

The development of the Amazonian mega-wetland (Miocene; Brazil, Colombia, Peru, Bolivia)

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Abstract

The scenery of Western Amazonia once consisted of fluvial systems that originated on the Amazonian Craton and were directed towards the sub-Andean zone and the Caribbean. In the course of the Early Miocene these fluvial systems were largely replaced by lakes, swamps, tidal channels and marginal marine embayments, forming a mega-wetland. In this chapter we will review the characteristics of this mega-wetland and its different phases of development. These aquatic environments hosted a diverse fauna whereas the shores of these systems were fringed by palm swamps, and a diverse rainforest occurred in the peripheral dry lands. The genesis of this wetland was primarily driven by geological mechanisms such as the Andean uplift, and an increase in accommodation space in the sub-Andean and intracratonic basins. Additionally, high precipitation rates also played an important role in wetland formation. The earliest phase of wetland development is recorded in boreholes drilled in the sub-Andean foreland basins of Peru and Colombia, and in the intracratonic Solimões Basin of western Brazil. During the latest Oligocene to Early Miocene (~24 to 16 Ma) lacustrine conditions alternated with episodes of Andean and cratonic fluvial drainage as well as marginal marine influence. In Amazonia, marine incursions are intercalated as thin beds in the Middle to Upper Miocene fluvial strata and contain marine and coastal taxa (foraminifera, mangrove pollen). Lacustrine conditions expanded further during the Middle Miocene to early Late Miocene (~16 to 11.3 Ma; *Pebas phase*). During this period the lake-embayment and swamp systems – fringed by forested lowland – reached their maximum extension. This wetland was subject to marginal marine influence and sustained a large radiation of endemic aquatic invertebrate faunas. During its maximum extent the wetland covered an area of more than 1.5×10^6 km² – comprising much of the Present western Amazonian lowlands. From the Late Miocene onwards uplift rates in the Eastern Cordillera, Cordillera Real and Cordillera de Merida substantially increased and the Andes became a continuous barrier. This barrier effectively separated lowland Amazonia from Orinoquia and the Magdalena Valley and closed off all lowland connections with the Pacific and the Caribbean. The wetland system became a complex environment where deltaic, estuarine and fluvial environments coexisted. This Late Miocene fluvial-tidal-dominated wetland (~11.3 to 7 Ma, *Acre phase*) hosted a species-rich vertebrate fauna, but (in contrast to the *Pebas phase*), the molluscan fauna was species poor and already strongly resembled the modern Amazonian fluvial fauna. This system represents the onset of the transcontinental Amazon River. From 11.3 Ma onwards, sediments of Andean origin reached the Atlantic continental shelf and initiated the build-up of the Amazon Fan.

Introduction

The Neogene sediments in the sub-Andean and cratonic sedimentary basins contain crucial information about the history of

Amazonia. However, the degree of exposure of these strata is poor, and stratigraphical relations are difficult to establish. Furthermore, the paucity of radiometric ages and the different interpretations regarding the depositional settings have severely complicated the reconstruction of the Neogene history of lowland Amazonia.

Outcrops along the Amazonian rivers can be an excellent source of sedimentological and palaeontological data, in particular during the dry seasons, when the river level drops by up to 10 m.

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However, outcrop data comprise relatively short time intervals and need to be used in combination with (large-timescale) subsurface data from oil companies and government agencies. Therefore data from the Companhia de Pesquisas e Recursos Minerais (CPRM), Petrobras, PetroPeru and Occidental Petrol de Peru S.A., obtained in the sub-Andean and the intracratonic basins, together with outcrop data have proved fundamental for the understanding of the dynamic Neogene history of Amazonia (Maia *et al.* 1977; Hoorn 1993a; Eiras *et al.* 1994; Vonhof *et al.* 2003; Hermoza *et al.* 2005; Roddaz *et al.* 2006a; Wesselingh *et al.* 2006b; Uba *et al.* 2007).

In this chapter we will review the main features of the latest Oligocene to Miocene depositional environments by assessing information concerning the Pebas and Solimões Formations from exploration wells and outcrop data (Fig. 8.1). In this review we subdivide the history of the wetland into a fluvio-lacustrine precursor phase (~24 to 16 Ma), the mega-wetland or *Pebas phase* (~16 to 11.3 Ma), and the fluvio-tidal-dominated wetland or *Acre phase* (<11.3 to 7 Ma), which represented the incipient transcontinental Amazon River system.

For an extensive discussion about the definitions of the sedimentary basins in Amazonia, the stratigraphy, the regional extent of the Neogene formations, and their relation with deposits in the sub-Andean zone we refer readers to Chapters 3 & 5. Miocene climate and its influence on the wetland is discussed in Chapter 12, whereas marine influence in the wetland and the regional character of the marine incursion will be discussed

in Chapter 9. Specific information about the wetland faunas is presented in Chapters 15–18, and the palaeoflora is reviewed in Chapter 19.

Definition of a wetland and mega-wetland

According to the Convention on Wetlands (Ramsar 1971) wetlands are areas where water is the primary factor controlling the environment and the associated plant and animal life. They occur where the water table is at or near the surface of the land, or where the land is covered by shallow water. Ramsar further defines these environments as following: ‘Wetlands are areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.’

Five major modern wetland types are generally recognized:

- 1 **marine** (coastal wetlands including coastal lagoons, rocky shores and coral reefs);
- 2 **estuarine** (including deltas, tidal marshes and mangrove swamps);
- 3 **lacustrine** (wetlands associated with lakes);
- 4 **riverine** (wetlands along rivers and streams);
- 5 **palustrine** (marshes, swamps and bogs).

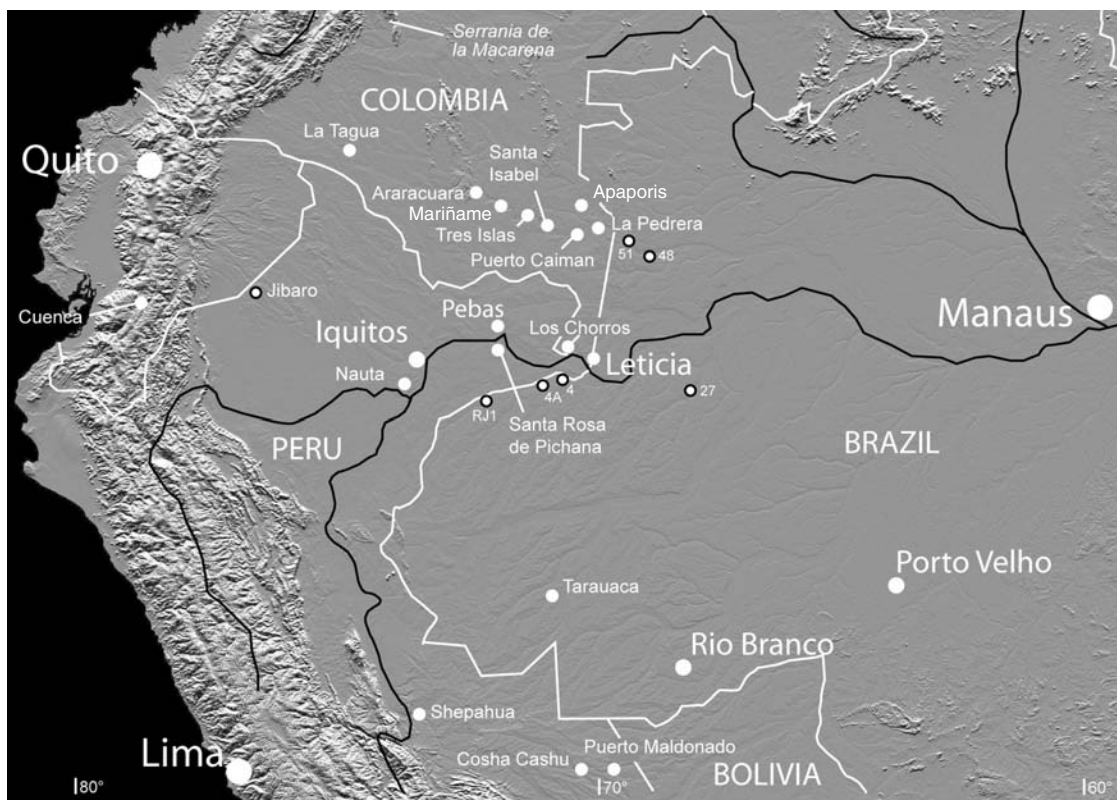


Fig. 8.1 Map of the area with the main (documented) localities where the Solimões and Pebas crop out. The boreholes referred to in this study are indicated with black circles.

Further description of modern wetlands can be found in Mitsch & Gosselink (2000).

In this chapter we use the term mega-wetland for the Miocene depositional system, composed of shallow lakes and swamps, which exceeded an area of one million square kilometres. The evolution of this Amazonian palaeowetland included four of the five wetlands types that are listed above.

Causes for wetland development during the Neogene in Amazonia

The genesis of the Miocene wetland in the sub-Andean-Amazonian region was driven by geological processes in the Andes, which, in turn, were initiated by the collision of the Caribbean Oceanic Plateau with the Northern Andean margin (75–65 Ma) and break-up of the Farallon Plate during the Oligocene (27–25 Ma) (Martin-Gombojav & Winkler 2008). Although tectonic pulses in the Andes are documented from Mesozoic onwards (Horton & DeCelles 1997; Lundberg *et al.* 1998; Guerrero *et al.* 2000; Guerrero 2002a, 2002b; Bayona *et al.* 2007a; Mora 2007; Ruiz *et al.* 2007), it is mainly the Late Paleogene and Neogene uplift of the Eastern Cordillera and Cordillera de Merida (i.e. Guerrero, 1997; Villamil 1999; Mora *et al.* 2008; Uba *et al.* 2007; Garziona *et al.* 2008; Bermúdez-Cella *et al.* 2008; Parra *et al.* 2009), the Cordillera Real (Steinmann, *et al.* 1999; Ruiz *et al.* 2007), and Nazca Ridge subduction (Espurt *et al.* 2007) that directly affected the sedimentary history of Amazonia. The immediate consequence of the uplift of the Eastern Cordillera was subsidence in the sub-Andean foreland basins and sediment supply of Andean source into the sub-Andean foreland and intracratonic sedimentary basins in Amazonia (Cooper *et al.* 1995; Hoorn *et al.* 1995; Steinmann *et al.* 1999; Hermoza *et al.* 2005; Roddaz *et al.* 2005), a topic that is further discussed in Chapters 4 & 5.

An Andean volcanic/metamorphic arc was present in the NW corner of South America since at least the Late Triassic and continued to be an important feature at the western flank of the back-arc Cretaceous Colombian Basin (Guerrero *et al.* 2000, 2002a, 2002b). An increase in the rate of Andean uplift and the beginning of a foreland basin formation occurred during the Paleocene, as indicated by the presence of the relatively coarse-grained fluvial deposits of the Lower Socha Formation (Guerrero & Sarmiento 1996). This regressive facies belt, which includes several formations, overlies the Cretaceous marine strata in a distinct erosional unconformity.

In Brazil evidence for Paleogene basin reactivation can be found in the Amazonian Solimões and Amazonas Basins and is represented by an unconformity between the Cretaceous-Paleogene Alter do Chaõ Formation and the Neogene Solimões Formation (Caputo *et al.* 1971, 1972; Maia *et al.* 1977; Eiras *et al.* 1994). Both subsurface records and outcrop data suggest that during the Cretaceous-Paleogene an E–W-directed fluvial system of cratonic origin existed that was followed by a period of exposure and non-deposition (see Chapter 7). From late Oligocene(?) to Early Miocene renewed basin subsidence occurred, and by Middle Miocene times a change from a cratonic to an Andean source was established. At the time, subsidence exceeded sediment input and resulted in the swampy and lacustrine environmental conditions

that characterize most of the Solimões Formation (Maia *et al.* 1977; Hoorn 1994a; Wesselingh 2006).

The Early Miocene incipient uplift of the Eastern Cordillera (Parra *et al.* 2009) thus formed a significant source of sediment supply that drove depositional regimes eastwards into Amazonia (Hoorn 1993a; Hoorn *et al.* 1995; Guerrero 1997; Steinmann *et al.* 1999; Villamil *et al.* 1999; Gregory-Wodzicki 2000; Hermoza *et al.* 2005; Burgos *et al.* 2005; Burgos 2006). In addition to this, isotope analysis of the mollusc shells (Kaandorp *et al.* 2005) and climate modelling (see Chapter 13) indicate that during the Middle Miocene Amazonia had a seasonal climatic regime with higher precipitation rates than at present. The combination of high precipitation rates, increased accommodation space and Andean sediment supply resulted in a mega-sized Amazonian wetland.

The main uplift of the Eastern Cordillera, however, took place during the Late Miocene and Pliocene (Van der Hammen *et al.* 1973; Guerrero 1997; Villamil 1999; Mora *et al.* 2008; Uba *et al.* 2007; see also Chapter 4). This resulted in isolation of the NW part of the basin and the initiation of the north-directed drainage of the Magdalena River as represented by the Neiva Formation (Guerrero 1997). A large increase of sediment supply and sedimentation rates was noted in the sub-Andean foreland basins, but also as far away as the Amazon Fan on the Atlantic Margin (Dobson *et al.* 2001; Mora 2007; Uba *et al.* 2007; Figueiredo *et al.* 2009). The Late Miocene uplift coincided with a period of global climatic cooling (Harris & Mix 2002) and global sea level fall (Haq *et al.* 1987; Miller *et al.* 2005) resulting in a reduction in size of the Amazonian wetland and the fluvial environments – with tidal influence – that predominated in the Acre and Solimões Basins (see Chapter 9). At the same time the connection between Andes and Atlantic was established due to the breach of the Purus High (Figueiredo *et al.* 2009).

During the Pliocene (~4 Ma), subduction of the Nazca Ridge (in the Pacific subduction zone) resulted in the uplift of the Fitzcarrald Arch and compartmentalization of the drainage systems in lowland western Amazonia (Espurt *et al.* 2007; see also Chapter 6). The sediment transport of the Amazon River increased during the Pliocene and the river acquired its present magnitude (Dobson *et al.* 2001; Figueiredo *et al.* 2009).

The Miocene Amazonian wetland: evidence from the sedimentary record

The Pebas and Solimões Formations have a wide geographic distribution and their extent, together with the sedimentary, palaeontological, and geochemical characteristics, support the existence of the Miocene Amazonian mega-wetland. These two units, which are partially time-equivalent, occur over an area of about 1.5×10^6 km² and, thanks to oil exploration wells in the Marañon Basin (Mathalone & Montoya 1995; Hermoza 2004; Wesselingh *et al.* 2006b) and the Solimões Basin (Maia *et al.* 1977; Eiras *et al.* 1994), we know that these units can reach a thickness of up to 1000 m.

The name Pebas Beds or Pebas Formation has been applied since the end of the 19th century (e.g., Gabb 1869; Katzer 1903; Rugg & Rozenzweig 1949; Pardo & Zuñiga 1975; Nutall 1990; Hoorn 1994b; Wesselingh *et al.* 2002; Räsänen *et al.* 1998; Wesselingh 2006). Boreholes in the Marañon Basin show the

most complete record of the Pebas Formation; they registered the (transitional) contact with the underlying (Oligocene) Chambira Formation and the concordant, diachronal contact between the Pebas Formation and the overlying Marañon Formation. In the Jibaro well from Occidental Petrol de Peru, the contact with the underlying Chambira and the overlying Marañon Formations suggests that the Pebas Formation has a thickness of about 1000 m (Wesselingh *et al.* 2006b).

The lower part of the Pebas Formation is typically represented by yellow sands and alternating layers of red and blue clays with some organic-rich beds and a low-diversity invertebrate fauna. The upper part of the formation presents the characteristic Pebas features described in existing literature. These features are: grey-blue smectite-rich mudstones and claystones, with minor interbeds of grey feldspar-rich sandstones, brown-black coals and organic-rich claystones. In the upper half of the Pebas Formation, sandstone and sandy shell beds are usually well expressed on the gamma ray and resistivity logs. Carbonate fossils are common throughout the Pebas Formation (Wesselingh *et al.* 2006a).

The Solimões Formation has an estimated maximum thickness of 980 m and was first described by Moraes Rego (1930) and

validated as a formation by Caputo *et al.* (1971, 1972). The reference section is interval 5–765 m of Petrobras borehole 2-RJ-1-AM (Fig. 8.2) and the additional reference section is 5–305 m in Petrobras borehole 1-BV-1-AM, both situated in the intracratonic Solimões Basin (Brazil) (Eiras *et al.* 1994). Ditch cutting samples of these wells are stored with Petrobras. Additional lithostratigraphic information, electrical log data and cores from this formation are property of CPRM and material is kept at the Manaus (Brazil) storage facilities.

The lithological record from the CPRM well 1AS-4A-AM shows that at a 350 m depth, Early and Middle Miocene deposits (*Psiladiporites-Crototricolpites* pollen zone; Hoorn 1993a) represent a lithological transition from coarse subangular quartz-rich cratonic sediments, to fine mixed sand of Andean origin. These sands can be differentiated based on heavy mineral composition (Hoorn 1993a) but also based on their grain size and angularity. A similar transition, albeit not dated, is observed in wells 4a, 27, 15 and 48. Maia *et al.* (1977) refer to the lower sandy unit as Ramon Formation (353 to 339 m depth; CPRM well 1AS-4A-AM, Fig. 8.3). However, this formation has not been formally described (J. Figueiredo, personal communication) and the

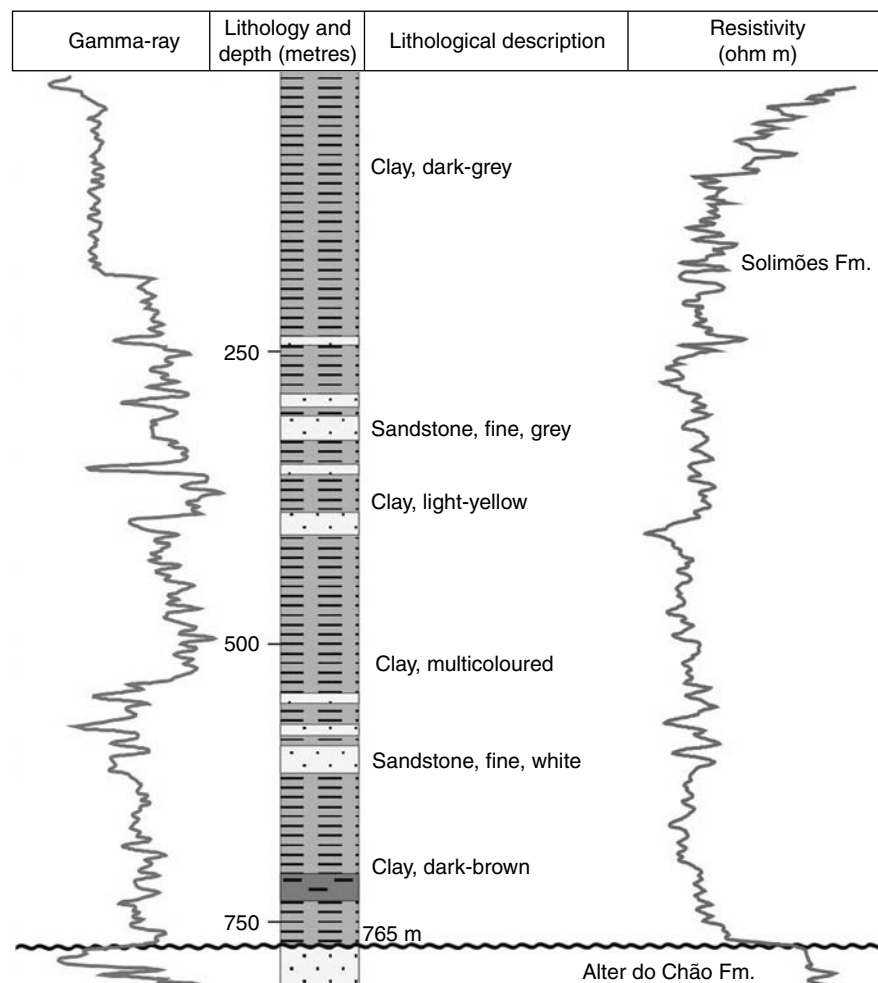


Fig. 8.2 The type location of the Solimões Formation in Brazil is Petrobras well 2-RJ-1-AM. Fm, Formation. Courtesy of Petrobras.

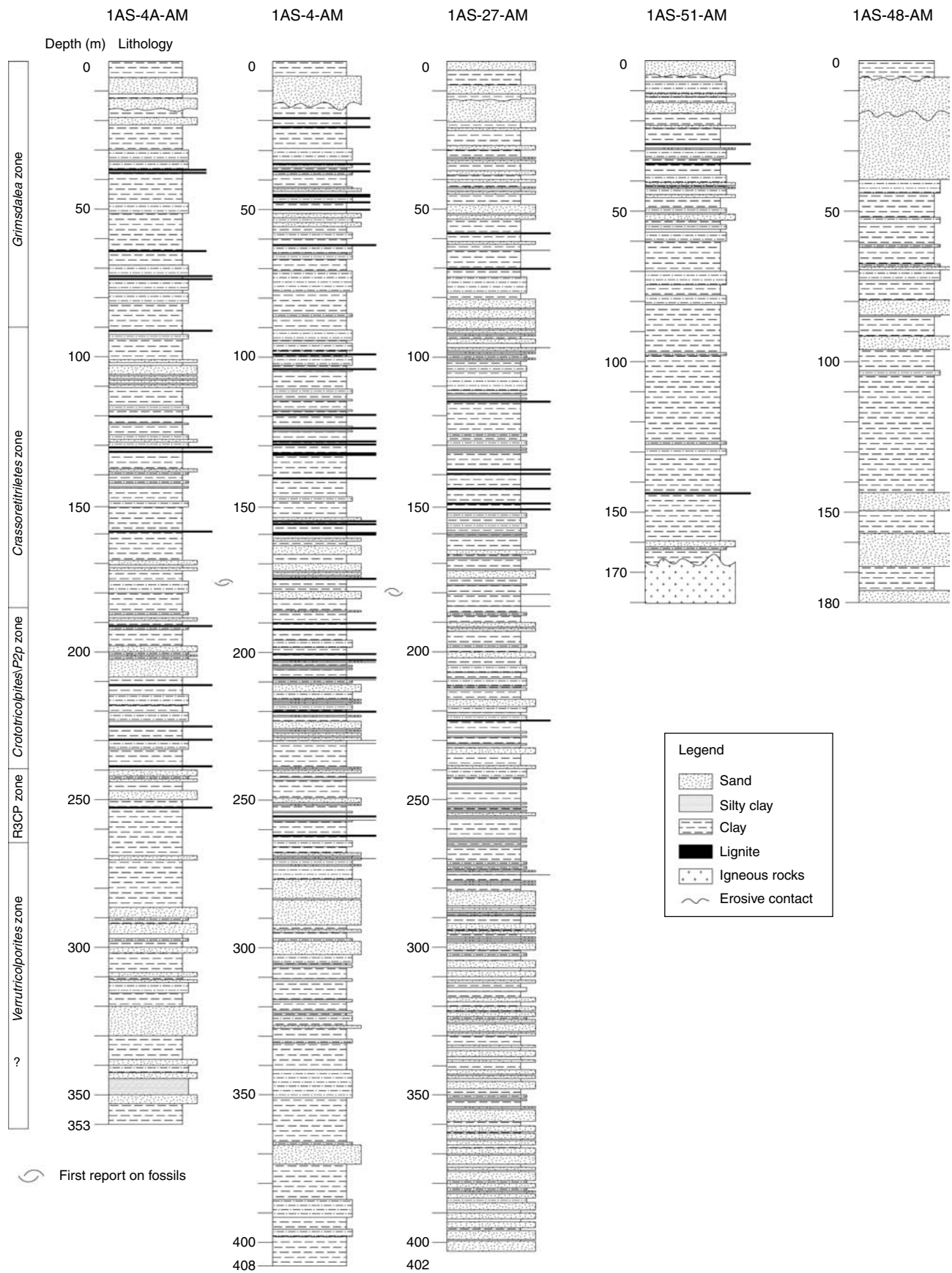


Fig. 8.3 Lithological columns of the Solimões Formation based on Companhia de Pesquisa de Recursos Minerais (CPRM) well data. The shallowing, coarsening-upward cycles (sand, silty clay, lignite) mostly occur at ~ 10 m intervals. The lower section is dominated by sands and represents a fluviially dominated environment. The sediments from well 51 are estimated by Maia *et al.* (1977) as Miocene to Pliocene. The sediments of well 48 are undated, but resemble the fluvial sequences typical for Late Miocene sediments of the Acre region. The pollen zonation in the left bar applies to well 1AS-4A-AM.

data suggest that most of the Solimões Formation (below 339 m depth) is of Paleogene age and was deposited in a fluvial environment. The Solimões Formation discordantly overlies the red clays and yellow sands of the Cretaceous-Paleogene Alter do Chaõ Formation (Eiras *et al.* 1994; see Chapter 7)

Fluvial environments and the incipient wetland (~24 to 16 Ma) (see Fig. 8.8a)

Lithostratigraphy and distribution

The lower Early Miocene sections of both the Pebas and Solimões Formations are poorly documented and, with the exception of the sub-Andean zone and the intramontane basins, which formerly were connected to Amazonia (e.g. Magdalena Basin, Colombia; Pilsbry & Olsson 1935; Pilsbry 1944), there are few outcrops representative of this time interval. The only evidence for a fluvial to lacustrine transition within the Early Miocene to Middle Miocene time interval can be observed along the Caquetá River (Santa Isabel; see Fig. 8.1). Other insights into the Early to Middle Miocene development of Amazonian environments derive from hydrocarbon exploration wells.

Colombian Amazonas Basin

The Colombian Amazonas Basin is situated north of the Solimões Basin and no divisor seems to exist between them. This basin is relatively shallow judging by the frequency of basement outcrops in riverbeds. Along the Caquetá River, between Araracuara and La Pedrera (near the border with Brazil), sediments become stratigraphically younger and – from west to east – range from Early to Middle/Late Miocene in age (Hoorn 1993a, 1994a, 1994b; Wesselingh *et al.* 2006c). The Early Miocene sediments include fluvial deposits of cratonic source (Hoorn 1994a; see also Chapter 7) that gradually change into the typical blue clays of the Pebas Formation, i.e. the Santa Isabel outcrop (see Fig. 8.1). The sediments from the Santa Isabel outcrop were dated as Early to Middle Miocene based on pollen (*Psiladiporites-Crototricolpites* Zone; Hoorn 1994a). From Santa Isabel towards the east, sediments become younger and acquire the typical Pebas features (e.g. Puerto Caiman; see Fig. 8.1). The shallow depth of the sedimentary basin is illustrated on the Brazilian side of the border, where CPRM borehole 1AS-51-AM (along the Japurá/Caquetá-River) registered the contact between the Solimões Formation and the Precambrian basement at 172.85 m (see Fig. 8.3b).

Solimões Basin

The lower section of the Solimões Formation (340 to 170 m depth; Early Miocene) in well 1AS-4A-AM, is composed of multicoloured – mostly red and yellow – clays and subangular quartz sands with intercalations of blue-green clays and lignites, and rarely shell beds. The transition from a multicoloured lithology that is poor in shells into dark and blue-green clay beds and lignites with an abundance of shells occurs within the *Psiladiporites-Crototricolpites* Zone (from 250 m onwards) and is concluded at a 170 m depth (*Crassoretitriletes* Zone). The typical blue-green clays

and lignites with shells and fine greyish sands of Andean origin continue until 25 m below the surface (Hoorn 1993a). Figure 8.3 represents five lithological columns based on CPRM borehole data of which 4, 4A and 27 illustrate well the transition from fluvial into wetland-dominated environments. The northward situated wells (51 and 48) are not dated but resemble the Late Miocene fluvial sequences that are known from the Acre region.

Marañon Basin

During the 1990s the Jibaro, Huayuri and Capahuari wells were drilled in the Marañon Basin by Occidental Petrol de Peru S.A., and these wells constitute our main data set for the lower Pebas Formation. In the Jibaro well the lower (Early Miocene) Pebas Formation occurs between 4700 and 2250 feet (~1400–700 m depth) and is predominantly composed of grey and occasionally varicoloured siltstones and claystones (Fig. 8.4). Lithic arenites,

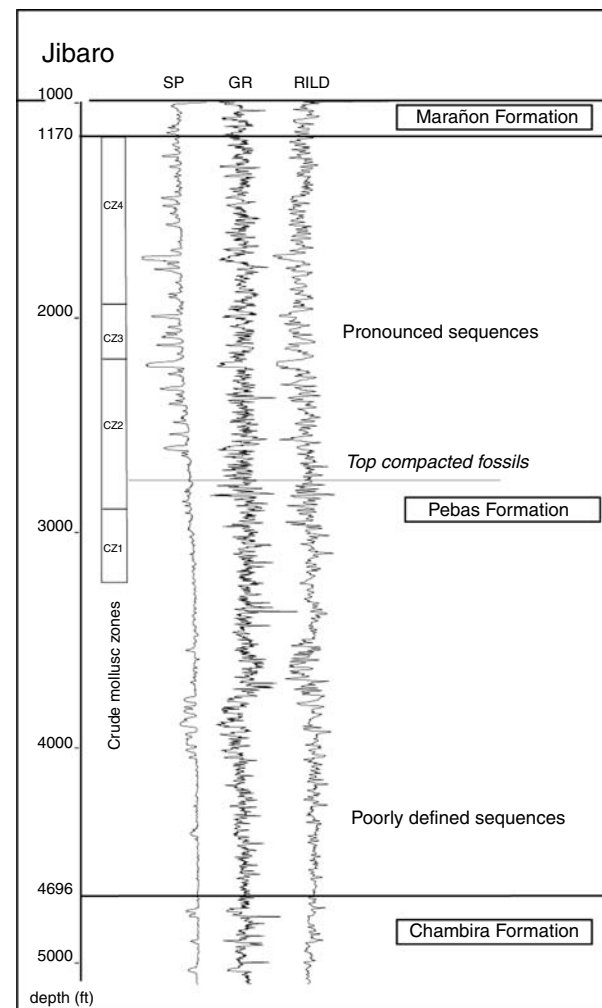


Fig. 8.4 The well log data – gamma-ray (GR), spontaneous potential (SP) and deep induction resistivity (RILD) – of borehole Jibaro in the Marañon Basin illustrate the physical properties of the rocks of the Pebas Formation in the subsurface, and distinguish sand and clay lithologies.

shell beds and lignite layers all occur in variable amounts, with rare occurrences of anhydrite crusts (Hermoza 2004; Wesselingh *et al.* 2006b). The mollusc fauna is relatively species poor in this part of the formation and is characterized by fluvial and lacustrine taxa. However, within the interval of 2250 to 1300 feet (~700 to 400 m depth) the molluscs are varied and abundant. The onset of these more diverse mollusc beds is mirrored by more densely spaced – and well-developed – sedimentary sequences that represent the boundary between the lower and the upper parts of the Pebas Formation. In the Huayuri and Capahuari a similar succession was observed (Wesselingh *et al.* 2006b). The contact between the Pebas and the overlying Marañon Formation is at 1150 feet (~350 m depth).

Eastern Amazonia

Rossetti & Góes (2004 and references therein) provide a detailed report on the calcareous lithologies of the Pirabas Formation and the clastic deposits of the Barreiras Formations. These formations represent the transition from littoral to fluvial deposition and occur in the Graben de Marajó and Plataforma de Pará, which neighbour the Foz do Amazonas Basin (Pasley *et al.* 2005). These sedimentary basins occur in the area where eastern Amazonia meets the Atlantic Ocean. The age of these formations was established through micropalaeontology and palynology as Oligocene to Early Miocene and Early to Middle Miocene, respectively. In addition the palynological and palaeobotanical data indicate the presence of tropical rainforest taxa. Other palaeontological studies further indicate the presence of a varied macrofauna.

Other sub-Andean basins

The stratigraphy of sub-Andean basins (also called Amazonian Foreland Basins) is reviewed in Chapter 5, but here we briefly discuss the sedimentary sequences that are relevant to the wetland development.

During the Late Paleogene and Early Neogene the Colombian *Llanos Basin* was situated more westward relative to its current position and in direct connection with Amazonia and the Caribbean. In this area the late Oligocene–Early Miocene period is represented by the Carbonera Formation, which is formed by fine-grained sands and clays, and was deposited in a fluvio-deltaic system with drainage towards the NNE (Cooper *et al.* 1995; Bayona *et al.* 2007b). Although at some levels the palynological association contains marine taxa, the composition is mostly dominated by freshwater taxa. A distinct mollusc level near the top of the Carbonera Formation, called the Heusser Horizon, was dated as Early Miocene. This 10 m-thick level – which is overlain by a marine interval – characterizes the freshwater, lacustrine nature of this depositional system (Gomez *et al.* 2009).

In the *Putumayo Basin* (Colombia) the Paleogene period is represented by clastic sequences that mostly are a product of the enhanced uplift of the Central Cordillera followed by lacustrine/fluvial sediments of the Oligocene to Middle Miocene Orito-Belen Group (Gonçalves *et al.* 2002). In the *Oriente Basin* of Ecuador the lacustrine Curaray Formation is a contemporary equivalent of the Orito-Belen Group, which to the west grades into the predominantly sandy, fluvial Arajuño Formation (Burgos *et al.* 2005;

Burgos 2006). The spatial and vertical extensions of the Curaray Formation are not well known yet; however, the formation is the lateral equivalent of the Peruvian Pebas Formation.

The Curaray Formation consists of light-grey to blue-green or reddish clays alternating with fine-to-medium-grained sandstones and is rich in fossils (Burgos *et al.* 2005; Burgos 2006). The fossil assemblage contains freshwater taxa (Wesselingh 2006a), but also a variety of foraminifera indicative of marginal marine conditions and which are in agreement with the tidal sedimentary structures that have been reported on the Curaray Formation. Although the predominant depositional setting was fluvial, marine influence is evident due to the presence of marine fossils (Burgos *et al.* 2005; Burgos 2006).

Age

No radiometric ages are available for the lower Pebas and Solimões Formations; however, the base of the Pebas Formation was estimated by Wesselingh *et al.* (2006b) at 22.5–23.9 Ma (Oligocene–Miocene boundary), based on a combination of palynology, mollusc studies, and a calculation of sedimentation rates from three wells in the Peruvian Marañon Basin. This date agrees with the base of the Curaray Formation in the adjacent Oriente Basin, which was estimated at 23 Ma (Burgos *et al.* 2005; Burgos 2006). In the Solimões Basin the lowest (accessible) part of the Solimões Formation is dated as Early to early Middle Miocene based on the presence of the *Verrutricolporites*, *Retitricolporites* and *Psiladiporites-Crototricolpites* Zones (274 to 181.8 m, well 1AS-4a-AM; Hoorn 1993a). The underlying Ramon Formation remains undated but is possibly of Paleogene age (Eiras & Wanderley 2006) and partially correlates with the Oligocene Chambira Formation of Peru.

Depositional environment and palaeogeography

During the latest Oligocene to Early Miocene the foreland basin axis formed a N–S-oriented depositional centre that received sediment input from the craton situated to the east and the Central Cordillera to the west. This N–S-oriented basin drained into the Caribbean and did not yet fully progress towards the east into Amazonia. At the time the fluvial overbanks repeatedly were exposed, as is suggested by anhydrite and red clay deposits. These mixed fluvial and lacustrine environments gradually changed into the humid, swampy and lacustrine wetland landscape.

Life in the fluvial environments and incipient wetland

Palynological analysis provided relative ages and an estimate of the palaeovegetation cover in Amazonia. The dark clays and lignites of the Early to early Middle Miocene (*Verrutricolporites* to *Psiladiporites-Crototricolpites* Zones) section of the Pebas Formation contain a highly diverse palynological assemblage with many species that have affinity with modern rainforest taxa. In addition, the abundance of *Mauritia* pollen suggests that palm swamps existed in proximity to the fluvial channels (Hoorn 1993a, 1994a; see also Chapter 19). The presence of mangrove pollen and foraminiferans in thin intervals within oxbow lake deposits further confirms that marine incursions reached the area at that time. Similar palynological features were identified further

to the north in the latest Oligocene to Early Miocene sediments of the Carbonera Formation in the Llanos Basin (Bayona *et al.* 2007b). This suggests that the marine incursions, albeit short-lived, affected a wide region. Beside pollen and palaeobotanical remains such as amber, leaves and seeds, few other fossils were found. The only known mollusc fauna of this period was reported from La Cira in the Magdalena Valley. This species-poor assemblage was mostly composed of fluvial taxa and some endemic genera such as *Pachydon* and *Dyris*, which are indicative of lacustrine environments.

The mega-wetland (*Pebas phase*, ~16 to 11.3 Ma) (see Fig. 8.8b)

Lithostratigraphy and distribution

The central part of the mega-wetland was situated in Western Amazonia, and the Middle to early Late Miocene sediments of the upper Pebas and Solimões Formations are testimony to this. These sediments are characterized by blue-green, black and grey clays, lignites and intercalations of fine-grained grey-brown lithic arenites. One of the most distinct features of these sediments is the abundance, variety and extremely good preservation of a highly diverse aquatic fauna (Plate 3e).

Typical exposures of this unit can be found along the Amazon River between Nauta (Peru) and Leticia (Colombia), along the Peruvian Napo River, and the Javari River in Brazil. Other exposures are known from the Putumayo and Caquetá Rivers in Colombia; a good example of the earliest known diverse mollusc faunas of the Pebas Formation can be found at La Tagua along the Caquetá River (Colombia) (Nuttall 1990; Hoorn 1994a; Wesselingh *et al.* 2006a). Isolated outcrops are reported from as far south as Shepahua (Ucayali, Peru) and as far north as the Serranía de la Macarena (Colombia).

Colombian Amazonas Basin

In southeastern Colombia, along the Amazon River and in the proximity of Leticia, some of the best exposures can be found at Puerto Nariño, Los Chorros and Santa Sofía (Hoorn 1993a, 1994b; Wesselingh *et al.* 2006a). The Colombian geological map (Ingeominas 2007) reports this geological unit as Terciario Inferior Amazonico (TIA) or 'Paleogene' (E-Stm code on map), but we favour the use of Pebas Formation instead, more so because the Terciario Superior Amazonico (N-Sc, or 'Neogene' on the map) is older than the TIA (Hoorn 1993a, 1994a, 1994b).

Solimões Basin

In the Solimões Basin the transition from lower (sandy) to upper (clayey) Solimões Formation is characterized by the disappearance of multicoloured reddish clays and coarse, subangular quartz sands of cratonic origin, in favour of dark-grey and blue-green silts and clays, lignites, and intercalations of Andean-derived fine, lithic sands. One of the most striking features is the appearance of a varied and abundant mollusc fauna. In well 1AS-4A-AM the transition occurs at 170 m depth (within the

Psiladioporites-Crototricolpites Zone) and the clayey upper Solimões Formation continues until about 30 m depth, at the contact between the Solimões Formation and the overlying Iça Formation (Hoorn 1993a). Petri & Fulfaro (1983) attribute the lithologies of the Upper Solimões Group to the Pebas Formation and describe the extensive distribution of this unit in the subsurface of Brazilian Amazonia.

Exploration wells in the southern and northernmost Brazilian Solimões Basin, and outcrops at the southern margins of the Acre Basin display an additional transition from bluish clays into reddish sand and silt sequences (Eiras *et al.* 1994; Cozzuol 2006). We attribute these younger sediments to the Late Miocene Acre phase (see below).

Marañon Basin

Middle and early Late Miocene deposits of the Pebas Formation are widespread in the subsurface of the Marañon Basin (Hermoza 2004; Hermoza *et al.* 2005; Wesselingh *et al.* 2006b) and were identified in the Jibaro, Huayuri and Capahuari wells. In the Jibaro well the transition occurs between 2250 and 1750 feet (~700 to 350 m depth) and is characterized by densely stacked 2–8 m sequences of blue smectitic clays, fine-grained lithic arenites, and lignite layers. This section is characterized by a rich and diverse assemblage of very well-preserved invertebrate and vertebrate fossils. This Middle to early Late Miocene part of the formation constitutes the 'archetypical' Pebas Formation, which we here call *Pebas phase*, and represents the mega-wetland at its maximum development.

Eastern Amazonia

In Eastern Amazonia the Middle Miocene period is represented by calcareous and clastic lithologies that were formed in a littoral to fluvial transition. These deposits are known as the Barreiras Formation and are further described in Rossetti & Góes (2004 and references therein). At the same time the Foz do Amazonas and the Ceara Rise registers clastic deposition from a fluvial system, and sediment analysis indicates a cratonic source (Dobson *et al.* 2001; Figueiredo *et al.* 2009).

Other Andean and sub-Andean basins

The Leon Formation in the Colombian Llanos Basin is contemporary with the upper Pebas Formation, and is composed of dark laminated mudstones and shales with some interbedded sands. The palynological assemblage is similar to that of the Pebas Formation and indicates a Middle Miocene age and a freshwater environment with some brief marine episodes (Bayona *et al.* 2007b).

In the Oriente Basin of eastern Ecuador exposures of the partially time-equivalent Curaray Formation were recorded (Burgos *et al.* 2005; Burgos 2006). Outside of Amazonia other important coeval sediments are the fluvial deposits of the Honda Group in the Middle Magdalena Basin, Colombia (Guerrero 1997; Kay *et al.* 1997) and the Loyola Formation in the Cuenca Basin in Ecuador (Bristow & Parodiz 1982).

Age

The first indication of a transition of fluvio-lacustrine environments into a species-diverse extensive wetland, with cyclical shallowing upward sequences, was registered within the *Psiladiporites-Crototricolpites* Zone, and was completed within the *Crassoretitriletes* Zone (Hoorn 1993a, 1994b; Wesselingh *et al.* 2006b). Therefore, based on the palynological marker species of the *Psiladiporites-Crototricolpites*, *Crassoretitriletes vanraadshovenii*, and *Grimsdalea magnaclavata* zones, a relative age of late Early to early Late Miocene was assigned to the upper part of the Pebas and Solimões Formations. The wetland, however, attained its maximum extent during the Middle to Late Miocene.

Other sediments of similar age are part of the Curaray Formation in eastern Ecuador, and were dated through apatite fission track analysis. Here the *Crassoretitriletes vanraadshovenii*-bearing intervals were dated as 14.5 ± 2 Ma and 15 ± 5.1 Ma (Burgos *et al.* 2005; Burgos 2006). Additionally, the Loyola Formation was dated through zircon fission track analysis as ranging between 12.1 ± 1.2 and 13.9 ± 1.4 Ma (Steinmann *et al.* 1999).

The Middle Miocene Honda Group from Colombia includes fluvial (mostly meandering) and lacustrine deposits proximal to the Central Cordillera in the west and connected at the time in the east with the Pebas Formation deposits. This unit was deposited between 13.5 and 11.5 Ma (Guerrero, 1997) and includes several fish species that at present occur in the Magdalena, Orinoco and Amazonas drainage basins, suggestive of the earlier connection between the areas in Middle Miocene times (i.e. Lundberg *et al.* 1998).

During the late Early to early Late Miocene an endemic invertebrate radiation took place in the Pebas system and this permitted a further subdivision of the biozonation, based on mollusc and ostracod data (Muñoz-Torres *et al.* 2006; Wesselingh *et al.* 2006a). The disappearance of this endemic invertebrate fauna at the end of the *Pebas* phase most likely coincided with the establishment of the transcontinental Amazon River system (Lundberg *et al.* 1998), which is dated at 11.8–11.3 Ma (Figueiredo *et al.* 2009).

The occurrence of mangrove pollen together with foraminiferan, marginal marine molluscan and ostracod taxa, and very rare barnacles is indicative of the marine incursions that reached Amazonia during both late Early and early Middle Miocene (Hoorn 1993a; Vonhof *et al.* 1998, 2003; Vermeij & Wesselingh 2002; see also Chapter 18). Additional indications from mollusc zone MZ9 (Wesselingh *et al.* 2006a; see also Chapter 9) in the uppermost Pebas Formation (late Middle to early Late Miocene) further extend the time range of marine influence in Amazonia. The regional character of the episodic marine influence during the Middle Miocene is further confirmed by similar findings in the Leon Formation (Llanos Basin) (Bayona *et al.* 2007b).

Sedimentological features

The upper Pebas and Solimões Formations are composed of bright-blue clays, greyish immature sands, and lignites. These sediments often are rich in organic matter and contain a wealth of carbonate fossils. The characteristic blue colour is derived from montmorillonite, a clay mineral from the smectite group, which also is responsible for the excellent preservation of organic and

carbonate fossils (Räsänen *et al.* 1998). Towards the sub-Andean zone in the west, bluish clays laterally grade into reddish-grey immature sands and clay deposits, with some minor gravel components (Burgos *et al.* 2005; Burgos 2006; Wesselingh *et al.* 2006a).

The upper Pebas strata are characterized by several facies including bioturbated mud, wave-ripple, current-ripple and combined-flow-ripple cross-stratified sand, various types of heterolithic bedding and lignite. Locally, sharp-based upward-fining successions occur, which can be interpreted as palaeochannels. Ripple structures and rare trough cross-stratification suggest low to moderate flow within the system. The rhythmic alternation of sands and clays indicates the tidal influence (Hoorn 1993b, 1994; Hovikoski *et al.* 2005) but is also partly of seasonal origin (Hovikoski *et al.* 2007; see also Chapter 9).

The sedimentary sequences constitute recurring coarsening-upward sequences of 2–8 m thickness, and represent transgressive-regressive cycles. Each sequence includes a succession of shallow, low-energy marine-influenced embayments that changes into tide- and wave-influenced bay-margins and swamps (Fig. 8.5) (e.g. Los Chorros – Vonhof *et al.* 2003; Santa Rosa de Pichana – Wesselingh *et al.* 2006d; Santa Teresa – see Chapter 9). At the top of these successions, the deposits grade into organic-rich mud/muddy sand or lignite (swamps). In some places inclined heterolithic stratification (IHS, following Thomas *et al.* 1987) was recognized, which is typical for fluvio-tidal channel deposits.

Heavy mineral analysis together with eastward transport directions, measured in the immature Pebas sands, indicates that the metamorphic rocks in the Ecuadorian Andes are the main source of sediment supply to Amazonia (Hoorn 1993a; Roddaz *et al.* 2006a). The Andes, however, is not the only source of sediment input into Amazonia. In the Colombian Apaporis region, sand outcrops with a distinct cratonic origin and palynologically dated as late Middle Miocene to Late Miocene suggest that the craton also continued actively to supply sediments into the intracratonic basins (Vonhof *et al.* 2003; Hoorn 2006).

Depositional environment and palaeogeography

During the Middle Miocene the wetland system reached its maximum development and consisted of a highly dynamic mosaic of lakes, embayments, swamps, rivers and fluvio-tidal environments. Along its periphery the system was bordered by alluvial plains of Andean rivers in the west, and lowland cratonic rivers to the east, whereas in the northeast, the wetland overlapped onto the cratonic rocks (Wesselingh *et al.* 2006a).

The wetland lake and embayment system was shallow (possibly up to 10 metres in depth) and repeatedly went through cycles of drowning and shallowing upwards. Each of these stages had its own characteristic taphonomic association. The base of the transgressive part is typically burrowed with *Glossifungites* ichnofacies. In the deepest part of the successions (zone of maximum flooding) molluscs such as *Pachydon* and *Dyris* predominate. In the shallow (regressive) intervals, however, molluscs are virtually absent, and the tidally and wave-influenced deposits are burrowed with low-diversity assemblages of mixed *Cruziana-Skolithos* ichnofacies (Wesselingh *et al.* 2006a; Hovikoski *et al.* 2007). These regressive episodes conclude with swamp development, which often is laterally continuous for hundreds of metres. Once the lakes were filled,

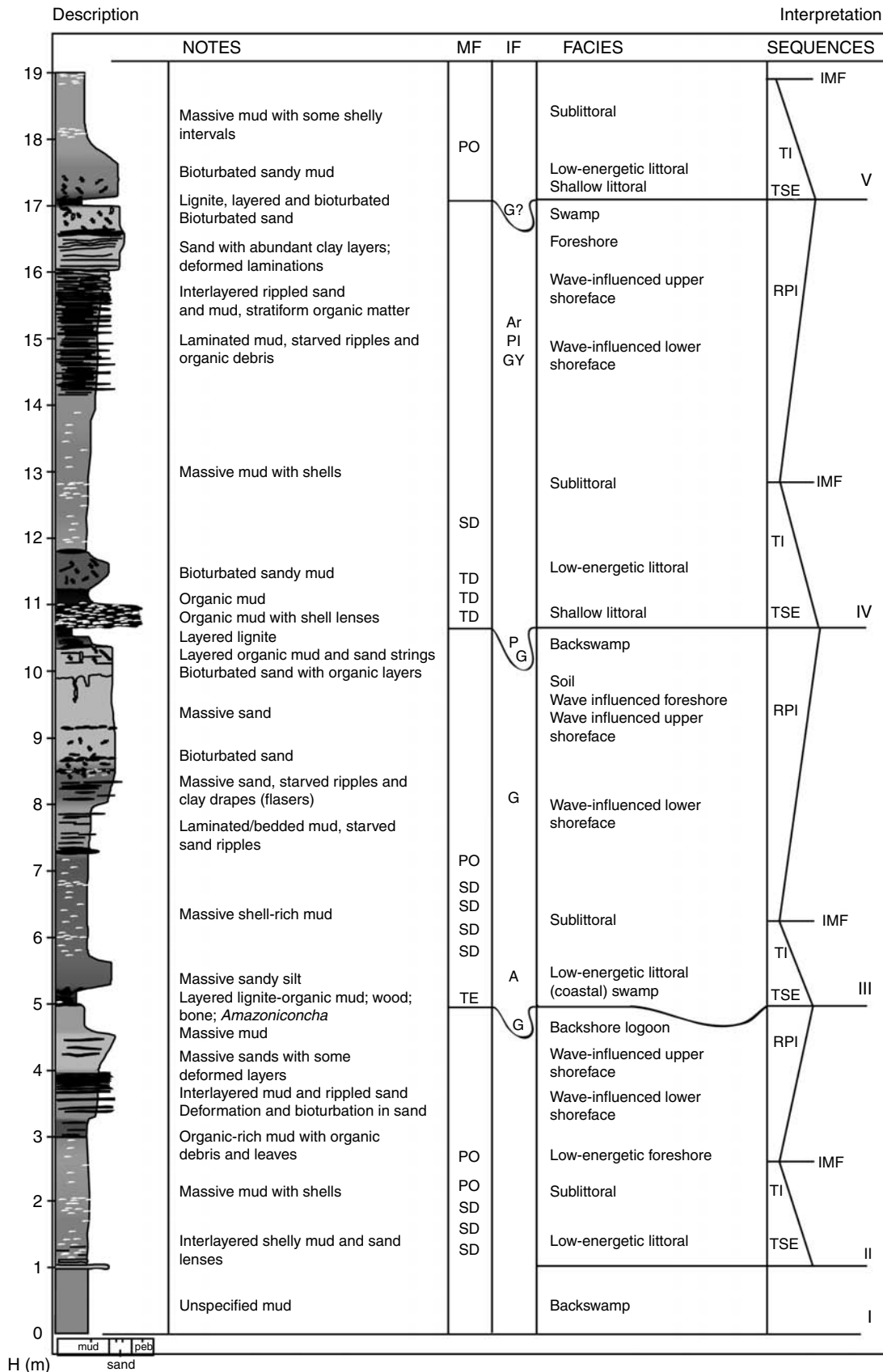


Fig. 8.5 The Middle to Late Miocene record at Santa Rosa de Pichana (Pebas Formation) shows the depositional cycles and shallowing phases that are characteristic for the wetland environment. IMF, interval of maximum flooding; PO, *Pachydon obliquus* assemblage; RPI, regressive/prograding interval; SD, Small *Dyrus* assemblage; TD, Tall *Dyrus* assemblage; TE, terrestrial molluscs; TI, transgressive interval; TSE, transgressive surface of erosion. *Ichnofossils*: A, *Asterosoma*; Ar, *Arenicolites*; G, *Glossifungites*; P, *Psilichnus*; PI, *Planolites*.

vegetation development was initiated on these poorly drained soils and is mostly formed of palm associations. Locally, swamp channels accumulated a mixture of macrofossils; in particular, seeds, logs, and fish, turtle and crocodile remains are extremely abundant in both the lake margins and swamp deposits. At some places logs occur exclusively, which represent old forest floors (see Plate 3d & f).

Geochemical evidence points to a predominance of Andean freshwater sources and limited influence of cratonic waters (Kronberg *et al.* 1989; Vonhof *et al.* 1998, 2003). Outcrop data from the Colombian Apaporis area further confirm that cratonic fluvial systems affected the eastern parts of the system. There is still some controversy about interpretations of salinity regimes of the Pebas Formation (e.g. Gingras *et al.* 2002a vs Vonhof *et al.* 2003). However, it is now believed that, although the repeated brackish water phases were temporally less significant than the freshwater phases, tidal processes played a significant role in the Neogene in Amazonia, indicating periods of prolonged connection between the sea and the depositional system (Hovikoski *et al.* 2005, 2007; Hoorn *et al.* 2006).

Palaeogeographically the foreland basins, which are situated parallel to the Andes, received the bulk of the sediments through fluvial input from the emerging Eastern Cordillera. In Amazonia, however, fluvial channels are rare and, if present, of modest size and rather distant from the Andean source. The entire wetland system was exposed to marine influence from the Caribbean although an additional port of marine entrance might have been the Essequibo gap in the Guiana Shield (G.F.W. Herngreen, personal communication) and the Cuenca corridor in the west cannot be excluded either (Wesselingh & Salo 2006).

Life in the mega-wetland

Neogene outcrops of Amazonia form a true paradise for palaeontological and palynological research because well-preserved fossils and organic material are plentiful. Palynological data suggest that the vegetation was extremely diverse, and the arthropod fauna enclosed in Middle Miocene amber (Antoine *et al.* 2006) further confirms this. The main components of the terrestrial vegetation were rainforest taxa, whereas the swamps were mainly populated by palms such as *Mauritia* and an extinct taxon called *Grimsdalea*. In addition, grass pollen are relatively common and were probably related to (aquatic) grass meadows – a vegetation type currently known from the white-water rivers of Andean origin. Their presence in the Miocene wetland is probably linked to the Andean fluvial influxes into the wetland system as this group was absent prior to the Middle Miocene. Other Andean taxa such as *Podocarpidiites* (*Podocarpus*), *Clavainaperturites* (*Hedyosmum*) and pteridophytes (related to Andean tree-fern taxa) (Hoorn 1993a, 1994a) further confirm this. Although there are sediment layers with mangrove pollen, the abundance of freshwater algae and pteridophytes underscores the dominant freshwater character of the deposits.

During the *Pebas phase* the molluscs and ostracods underwent extensive evolutionary radiations. Cochliopid snails dominate the mollusc fauna in species numbers, but in terms of abundance pachydontine bivalves prevail. The ostracod fauna is dominated by endemic species of the genus *Cyprideis*. To date, about 160 species of molluscs and about 45 species of ostracods have been described,

and these numbers are only expected to rise with further work (Wesselingh 2006a; Muñoz-Torres *et al.* 2006; see also Chapter 18).

The vertebrate fauna in the mega-wetland contained a diverse suite of fish species including piranhas, Amazonian stingrays (*Potamotrygon*) and sharks (*Carcharinus*) (Monsch 1998; see Chapter 17). In addition to this, a wide variety of turtles, crocodylians and mammal fossils was found in the swamp channels that are preserved in the upper Pebas Formation (Salas-Gismondi *et al.* 2007; see also Chapter 16). In general, Middle to Late Miocene wetland fauna was dominated by aquatic taxa of neotropical lowland character. In addition, the Middle Miocene terrestrial mammal assemblage – as reported in the proximities of the Fitzcarrald Arch (Peru) – was composed of taxa typical for an open environment (hypsodont notoungulates) and dense tropical forest habitats (astrapotheres, litopterns and xenarthrans) (Antoine *et al.* 2007; see also Chapter 15).

The episodic marine character of the environment is illustrated by the presence of benthic foraminifera, barnacles and dinoflagellates, which are restricted to thin beds deposited during marine influxes (Hoorn 1993a; Vonhof *et al.* 1998; Vermeij & Wesselingh 2002). Additionally, the trace fossils described above further confirm the episodically brackish nature of the environment. Brackish water ichnofossils are most common in the lower part of sedimentary sequences, but occur also locally in the regressive part of the sequences (Gingras *et al.* 2002b; Hovikoski *et al.* 2007).

The marine influence in Amazonia played a long-running role and traces of it can be recognized in Amazonia today. For instance the freshwater dolphin *Inia* together with fishes such as stingrays and needlefish, amongst others, are thought to have adapted from marine to fresh water in Miocene times. Although at present marine taxa can reach into the heart of the continents, these taxa are thought to have arrived in Amazonia through marine connections with the Caribbean (Lovejoy *et al.* 1998, 2006; see also Chapter 25).

The fluvio-tidal wetland and the early Amazon River (*Acre phase*, ~11.3 to 7 Ma) (see Fig. 8.8c)

Late Miocene sediments were documented in the Marañon Basin (northwest Peru), the Acre Basin (Brazil) and the Madre de Dios Basin (southeast Peru and adjacent Bolivia; see Fig. 8.1) and are here referred to as the *Acre phase*. These sediments are characterized by a series of fining-upward successions that are composed of sand and clay and are estimated to have a total thickness of 400 m (Hermoza 2004). They are known under a variety of names, depending on the sedimentary basin in which they occur. The strata are separated from the overlying conglomeratic units by a marked regional stratigraphic discontinuity (Campbell *et al.* 2001; see also Chapter 5), which is best observed in the Madre de Dios area (see Fig. 8.1). The main difference between the *Acre phase* and the *Pebas phase* is the absence of dark clay, lignite and carbonate fossil deposition during the *Acre phase*.

Lithostratigraphy and distribution

Upper Miocene strata that crop out in the Madre de Dios Basin (Peru) are informally referred to as Ipururo and Madre de Dios

formations – Kummel (1948) and Oppenheim (1946), respectively. Kummel (1948) applied the name Ipururo formation to strata outcropping in the Contamana area, ~600 km north from the Madre de Dios Basin. However, the original description lacks sufficient detail adequately to characterize the formation; therefore, it is proposed that the use of ‘Ipururo formation’ is modified or dropped in the Madre de Dios Basin (H. Nuñez *et al.* unpublished data).

According to the original description, the overlying Madre de Dios Formation (Oppenheim 1946; Campbell *et al.* 2001, 2006) consists of a sequence of fining-upward sand and clay channel successions, and a conglomeratic unit that erosionally truncates the Miocene sediments (Fig. 8.6). This marks a major stratigraphic boundary in the area, which possibly is of Plio-Pleistocene age (M. Räsänen & L. Romero, unpublished ¹⁴C datings; see also Chapter 6). The conglomerates, which here are excluded from further discussion, have different formation names including Quimiri Formation, ‘Secuencias Superiores’ and Juanjui Formation (e.g. Hermoza 2004; Espurt *et al.* 2007)

Solimões Basin

In the Solimões Basin this interval is only known through well log data from wells drilled in the northern end of the basin (see CPRM wells 48 and 51 in Fig. 8.3). These data suggest the absence of carbonate fossils and lignites, and the presence of sand and clay sequences similar to those described in the Acre Basin.

Marañon Basin

In the Marañon Basin (Peru), the *Acre phase* is represented by the Marañon Formation (Hermoza 2004; Wesselingh *et al.* 2006b), which diachronically overlies the Pebas Formation and is only known from well data. The formation possibly correlates partially with the Nauta Formation in the Nauta area (Rebata *et al.* 2006), and Räsänen *et al.* (1998) refer to these deposits as Unit B and Unit C. The Marañon Formation is composed of reddish-grey immature sandstones and siltstones that were deposited in fluvial settings (Hermoza 2004; Wesselingh *et al.* 2006b). Lignites and carbonate fossils are absent in the formation.



Fig. 8.6 The contact between the Madre de Dios Formation and the overlying conglomerates. Location Inambari River (12.922098S, 70.349118W).

In the Nauta area (Loreto, Peru) the outcrops of the Nauta Formation typically consist of 7–9 m-thick inclined heterolithic stratification (IHS)-bearing channel deposits similar to those of the uppermost Solimões Formation (see below). The base of the successions is commonly composed of mud-draped, trough cross-stratified sand that grades upwards into bioturbated IHS. The IHS is variable, containing interstratified sand and mud beds/lamina of various orders. The strata from the Nauta Formation are thought to represent seasonally and tidally controlled estuarine or deltaic channel complexes (Rebata *et al.* 2006).

Acre Basin

In the Acre region outcrops are characterized by fining-upward sand-channel sequences that are attributed to the upper Solimões Formation and considered time-equivalent to the Ipururo and Madre de Dios Formations (Maia *et al.* 1977). These sediments represent megafan deposits (Latrubesse *et al.* 1997) and were dated using macrofossils that were collected from channel deposits (Cozzuol 2006). The Universidade Federal do Acre (at the Laboratório de Pesquisas Paleontológicas) stores an extensive collection of fossils that has been assembled during decades of research (see Chapters 15 & 16). Amongst others the collection holds examples of the giant caiman, *Purussaurus brasiliensis*.

Eastern Amazonia

The Late Miocene is characterized by a regional hiatus and lateritic palaeosols (Rossetti & Góes 2004, and references therein). However, the Foz do Amazonas Basin and the Ceara Rise (Dobson *et al.* 2001; Pasley *et al.* 2005; Figueiredo *et al.* 2009) register the arrival of the first Andean sediment influx. Around 6.8 Ma sedimentation rates increased and from 2.4 Ma onwards this river system resembled the modern Amazon River (Figueiredo *et al.* 2008).

Other Andean/sub-Andean basins

The Late Miocene alluvial fan deposition in the Andean/sub-Andean basins was a direct result of intensified Andean uplift (Guerrero 1997; Mora 2007; Uba *et al.* 2007). In the Llanos region (Colombia) these Late Miocene deposits are known as the Guayabo Formation (Cooper *et al.* 1995); the conglomeratic Ospina Formation (Gonçalves *et al.* 2002) is their equivalent in the Putumayo Basin, and in the Oriente Basin it is the lower part of the Ecuadorian Chambira Formation (Hermoza 2004; see also Chapter 5). The latter is much younger than the Oligocene Chambira Formation of adjacent Peru and represents a more proximal fluvial setting.

Age

Several radiometric ages are reported for the sediments deposited during the *Acre phase*. Campbell *et al.* (2001) presented two Late Miocene argon-40/argon-39 (⁴⁰Ar/³⁹Ar) ages, which are close to 9 Ma. Similarly, Roddaz (2004) dated the same tuffaceous level by apatite fission track dating at 9.31 ± 3.39 Ma (Puerto Maldonado; see Fig. 8.1). Continental vertebrate taxa from apparently coeval strata in the Acre region were assigned to the Huayaquerian

mammal age, which further confirms the Late Miocene (Tortonian) age (e.g. Frailey 1986; Cozzuol 2006; Latrubesse *et al.* 2007). Finally, pollen assemblages reported by Silva (in Latrubesse *et al.* 2007) and by Rebata *et al.* (2006) are attributed to the Late Miocene *Asteraceae* Zone. However, it is also possible that the latter relate to the Ipururo Formation, which is coeval with the upper part of the Pebas Formation (see Chapter 5).

Sedimentological signature

The Madre de Dios Formation and the uppermost Solimões Formation typically consist of various types of sharp-based, 2–15 m-thick, upward-fining successions, which are interpreted as channel deposits and are intercalated with pedogenic or root-bearing horizons (Fig. 8.7a,b). The lower part of the fining-upward successions generally consists of yellowish, massive or cross-stratified fine-to-medium-grained sands. Upwards in the succession, the deposits grade into mud-dominated homolitic sediments, or into various types of IHS (following Thomas *et al.* 1987). The IHS consist of alternating beds of sand, mud and calcareous mud-bearing strata of variable thickness and lateral extent. At the top, the channel successions grade into massive, pedogenically altered clay horizons. Locally, rooted mudstone makes up for the majority of the sedimentary record, especially in the Acre region (Hovikoski *et al.* 2008).

The IHS deposits are highly variable in terms of sedimentological features and fossilized burrowing traces of animals (ichnofossils; see Chapter 9 for methodology) and are thought to represent floodplain to tidally influenced estuarine conditions. Most commonly though, IHS units lack burrows or bear monospecific to low-diversity ichnofossil assemblages, including *Gyrolithes*, *Skolithos* and/or *Cylindrichnus*. Assemblages containing *Asterosoma*, *Thalassinoides*, *Ophiomorpha* and *Laminites* occur. Channels burrowed by near monospecific suites of *Taenidium* or *Planolites*, unnamed irregularly branching burrows, or suites containing elements of *Mermia* ichnofacies are locally present. The tops of most channel deposits and pedogenically altered horizons are commonly burrowed with terrestrial *Scyenia* ichnofacies.

Depositional environments and palaeogeography

The Late Miocene sediments in the Acre region were deposited in fluvial, deltaic and estuarine channel complexes that were interbedded with a variety of alluvial strata. The fossil record of these strata is dominated by continental vertebrates, which has led some researchers to consider the *Acre phase* as fully continental (Campbell *et al.* 2006; Cozzuol 2006; Latrubesse *et al.* 2007). In addition it was proposed that seasonal processes in a continental depositional system could explain the heterolithic patterns in these deposits (e.g. Westaway 2006).

While the notion of prominent seasonal variation in energy levels is true, there is also strong evidence for semi-diurnal tidal processes in many IHS channels. These include local current reversals (measured from foreset of adjacent ripples), double mud-drapes, regular reactivation surfaces in heterolithic cross-strata, sigmoidal ripples and statistically verified cyclic rhythmmites. The rhythmmites show evidence of superposition of several tidal cycles including flood-ebb, diurnal inequality, neap-spring and anomalistic

month cycles (e.g. Rebata *et al.* 2006; Hovikoski *et al.* 2005, 2007, 2008; Hovikoski 2006) and are further discussed in Chapter 9.

The complexity of the depositional setting is well illustrated by the sedimentary sequence at the Acca biological station, studied by both Campbell *et al.* (2006) and Hovikoski *et al.* (2005). This sequence consists of three stacked channel belt successions. The lowermost succession overlies a palaeosol and is a typical fluvial point bar displaying nearly homolitic upward-fining succession. However, towards the top of the succession, the channel

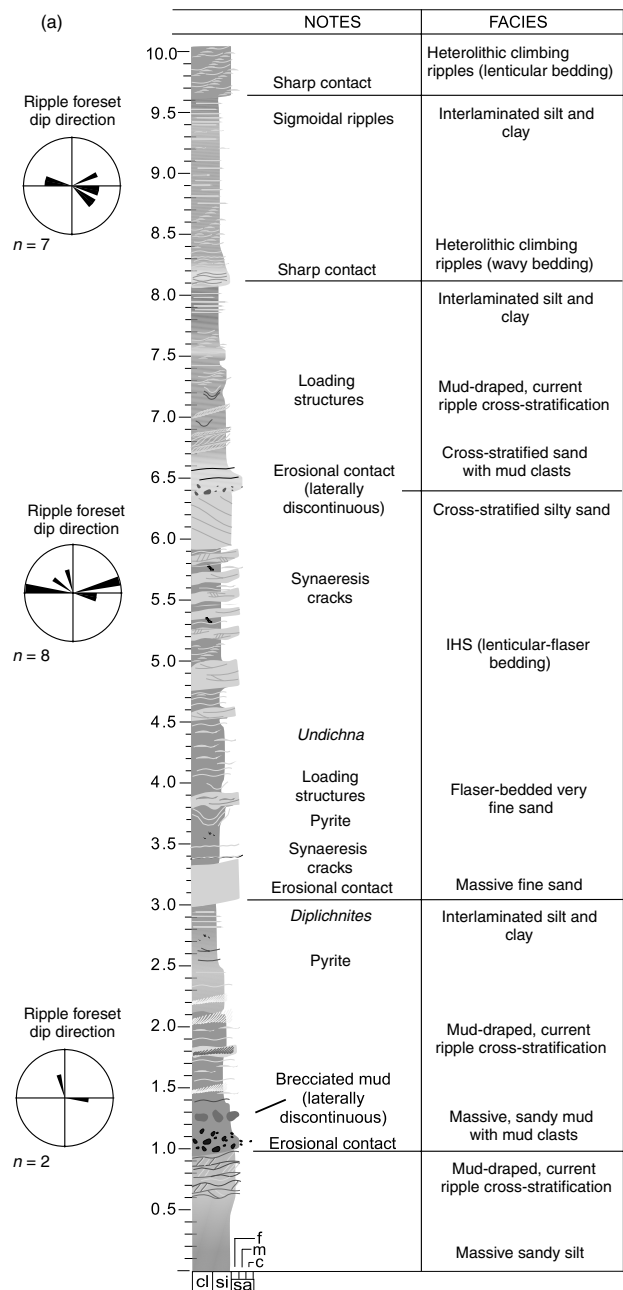


Fig. 8.7 (a,b) Examples of Late Miocene sedimentary successions from (a) Cocha Cashu (Madre de Dios, Peru) and (b) Tarauaca (Acre, Brazil). c, coarse; cl, clay; f, fine; m, medium; sa, sand; si, silt. Modified after Hovikoski *et al.* (2005) and (2008), respectively.

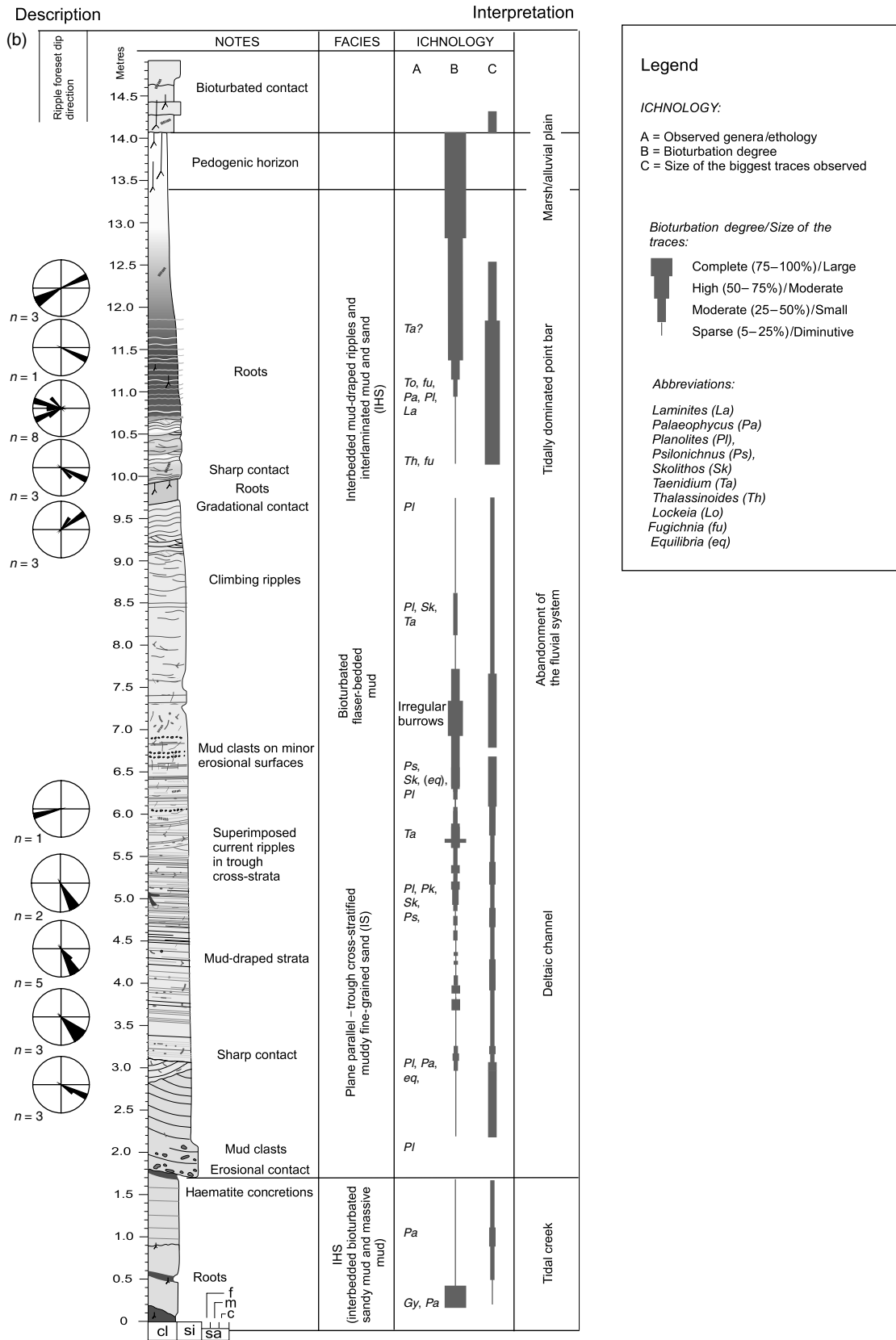


Fig. 8.7 Continued.

units display an increasing heterolithicity, including rhythmically occurring sand-clay couplets that form statistically verified semi-diurnal tidal rhythmites. Ichnological data suggest that the *Acre phase* tidal facies was accumulated in both brackish and freshwater settings in deltaic and middle-upper estuarine environments (Hovikoski *et al.* 2008; see also Chapter 9). Moreover, sediments with typical tidal features were described from various outcrops in the area (Madre de Dios – Hermoza 2004; Roddaz *et al.* 2006b; Hovikoski *et al.* 2005; Acre – Räsänen *et al.* 1995; Gingras *et al.* 2002b; Hovikoski *et al.* 2007, 2008 and see Chapter 9; Nauta – Rebata *et al.* 2006).

The implications of these findings for the palaeogeographical interpretation of this region are still not entirely clear. At the time of the *Acre phase* the transcontinental Amazon River system had just connected with the Atlantic, and former pathways of marine influence into Amazonia along the northern Andean foreland basins were closed. Although this topic is subject to further study it would be plausible to expect a new route of marine influence, namely the Atlantic through the mouth of the newly formed Amazon River (see also Chapter 9).

Life in the transition from wetland to Amazon River system

Pollen records are rare for this interval; however, where available the records suggest the presence of rainforest combined with grasslands and/or floating meadows (Rebata *et al.* 2006; Latrubesse *et al.* 2007; see also Chapter 19).

The vertebrate fauna of the *Acre phase* is extremely rich, both in abundance and in species numbers, and is typical for terrestrial and freshwater settings, although teeth of euryhaline sharks have also been reported (Räsänen *et al.* 1995; Monsch 1998). This fauna is further described in Chapters 15 & 16. In contrast, invertebrate faunas are relatively rare and poorly preserved. The mollusc faunas that were sampled from study sites in Acre are dominated by pearly freshwater mussel taxa that closely resemble present-day fluvial faunas of the region (Wesselingh *et al.* 2006e).

Case studies: the Cocha Cashu and Tarauaca outcrops

The Cocha Cashu outcrop is situated along the Manu River, a few hundred metres down river from the Cocha Cashu biological station (see Figs. 8.1 and 8.7a). The outcrop is 10 m high and can laterally be followed for about 100 m. The facies consist of a bluish mud-dominated, inclined, heterolithic stratification, and form sharp-based fining-upward successions up to 3 m thick. The successions begin with massive or cross-stratified, fine-grained sands with mud clasts. Upwards in the section the deposits commonly turn into clay-draped, cross-stratified sand and silt. Statistical analysis shows that these strata are semi-diurnal tidal rhythmites and possibly also related to seasonalities. The top of the succession generally consists of interlaminated silt and clay, and soft-sediment deformation is common. Palaeocurrent directions are predominantly toward the east and west, whereas locally the foresets display bipolarity. Sedimentary accessories include synaeresis cracks and pyrite. Bioturbation is generally absent, but where present, the trace fossil genera observed include bedding-plane traces such as *Diplichnites*, *Undichna* and (?)*Phycodes*. Near the top of the outcrop, a low-density assemblage of *Taenidium* is observed. The contact with the overlying deposits is not seen in detail, but

the overlying sediments consist of a succession similar to that at the ACCA (Asociación para las Conservación de la Cuenca Amazónica) research station. The trace fossil fabric consists of reburrowed (by *Planolites*) *Ophiomorpha*, *Thalassinoides* and *Gyrolithes*.

The Tarauaca outcrop (see Figs. 8.1 and 8.7b) is about 15 m high and can laterally be followed for ~100 m. The deposits form a 12 m-thick fining-upward succession. The lower contact is sharp and bears mud-clasts. The overlying strata consist of trough cross-stratified or low-angle, planar-stratified silty sand. The dunes are most commonly 10–30 cm high (highest 70 m), and as co-sets they form 1–3.5 m-high compound units. Where observed, the width of the larger troughs was typically more than 5 m. The cross-strata are commonly mud-draped, or bear minute mud-draped ripples. Double mud-drapes are present regularly. Upwards, these deposits grade into inclined heterolithic stratification (IHS) that consists of a coarse-to-fine (sand to mud) couplet. The members are cross-stratified or massive silty sand and inclined, laminated mud. The coarse member can be 0.5–2 m thick, and the fine member 20–60 cm thick. The contact from coarse-to-fine is sharp, although the grain size change is slightly gradational (normally graded). The contact from fine-to-coarse is sharp and often truncated. The fine-members form intraformational breccia in the down-dip direction. IHS can be followed laterally for up to 70 m. This interbedding is interpreted to reflect seasonal changes in energy levels (Hovikoski *et al.* 2008). Both the IS and IHS sets may bear poorly cyclic rhythmites (a cycle comprising 15–21 sand-clay lamina couplets, $n = 5$). These strata are overlain by rhythmically occurring, mud-draped current ripple-bearing sand and silt, and interlaminated mud and sand. The thickness of the coarse member ranges from 0.5 to 8 cm. The thicker layers form flaser-bedding as co-sets. The thickness of the fine member is generally 1–5 cm. Contacts between the members are most commonly bigradational (i.e. both contacts are gradational), typically marked by mud-draped climbing ripples. As couplets they form statistically verified cyclic tidal rhythmites. Asymmetric lamina couplets, countercurrent ripples, and scour-and-fill structures are observable locally.

The Amazonian Miocene mega-wetland in its regional context

The Miocene mega-wetland connected most of South America through both fluvial and marine pathways. Towards the north this wetland was linked with the Caribbean through the Llanos region, a connection that existed until the Late Miocene (see Fig. 8.8). This pathway permitted sporadic marine influences into the Amazon drainage basin. Proof of this are the similarities between Caribbean and Amazonian fish faunas (Lundberg *et al.* 1986; Lovejoy *et al.* 1998), the migration pathway of the mollusc *Pachydon* (Wesselingh & Mactosay 2006), the overall resemblance of the vertebrate faunas of La Venta, Urumaco and Amazonia (Cozzuol 2006) and the coeval Miocene marine-influenced deposits in the Llanos and Amazonia. No firm evidence exists regarding southern connections; however, possible fluvial pathways with the Paraná region are explored in Chapter 17.

These data imply that prior to the Late Miocene the present Orinoco, Amazon and Magdalena drainage basins and their fauna and flora were all connected. During the Late Miocene

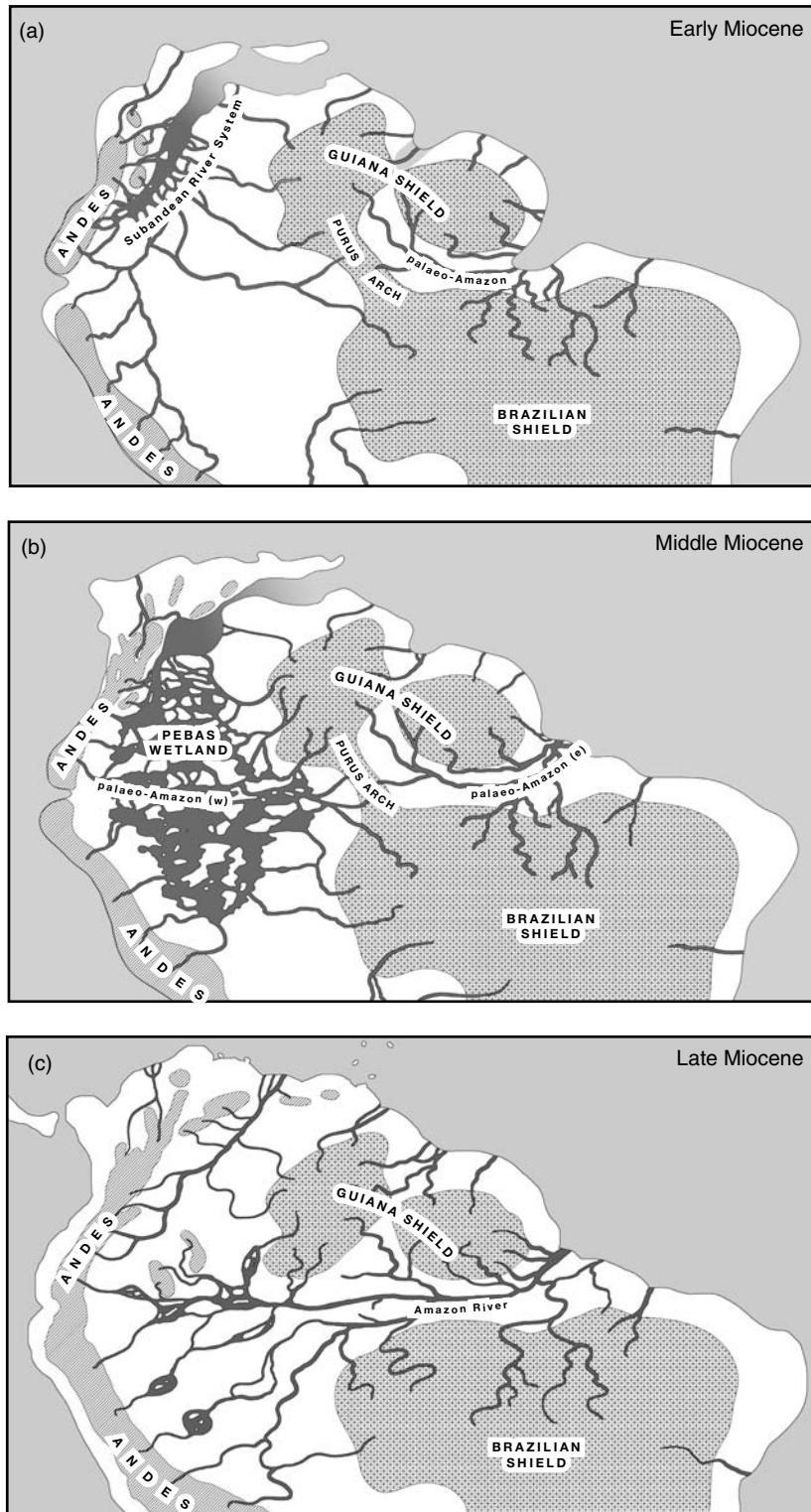


Fig. 8.8 Palaeogeographical maps showing the evolution of the wetland through time. **(a)** The latest Oligocene to Early Miocene Andean and cratonic fluvial systems with an incipient wetland in the sub-Andean region. The palaeo-Magdalena flows eastwards and is connected with the sub-Andean and cratonic drainages, which all flow northwards to the Caribbean. Together these rivers form the sub-Andean River system. **(b)** The Middle Miocene wetland at its maximum but still disconnected from the Atlantic. **(c)** The Late Miocene fluvial system, with localized wetland development. The Purus Arch barrier is cut by the fluvial system, which now connects with the Atlantic.

and Pliocene, accelerated uplift of the Eastern Andes and uplift of the Cordillera de la Costa (Venezuela) led to the separation of these drainage basins (Hoorn *et al.* 1995; Diaz de Gamero 1996; Potter 1997; Lundberg *et al.* 1998; Albert *et al.* 2006). This provided a completely new geographical scenario for species evolution. At the same time, an additional new palaeogeographical setting was developed through the establishment of the Amazon River, a transcontinental fluvial route that connected the Andes and the Amazon (Hoorn *et al.* 1995; Figueiredo *et al.* 2009). This event subsequently led to another major palaeogeographical development, which was the start of deposition of the Amazon Fan (Pasley *et al.* 2005; Figueiredo *et al.* 2009). The onset of this giant new depositional system along Brazil's equatorial Atlantic margin is dated by Figueiredo *et al.* (2009) as 11.8–11.3 Ma, a date that coincides with the onset of terrigenous sedimentation on the deep-sea Ceara Rise (Dobson *et al.* 2001).

After the Andes–Atlantic connection was established the Amazonian mega-wetland became a fluvio-estuarine system with a distinct tidal signature (Hovikoski *et al.* 2005). Although this needs to be investigated further (i.e. by searching for Atlantic influence in these sediments) it is plausible that the tidal influence originated in the Atlantic. This is particularly likely if we consider that the Amazon drainage basin is the only basin in the world where, at present, tidal (wave) influence can reach as far as 1000 km inland (see Chapter 11).

Conclusions

The Miocene Amazonian mega-wetland was one of the largest and longest-lived wetland environments in geological history. The evolution of this depositional system was controlled by a myriad of factors such as global sea level change, subsidence and a seasonally wet climate. The most important driving mechanism, however, was the uplift of the Andes.

The immediate predecessor of the wetland was the Oligocene to Early Miocene fluvial system that originated in the Central Andes and the craton and flowed towards the Caribbean. The transition from a fluvially dominated environment towards lacustrine-dominated conditions occurred during the Early to early Middle Miocene (*Psiladiporites-Crototricolpites* pollen zone), and by the Middle Miocene (*Crassoretitriletes* pollen zone) the mega-wetland reached its maximum extent. This predominantly freshwater lacustrine system had sediment input from the Andes and marginal marine influence from the Caribbean. At the same time the Amazonian Craton remained an additional source of sediment supply, and minor fluvial systems contributed to the wetland system.

One of the most outstanding features of this depositional setting was the highly diverse aquatic vertebrate and invertebrate fauna. Although the vertebrate fauna remained diverse throughout the Late Miocene, the endemic invertebrates virtually disappeared and have remained comparatively poor ever since. The termination of this fauna during the early Late Miocene correlates with the establishment of the modern Amazon River.

Andean uplift dramatically increased during the Late Miocene and the sedimentary wedge progressed to the east, beyond the sub-Andean and Amazonian sedimentary basins. As a result the

wetland disappeared and, after connecting with fluvial systems of eastern Amazonia, the Andean fluvial systems merged into the Amazon transcontinental river system. Around 6 Ma further uplift in the Andes caused relocation of the depositional centre towards the east and abandonment of the continental basins. From then on the bulk of sediment deposition took place in the Foz do Amazonas Basin (Equatorial Atlantic Margin).

The Miocene Amazonian wetland system was unique not only because of its extent and species diversity but also because it was concurrent with major changes in northern South American geography. After the disappearance of this system Amazonia suffered a decline in species diversity as result of the geographical changes and climatic cooling, the latter the possible cause for a decrease in diversity of the reptile fauna.

The nature of this complex inland environment, where freshwater, marine and tidal conditions coexisted under the influence of a warm, humid climate, as well as its transition to the present, still poses many questions that remain unanswered. Ultimately, a deeper understanding of this system and its evolution up to the present might help us to understand the evolution of Amazonian biodiversity.

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References

- Albert, J.S., Lovejoy, N.R., Crampton, W.G.R. (2006). Miocene tectonism and the separation of cis- and trans-Andean river basins: Evidence from Neotropical fishes. *J S Am Earth Sci* 21, 14–27.
- Antoine, P.-O., De Franceschi, D., Flynn, J.J., Nel, A., Baby, P., Benammi, M., Calderón, Y. *et al.* (2006) Amber from western Amazonia reveals Neotropical diversity during the middle Miocene. *PNAS* 103, 13595–13600.
- Antoine, P.-O., Salas-Gismondi, R., Baby, P., Benammi, M., Brusset, S., de Franceschi, D. *et al.* (2007) The Middle Miocene (Laventan) Fitzcarrald fauna, Amazonian Peru. In: Díaz-Martínez, E., Rábano, I. (eds) *Fourth European Meeting on the Palaeontology and Stratigraphy of Latin America*, Instituto Geológico y Minero de España, Madrid. Cuadernos del Museo Geominero 8, pp. 19–24.
- Bayona, G., Cortés, M., Jaramillo, C., Ojeda, G., Aristizabal, J., Reyes, A. (2007a) La Deformación Pre-neógena de la Cordillera Oriental definida por depósitos de antepaís. *Boletín de Geología* 29, 51–59.
- Bayona, G., Jaramillo, C., Rueda, M., Reyes-Harker, A., Torres, V. (2007b) Paleocene-Middle Miocene flexural-margin migration of the nonmarine Llanos foreland basin of Colombia. *Ciencia, Tecnología y Futuro* 3, 141–160.
- Bermúdez-Cella, M., Van der Beek, P., Bernet, M. (2008) Spatial and temporal patterns of exhumation across the Venezuelan Andes from in-situ and detrital apatite fission-track analysis: Implications for Cenozoic tectonics. In: Garver, J.I., Montario, M.J. (eds) *Proceedings from the 11th International Conference on Thermochronometry, Anchorage, Alaska*, pp. 25–27.

- Bristow, C.R., Parodiz, J.J. (1982) The stratigraphical paleontology of the Tertiary non-marine sediments of Ecuador. *Bull Carnegie Mus Nat Hist* 19, 1–53.
- Burgos, J.D.Z. (2006) Genese et progradation d'un cone alluvial au front d'une chaine active: exemple des Andes Equatoriennes au Neogene. PhD thesis, Université Paul Sabatier, Toulouse, 373 pp.
- Burgos, J.D.Z., Christophoul, F., Baby, P., Antoine, P.-O., Soula, J.-C., Good, D., Rivadeneira, M. (2005) Dynamic evolution of Oligocene–Neogene sedimentary series in a retro-foreland basin setting: Oriente Basin, Ecuador. In: *6th International Symposium on Andean Geodynamics (ISAG 2005, Barcelona)*, extended abstracts, pp. 127–130.
- Campbell, K.E., Heizler, M., Frailey, C.D., Romero-Pittman, L., Prothero, D.R. (2001) Upper Cenozoic chronostratigraphy of the southwestern Amazon Basin. *Geology* 29, 595–98.
- Campbell, K.E., Frailey, C.D., Romero-Pittman, L. (2006) The Pan-Amazonian Ucayali Peneplain, late Neogene sedimentation in Amazonia, and the birth of the modern Amazon River system. *Palaeogeogr Palaeoclimatol* 239, 166–219.
- Caputo, M.V., Rodrigues, R., Vasconcelos, D.N.N. (1971) *Litoestratigrafia da Bacia do Amazonas*. Relatório Interno. Belem: Petrobras, 92 pp.
- Caputo, M.V., Rodrigues, R., Vasconcelos, D.N.N. (1972) Nomenclatura estratigráfica da Bacia do Rio Amazonas. In: *Congresso Brasileiro de Geologia* 26, Belem. Anais 3, 35–46.
- Cooper, M.A., Addison, F.T., Alvarez, R., Coral, M., Graham, R.H., Hayward, A.B. et al. (1995) Basin development and tectonic history of the Llanos Basin, Eastern Cordillera, and Middle Magdalena Valley, Colombia. *Am Assn Petrol Geol Bull* 79, 1421–1443.
- Cozzuol, M.A. (2006) The Acre vertebrate fauna: Age, diversity, and geography. *J S Am Earth Sci* 21, 185–203.
- Diaz de Gamero, M.I. (1996) The changing course of the Orinoco River during the Neogene: a review. *Palaeogeogr Palaeoclimatol* 123, 385–402.
- Dobson D.M., Dickens G.R., Rea D.K. (2001) Terrigenous sediment on Ceara Rise: a Cenozoic record of South American orogeny and erosion. *Palaeogeogr Palaeoclimatol* 165, 215–229.
- Eiras, J.F., Wanderley, J.R. (2006) Bacias sedimentares brasileiras, Bacia do Solimões. Fundação Paleontologica Phoenix: *Phoenix* 8, 1–6.
- Eiras, J.F., Becker, C.R., Souza, E.M., Gonzaga, F.G., da Silva, J.G.F., Daniel, L.M.F. et al. (1994) Bacia do Solimões. *Boletim Geociencias Petrobras, Rio de Janeiro* 8, 17–45.
- Espurt, N., Baby, P., Brusset, S., Roddaz, M., Hermoza, W., Regard, V. et al. (2007) How does the Nazca Ridge subduction influence the modern Amazonian foreland basin? *Geology* 35, 515–518.
- Figueiredo, J., Hoorn, C., van der Ven, P., Soares, E. (2009) Late Miocene onset of the Amazon River and the Amazon deep-sea fan: Evidence from the Foz do Amazonas Basin. *Geology* 37, 619–622.
- 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.
- Gabb, W.M. (1869) Descriptions of fossils from the clay deposits of the Upper Amazon. *Am J Conchology* 4, 197–200.
- Garzzone, C.N., Hoke, G.D., Libarkin, J.C., Withers, S., MacFadden, B., Eiler, J. et al. (2008) Rise of the Andes. *Science* 320, 1304–1307.
- Gingras, M.K., Räsänen, M.E., Pemberton, S.G., Romero, L.P. (2002a) Ichnology and sedimentology reveal depositional characteristics of bay margin parasequences in the Miocene Amazonian foreland basin. *J Sediment Res* 72, 871–883.
- Gingras, M.K., Räsänen, M.E., Ranzi, A. (2002b) The significance of bioturbated inclined heterolithic stratification in the southern part of the Miocene Solimões Formation, Rio Acre: Amazonia Brazil. *Palaios* 17, 591–601.
- Gomez, A., Jaramillo, C.A., Parra, M., Mora, A. (2009) Huesser horizon: a lake and a marine incursion in northwestern South America during the Early Miocene. *Palaios* 24, 199–210.
- Gonçalves, F.T.T., Mora, C.A., Cordoba, F., Kairuz, E.C., Giraldo, B.N. (2002) Petroleum generation and migration in the Putumayo Basin, Colombia: insights from an organic geochemistry and basin modeling study in the foothills, 2002. *Mar Petrol Geol* 19, 711–725.
- Gregory-Wodzicki, K.M. (2000) Uplift history of the Central and Northern Andes: A review. *GSA Bulletin* 112, 1091–1105.
- 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*. Washington DC: Smithsonian Institution Press, pp. 15–43.
- Guerrero, J. (2002a) A proposal on the classification of systems tracts: application to the allostratigraphy and sequence stratigraphy of the Cretaceous Colombian Basin. Part 1: Berriasian to Hauterivian. *Geología Colombiana* 27, 3–25.
- Guerrero, J. (2002b) A proposal on the classification of systems tracts: application to the allostratigraphy and sequence stratigraphy of the Cretaceous Colombian Basin. Part 2: Barremian to Maastrichtian. *Geología Colombiana* 27, 27–49.
- Guerrero, J., Sarmiento, G. (1996) Estratigrafía física, palinológica, sedimentológica y secuencial del Cretácico Superior y Paleoceno del Piedemonte Llanero. Implicaciones en exploración petrolera. *Geología Colombiana* 20, 3–66.
- Guerrero, J., Sarmiento, G., Navarrete, R. (2000) The stratigraphy of the W side of the Cretaceous Colombian Basin in the Upper Magdalena Valley. Reevaluation of selected areas and type localities including Aipe, Guaduas, Ortega, and Piedras. *Geología Colombiana* 25, 45–110.
- Haq, B.H., Hardenbol, J., Vail, P.R. (1987) Chronology of fluctuating sea-levels since the Triassic. *Science* 235, 1156–1166.
- 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.
- Hermoza, W. (2004) Dynamique tectono-sédimentaire et restauration séquentielle du retro-bassin d'avant-pays des Andes centrales. PhD thesis, University of Paul Sabatier de Toulouse III, 296 pp.
- Hermoza, W., Brusset, S., Baby, P., Gil, W., Roddaz, M., Guerrero, N., Bolaños, R. (2005) The Huallaga foreland basin evolution: thrust propagation in deltaic environment, in the northern Peruvian Andes. *J S Am Earth Sci* 19, 21–34.
- Hoorn, C. (1993a) Marine incursions and the influence of Andean tectonics on the Miocene depositional history of northwestern Amazonia: Results of a palynostratigraphic study. *Palaeogeogr Palaeoclimatol* 105, 267–309.
- Hoorn, C. (1993b) Geología del Nororiente de la Amazonia Peruana: la Formación Pebas. In: Kalliola, R., Puhakka, M., Danjoy, W. (eds) *Amazonia Peruana – Vegetación Húmeda Tropical en el Llano Subandino*. Jyväskylä, Finland: Proyecto Amazonia Universidad de Turku (PAUT) and Oficina Nacional de Evaluación de Recursos Naturales (ONERN) pp. 69–85.
- Hoorn, C. (1994a) Fluvial palaeoenvironments in the intracratonic Amazonas Basin (Early Miocene–early Middle Miocene, Colombia). *Palaeogeogr Palaeoclimatol* 109, 1–54.
- Hoorn, C. (1994b) An environmental reconstruction of the palaeo-Amazon River system (Middle to Late Miocene, NW Amazonia). *Palaeogeogr Palaeoclimatol* 112, 187–238.
- Hoorn, C. (2006) Mangrove forests and marine incursions in Neogene Amazonia (Lower Apaporis River, Colombia). *Palaios* 21, 197–209.

- 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.
- Hoorn, C., Aalto, R., Kaandorp, R.J.G., Lovejoy, N.R. (2006) Miocene semidiurnal tidal rhythmites in Madre de Dios, Peru: Comment. GSA, Forum. *Geology*; doi: 10.1130/G22115.1.
- Horton, B.K., DeCelles, D.G. (1997) The modern foreland basin system adjacent to the Central Andes. *Geology* 25, 895–898.
- Hovikoski, J. (2006) Miocene Western Amazonia in the light of sedimentological and ichnological data. PhD thesis, Annales Universitatis Turkuensis, Ser. AII, University of Turku, 138 pp.
- Hovikoski, J., Räsänen, M.E., Gingras, M., Roddaz, M., Brusset, S., Hermoza, W. et al. (2005) Miocene semidiurnal tidal rhythmites in Madre de Dios, Peru. *Geology* 33, 177–180.
- Hovikoski, J., Gingras, M., Räsänen, M., Rebata, L., Guerrero, J., Ranzi, A. et al. (2007) The nature of Miocene Amazonian epicontinental embayment: High-frequency shifts of the low-gradient coastline. *GSA Bulletin* 119, 1506–1520.
- Hovikoski, J., Räsänen, M.E., Gingras, M., Ranzi, A., Melo, J. (2008) Tidal and seasonal controls in the formation of late Miocene IHS deposits, western Amazonian Foreland Basin. *Sedimentology* 55, 499–530.
- Ingeominas (2007) *Atlas Geológico de Colombia*. URL: <http://www.ingeminas.gov.co/>
- Katzer, F. (1903) *Grundzüge der Geologie des unteren Amazonasgebietes (des Staates Para in Brasilien)*. Leipzig: Max Weg, 298 pp.
- Kay, R.F., Madden, R.H., Cifelli, R.L., Flynn, J.J. (eds) (1997) *Vertebrate Paleontology in the Neotropics: The Miocene Fauna of La Venta, Colombia*. Smithsonian Institution Press, 592 pp.
- Kaandorp, R.J.G., Vonhof, H.B., Wesselingh, F.P., Romero-Pittman, L., Kroon, D., van Hinte, J.E. (2005) Seasonal Amazonian rainfall variation in the Miocene Climate Optimum. *Palaeoogeogr Palaeoclimatol* 221, 1–6.
- Kronberg, B.I., Franco, J.R., Benchimol, R.E., Hazenberg, G., Doherty, W., VanderVoet, A. (1989) Geochemical variations in Solimões Formation sediments (Acre Basin, western Amazonia). *Acta Amazonica* 19, 319–333.
- Kummel, B. (1948) Geological reconnaissance of the Contamana Region, Peru. *Geol Soc Am Bull* 69, 1217–1266.
- Latrubesse, E.M., Bocquentin, J., Santos, J.C.R., Ramonell, C.G. (1997) Paleoenvironmental model for the late Cenozoic of Southwestern Amazonia: paleontology and geology. *Acta Amazonica* 27, 103–118.
- Latrubesse, E., da Silva, S., Cozzuol, M., Absy, M. (2007) Late Miocene continental sedimentation in southwestern Amazonia and its regional significance: Biotic and geological evidence. *J S Am Earth Sci* 23, 61–80.
- Lovejoy, N.R., Bermingham, E., Martin, A.P. (1998) Marine incursion into South America. *Nature* 396, 421–422.
- Lovejoy, N.R., Albert, J.S., Crampton, W.G.R. (2006) Miocene marine incursions and marine/freshwater transitions: evidence from Neotropical fishes. *J S Am Earth Sci* 21, 5–13.
- Lundberg, J., Machado-Allison, A., Kay, R.F. (1986) Miocene characid fishes from Colombia: Evolutionary stasis and extirpations. *Science* 234, 208–209.
- Lundberg, J.G., Marshall, J.G., Guerrero, J., Horton, B., Malabarba, M.C.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.S., Lucena, C.A.S. (eds) *Phylogeny and Classification of Neotropical Fishes*. Porto Alegre, Brazil: EDIPUCRS, pp. 13–48.
- Maia, R., Godoy, H., Yamaguti, H., de Moura, P., da Costa, F., de Holanda, M., Costa, J. (1977) *Projecto de Carvão no Alto Solimões*. CPRM-DNPM, 137 pp.
- Martin-Gombojav, N., Winkler, W. (2008) Multiple recycling of Proterozoic crust in the Andean Amazon foreland of Ecuador: Implications for orogenic development of the Northern Andes. *Terra Nova* 20, 22–31.
- Mathalone, J.M.P., Montoya, M. (1995) Petroleum geology of the sub-andean basins of Peru. In: Tankard, A.J., Suárez-Soruco, R., Welsink, H.J. (eds) *Petroleum Basins of South America*. Memoir 62, American Association of Petroleum Geologists, pp. 423–444.
- Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E. et al. (2005) The Phanerozoic record of global sea-level change. *Science* 310, 1293–1298.
- Mitsch, W.J., Gosselink, J.G. (2000) *Wetlands*, 4th edn. New York: John Wiley & Sons, 600 pp.
- Monsch, K.A. (1998) Miocene fish faunas from the northwestern Amazonia basin (Colombia, Peru, Brazil) with evidence of marine incursions. *Palaeoogeogr Palaeoclimatol* 143, 31–50.
- Mora, A. (2007) Inversion tectonics and exhumation processes in the Eastern Cordillera of Colombia. Dissertation. Institut für Geowissenschaften, Universität Potsdam, Germany, 177 pp.
- Mora, A., Parra, M., Strecker, M.R., Kammer, A., Dimaté, C., Rodríguez, F. (2006) Cenozoic contractional reactivation of Mesozoic extensional structures in the Eastern Cordillera of Colombia. *Tectonics* 25, TC2010. doi: 10.1029/2005TC001854.
- Mora, A., Parra, M., Strecker, M.R., Sobel, E.R., Hooghiemstra, H., Torres, V., Vallejo-Jaramillo, J. (2008) Climatic forcing of asymmetric orogenic evolution in the Eastern Cordillera of Colombia. *Bull Geol Soc Am* 120, 930–949.
- Moraes Rego, L.F. (1930) *Notas sobre a Geologia do território de Acre e da bacia do Javari*. Manaus: Cezar, Cavalcante and Cia, 45 pp.
- Muñoz-Torres, F.A., Whatley, R.C., Van Harten, D. (2006) Miocene ostracod (Crustacea) biostratigraphy of the Upper Amazon Basin and the *Cyprideis* genus evolution. *J S Am Earth Sci* 21, 75–86.
- Nuttall, C.P. (1990) A review of the Tertiary non-marine molluscan faunas of the Pebasian and other inland basins of north-western South America. *Bull Brit Mus Nat Hist (Geol)* 45, 165–371.
- Oppenheim, V. (1946) Geological reconnaissance in southeastern Peru. *Geol Soc Am Bull* 30, 254–264.
- Pardo, A.A., Zuñiga, F. (1976) Estratigrafía y evolución tectónica de la región de la selva del Perú. (I) Paleozoico y (II) Mesozoico y Cenozoico. Memorias Segundo Congreso Latinoamericano de Geología. *Bol Geol., Caracas, Publ. Esp.* 7(2), 588–608.
- Parra, M., Mora, A., Jaramillo, C., Strecker, M.R., Sobel, E.R., Quiroz, L. et al. (2009) Orogenic wedge advance in the northern Andes: Evidence from the Oligocene-Miocene sedimentary record of the Medina Basin, Eastern Cordillera, Colombia. *GSA Bulletin* 121, 780–800.
- Pasley, M.A., Shepherd, D.B., Pocknall, D.T., Boyd, K.P., Vander Andrade, Figueiredo, J.P. (2005) Sequence stratigraphy and basin evolution of the Foz do Amazonas Basin, Brazil. *Search and Discovery Article #10082*. URL: <http://www.searchanddiscovery.net/documents/2005/pasley/images/pasley.pdf>.
- Petri, S., Fulfaro, V.J. (1983) *Geologia do Brasil*. São Paulo: Editora da Universidade de São Paulo, 631 pp.
- Pilsbry, H.A. (1944) Molluscan fossils from the Rio Pachitea and vicinity in eastern Peru. *Proc Acad Nat Sci, Philadelphia*, 96, 137–153.
- Pilsbry, H.A., Olsson, A.A. (1935) Tertiary fresh-water mollusks of the Magdalena embayment, Colombia. *Proc Acad Nat Sci, Philadelphia*, 87, 7–39.
- Potter, P.E. (1997) The Mesozoic and Cenozoic paleodrainage of South America: A natural history. *J S Am Earth Sci* 10, 331–344.
- Ramsar, Iran (1971) *The Ramsar Convention Manual. A Guide to the Convention on Wetlands*, 4th edn, 114 pp. URL: http://www.ramsar.org/lib/lib_manual2006e.pdf.

- 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., Linna, A., Irion, G., Rebata Hernani, L., Vargas Huaman, R., Wesselingh, F. (1998) Geología y geoformas de la zona de Iquitos. In: *Geoecología y desarrollo Amazónico: estudio integrado en la zona de Iquito, Peru. Annales Turkuensis* (AII) 114, 59–137.
- Rebata, L., Gingras, M., Räsänen, M., Barberi, M. (2006) Tidal-channel deposits on a delta plain from the Upper Miocene Nauta formation, Marañon Foreland Sub-basin, Peru. *Sedimentology* 53, 971–1013.
- Roddaz, M. (2004) Transition des stades alimentés à suralimentés dans les systèmes de rétro-bassin d'avant-pays: exemple du bassin amazonien. PhD thesis, Université de Toulouse, Toulouse, 332 pp.
- 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.
- Roddaz, M., Viers, J., Brusset, S., Baby, P., Boucayrand, C., Herail, G. (2006a) Controls on weathering and provenance in the Amazonian foreland basin: Insights from major and trace element geochemistry of Neogene Amazonian sediments. *Chem Geol* 226, 31–65.
- Roddaz, M., Brusset, S., Baby, P., Herail, G. (2006b) Miocene tidal-influenced sedimentation to continental Pliocene sedimentation in the forebulge-backbulge depozones of the Beni-Mamore foreland Basin (northern Bolivia). *J S Am Earth Sci* 20, 351–368.
- Rossetti, D.F., Góes, A.M. (2004) *O Neógeno da Amazônia Oriental*. Belém, Pará: Museu Paraense Emílio Goeldi, Coleção Friedrich Katzer, 222 pp.
- Ruegg, W., Rosenzweig, A. (1949) Contribución a la geología de las formaciones modernas de Iquitos y la Amazonia superior. *Volumen Jubilar de la Sociedad Geológica del Perú* (II)3, 1–24.
- Ruiz, G.M.H., Seward, D., Winkler, W. (2007) Evolution of the Amazon Basin in Ecuador with special reference to hinterland tectonics: Data from zircon fission-track and heavy mineral analysis. *Dev Sedimentol* 58, 907–934.
- Salas-Gismondí, R., Antoine, P.-O., Baby, P., Brusset, S., Benammi, M., Espurt, N. et al. (2007) Middle Miocene crocodiles from the Fitzcarrald Arch, Amazonian Peru. In: Díaz-Martínez, E., Rábano, E.I. (eds) *4th European Meeting on the Palaeontology and Stratigraphy of Latin America, Cuadernos del Museo Geominero 8*. Madrid: Instituto Geológico y Minero de España, pp. 355–360.
- 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, 255–279.
- Thomas, R.G., Smith, D.G., Wood, J.M., Visser, J., Calverly-Range, E.A., Koster, E.H. (1987) Inclined heterolithic stratification; terminology, description, interpretation and significance. *Sediment Geol* 53, 123–179.
- Uba, C.E., Strecker, M.R., Schmitt, A.K. (2007) Increased sediment accumulation rates and climatic forcing in the central Andes during the late Miocene. *Geology* 35, 979–982.
- Van der Hammen, T., Werner, J. H., van Dommelen, H. (1973) Palynological record of the upheaval of the Northern Andes: A study of the Pliocene and lower Quaternary of the Colombian Eastern Cordillera and the early evolution of its high-Andean biota. *Rev Palaeobot Palynol* 16, 1–42.
- Vermelj, G.J., Wesselingh, F.P. (2002) Neogastropod molluscs from the Miocene of Western Amazonia, with comments on marine to freshwater transitions in molluscs. *J Paleontol* 76, 265–270.
- Villamil, T. (1999) Campanian-Miocene tectonostratigraphy, depositional evolution and basin development of Colombia and western Venezuela. *Palaeogeogr Palaeoclimatol* 153, 239–275.
- Vonhof, H.B., Wesselingh, F.P., Ganssen, G.M. (1998) Reconstruction of the Miocene western Amazonian aquatic system using molluscan isotopic signatures. *Palaeogeogr Palaeoclimatol* 141, 85–93.
- Vonhof, H.B., Wesselingh, F.P., Kaandorp R.J.G., Davies, G.R., van Hinte, J.E., Guerrero, J. et al. (2003) Paleogeography of Miocene Western Amazonia: isotopic composition of molluscan shells constrains the influence of marine incursions. *Geol Soc Am Bull* 115, 983–993.
- Wanderley Filho, J.R., Gonçalves de Melo, J.H., Medina da Fonseca, V.M., da Costa Machado, D.M. (2005) Bacias sedimentarias, Bacia do Amazonas. *Fundação Paleontológica Phoenix. Phoenix* 7, 1–6.
- Wesselingh, F.P. (2006) Miocene long-lived lake Pebas as a stage of mollusc radiations, with implications for landscape evolution in western Amazonia. *Scripta Geologica* 133, 458 pp.
- Wesselingh, F.P., Macsotay, O. (2006) *Pachydon hettneri* (Anderson, 1928) as indicator for Caribbean-Azonian lowland connections during the Early-Middle Miocene. *J S Am Earth Sci* 21, 49–53.
- Wesselingh, F.P., Salo, J.A. (2006) A Miocene perspective on the evolution of the Amazonian biota. *Scripta Geologica* 133, 439–458.
- Wesselingh, F.P., Räsänen, M.E., Irion, G., Vonhof, H.B., Kaandorp, R., Renema, W. et al. (2002) Lake Pebas: a palaeoecological reconstruction of a Miocene, long-lived lake complex in western Amazonia. *Cainozoic Res* 1, 35–81.
- Wesselingh, F.P., Guerrero, J., Räsänen, M., Romero Pitmann, L., Vonhof, H. (2006a) Landscape evolution and depositional processes in the Miocene Amazonian Pebas lake/wetland system: evidence from exploratory boreholes in northeastern Peru. *Scripta Geologica* 133, 323–361.
- Wesselingh, F.P., Kaandorp, R.J.G., Vonhof, H.B., Räsänen, M.E., Renema, W., Gingras, M. (2006b) The nature of aquatic landscapes in the Miocene of western Amazonia: an integrated palaeontological and geochemical approach. *Scripta Geologica* 133, 363–393.
- Wesselingh, F.P., Hoorn, M.C., Guerrero, J., Räsänen, M.E., Romero Pittmann L., Salo, J. (2006c) The stratigraphy and regional structure of Miocene deposits in western Amazonia (Peru, Colombia and Brazil), with implications for Late Neogene landscape evolution. *Scripta Geologica* 133, 291–322.
- Wesselingh, F.P., Kaandorp, R.J.G., Vonhof, H.B., Räsänen, M.E., Renema, W. (2006d) The nature of aquatic landscapes in the Miocene of western Amazonia: an integrated palaeontological and geochemical approach. *Scripta Geologica* 133, 363–393.
- Wesselingh, F.P., Ranzi, A., Räsänen, M.E. (2006e) Miocene freshwater Mollusca from western Brazilian Amazonia. *Scripta Geologica* 133, 419–437.
- Westaway, R. (2006) Late Cenozoic sedimentary sequences in Acre state, southwestern Amazonia: Fluvial or tidal? Deductions from the IGCP 449 fieldtrip. *J S Am Earth Sci* 21, 120–134.