quincemil, Masuco, Astillero y Tambopata. Instituto Geológico Minero y Metalúrgico, Carta Geológica Nacional, Boletín, Serie A, vol. 81, pp. 171–178.

Rossetti, D., Toledo, P.M., Góes, A.M., 2005. New geological framework for Western Amazonia (Brazil) and implications for biogeography and evolution. Quaternary Research 63, 78–89.

Rüegg, W., 1952. Rasgos geológicos y geomorfológicos de la depresión del Ucayali y Amazonas Superior. Revista de la Asociación Geológica de Argentina 7, 106–124.

Rüegg, W., 1956. Geología y petróleo en la faja subandina Peruana. Simposia Sobre Yacimientos de Petróleo y Gas, XX Congreso Geológico International IV, Mexico, pp. 89–139.

Rüegg, W., Rosenzweig, A., 1949. Contribución a la geología de las formaciones modernas de Iquitos y de la Amazonia Superior. Boletín de la Sociedad Geológica del Peru, Volumen Jubilar Parte II (3), 1–24.

Santos, J.O.S., 1974. Considerações sobre a bacia cenozõica Solimões. Anais do XXVIII Congresso, Sociedade Brasileira de Geologia, Pôrto Alegre, vol. 3, pp. 3–11.

Santos, J.O.S., Silva, L.L., 1976. O exogeossinclíneo andino e a Formação Solimões. Anais do XXIX Congresso, Sociedade Brasileira de Geologia, vol. 1, pp. 135–147.

Schneider, R.R., Müller, P.J., Schlünz, B., Segl, M., Showers, W.J., Wefer, G., 1997. Upper Quaternary western Atlantic paleoceanography and terrigenous sedimentation on the Amazon Fan: a view from stable isotopes of planktonic foraminifers and bulk organic matter. In: Flood, R.D., Piper, D.J.W., Klaus, A., Peterson, L.C. (Eds.), Proceeding of the Ocean Drilling Program, Scientific Results, vol. 155. Ocean Drilling Program, College Station, TX, pp. 319–333.

Schobbenhaus, C., Almeida Campos, D. de, Derze, G.R., Asmus, H.E. (Eds.), 1984. Geologia do Brasil. Departamento Nacional da Produção Mineral, Brasilia. 501 pp.

Sébrier, M., Soler, P., 1991. Tectonics and magmatism in the Peruvian Andes from late Oligocene time to the Present. Special Paper-Geological Society of America 265, 259–278.

Sébrier, M., Lavenu, A., Fornari, M., Soulas, J.-P., 1988. Tectonics and uplift in Central Andes (Peru, Bolivia and Northern Chile) from Eocene to present. Géodynamique 3 (1/2), 85–106.

Servant, M., Sempere, T., Argollo, J., Bernat, M., Feraud, G., Lo Bello, P., 1989. Morphogenese et soulevement des Andes de Bolivie au Cenozoique. Comptes Rendus de l'Academie des Sciences de Paris 309, 417–422.

Shackleton, N.J., Hall, M.A., 1997. The late Miocene stable isotope record, Site 926. In: Shackleton, N.J., Curry, W.B., Richter, C., Bralower, T.J. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 154. Ocean Drilling Program, College Station, TX, pp. 465–473.

Shackleton, N.J., Curry, W.B., Richter, C., Bralower, T.J. (Eds.), 1997. Proceeding of the Ocean Drilling Project, Scientific Results, vol. 154. Ocean Drilling Program, College Station, TX. 552 pp.

Shipboard Scientific Party, 1995. Leg 154 synthesis. In: Curry, W.B., Shackleton, N.J., Richter, C. (Eds.), Proceeding of the Ocean Drilling Program, Initial Reports, vol. 154. Ocean Drilling Project, College Station, TX, pp. 421–442.

Silva, L.L., 1988. A estratigrafia da Formação Solimões: uma análise crítica. Anais do XXXV Congresso Brasileiro de Geologia Belém. Pará, vol. 2, pp. 725–737.

Simpson, G.G., 1961. The supposed Pliocene Pebas beds of the Upper Juruá River, Brazil. Journal of Paleontology 35, 620–624.

Simpson, G.G., 1980. Splendid Isolation: The Curious History of South American Mammals. Yale University Press, New Haven. 266 pp.

Simpson, G.G., Paula Couto, C. de, 1981. Fossil mammals from the Cenozoic of Acre, Brazil: III. Pleistocene Edentata Pilosa, Proboscidea, Sirenia, Perissodactyla and Artiodactyla. Iheringia. Série Geologia 6, 11–73.

Sioli, H., 1984. The Amazon and its main affluents: hydrography, morphology of the river courses, and river types. In: Sioli, H. (Ed.), The Amazon. Limnology and Landscape Ecology of a Might Tropical River and its Basin. W. Junk Publishers, Dordrecht, pp. 127–165.

Spikings, R.A., Seward, D., Winkler, W., Ruiz, G.M., 2000. Low-temperature thermochronology of the northern Cordillera Real, Ecuador: tectonic insights from zircon and apatite fission track analysis. Tectonics 19, 649–668.

Spikings, R.A., Winkler, W., Seward, D., Handler, R., 2001. Along-strike variations in the thermal and tectonic response of the continental Ecuadorian Andes to the collision with heterogeneous oceanic crust. Earth and Planetary Science Letters 186, 57–73.

Steinmann, M., Hungerbühler, D., Seward, D., Winkler, W., 1999. Neogene tectonic evolution and exhumation of the southern Ecuadorian Andes; a combined stratigraphy and fission-track approach. Tectonophysics 307, 255–276.

Sternberg, H.O., 1950. Vales Tectônicos na Planície Amazônica? Revista Brasileira de Geografia 4, 511–534.

Stewart, J.W., 1971. Neogene peralkaline igneous activity in eastern Peru. Geological Society of America Bulletin 82, 2307–2312.

Thorson, T.B., 1972. The status of the bull shark, *Carcharhinus leucas*, in the Amazon River. Copeia 1972 (3), 601–605.

Tiedemann, R., Franz, S.O., 1997. Deep-water circulation, chemistry, and terrigenous sediment supply in the equatorial Atlantic during the Pliocene, 3.3–2.6 and 5.4.5 Ma. In: Shackleton, N.J., Curry, W. B., Richter, C., Bralower, T.J. (Eds.), Proceeding of the Ocean Drilling Program, Scientific Results, vol. 154. Ocean Drilling Program, College Station, TX, pp. 299–318.

Tosdal, R.M., Clark, A.H., Farrar, E., 1984. Cenozoic polyphase landscape and tectonic evolution of the Cordillera Occidental, southernmost Peru. Geological Society of America Bulletin 95, 1318–1332.

Tschopp, H.J., 1953. Oil explorations in the Oriente of Ecuador 1938–1950. Bulletin of the American Association of Petroleum Geologists 37 (10), 2303–2347.

Tye, R.S., Coleman, J.M., 1989a. Depositional processes and stratigraphy of fluvially dominated lacustrine deltas: Mississippi Delta Plain. Journal of Sedimentary Petrology 59, 973–996.

Tye, R.S., Coleman, J.M., 1989b. Evolution of Atchafalaya lacustrine deltas, south-central Louisiana. Sedimentary Geology 65, 95–112.

Vonhof, H.B., Wesselingh, F.P., Ganssen, G.M., 1998. Reconstruction of the Miocene western Amazonian aquatic system using molluscan isotopic signatures. Palaeogeography, Palaeoclimatology, Palaeoecology 141, 85–93.

Vonhof, H.B., Wesselingh, F.P., Kaandorp, R., Davies, G., van Hinte, J., Guerrero, J., Räsänen, M., Romero-Pittman, L., Ranzi, A., 2003. Paleogeography of Miocene western Amazonia: isotopic composition of molluscan shells constrains the influence of marine incursions. Geological Society of America Bulletin 115, 983–993.

Vrba, E.S., 1993. Mammal evolution in the African Neogene and a new look at the Great American Interchange. In: Goldblatt, P. (Ed.), Biological Relationships between Africa and South America. Yale University Press, New Haven, pp. 393–432.

Walton, A., 1997. Rodents. In: Kay, R.F., Madden, R.H., Cifelli, R.L., Flynn, J.J. (Eds.), Vertebrate Paleontology in the Neotropics, The Miocene Fauna of La Venta, Colombia. Smithsonian Institution Press, Washington, pp. 392–409.

Webb, S.D., Rancy, A., 1996. Late Cenozoic evolution of the Neotropical mammal fauna. In: Jackson, J.B.C., Budd, A.F., Coates, A.G. (Eds.), Evolution and Environment in Tropical America. University of Chicago Press, Chicago, pp. 335–358.

Wesselingh, F.P., Räsänen, M.E., Iron, G., Vonhof, H.B., Kaandorp, R., Renema, W., Romero Pittman, L., Gingras, M., 2002. Lake Pebas: a palaeoecological reconstruction of a Miocene, long-lived lake complex in western Amazonia. Cainozoic Research 1 (2001), 35–81.