The nature of Miocene Amazonian epicontinental embayment: High-frequency shifts of the low-gradient coastline

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ABSTRACT

A sedimentological and ichnological data set that covers the Lower-Upper Miocene sedimentary series of western Amazonian foreland basin indicates that widespread, restricted marine ingressions shaped western Amazonia throughout the Miocene. The late Lower–early Upper Miocene sedimentary series (Pebas Formation) consists of stacked, 3- to 10-m-thick, tidally influenced, brackish to freshwater, bay-margin sequences. The overlying Upper Miocene ("post-Pebas") strata bear tidally influenced, low-salinity, channel deposits that are interbedded with continental deposits. The data suggest that several tens of high-frequency ingressions reached the basin during the Miocene. The ingressions were shallow and restricted, and were interspersed with rapid progradation. Along with the prograding shorelines, the continental environments—swamps, lagoons, floodplains and forests—constrained the extent of the marginal marine embayment. Consequently, the Miocene marginal marine and continental strata are closely interbedded throughout the basin. These results refine the recent depositional models for Miocene Amazonia, and challenge the theory that marine ingressions shaped the area only during one brief time interval (late Middle-early Late Miocene) during the epoch.

Much of recent literature has documented fossils of mangrove pollen, brackish-euryhaline fish and brackish-water ostracods, brackish-water trace fossil assemblages, and tidal deposits from various Miocene stratigraphic levels. Commonly, these data sets are collected from the same outcrops as those for which data sets imply freshwater conditions. We propose that these seemingly contrasting data sets can be unified, if the repetitive nature of the ingressions is considered, and all the paleoenvironmental data are presented in a detailed lithological and stratigraphical context.

Keywords: sedimentology, ichnology, tidal deposits, brackish water, western Amazonia, Miocene.

INTRODUCTION

Proposed depositional models for Miocene Amazonia are contentious. Most of the recent paleoenvironmental literature pertaining to Miocene Amazonia has suggested that during the Miocene the area was covered by an extensive wetland system consisting of lakes, swamps, forests, and rivers (Campbell et al., 2006; Cozzuol, 2006; Hoorn, 2006b; Hoorn and Vonhof, 2006; Kaandorp et al., 2006), much like the present-day Pantanal (Brazil, Bolivia, and Paraguay). This interpretation is based largely on studies applying isotope geochemistry on mollusk-fauna (Pebas Formation) that suggest that only during the late Middle-early Late Miocene (*Grimsdalea* pollen zone of Hoorn, 1993) did a meso-oligohaline ingression reach the western Amazonian basin, while the Lower and Middle Miocene strata are exclusively of a freshwater origin

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(Vonhof et al., 2003; Kaandorp et al., 2006). Similarly, the Upper Miocene deposits ("post-Pebas") are traditionally interpreted as continental, based on vertebrate fossil finds (Campbell et al., 2006; Cozzuol, 2006). Complicating these interpretations, an increasing body of literature has documented mangrove pollen, brackish-euryhaline fish fossils, brackish-water ostracods, brackish-water trace fossil assemblages, and tidal deposits from various Miocene stratigraphic levels (Hoorn, 1993; Räsänen et al., 1995; Monsch, 1998; Gingras et al., 2002ab; Hovikoski et al., 2005; Muñoz-Torres et al., 2006; Rebata et al., 2006a; Hovikoski et al., 2007a). Commonly, these data sets are collected from the same outcrops as those for which data sets imply freshwater conditions. These seemingly contrasting data sets are worth discussing, because comprehension of the Miocene paleoenvironmental history would greatly improve understanding of Amazonia's biotic evolution.

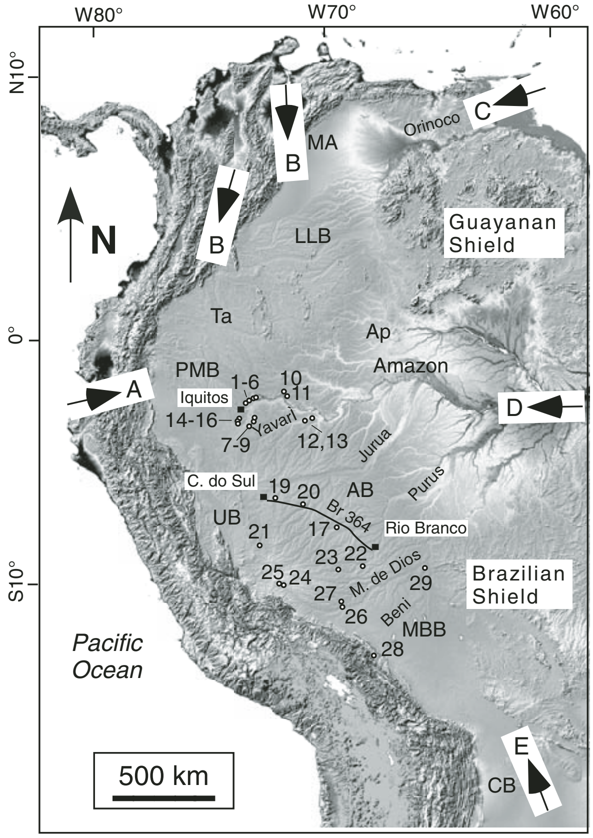

Figure 1. The study locations (numbers) and main geological units of western Amazonia and possible sea connections. AB—Acre Sub-basin (Table 1); Ap—Apaporis sand unit (fluvial/coastal setting, late Middle/early Late Miocene [Hoorn, 2006a]); CB—Chaco Sub-basin (coastal setting, Late Miocene [e.g., Hernández et al., 2005]); MA—Mérida Andes (coastal setting with marine episodes, Early-Middle Miocene [Hoorn et al., 1995 and references therein]); MBB—Madre de Dios-Beni Sub-basin (Table 1); LLB—Llanos Sub-basin (coastal/lagoonal setting with marine episodes, Early-Middle Miocene [Hoorn et al., 1995 and references therein]); PMB—Pastaza-Marañón Sub-basin (Table 1); Ta—La Tagua; UB–Ucayali Sub-basin. Other: A—likely sea connection at least during Early-Middle Miocene (Nuttall, 1990); B—likely sea connection during Early-early Late Miocene (Hoorn et al., 1995); C—likely sea connection at least during late Middle-early Late Miocene (Vonhof et al., 1998); D—possible sea connection; and E—probable hydrographic connection. Satellite image provided courtesy of NASA/JPL-Caltech.

In this study, we present a spatially and temporally large sedimentological and ichnological data set that covers all three of the established pollen zones of Hoorn (1993), which span the late Early to early Late Miocene (see discussion later in this paper) and the overlying Upper Miocene strata. These data are discussed in the context of other published paleoenvironmental interpretations. The aim of the study is to refine the existing depositional models for Miocene Amazonia. We argue that widespread, recurring, shallow and restricted marine ingressions shaped Amazonia throughout the Miocene, even during the Early and Middle Miocene, when the published isotopic data show only a freshwater signal, and the Late Miocene, when diverse continental vertebrate fauna developed. We propose that these contrasting data sets can be reconciled, if the repetitive nature of the marine ingressions is considered, and all the paleoenvironmental data are presented in a detailed lithological and stratigraphical context.

MATERIALS AND METHODS

The data set consists of sedimentological and ichnological field descriptions. In all, twenty-nine representative outcrops are selected (Fig. 1). The northernmost studied outcrops are near Iquitos in Peru, and the southernmost are in Beni (northern Bolivia), which is situated ~1500 km to the southeast of Iquitos. These deposits include the Pebas, Solimões, Nauta, Madre de Dios, Ipururo, and Quendeque formations. The outcrops studied were usually 5- to 40-m-high river banks or road cuts. Laterally, they could be followed from several tens of meters to hundreds of meters. The sedimentological approach included documentation of grain size, sedimentary structures, paleocurrent directions (measured from ripple and dune foresets), nature of bedding, bedding contacts, and lateral variability. Ichnological data collection included description of ichnogenera, size of the trace fossils, bioturbation intensity, cross-cutting relationships of traces fossils and tiering depth.

The data collected are summarized by region and grouped by stratigraphic level in Tables 1 and 2. The dating of the Pebas Formation sediments (Iquitos, Pebas, and Benjamin Constant regions) is based on palynostratigraphy of Hoorn (1993) and includes the following zones: late-Early to early Middle Miocene *Psiladiporite-Crototricolpites* pollen zone (PC-zone), Middle Miocene *Crassoretitriletes* pollen zone (C-zone), and late Middle to early Late Miocene *Grimsdalea* pollen zone (G-zone). The

TABLE 1. SUMMARY OF INTERPRETED OCCURRENCE OF TIDAL SEDIMENTARY STRUCTURES AND BRACKISH-WATER TRACE FOSSILS IN PEBAS FORMATION

Location	Formation, age, and nature of outcrops	Interpreted presence of tidal sedimentary structures	Inclined heterolithic stratification	Interpreted presence of brackish-water bioturbation	Interpreted presence of continental ichnofossils/other	Interpretation of depositional setting
Iquitos Region						
(1–5) Indiana and (6) Santa Teresa (DR1 and DR5) Localities between S 03°31′03″ W 73°04′27″ and S 03°29′19″ W 73°00′17″	• Pebas Formation • Late Early–early Middle Miocene, PC-zone • Fluvial cutbank, up to 28-m exposure • Generally unweathered exposure	• mm-scale sedimentary couplets • Asymmetric couplets • Rare current reversals measured from ripple foresets	• Locally present in all studied outcrops • Composed of cm-scale mud beds with mm-scale sand laminae • Locally burrowed from base of sand	• In general, a robust ichnofauna comprising large examples of Op, Pl, La, Th, Sk, and Ch • Common Th Glossifungites ichnofacies associated with parasequence boundaries • Large-diameter ichnofossils that contain rhythmic lamination	• Present only at the tops of parasequences, usually below lignitic facies • Rhizoliths	• Complex association of bay-margin facies. Includes shoreline, bay, delta/channel facies, and marsh
(7) Tamshiyacu S 04°00′36″ W 73°09′24″ and (8) San Rafael S 04°02′14″ W 73°08′37″	• Pebas Formation • Middle Miocene, C-zone • Fluvial cutbank, up to 8-m exposure • Generally unweathered exposure	• Mud-flasers on ripple/dune foresets • mm-scale sedimentary couplets • Rare current reversals measured from ripple foresets	• Locally present in half of studied outcrops • Composed of cm-scale mud beds with mm-scale sand laminae: rarer cm-scale sand beds in IHS	• Moderate diversity, includes Ar, Sk, Pl, Th, Te, Op, and Ch • Traces small to moderate in size • Several sections void of ichnofauna • Common Th Glossifungites ichnofacies	• Thick lignitic horizons (in location 8) • Rhizoliths near parasequence tops	• Complex association of bay-margin facies; includes shoreline, bay, delta/channel facies, and marsh
(9) Porvenir (DR3) S 04°13′34″ W 73°22′10″	• Pebas Formation • Late Middle–early Late Miocene, G-zone • Fluvial cutbank, up to 20-m exposure	• Rare heterolithic bedding	• Absent	• Common Th Glossifungites ichnofacies; • Low-diversity assemblage consisting of Pl, Pa, Ch, Cy, Te, and Th • Traces usually very small in size	• Non-rooted lignitic horizons • Freshwater mollusks in situ posture below lignite	• Transgressive/regressive bay-margin parasequences
Pebas Region						
(10) Ave Maria (DR2) S 03°20′02″ W 71°49′16″ and (11) Santa Julia S 03°20′17″ W 71°48′56″	• Pebas Formation • Middle Miocene, C-zone • Fluvial cutbanks up to 12-m exposure	• Sedimentary couplets in burrow infills • Upward-fining shoreface profile	• Absent	• Moderate- to low diversity-assemblages of Ar, Th, Pl, Op, Te, Pa, Cy, Ch, and Tr • Common Glossifungites ichnofacies	• Trace fossils consisting of irregularly shaped, open constructions near lignitic horizons • Rhizoliths near parasequence tops	• Transgressive/regressive bay-margin parasequences • Proximal bay-offshore–marsh successions
Benjamin Constant Region						
(12 and 13) Rio Yavari S 04°21′38″ W 70°54′48″ and S 04°08′02″ W 70°22′37″	• Pebas Formation • Late Middle–early Late Miocene, G-zone • Fluvial cutbanks up to 10-m exposure	• Locally flaser bedding and mud-draped ripple foresets	• Absent	• Moderate diversity assemblages of Th, Pl, Op, Ch, Ar • Common Th Glossifungites ichnofacies	• Thick lignitic horizons	• Bay-margin parasequences • Aggradational marsh deposits

Note: Key to trace fossil abbreviations: As–*Asterosoma*, Ar–*Arenicolites*, Ch–*Chondrites*, Cy–*Cylindrichnus*, Gy–*Gyrolithes*, La-*Laminites,* Lo–*Lockeia*, Op–*Ophiomorpha*, Pa–*Palaeophycos*, Pl–*Planolites*, Ps-*Psilonichnus*, Sk–*Skolithos*, Te–*Teichichnus*, Th–*Thalassinoides*, and Tr–*Trichichnus*.

TABLE 2. SUMMARY OF INTERPRETED OCCURRENCE OF TIDAL SEDIMENTARY STRUCTURES AND BRACKISH-WATER TRACE FOSSILS IN POST-PEBAS STRATA

Location	Formation, age, and nature of outcrops	Interpreted presence of tidal sedimentary structures	Inclined heterolithic stratification	Interpreted presence of brackish-water bioturbation	Interpreted presence of continental ichnofossils/other	Interpretation of depositional setting
Nauta Region						
(14–16) Nauta S 4°18′42″ W 73°31′23″ S 4°24′37″ W 73°34′56″ S 4°29′31″ W 73°35′52″	• Nauta Formation • Late Miocene, post-Pebas • Road cuts up to 15 m	• mm-scale sedimentary couplets • Assymetric couplets • Bipolar paleocurrent directions • Rare, mud-draped dune foresets	• Locally present in half of studied outcrops • Composed of cm-scale mud beds with mm- to cm-scale sand laminae • Rarely to locally burrowed	• Robust, sporadically occurring ichna • Includes large examples of Th, La, Pl, Sk, Ar, Ps, and rare Op	• Well-developed assemblage that can include Ta and Pl most common near parasequence tops • Rhizoliths near parasequence tops	• Deltaic-estuarine channel complexes • Paleosols
Acre Region						
(17) Purus (Oriental) (DR5) S 08°49′19″ W 69°13′45″	• Solimões Formation • Late Miocene, post-Pebas • Fluvial Cutbank, up to 12-m exposure	• Flasers on ripple foresets • mm-scale sedimentary couplets	• Locally present in all studied outcrops • Composed of cm-scale mud beds w/ mm- to cm-scale sand laminae; • Locally to commonly burrowed	• In general, a robust ichnofauna comprising large examples of Op, Pl, La, Th, Te, Sk, and Lo	• Insect larvae traces and trace fossils consisting of small Ta • Rhizoliths near parasequence tops	• Tidally and seasonally influenced delta plain-estuarine channel complexes • Paleosols
(18) Seringal Amapa S 10°00′45″ W 67°50′23″	• Solimões Formation • Late Miocene, post-Pebas • Fluvial cutbank, up to 15-m exposure	• Sedimentary couplets • Asymmetric couplets • Cyclic rhythmites	• Locally present in all studied outcrops • Composed of cm-scale mud beds w/ mm- to cm-scale sand laminae	• Low-diversity trace fossil assemblage consisting of very rare Sk, Ar, and Pl	• Insect larvae traces and trace fossils consisting of small Ta only near parasequence tops	• Tidally influenced estuarine channels • Paleosol
(19) Community Katukina S 07°46′17″ W 72°13′14″ (20) Tarauacá 16.5 km west of Tarauacá (21) Volta Grande S 9°05′54″ W 72°41′52″	• Solimões Formation; • Late Miocene, post-Pebas • Road cuts along Br 364 (18, 19), river cutbank (20), up to 15-m exposure	• Mud-draped dune foresets • Cyclic thickness variation in strata • Bipolar paleocurrent directions	• From cm- to m-scale sand beds and cm-scale mud beds • Articulated Purussaurus fossil discovered in an unbioturbated, organic-rich channel near Feijó	• Moderate- to low-diversity and density assemblages comprising Sk, Pa, Gy, La, Pl, Th, Lo, and fu	• Low-diversity, monospecific assemblages of irregular or meniscus-bearing burrows usually in the top of channel units or as thin intervals	• Tidally and seasonally influenced delta plain-estuarine channel complexes intercalated with continental environments
(22) Rio Branco–Bolivia Hwy. S 10°42′18″ W 68°23′55″	• Solimões Formation—Late Miocene • Road cuts, up to 7-m exposure; • Severely weathered	• Rare, mud-draped dune foresets • Generally devoid of tidal indicators	• Absent	• High- to moderate-diversity assemblages of Op, Th, Pl, Rh, Te, and Sk	• Low-diversity monospecific assemblages of irregular or meniscus-bearing burrows near top of sequence	• Upward-fining brackish-water channel • Paleosol
(23) Boca de Santa Pedro S 10°55′36″ W 69°25′27″	• Solimões Formation—Late Miocene • Fluvial cutbank, up to 10-m exposure • Severely weathered	• Flasers on ripple foresets • mm-scale sedimentary couplets • Rare, mud-draped dune foresets	• Composed of cm-scale mud beds with mm- to cm-scale sand laminae • Locally to commonly burrowed	• High- to moderate-diversity assemblages of Op, Th, Pl, La, Te, and Ch	• Low-diversity monospecific assemblages of irregular or meniscus-bearing burrows near top of sequence	• Tidally influenced estuarine channels • Strong seasonal signal preserved • Paleosols

(*continued*)

TABLE 2. SUMMARY OF INTERPRETED OCCURRENCE OF TIDAL SEDIMENTARY STRUCTURES AND BRACKISH-WATER TRACE FOSSILS IN POST-PEBAS STRATA (*continued*)

Location	Formation, age, and nature of outcrops	Interpreted presence of tidal sedimentary structures	Inclined heterolithic stratification	Interpreted presence of brackish-water bioturbation	Interpreted presence of continental ichnofossils/other	Interpretation of depositional setting
Madre de Dios Region						
(24 and 25) Cocha Cashu S 11°54′11″ W 71°23′39″ S 11°53′47″ W 71°25′31″	• Madre de Dios–Ipururo Formation • Late Miocene, post-Pebas • Fluvial cutbanks (Río Manu), up to 30-m exposure	• Sedimentary couplets • Asymmetric couplets • Cyclic rhythmites • Bipolar paleocurrent directions • Locally regular reactivation surfaces	• Locally present • Composed of cm-scale mud and sand beds consisting of wavy-flaser bedding	• In general unbioturbated • In the top of the succession Th, Gy, and Op (reburrowed by Pl)	• In the lower part of the succession bedding plane trackways (Un , Di) • Meniscus-bearing burrows in paleo-soils	• Tidally influenced–dominated deposits predominately in inner estuarine setting • Paleosols
(26) Pastora S 12°34′333″ W 69°12′180″	• Madre de Dios–Ipururo Formation • Late Miocene, post-Pebas	• Flasers on ripple foresets • mm-scale sedimentary couplets	• Composed of cm-scale mud beds with mm- to cm-scale sand laminae • Sands typically planar to ripple laminae	•Very rare Sk, Pl, and Th •Generally unburrowed	• Ta, Di, and irregular burrows that descend from pedogenic intervals	• Tidally and seasonally influenced delta plain-estuarine channel complexes.
(27) Rio de las Piedras S 12°29′ W 69°15′ (approx.)	• Madre de Dios–Ipururo Formation • Few meters thick exposure	• Mud draped dune foresets • Regular reactivation surfaces	• Absent	• Unburrowed	• Unburrowed	• Tidal channel
Beni Region						
(28) Rio Quendeque S 14°59'39" W 67°47'18" and (29) Camboya (Riberalta) S 11°06′ W 66°35′	• Quendeque Formation (28) and Cobija Formation (29) • Middle-Late Miocene? • Fluvial cutbanks	Locally present are: • Double mud drapes • Mud-draped dune foresets • Cyclic rhythmites (28) • Current reversals (29)	• cm-scale sand-mud beds	• Very rare low-diversity assemblages comprising Gy, Th, and Te (in location 28)	• Common meniscus-bearing burrows in pedogenic intervals, Pl • Locally dense assemblages consisting of irregularly shaped, open constructions	• Fluvio-lacustrine setting with occasional tidal influence • Paleosols, flood plain facies

Note: Key to trace fossil abbreviations: As—*Asterosoma*, Ar—*Arenicolites*, Ch—*Chondrites*, Cy—*Cylindrichnus*, Di-*Diplichnites*, fu—fugichnia, Gy—*Gyrolithes*, La-*Laminites*, Lo—*Lockeia*, Op—*Ophiomorpha*, Pa—*Palaeophycos*, Pl—*Planolites*, Ps—*Psilonichnus*, Sk—*Skolithos*, Te—*Teichichnus*, Th—*Thalassinoides*, Tr—*Trichichnus*, and Un—*Undichna*.

other regions (Nauta, Acre, Madre de Dios, and Beni Region) are mainly considered to be Late Miocene ("post-Pebas") based on fossil content, stratigraphic location, and ^{40}Ar/^{39}Ar dates (Campbell et al., 2001; Hermoza, 2004; Cozzuol, 2006). Dates of deposits at locality 28 are inconclusive; the deposits may correlate with the Pebas Formation.

RESULTS

Below is a synthesis of common sedimentological and ichnological characteristics of the Lower-Upper Miocene Pebas Formation and Upper Miocene ("post-Pebas") strata. The key sedimentary structures (e.g., Nio and Yang, 1991) and ichnological features are summarized in Tables 1 and 2 for Pebas and "post-Pebas" deposits, respectively. Detailed examples of lithological columns from each studied stratigraphic level are presented in the GSA Data Repository (Figs. DR1–DR5[1]).

Late Early-Early Late Miocene (Pebas Formation)

The Pebas Formation deposits (localities 1–14) consist of 3- to 10-m-thick, sharp-based, upward-fining or upward-coarsening successions (DR1–DR3). The lower contact is laterally extensive, nearly flat, and typically possesses tubular, regularly branching, medium- to large-diameter (10–25 mm) *Thalassinoides* or *Psilonichnus* (Figs. 2A–2C). The *Thalassinoides* bear bulbous enlargements at burrow intersections (Fig. 2A). *Psilonichnus* may contain passively laminated, rhythmic infill. In most of the examples, the trace fossils descend into organic-rich mud, cross-cut rhizoliths, and are unlined and infilled with overlying sediment and shell hash, defining a *Glossifungites*-demarcated discontinuity.

The deposits overlying the contact consist of 0.5- to 1-m-thick, upward-fining, massive appearing, blue-colored sandy mud. The unit bears a low- to moderate-diversity, mixed ethology suite of trace fossils, but unburrowed, shell-hash-rich intervals also occur. Observed ichnogenera include *Thalassinoides, Ophiomorpha, Arenicolites, Chondrites, Asterosoma, Planolites,* and *Teichichnus.* Moderate diversity trace-fossil suites are common in PC- and G-zones; in this facies, C-zone strata typically display a low-diversity suite of trace fossils.

Upward, the sandy mud facies grades into *Planolites-Chondrites*-bearing, laminated clayey

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[1] GSA Data Repository Item 2007210, Figures DR1–DR5, is available at www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

mud (Figs. 3A, 3B). The *Planolites* examples are 2–3 mm in diameter, may display meandering, and are typically reburrowed by diminutive *Chondrites* (Fig. 3B). Bioturbation intensity is evenly distributed in this facies and is typically high (60%–100%).

The clayey mud gradually coarsens upward into interbedded sand and mud that is lightly burrowed by a low-diversity suite comprising lined and unlined *Skolithos, Arenicolites, Teichichnus, Ophiomorpha irregulaire* (Figs. 3C–3E), *Gyrolithes, Cylindrichnus, Thalassinoides, Planolites,* and fugichnia. Large, rhythmically infilled, horizontally oriented *Psilonichnus* are present in places (Fig. 3F). Equilibrium structures *(Teichichnus)* and dense monospecific suites of *Arenicolites* and lined *Skolithos* are locally common (Fig. 3G). The sedimentary structures consist of wave ripples, combined-flow ripples, and current ripples. Ripple foresets are typically mud-draped or bear organic matter (Figs. 3D, 3E, 4A, and 4B). In addition, double mud drapes are present locally, as are current reversals (measured from the ripple foresets). Double mud drapes are especially well developed in tubular burrow infills. Finally, in places, the deposits consist of heterolithic bedding that bears 0.5- to 2-cm-thick, white-colored, calcium carbonate-rich, laminated mud beds, which are interbedded with blue-colored sandy mud beds (Figs. 3F, DR1, DR2).

Toward the top of the heterolithic units, ichnological diversity decreases, and bioturbation becomes sporadic; only rare *Skolithos*, *Ophiomorpha, Arenicolites,* or indistinct, diminutive burrow mottling are present. Contemporaneously, synaeresis cracks become common in the mud interbeds (Figs. 3C, 4B).

Near the top of the succession, the heterolithic bedding grades into a root-bearing mud and finally into a 20- to 150-cm-thick, organic-rich mud or lignitic interval that contains common freshwater fossils such as turtles, caimans, and undifferentiated bones of continental vertebrates. Also, non-rooted lignitic intervals are present, especially in G-zone sediments.

In addition, sharp-based, laterally limited, upward-fining successions (Fig. DR4) are observed in the Pebas Formation. Their lower contact is erosional, trough-shaped, and laterally discontinuous. The deposits consist of mud-draped cross-stratification or vertically stacked, Inclined Heterolithic Stratification (IHS) (Figs. 4C–4E). Bipolar dune foresets are common in these deposits (Fig. DR4). The IHS comprises millimeter-scale mud, sand, and organic matter alternations, but decimeter-scale sand and mud alternations are also observed. Soft-sediment deformation is common. IHS is reported from the C-and G-zones.

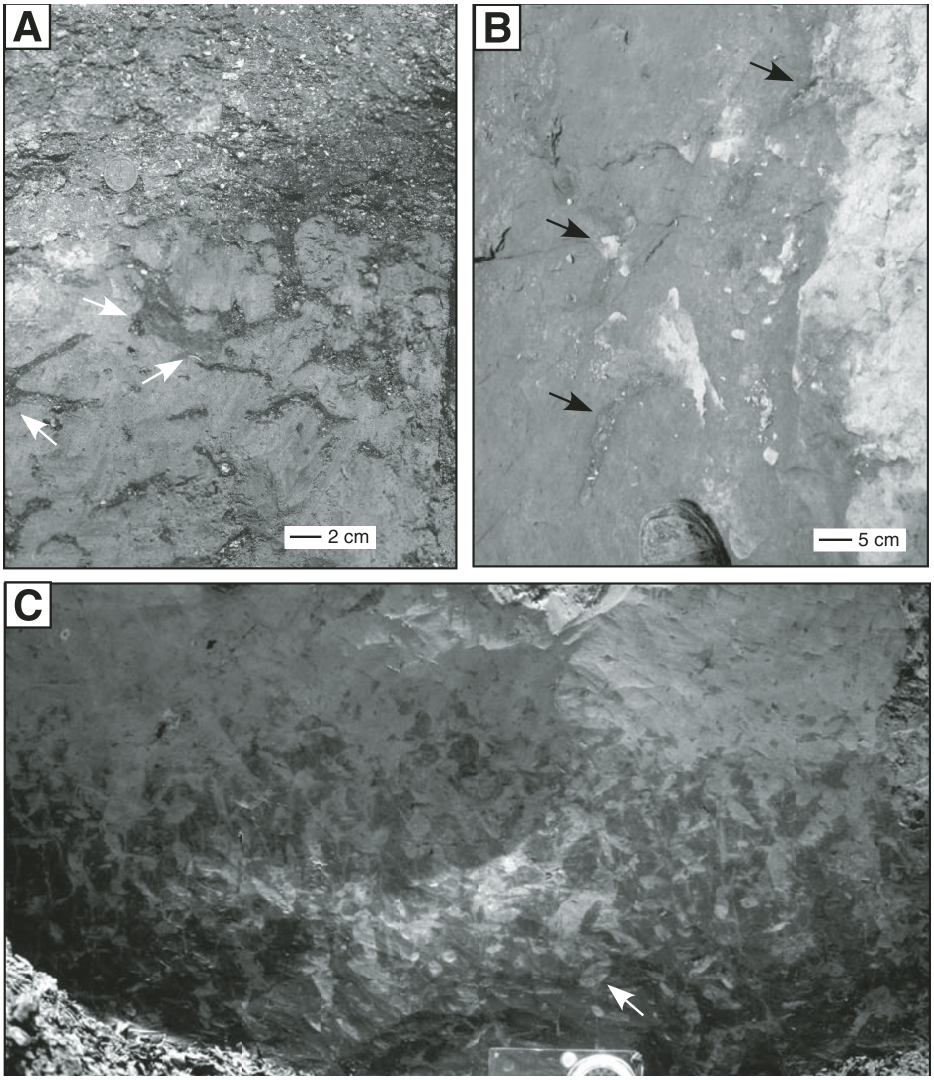

Figure 2. Examples of the *Glossifungites* Ichnofacies, consisting of *Thalassinoides*. (A) *Thalassinoides* descending from the base of a sequence into pedogenically altered mud. White arrows—enlarged burrow intersections. Locality 9, G-zone. (B) Regularly branching *Thalassinoides* (black arrows) burrowing into pedogenically altered mud. Horizontal view. Locality 7, C-zone. (C) A similar example in a vertical section. Arrows indicate an oval-shaped burrow cross-section. Compass is shown for scale. Locality 10, C-zone.

Late Miocene (“Post-Pebas”)

The “post-Pebas” outcrops (localities 14–29; date of locality 28 is unclear) dominantly comprise sharp-based, 3- to 16-m-thick, upward-fining IHS successions that are gradationally capped by root-bearing mud or a pedogenically altered horizon (Figs. 5A–5F, DR5). The basal contacts are erosional and trough-shaped and bear mud clasts. The lower parts of the successions consist of massive or trough cross-stratified silty sand. The cross-strata are typically mud-draped, or display minute, superimposed mud-draped ripples. Double mud drapes, sigmoidal ripples, and regular reactivation surfaces are present (Figs. 5D–5F). Upward, the sandy deposits grade into IHS. The IHS commonly contains sedimentary rhythmites (Figs. 5B and 5C) or laterally extensive, decimeter-scale sand and mud alternations. Bipolar sediment-transport indicators (current ripples) and soft sedimentary deformation are common. Synaeresis cracks are present locally.

Although the above-mentioned deposits are typically unburrowed, they locally contain rare *Skolithos, Cylindrichnus, Planolites, Palaeophycus, Laminites,* and/or *Gyrolithes* (Figs. 6A–6F). Very rarely present are smooth-walled, regularly branching *Thalassinoides, Ophiomorpha,* and *Asterosoma* (Figs. 6A and 6B; DR5).

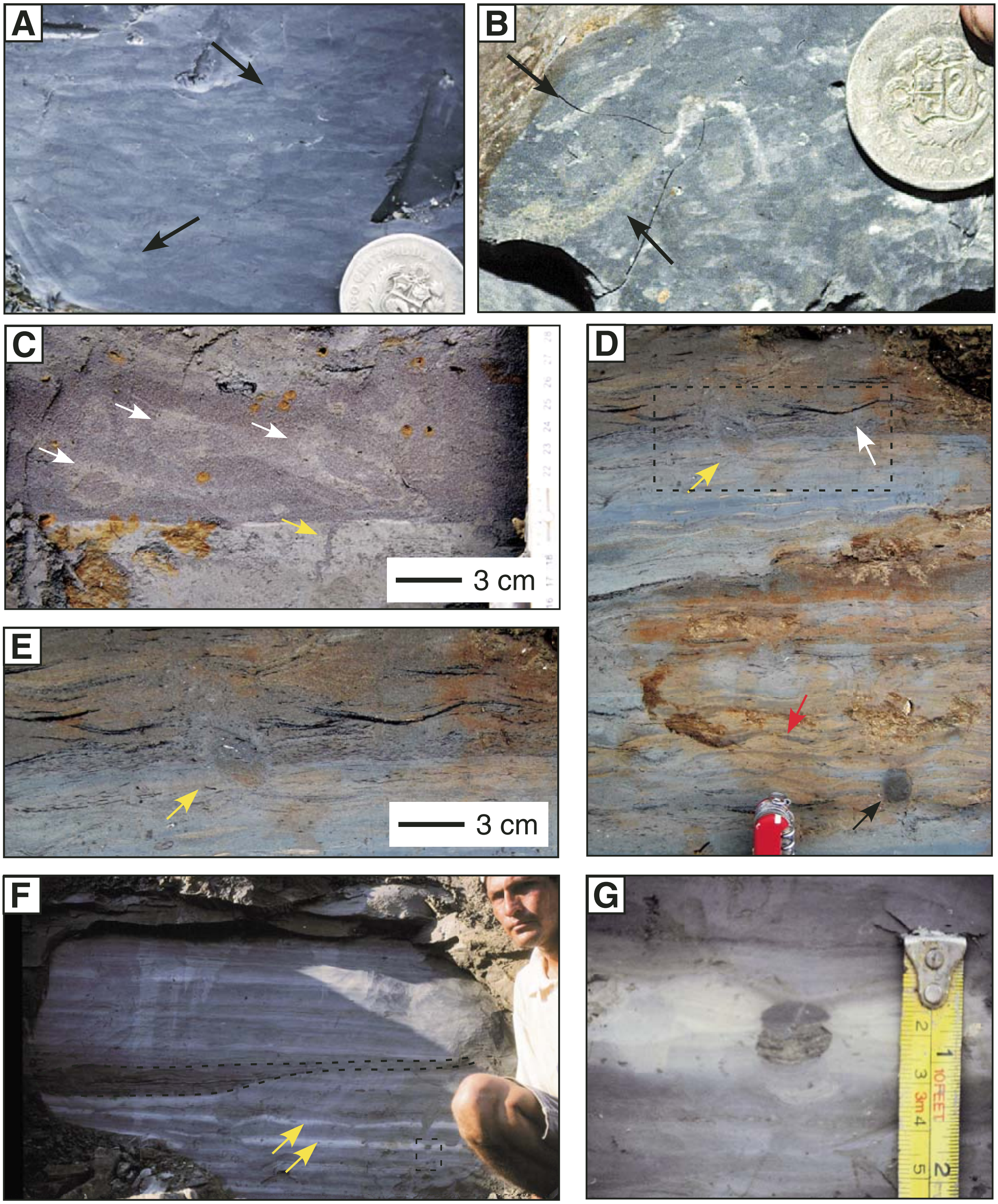

Figure 3. (A) *Planolites-Chondrites* suite (black arrows point to some examples) bearing clayey mud. The coin is ~2 cm in diameter. C-zone. (B) Horizontal view of the same facies. Diminutive *Chondrites* (black arrows) reburrow *Planolites*. (C) *Ophiomorpha* (white arrows) in massive muddy sand. Yellow arrow—a synaeresis crack at the sand-mud interface. Locality 11, G-zone. (D) *Ophiomorpha* (yellow arrow) in heterolithic bedding. Black arrow—*Thalassinoides* associated with an overlying *Glossifungites*-demarcated surface; red arrow—heterolithic combined flow ripples; white arrow—erosional remnants of organic matter-draped ripples. Lined square indicates the location of (E). Locality 7, C-zone. (E) A close-up of *Ophiomorpha*, at the same locality as (D). (F) A large, horizontally oriented burrow containing passively laminated, rhythmic infill. Yellow arrows indicate whitish, Ca-rich interbeds that are interpreted as dry seasonal. Lined square indicates the location of (G). Locality 10, C-zone. (G) *Teichichnus* crossing a Ca-interbed at the same locality as (F).

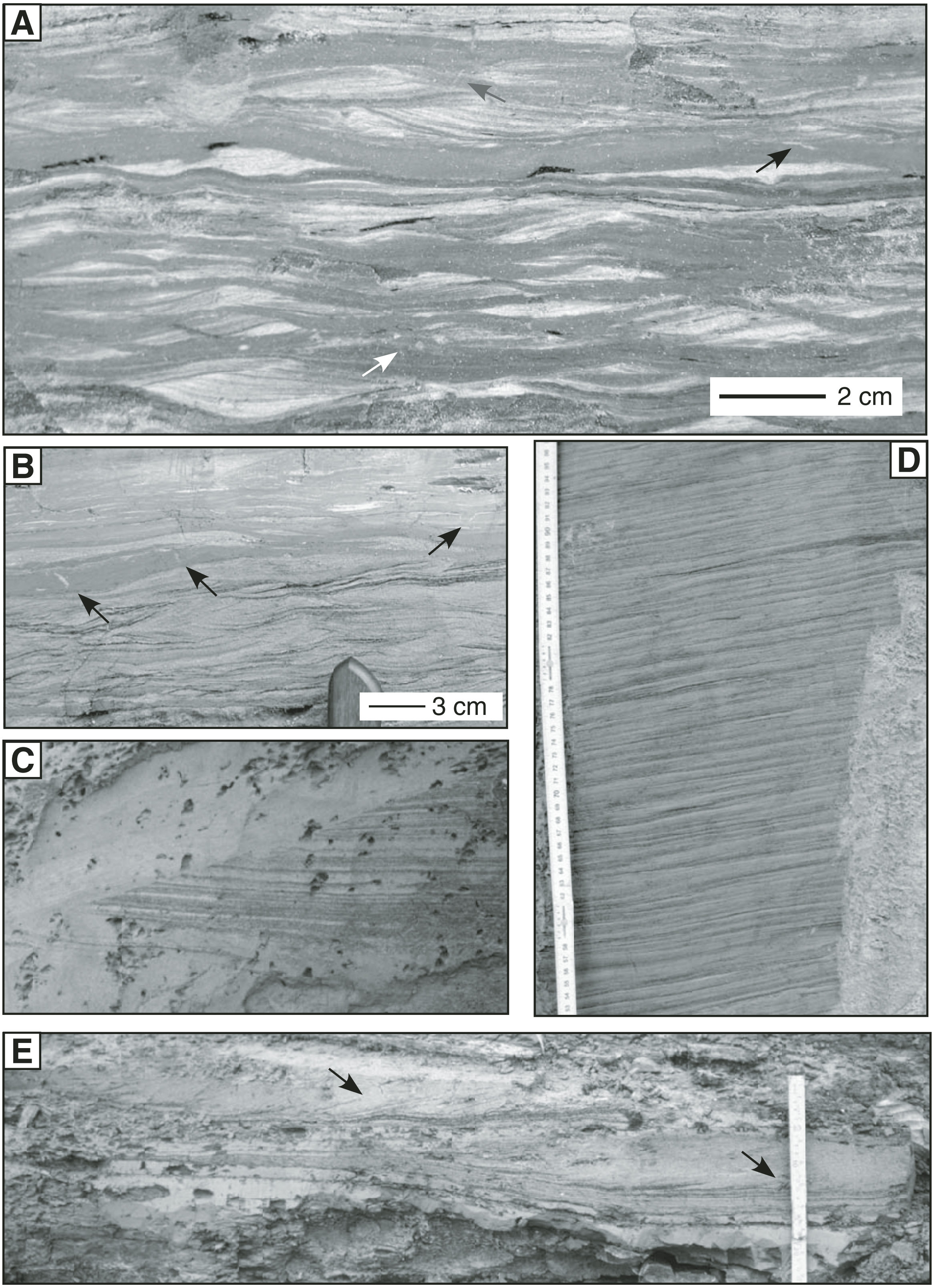

Figure 4. (A) Heterolithic combined-flow ripples. Possible *Thalassinoides* is present in the top left corner of the photo. Other background bioturbations include small *Arenicolites* (black arrow), *Skolithos* (gray arrow), and *Planolites* (white arrow). Locality 7, C-zone. (B) Synaeresis cracks bearing heterolithic bedding. Locality 7, C-zone. (C) Truncated muddy rhythmites. Locality 4, PC-zone. (D) IHS consisting of sedimentary rhythmites. Locality 1–5, PC-zone. (E) Mud-draped dune bottom-foresets. Locality 4, PC-zone (DR4).

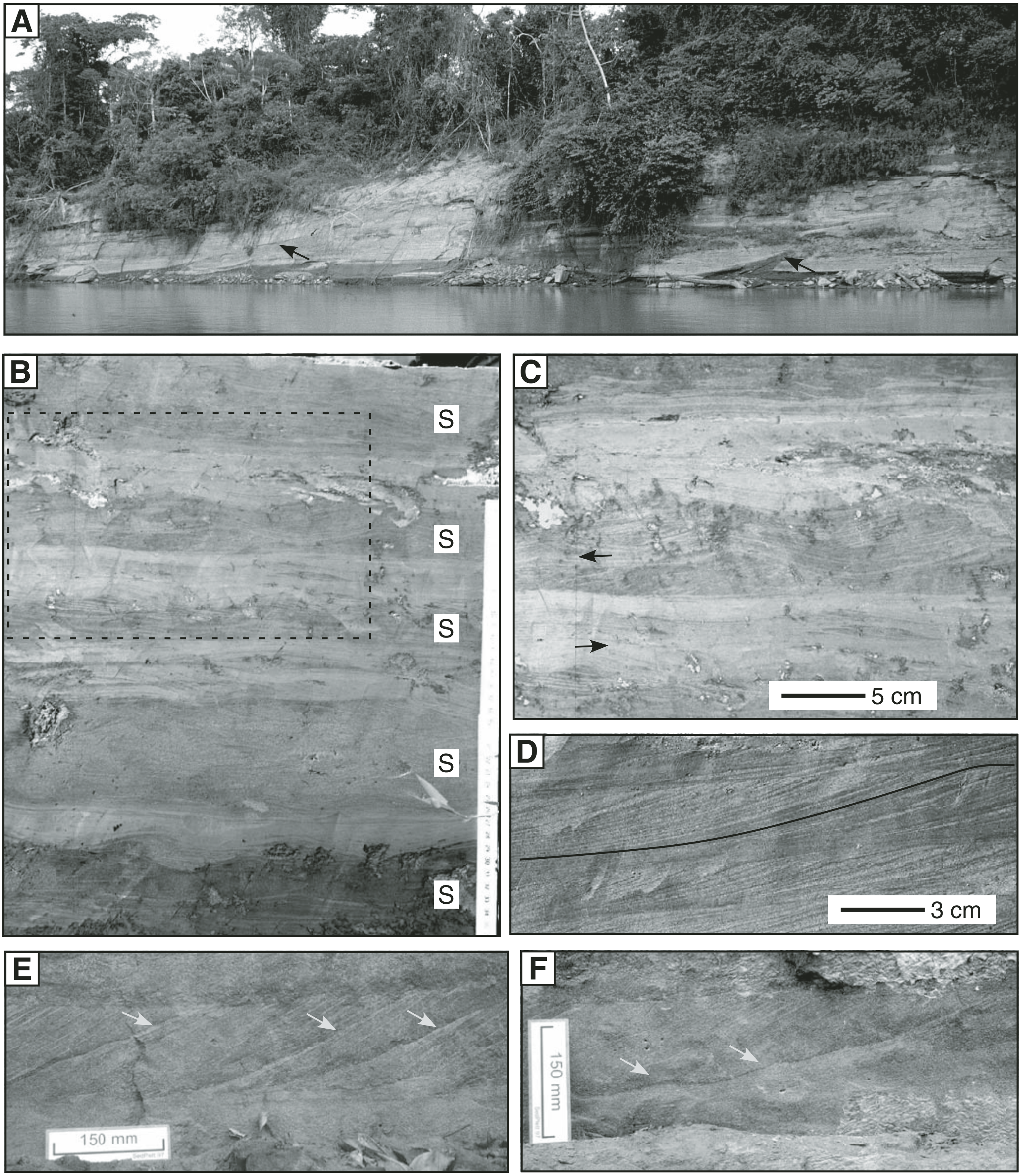

Figure 5. Examples of facies interpreted as tidally influenced from "post-Pebas" deposits. (A) An outcrop example of low-angle IHS. Arrows indicate inclined erosional contacts that divide IHS into imbricate cosets. Field of view is ~50 m. Locality 22. (B) Low-angle IHS consisting of statistically verified cyclic rhythmites (cf. Hovikoski et al., 2007a, Fig. 7I therein). "S" indicates interpreted occurrence of spring tides. Lined square indicates the location of C. The locality is the same as (A). (C) Close-up view of IHS. Black arrows—opposing foreset dip directions. (D) Sigmoidal ripples displaying sedimentary rhythmites. (E) Mud-draped dune foresets displaying regular reactivation surfaces (white arrows). Locality 27. (F) An example similar to (E). Note the probable counter-current ripples on the reactivation surfaces (white arrows). The locality is the same as (E).

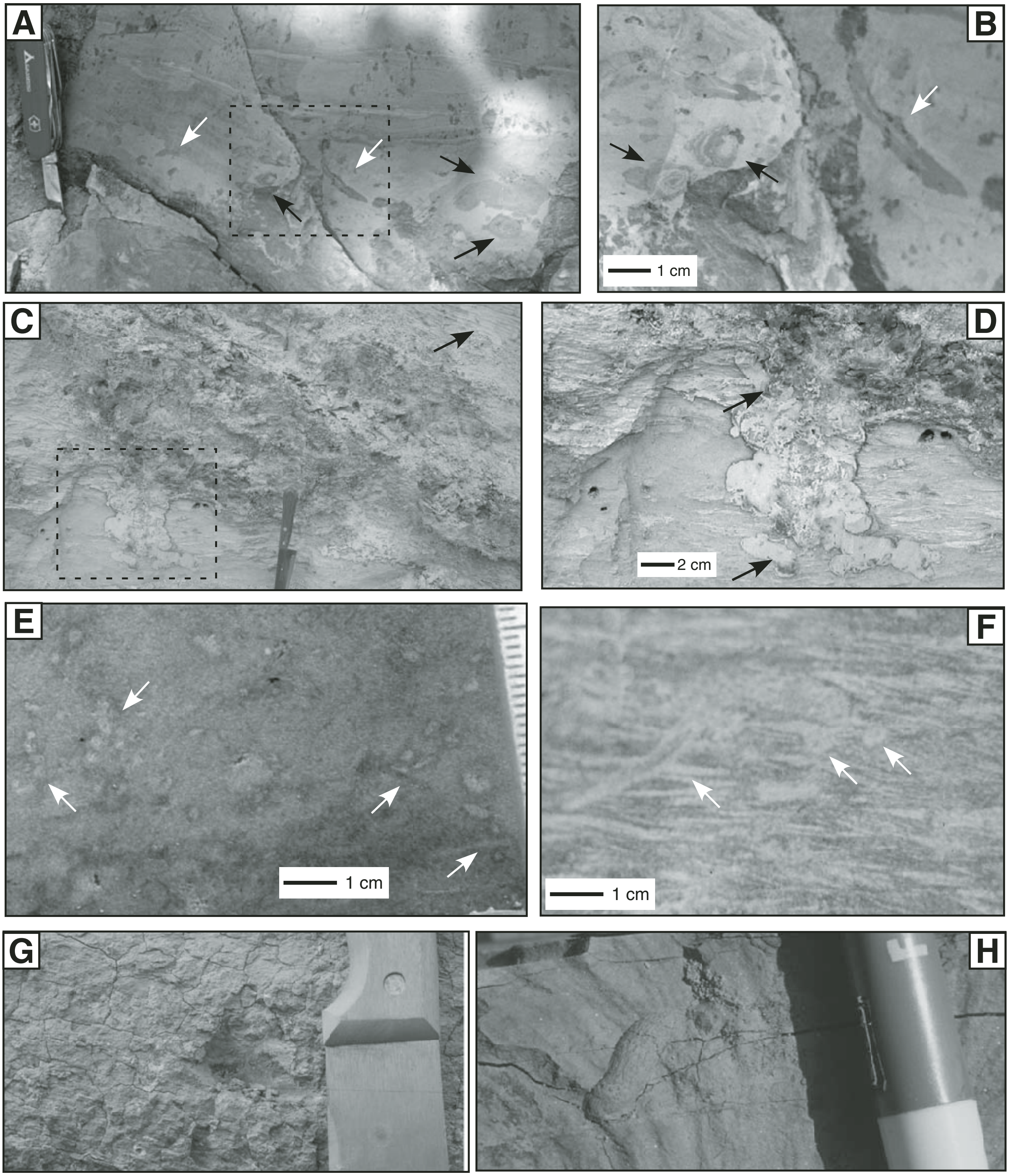

Figure 6. (A) ***Asterosoma*** **(black arrows)—*****Cylindrichnus*** **suite (white arrows). Lined square indicates the location of (B). Knife is shown for scale. Madre de Dios/Ipururo Formation. (B) A close-up view of previous ichnofabric. (C)** ***Laminites*****-bearing IHS. Bioturbation descends from the fine-grained IHS member into the coarse-grained member (flaser bedded sand). The cyclicity is interpreted as seasonal within a tidally influenced system (cf. Rebata et al., 2006a). Black arrow—sedimentary rhythmites; lined square—location of (D). Knife is ~20 cm long. Nauta Formation. (D) A close-up view of (C). Black arrow—examples of** ***Laminites*****. (E)** ***Gyrolithes*** **(white arrows) in massive sand (coarse member of IHS). Locality 19, Upper Solimões Formation. (F)** ***Cylindrichnus*** **(white arrows) in mud-draped ripples (coarse member of IHS). Upper Solimões Formation. (G) and (H) Suites interpreted as continental. (G) Monospecific occurrence of** ***Taenidium*** **concentrated near the top of an IHS succession. The blade of a knife is ~4 cm wide. Locality 19, Upper Solimões Formation. (H) Monospecific suite of** ***Scoyenia*** **in a pedogenically altered horizon. The pen is ~0.6 cm wide. Madre de Dios Formation.**

Notably, higher diversity assemblages are reported from the Nauta Formation (localities 14–16; Rebata et al., 2006a).

The IHS successions grade upward into pedogenically altered sediment, wherein discrete ichnofossils dominantly comprise *Taenidium*, *Scoyenia, Planolites*, unnamed chaotically branched burrows, and root traces (Figs. 6G and 6H). The trace fossils descend downward at angles between 90° and 30°, and commonly branch to smaller burrows at irregular angles. This facies is locally present in all the studied outcrops.

Finally, in addition to IHS succession, locally present are unburrowed, sharp-based, upward-fining successions that do not display heterolithic bedding. Such successions may be rich in organic matter.

INTERPRETATION

Depositional Setting

Late Early-Early Late Miocene (Pebas Formation)

The *Glossifungites*-demarcated lower contact of most Pebas successions is interpreted to represent a transgressive surface of erosion (TSE). This interpretation is based on the occurrence of the surface on top of pedogenically altered sediments and the presence of smooth-walled, regularly branching, firm-ground *Thalassinoides*, which descend into underlying root-bearing mud (Figs. 2A–2C). Such burrow morphologies are observed only in marginal-marine to marine deposits, and are attributed primarily to the work of thalassinid shrimp (Shinn, 1968; Rice and Chapman, 1971; Frey and Howard, 1975; Frey et al., 1978; Dworschak, 1982; Dworschak, 2000; Gingras et al., 2000; Nesbitt and Campbell, 2002). Also, complex subaperture geometries are commonly present in thalassinid burrows, but are absent in the burrows of other crustaceans (Fig. 2B). Furthermore, the irregular burrows of crabs, lobsters, and crayfish are equally well known, and they characteristically have simple U-, J-, or Y-shaped subapertures with rare or no basal branching (Shinn, 1968; Frey et al., 1978; Gingras et al., 2000; Nesbitt and Campbell, 2006), as is the case with the *Psilonichnus* examples noted earlier in this paper (Fig. 3F).

Above the basal contact, the mixed ethology suite of trace fossils (in the sandy mud) fines upward into a *Planolites-Chondrites*-bearing, laminated, clayey mud (Figs. 3A and 3B). This gradation is interpreted as a gradual deepening into a low-energy, dysoxic, distal bay environment. The grazing behavior, as expressed by the meandering *Planolites*, points to deposit feeding, and supports the interpretation of a quiescent setting below storm-weather wave base or in a sheltered locale. The co-occurrence of *Planolites* and *Chondrites* is interpreted to result from low-oxygen conditions (cf. Martin, 2004). Based on their typical position within a unit, the laminated clayey mud facies are interpreted as the zone of maximum flooding of a sequence.

Upward in the succession, the sediments coarsen, and signs of wave-reworking are evident (wave ripples, low-angle laminae truncation). Simultaneously, the ichnofossil suites grade into mixed-ethology, ichnofossil assemblages, indicating increased oxygen availability. This is best explained by the progradation and thereby shoaling of the bay margin. The low-diversity, mixed ethology suites, and the presence of monospecific, dense occurrences of morphologically simple trace fossils, such as lined *Skolithos* and *Arenicolites,* are characteristic of brackish-water settings (cf. Pemberton and Wightman, 1992; MacEachern et al., 2007). Particularly, trace fossils such as lined *Skolithos*, *Chondrites, Ophiomorpha, Cylindrichnus*, and *Gyrolithes* are not typically reported from freshwater deposits. The pervasive presence of synaeresis cracks (Figs. 3C and 4B) and alternation of unburrowed and densely burrowed monospecific sediment near the top of the sequences may further indicate that the salinity was rapidly fluctuating (Plummer and Gostin, 1981).

The Pebas deposits are interpreted to be tidally influenced because of the presence of: (1) various types of heterolithic bedding; (2) double mud drapes preserved, e.g., in tubular burrow infills (Table 1); (3) mm-scale rhythmites; (4) bipolar paleocurrents; (5) IHS-bearing channels; and (6) local upward-fining, bay-margin/shoreface profiles.

A range of hydraulic conditions can produce rhythmic lamination. These include regular waxing and waning of fluvial currents and daily or seasonal variations of sediment input into a depositional setting (as with varves). Commonly, tidal processes provide the most parsimonious explanation for rhythmic lamination. For example, tidal currents best explain current reversals, asymmetric sedimentary couplets, and burrows infilled with asymmetric sedimentary couplets (tubular tidalites). In each case, a regular variation or reversal of hydraulic current is required to produce the sedimentary structure. Moreover, the upward-fining, bay-margin profiles may result from the presence of tidal flats. It should be noted that high-certainty, cyclic tidal rhythmites have yet to be described from the Pebas Formation. Statistical analysis of rhythmites from IHS channels (Fig. 4C) has so far been hindered by methodological problems (i.e., high-swelling clay content obstructs thin-section analysis).

The Pebas Formation deposits are also interpreted to be seasonally influenced. This interpretation is based on superimposition of lower frequency cycles on tidally influenced deposits and regular occurrence of calcium carbonate-rich mud interbeds in the bay-margin deposits (Fig. 3F). The Ca-enrichment is interpreted to be due to dry seasonal conditions.

In summary, the Pebasian sequences are interpreted as transgressive-regressive, bay-margin successions. The depositional environments include dysoxic distal bay, brackish, tidally influenced bay margin, and freshwater swamp and lagoon environments. Locally present are fluvio-tidal channels.

Late Miocene ("Post-Pebas")

The sharp-based, upward-fining nature and overall lenticular occurrence of "post-Pebas" deposits are best explained as deposition within a channel environment. An array of evidence points to tidal influence within these channels. These include statistically verified tidal rhythmites that point to semi-diurnal rhythmites (Madre de Dios Formation, Solimões Formation, and Quendeque Formation; Hovikoski et al., 2005; 2007a), common current reversals (Madre de Dios Formation, Solimões Formation, and Nauta Formation), double mud drapes, regular reactivation surfaces, sigmoidal ripples, and a variety of IHS successions (Figs. 5A–5F; Table 2). The primary IHS-generating cycle is interpreted to be seasonal within a tidally influenced system. This interpretation is based on the thickness of the IHS couplets (up to 2 m), locally high bioturbation intensity in decimeter-scale IHS, and a high number of heterolithic laminae superimposed upon the lower frequency cycles (Gingras et al., 2002b; Hovikoski et al., 2007b; Rebata et al., 2006a and b). Statistically verified, neap-spring-generated IHS occurred only in low-energy, combined-traction, and suspension-driven localities, such as in prodeltaic creeks and deltaic channels that bear estuarine characteristics after abandonment from the fluvial system (Localities 20 and 24 in Table 2).

Ichnological data suggest that much of the Late Miocene tidally influenced channels accumulated in low-salinity settings. This is evidenced by monospecific or low-diversity suites of *Gyrolithes, Cylindrichnus,* and lined *Skolithos.* In places, however, trace fossil assemblages associated with higher salinities are present. In addition to the above-mentioned genera, these may comprise *Laminites*, *Asterosoma, Ophiomorpha,* and *Thalassinoides.* Finally, also locally present are unburrowed, meandering fluvial channels.

In contrast, the monospecific suites of meniscus-bearing burrows are typical of continental bioturbation restricted to subaerially exposed depositional surfaces (Frey et al., 1984;

Hasiotis, 2002; Buatois et al., 2007). This is further supported by intensely cross-cutting burrows, the presence of common branches of different diameters, the presence of pedogenically altered media, and the fact that their backfill is derived from the pedogenically altered media (cf. Hasiotis, 2002).

In summary, the Late Miocene deposits represent commonly estuarine, deltaic, and fluvial channel complexes. These deposits typically interfinger with alluvial coastal plain deposits. The paleontological evidence supporting some marine influence in these strata includes mangrove pollen (Nauta Formation; Rebata et al., 2006a) and teeth of euryhaline shark from Acre (upper Solimões Formation; Räsänen et al., 1995). Moreover, foraminifera, cirripeds, marine gastropods, and brachiopods are reported from the contemporaneous Yecua Formation, Southern Bolivia (Hernández et al., 2005; Hulka et al., 2006).

DISCUSSION

The Nature of Miocene Amazonian Embayment

During the late Early to early Middle (PC-zone) to late Middle-early Late Miocene (G-zone), sedimentological and ichnological data show that tidewaters and a large brackish-water bay repeatedly occupied large portions of Amazonia. The main evidence for this interpretation includes: (1) low-diversity, brackish-water assemblages attesting to low-salinity conditions; (2) abundant tidal sedimentary structures indicating propagation of tidal energy well inland; (3) sedimentary successions/sequences are commonly less than 10-m thick, indicating a shallow depositional depth; (4) much of the strata is laminated and unburrowed, suggesting that the depositional system was prone to low-energy, stagnant conditions that promoted dysaerobic conditions in the water column; and (5) the close juxtaposition of continental and brackish-water trace fossils and body fossils in the same outcrops resulted from the bay margin(s) repeatedly prograding into the bay. Behind the prograding shoreline, freshwater swamps and forest replaced the brackish embayment (cf. Hoorn, 1993). However, the persistence of endemic, euryhaline ostracod and mollusk species throughout the Pebas Formation suggests that during the Miocene, the embayment was never totally replaced by continental conditions; only its size was variable (cf. Wesselingh et al., 2002).

The Pebasian sequences are interpreted to be allocyclically generated because: (1) in spite of their shallow depositional nature and overall thin character, they can be followed laterally up to several kilometers (outcrop limitation); (2) the strata demonstrate minimal lateral variability in facies; and (3) the strata are tabular (do not pinch out). In concert, these factors are more easily explained by base-level changes than by autocyclic processes such as delta lobe abandonment. The number of these brackish-water to freshwater parasequences through the Pebas Formation indicates that there were several tens of marine ingressions into the Amazonian basin during the Miocene. Although there are no means of discerning the duration of one parasequence, considering the average sequence thickness (~5 m), the thickness of the formation (~300 m; cf. Hoorn, 1993) and its time span (ca. 10 Ma; Hoorn, 1993), one sequence might represent ca. 100,000–200,000 yr, corresponding to fifth-order cyclicity.

Late Miocene ("post-Pebas") differs from Pebas strata in three key ways: (1) brackish-water ichnofossil assemblages are commonly poorly developed or absent; (2) tidal rhythmites are more common; and (3) channelized deposits dominate the preserved strata. Also, within this stratigraphic interval, the tidally influenced, embayment-related strata are closely interbedded with continental strata. The "post-Pebas" strata also suggest a complex depositional system, similar to modern estuarine and deltaic systems. The accelerated tectonic subsidence of the Andean foreland in Middle-Late Miocene (Hermoza, 2004) was probably characterized by extremely low relief, evoking rapid autocyclically and allocyclically driven shifts in the shoreline. In modern settings, such as the Fly River delta in Papua New Guinea, such conditions promote the juxtaposition of continental delta-plain facies/forest, fluvially dominated, active deltaic channels, and tidally dominated channels that maintain an estuarine character following abandonment of the fluvial system (cf. Dalrymple et al., 2003; Rebata et al., 2006a). The common occurrence of continental bioturbation and the dominance of terrestrial vertebrate fossils in these Late Miocene strata (e.g., Cozzuol, 2006) most probably indicate that the marginal-marine-influenced deposits represent briefer time cycles and/or had spatially narrower occurrence than the intercalated continental strata.

Contrasting Paleoenvironmental Interpretations

Most of the contrasting paleoenvironmental data can be explained by the repetitive marine-ingression model discussed earlier in this paper. It explains, for example, the reported co-occurrence of pollen of continental plants and mangroves, fresh and euryhaline fish, and mollusk fossils (Hoorn, 1993; Monsch, 1998; Wesselingh et al., 2002). Major disagreement arises from stable-isotopic data that suggest only one ingression level in the Pebas Formation strata (Vonhof et al., 2003). This controversy can be explained in several ways: (1) the tidal sedimentary structures occur in a lake setting (Wesselingh et al., 2002; Vonhof et al., 2003; Hoorn et al., 2006); (2) freshwater adaptation of the marginal-marine-burrowing invertebrates (e.g., Wesselingh et al., 2002); (3) the isotopic data record mainly the intercalating continental strata (cf. Gingras et al., 2002a); and (4) some stable isotope-based salinity calculations involve uncertainties (cf. Lorrain et al., 2005; Gillikin et al., 2006).

Firstly, it has often been postulated in the literature pertaining to Miocene western Amazonia that tides can occur in large lakes such as in the Great Lakes in North America, and, consequently, that the Miocene tidal deposits observed in the upper Amazonian basin do not need to possess an oceanic connection (e.g., Hoorn et al., 2006; Hoorn, 2006b). However, when erecting such a scenario (i.e., a closed equatorial setting), the tidal regime and range must be considered, and it is accepted that a closed equatorial lake would probably be dominated by diurnal tides (de Boer et al., 1989). Although no statistically verified semidiurnal rhythmites have been reported from the Pebas Formation sediments, the common asymmetric couplets present throughout the Miocene series (from lower Pebas to "post-Pebas") are best explained by the presence of a semi-diurnal/mixed tidal regime. A second problem is the limited tidal range characteristic of closed systems. No closed basin today has more than centimeter-scale tides (Eisma et al., 1998). For instance, theoretical spring tidal maxima are <5 cm in the Great Lakes, which are masked by the greater fluctuations in lake levels produced by wind and barometric pressure changes (NOAA, 2005; cf. Hovikoski et al., 2006). Thus, such a system would be incapable of producing many of the observed tidal features in Miocene Amazonian deposits. For instance, both IHS-channels and tidal rhythmites appear to be exceedingly common in mesotidal settings (cf. Smith, 1988; Archer, 1998). Finally, although tidal deposits also occur in freshwater parts of marginal-marine systems, features such as high-certainty tidal rhythmites have never been reported from lake settings.

Recently, it has been proposed that minor internal tides occurred in the vast epicontinental sea of Carboniferous NW Europe (extent: 7.5×10^6 km^2; maximal depth: 1 km; average depth: 50 m), resulting in sporadically appearing, cryptic tidal influences in the rock record (Brettle et al., 2002; Wells et al., 2005). The maximal estimated size of the Pebasian system was far smaller (~1.1×10^6 km^2), and the water depth was more shallow (a few tens of meters maximum) (e.g., Wesselingh et al., 2002). Consequently, the volume of the water column that could be affected by the tide-generating gravitational forces was minimal compared to the Carboniferous European Sea, and hence the probability of purely internal tides in the Pebasian embayment is far less likely. A closer analogy to the Pebas Formation in terms of water volume is the Caspian Sea (371,000 km^2, average depth: 184 m), which is essentially tideless (Eisma et al., 1998).

The second hypothesis, that the Miocene trace-fossil assemblages can be ascribed to long-term radiation of marginal-marine animals into freshwater habitats (Hoorn et al., 2006), requires extraordinary adaptation of those animals into freshwater biomes. Remarkable adaptation has been demonstrated in modern (Amazonian), mobile vertebrate fauna (fishes and dolphins) and at least one gastropod (Wesselingh et al., 2002; Lovejoy et al., 2006). However, "trace fossils" represent behavioral adaptations that demonstrate successful survival strategies for a set of depositional parameters. Although animals may physiologically adapt to fresh water, it is optimistic to suppose that behaviors can *simply* be transported from one set of depositional conditions to another. For the sake of analogy, humans live in snow houses in the Arctic and grass-thatched homes in equatorial regions—such behaviors are successful, and yet cannot be simply imported from one environment to the other. Therefore, even if marginal-marine decapods and polychaetes radiated into freshwater biomes, it is not likely that their behavioral adaptations accompanied them. In large, modern, tropical lake systems, no patterns of bioturbation similar to brackish-water ichnofossil assemblages are reported. For example, Hasiotis et al. (2005) showed that Lake Tanganyika is dominated by shallow-tiered, unlined, simple ichna that could only be described as small *Skolithos*, small *Lockeia,* and common hypichnial grooves. Finally, considering that the brackish-water ichnofossil assemblages are associated with tidal sediments, brackish-water ostracods (Muñoz-Torres et al., 2006), coastal fish fossils (Monsch, 1998), mangrove pollen (Hoorn, 1993), and possibly glauconite (e.g., in the controversial lower Pebas; Hermoza, 2004), this unique crossing of the salinity barrier is not the most parsimonious explanation.

Although mollusk fossils are abundant in the Pebas Formation, they do not form a continuum throughout the formation (Vonhof et al., 2003). So far, to our knowledge, no in situ mollusks have been reported, e.g., from the lower part of parasequences, typically burrowed by the most diverse trace-fossil assemblages. Moreover, the Early Miocene ingression, which is evident in the many data sets mentioned earlier in this paper, is not visible in the isotopic data. This may point to resolution gaps in the otherwise valuable stable-isotopic data sets.

The peculiar invertebrate fossil-faunal structures of the Pebasian system are also worth noting. Only a small percentage of the Pebasian mollusks and ostracods are cosmopolitan freshwater species, whereas the vast majority of them comprise endemic species of a few euryhaline genera (Whatley et al., 1998; Wesselingh et al., 2002; Muñoz-Torres et al., 2006). Brackish-water influence, seasonality, and especially dysoxia have been proposed to explain the peculiar faunal structure (Whatley et al., 1998; Vermeij and Wesselingh, 2002). Although the common dysoxia probably shaped the faunal composition, the upper part of the sequences (shorefaces) are typically oxygenated, as demonstrated by the presence of trace fossils. In light of ichnological (stressed brackish-water assemblages), paleontological (euryhaline fish), and sedimentological (common synaeresis cracks) data, very low salinity and/or rapid brackish-freshwater fluctuations constitute the best explanation for the absence of both cosmopolitan fresh water and fully marine species in the Pebasian strata. Thus, we propose that the Pebasian endemic mollusks and ostracods maintained their euryhaline character like the majority of their present-day relatives.

Finally, recent studies have shown that some stable isotope concentrations (e.g., $\delta^{13}C$ and Sr/C) in mollusk shells are also affected by biological factors (Lorrain et al., 2005; Gillikin et al., 2006). $^{87}Sr/^{86}Sr$ ratio-based salinity calculations are independent of the biology of the organism, but require several assumptions of the $^{87}Sr/^{86}Sr$ ratios, which can lead to significant uncertainty.

Miocene Paleogeography of Western Amazonia

The paleogeographical configuration of Miocene Amazonia is still only partially understood. The biogeography and phylogenetic relationships of many aquatic taxa have indicated sea connections at least through the Magdalena valley, the Maracaibo Basin, and the Orinoco area during the accumulation of the Pebas Formation (Nuttall, 1990; Lovejoy et al., 2006). A restricted connection to the Pacific Ocean through the Guayaquil Bay was also probable (Nuttall, 1990). Other potential connections during this time (labeled C and D in Fig. 1) are possible, but remain speculative due to lack of data.

The early Late Miocene uplift of the northeastern Andes cut off the Caribbean connection around 10 Ma and restricted the Orinoco connection (Hoorn et al., 1995). No marine-influenced deposits younger than *Grimsdalea* pollen zone are so far known from the Colombian Amazonia. The restricted Pacific (Fig. 1, location A) inlet probably remained open until ca. 9.5 Ma (Steinmann et al., 1999). Recent studies also suggest that some sort of hydrographic connection between the Paranan Sea and western Amazonia was feasible at least during the Late Miocene. Our data coupled with the data of recent papers from central and southern Bolivia suggest that thin Miocene tidally/marine influenced levels are probably present throughout the Bolivian forelands (Hernández et al., 2005; Hulka et al., 2006; Hovikoski et al., 2007a). A distal-proximal facies relationship, for instance, is noted between the contemporaneous (Upper Miocene) Madre de Dios (landward) and Chaco (seaward) strata. The presence of a hydrographic connection between southwestern Amazonia and the Paraná Basin is also supported by (fossil) faunal similarities and the modern biogeography of certain aquatic taxa (e.g., Cione et al., 2000; Hamilton et al., 2001; Cozzuol, 2006).

CONCLUSIONS

Miocene Amazonian strata consist of complex, high-frequency intercalation of marginal marine and continental strata. Widespread, shallow and restricted marine-ingressions shaped Amazonia throughout the Miocene—also during the Early and Middle Miocene when the published isotopic data show only a freshwater signal (Vonhof et al., 2003), and during the Late Miocene when diverse continental vertebrate faunas developed (Cozzuol, 2006). The controversy can be explained by the repetitive nature of the ingressions that is revealed by the sedimentological and ichnological data. (1) The Pebas Formation deposits consist of recurring 3- to 10-m-thick, transgressive to regressive bay-margin parasequences. Each parasequence grades through brackish water (*Glossifungites* and/or mixed *Cruziana-Skolithos* ichnofacies) into a freshwater setting (pedogenically altered, continental fossil-bearing, organic-rich sediments). The number of these sequences in the Pebas Formation indicates that there were probably several tens of short-lived, marine ingressions into the western Amazonian basin during the Miocene. (2) The "post-Pebas" deposits consist of estuarine/deltaic channels that are interbedded with a variety of continental strata. The tidally dominated estuarine channel bodies commonly show evidence of low-salinity conditions by the presence of monospecific suites of *Gyrolithes, Cylindrichnus*, or lined *Skolithos*. The brackish-water ichnofossil assemblages are replaced upwards by a *Taenidium*-dominated suite indicative of a continental setting in the top of successions. As a consequence, in any one outcrop, there may be several intercalations of brackish-water and freshwater intervals. Especially, in the Late Miocene strata, the continental environments—swamps, flood plains, forests floors, and fluvial channels—were most probably temporally and/or spatially more significant than the co-occurring, restricted marginal-marine strata.

Despite high-frequency changes of the shoreline, the overall variability of the paleoenvironments was limited to restricted marginal-marine and continental environments. This prolonged "stability of instability" provides a logical explanation for the extraordinary species composition of the aquatic fauna of present-day Amazonia. The fluctuating salinity-fresh water setting would have allowed euryhaline mobile aquatic groups to compete successfully against their freshwater rivals and to ultimately adjust to continental conditions when the epeiric system finally terminated (cf. Hoorn and Vonhof, 2006; Lovejoy et al., 2006). As a result, the modern Amazonian rivers are exceptionally rich in groups that are closely related to near-shore marine species, including stingrays, dolphins, anchovies, flatfish, toadfish, needlefish, and drums (Lovejoy and Collette, 2001).

A Miocene embayment would have also greatly influenced biodiversity patterns in that: (1) it might have acted as a barrier between topographical highs (e.g., between the Andes and the shield areas) that are centers of endemism for many forest-dwelling taxa today (Alexio, 2002; Hall and Harvey, 2002; Nores, 2004); and (2) the geographical extent of the proposed Amazonian embayment and its interconnection with the Paranan embayment would explain and provide a time frame for the biogeographical distribution of certain modern aquatic taxa, such as river dolphins, stingrays, and electric fish (cf. Hamilton et al., 2001; Lovejoy et al., 2006).

Finally, the Miocene depositional history continues to influence the modern biota of Amazonia in a surprising way. Due to the complex geological history and the post-Miocene tectonic deformation, the forest floor of present-day Amazonia consists of a complex jigsaw puzzle of interfingering geological formations of different ages, most of which have distinctive hydrological and geochemical characteristics (e.g., Linna, 2001; Klemola, 2003). Many of these formations—especially the Pebas Formation—bear distinct floral and faunal properties, including their own endemic species (Ruokolainen et al., 2005). These strong edaphic controls probably influence even the distribution of primates (Salovaara, 2005) and activities of indigenous tribes. Hence, a detailed geological mapping of Amazonia is important in directing sustainable land use and conservation in the area, which is facing increasing pressure by human activities. In fact, in the ongoing biodiversity project (BIODAMAZ), geological formations are carefully considered in the planning of ecological conservation and economical use of the Peruvian Amazonia.

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