

Multi-proxy evidence of Caribbean-sourced marine incursions in the Neogene of Western Amazonia, Brazil

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ABSTRACT

The timing of continental-scale marine flooding events in Western Amazonia during the Neogene is still an unsolved question. Despite broad proxy-based evidence of such events, the pathways and duration of late Miocene marine incursions remain controversial. We provide coupled calcareous and organic microfossil and geochemical data from six onshore cores from Neogene sequences of the Solimões Basin, Brazil. Our records support minor marine influence in the early Miocene (23.0, 21.1, 18.6, and 16.3 Ma), middle Miocene (14.9, 13.7, and 12.9 Ma) and early Pliocene (4.7, 4.2–4.1, and 3.8 Ma), and conspicuous marine incursions in the late Miocene (11.1–8.8 Ma) suggested by the consistent presence of salinity-indicative microfossils and geochemical data. Our findings challenge the view of major marine incursions in the early and middle Miocene in the studied area. We propose for the first time a new late Miocene incursion (LMI) event as the main marine flooding event in Western Amazonia during the Neogene. These onshore records are compared with three offshore cores from the Atlantic and Pacific Oceans. The similarity between microfossil assemblages of the Solimões Basin and the Caribbean Sea, and evidence of increased runoff from the Orinoco river drainage system, strongly suggest the Caribbean Sea as the primary source area of the marine incursions, supporting a Venezuelan seaway. We further show for the first time the potential linkage between Neogene marine incursions (mainly the LMI) into the Solimões Basin and major disturbances in the global carbon cycle.

INTRODUCTION

There has been a wide debate about the timing of Neogene marine flooding events in Western Amazonia (e.g., Hovikoski et al., 2010; McDermott, 2021). However, fossil and geochemical records provide clear evidence of marine incursions in the early (e.g., Antoine et al., 2016) and middle Miocene (e.g., Hoorn, 1993; Boonstra et al., 2015). Although late Miocene marine flooding events have also been suggested (e.g., Linhares et al., 2017; Espinosa et al., 2021), the source area, pathways, and duration of these incursions are still poorly understood (Hoorn, 1996).

We present multi-proxy analyses of Neogene records from six cores from the Solimões Basin in Brazil. These include our data and published data from previous studies (Linhares et al., 2011, 2017, 2019; Jaramillo et al., 2017; Leandro et al., 2019) on calcareous and organic microfossils, organic carbon isotopic data ($\delta^{13}\text{C}_{\text{org}}$), bulk sediment carbonate content (percent CaCO_3), total nitrogen (TN), and sulfur to total organic carbon (S/TOC) ratio. These provide robust evidence of marine influence throughout the Neogene and are compared with three time-related cores from the Deep Sea Drilling Project (DSDP) to infer the source of the marine incursions.

MATERIALS AND METHODS

To investigate the marine records in Western Amazonia, we studied nine cores: six from the Solimões Basin drilled by the Brazilian Geological Survey (CPRM/Brazil), during the “Carvão no Alto Solimões” Project (1AS-51-AM, 1AS-52-AM, 1AS-105-AM, 1AS-7D-AM, 1AS-8-AM, and 1AS-31-AM) (Maia et al., 1977), selected based on previously published data on brackish-water and/or marine fossil evidence, which were also used in this study (Linhares et al., 2011, 2017, 2019; Jaramillo et al., 2017; Leandro et al., 2019); and three near-field DSDP cores drilled in the Atlantic Ocean (Site 153 in the Caribbean Sea [Edgar et al., 1973] and Site 354 at the Ceará Rise [Perch-Nielsen et al., 1977]), and in the Pacific Ocean (Site 321 in the Peru Basin [Yeats et al. [1976]). We generated 553 new $\delta^{13}\text{C}_{\text{org}}$, percent CaCO_3 , TN, S/TOC ratio, and calcareous and organic microfossil data that were integrated with 278 published microfossil data. Age-depth models for most onshore cores were based on the sporomorph (spore and pollen) content and correlated to the regional compilation of age-calibrated bioevents from Venezuela (Lorente, 1986). Age controls for the onshore core 1AS-31-AM were based on the regional ostracod zonation (Linhares et al., 2011). Age controls for the DSDP Site 153 core were based on planktonic foraminifera from the Caribbean Sea (Bolli and Premoli Silva, 1973) and correlated to the global zonation scheme (Bolli and Saunders, 1985). All age assignments were adjusted to the Geologic Time Scale 2012 (Gradstein et al., 2012). Further details on the core locations, materials,

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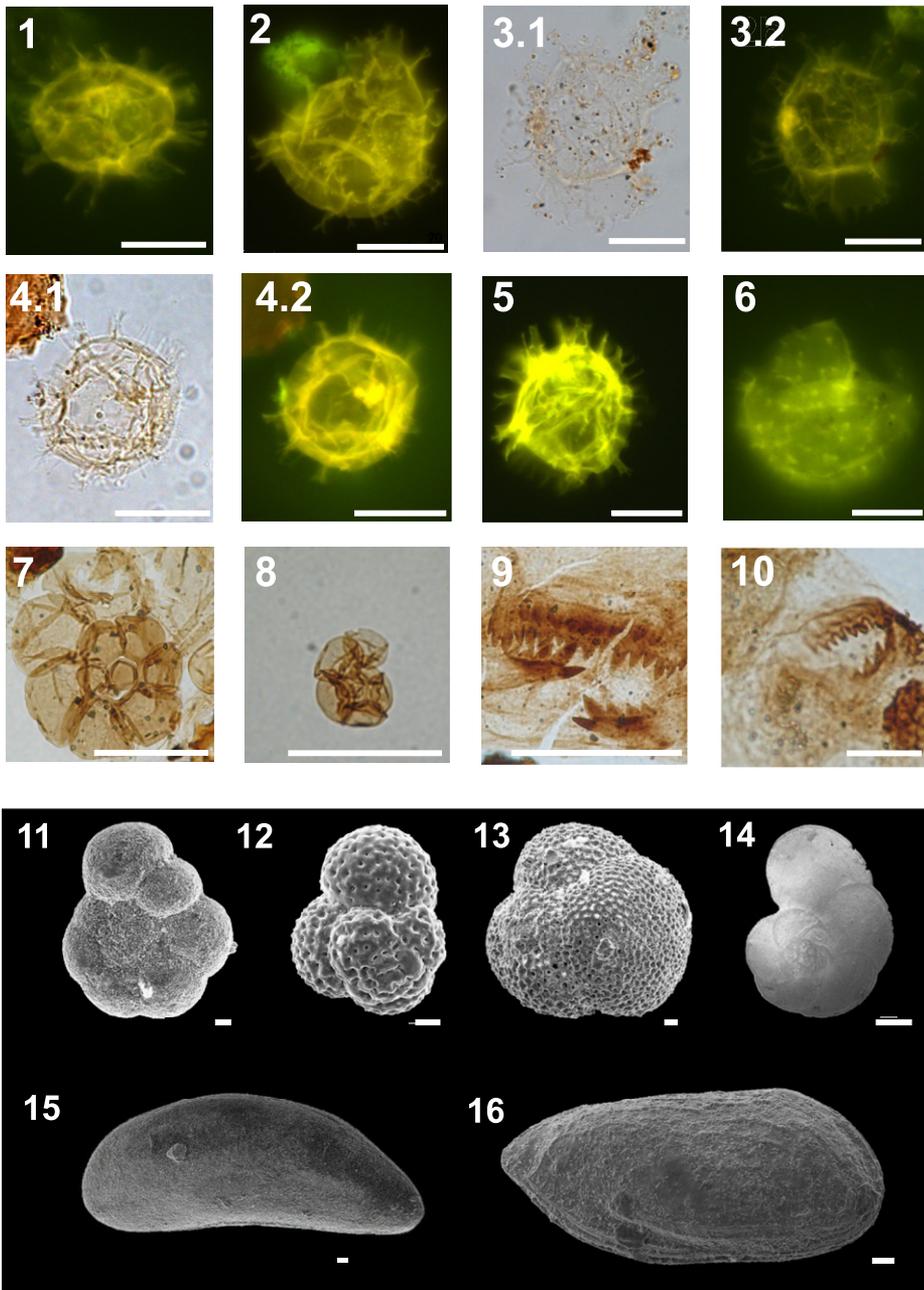


Figure 1. Organic and calcareous marine microfossils from Solimões Basin (Brazil) sediment cores. (1–6) Dinocysts: *Homotryblium* sp. (1); *Spiniferites* sp. (2, 4.1, 4.2); *S. mirabilis* (3.1, 3.2); *S. ramosus* (5); *Operculodinium centrocarpum* (6). (7,8) Foraminiferal linings. (9,10) Scolecodonts. (11–14) Foraminifera: *Ammonia tepida* (11); *Globigerinoides* sp. (12,13); *Globorotalia* sp. (14). (15,16) Ostracods: *Paracypris* sp. (15); *Pellucistoma* sp. (16). Source of photos 14–16: Linhares et al. (2011, 2017). Scale bars are 20 μm .

and methods are provided in the Supplemental Material¹.

¹Supplemental Material. Additional information on geological settings; materials and methods; references; supplemental Figures S1–S5; a summary of samples processed and analyzed in this study by site and technique; and full age-calibrated microfossil and geochemical data sets. Please visit <https://doi.org/10.1130/GEOL.S.17139308> to access the supplemental material, and contact editing@geosociety.org with any questions.

RESULTS

The rich and well-preserved Amazonia microfossil assemblages in the studied cores provide the basis for a detailed assessment of the early Miocene (23.0 Ma) to early Pliocene (3.8 Ma) (see the Supplemental Material) through the recognition of six sporomorph and two ostracod biozones (Lorente, 1986; Linhares et al., 2019; see the Supplemental Material).

The palynoflora of the Solimões Formation in the cores is highly diverse (Jaramillo et al., 2017; Leandro et al., 2019; Linhares et al.,

2019). Marine palynomorphs also occur in the studied sections, including 15 dinoflagellate cyst (dinocyst) taxa (mainly *Operculodinium* and *Spiniferites*), scolecodonts (jaws of polychaete annelids), and foraminiferal linings. These marine palynomorphs are more abundant in the late Miocene (11.0–10.5 Ma) (Figs. 1 and 2; see Fig. S5 and the data set in the Supplemental Material).

Foraminifera analyses yield benthic (*Amphistegina*, *Quinqueloculina*, *Planorbulina*), euryhaline (*Ammonia*), agglutinated (*Miliammina*, *Textularia*), and, to a lesser extent, planktonic forms (*Globigerinoides*, *Globigerina*, and *Globorotalia*) (Figs. 1 and 2; see Supplemental Material). The ostracod fauna consists mainly of the euryhaline genus *Cyprideis*, which is the most abundant (>90%) and diverse (>30 species) genus present. Other genera include the brackish-water and/or marine genera *Pellucistoma*, *Paracypris*, *Perissocytheridea*, *Rhadinocytherura*, and *Skopaeocythere*, and, to a lesser extent, the freshwater genera *Cypria*, *Cytheridella*, and *Penthesilenula* (Figs. 1 and 2; see the Supplemental Material). Markedly high calcareous microfossil abundance occurs at 11.1–8.8 Ma.

The percent CaCO_3 values rise above the average ($\sim 5\%$) at 10.9–10.1 Ma ($\sim 36\%$), and 8.5 Ma ($\sim 28\%$) (see the Supplemental Material). Similarly, S/TOC rises above the average (~ 1.0) at 22.7 Ma (~ 1.5), 21.1–21.1 Ma (~ 1.1), 14.9–14.8 Ma (~ 2.0), 12.1–11.9 Ma (~ 1.3), 10.8–10.7 Ma (~ 6.9), 10.5–10.4 Ma (~ 10.0), 8.5 Ma (~ 1.0), 5.4–5.2 Ma (~ 2.1), 4.7 Ma (~ 2.2), and 3.9 Ma (~ 1.5). Our $\delta^{13}\text{C}_{\text{org}}$ data present a relatively flat pattern through most of the record (average $\sim 25\text{‰}$), with little noise ($\pm 4\%$, 1σ), except for a single outlier at 10.0 Ma representing an $\sim 18\text{‰}$ positive excursion. The TOC/TN ratios in core 1AS-52-AM show consistently low values (< 10), whereas cores 1AS-51-AM and 1AS-105-AM present low-resolution and “noisy” TOC/TN records.

The microfossil content from the DSDP cores consists of well-preserved assemblages. Site 153 (Caribbean Sea) is dominated by dinocysts and scolecodonts (Leandro et al., 2020); Site 354 (Ceará Rise) shows low abundance of palynomorphs; and Site 321 (Peru Basin) presents low abundance of dinocysts and abundant radiolarians (see the Supplemental Material). Detailed analysis of the dinocyst-rich assemblage recovered from Site 153 shows a significant increase in both the dinocyst-based peridinioid-gonyaulacoid (P/G) ratio and the relative abundance of reworked dinocysts toward the late Miocene (9.9–9.0 Ma).

DISCUSSION AND CONCLUSIONS Neogene Marine Records in the Solimões Basin

Considering the distance between the Western Amazonia cores and the nearby coastal

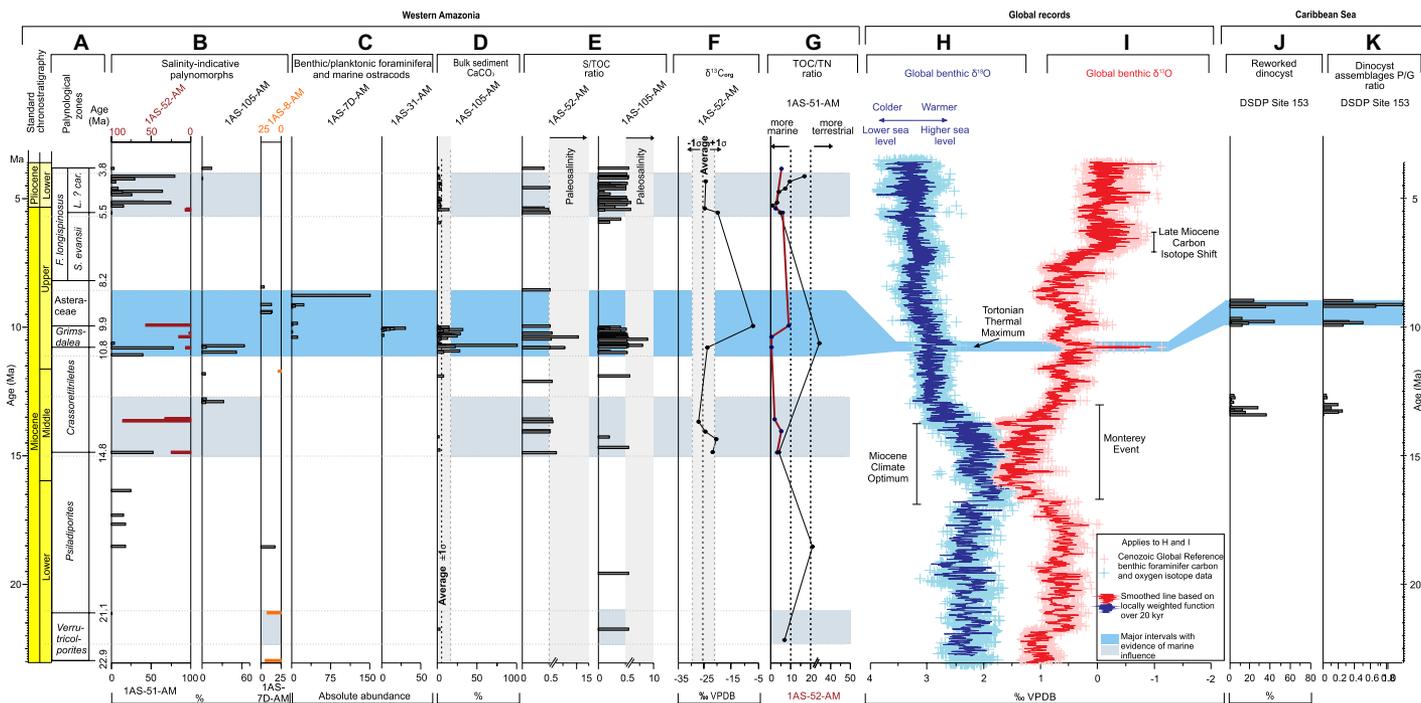


Figure 2. Multi-proxy records from the Solimões Basin (Brazil) and Caribbean Sea, and correlation with global carbon records. (A–G) Solimões Basin records: regional palynological zones (A; Lorente, 1986); relative abundance of salinity-indicative palynomorphs (B); absolute abundance of calcareous microfossils (C); bulk sediment percent CaCO_3 (D); sulfur to total organic carbon (S/TOC) ratio (E); organic carbon isotopic data ($\delta^{13}\text{C}_{\text{org}}$) record (F); and total organic carbon to total nitrogen (TOC/TN) ratio (G). (H,I) Global oxygen and carbon records (Westerhold et al., 2020): high-resolution benthic oxygen (H) and carbon (I) isotope. (J,K) Caribbean Sea records: relative abundance of reworked dinocysts (J); and dinocyst peridinioid-gonyaulacoid (P/G) ratio (K). VPDB—Vienna Pee Dee belemnite; DSDP—Deep Sea Drilling Project.

regions, we interpret the consistent presence of salinity-indicative microfossils at onshore cores as evidence of marine influence in the Solimões Formation. The distribution of these microfossils and the geochemical proxies show pulse-like patterns through the early Miocene–early Pliocene, with the most continuous and robust records occurring in the late Miocene (Fig. 2; for a full version of Figure 2, see Figure S5).

Organic-walled microfossils (dinocysts, foraminiferal lining, and mangrove pollen grains of *Zonocostites ramonae* and *Verrucolporites rotundiporus*) dominate the early Miocene marine records (23.0, 21.1, 18.6, and 16.3 Ma; Hoorn, 1993; Salamanca Villegas et al., 2016; Jaramillo et al., 2017). This association indicates well-developed transitional paleoenvironments, and reducing conditions would explain the absence of calcareous microfossils (Boonstra et al., 2015; Jaramillo et al., 2017). However, short-lived marine incursions and/or poor preservation conditions would have prevented abundant and diverse assemblages.

The emergence of brackish-water and/or marine-indicative calcareous microfossils and minor occurrences of palynomorphs mark the middle Miocene (14.9, 13.7, and 12.9 Ma). Despite the difference from coeval sequences (e.g., Hoorn, 1993), our associations show partial similarity with findings for the middle Miocene–to–late Miocene transition from the Contamana region, Peru (Antoine et al., 2016).

Late Miocene Incursion

The biotic and geochemical features provide strong evidence for a late Miocene incursion (LMI; 11.1–8.8 Ma) in the Solimões Basin. This newly proposed event starts with a prominent increase in the abundance of salinity-indicative palynomorphs (mainly dinocysts). The increase in salinity is supported by consistently high S/TOC ratios, an independent paleosalinity indicator (Wei and Algeo, 2019). At 10.8 Ma, the plankton community shifts from a dinocyst- to a foraminifera-rich association. The emergence and stepwise increase in abundance of foraminifera and the abrupt decline of the dinocysts assemblage suggest a rapid and probably deeper flooding (relative to other intervals of marine flooding in the Neogene of our records) (Linhares et al., 2011). This further supports marine biogenic activity as the driver of the substantial increase in the CaCO_3 content during the biotic shift.

The establishment of a foraminifera-rich community in Western Amazonia coincides with a conspicuous ($\sim 18\text{‰}$) positive excursion in the $\delta^{13}\text{C}_{\text{org}}$ record at core 1AS-52-AM. Typical $\delta^{13}\text{C}$ values of our onshore cores vary between -30‰ and -21‰ , which is within the range of C3 plants (-37‰ to -20‰ ; Kohn, 2010), the dominant plant group before ca. 8.0–7.0 Ma (Cerling et al., 1997). This strongly indicates they were the main source of ^{12}C -rich carbon to the Pebas Mega-Wetland System (Fig. 3) during

the Miocene. We contend the positive excursion in our $\delta^{13}\text{C}_{\text{org}}$ record can be explained by a rapid marine incursion and the addition of ^{13}C -rich oceanic dissolved inorganic carbon ($\delta^{13}\text{C}$: 0.4‰ ; Ridgwell and Arndt, 2015) into Western Amazonia. This is best observed at the core 1AS-52-AM due to its paleogeographic setting within the basin depocenter. Consistently low TOC/TN ratios for this core suggest marine-sourced organic matter (McKay et al., 2004).

Pathway of the Late Miocene Marine Incursions

The geographic distribution of dinocyst assemblages is usually restricted to shallow-marine paleoenvironments; even though some genera are cosmopolitan, assemblage compositions across shelves are distinct within and/or between ocean basins (Sluijs et al., 2005, and references therein).

We thus compared dinocyst assemblages from our six onshore study sites in the Brazilian Western Amazonia with nine newly studied and published records from coeval, late Miocene offshore sites in nearby ocean basins—Caribbean Sea, equatorial Atlantic, and eastern Pacific (Fig. 3; for a detailed compilation and referencing, see the Supplemental Material). We observed that Western Amazonia and Venezuelan Caribbean Sea cores share several dinocyst genera, including *Lingulodinium* spp., *Operculodinium* spp., *Selenopemphix* spp., *Spiniferites*

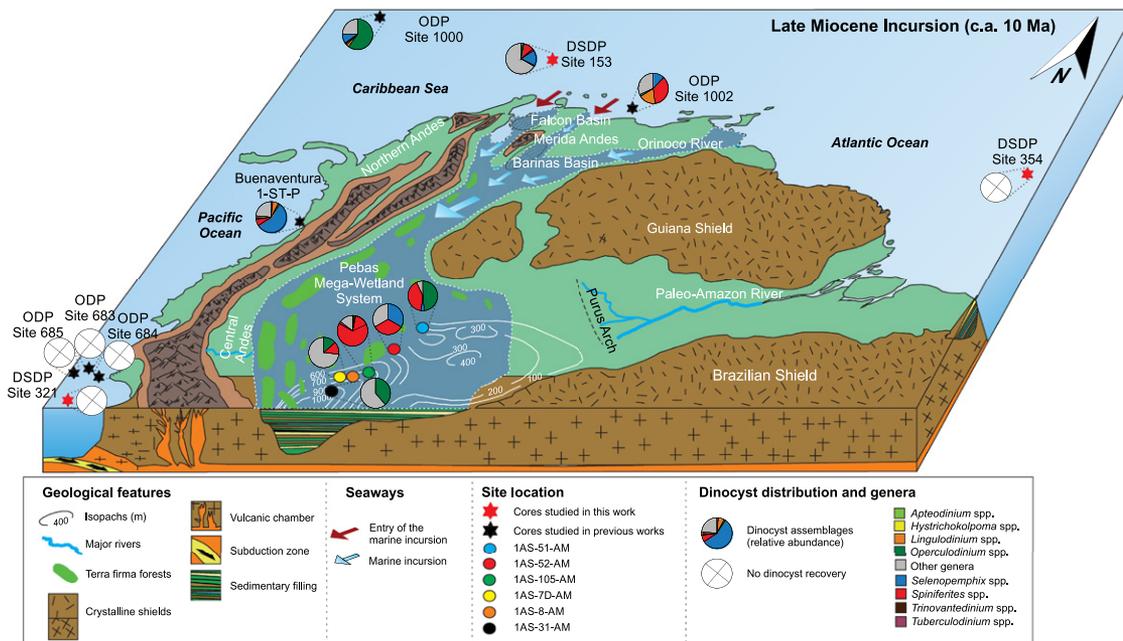


Figure 3. Paleogeography of northern South America during the middle to late Miocene, and the Venezuelan seaway for marine incursions supported by this study (from the Caribbean Sea to Pebas Mega-Wetland System). DSDP—Deep Sea Drilling Project; ODP—Ocean Drilling Program. Cores studied in previous works (Lewis, et al., 1990; Mertens et al., 2009; Mahdviourshari, 2014; Duque-Herrera et al., 2018; Leandro et al., 2020) are also shown.

spp., *Trinovantedinium* spp., and *Tuberculodinium* spp. (Fig. 3; see the Supplemental Material). The equatorial Atlantic and eastern Pacific, on the other hand, usually present dinocyst-poor surface waters (Lewis et al., 1990), despite a recent Caribbean-like assemblage recovered from the Colombian Pacific (Duque-Herrera et al., 2018) (Fig. 3).

Furthermore, planktonic foraminifera genera *Globigerina* spp., *Globigerinoides* spp., and *Globorotalia* spp. recovered at Western Amazonia cores (1AS-7D-AM, 1AS-8-AM, 1AS-31-AM, and 1AS-51-AM) suggest strong similarity with the Caribbean Sea plankton assemblage (Bolli and Premoli-Silva, 1973), and scolecodonts recovered from core 1AS-51-AM resemble forms found at DSDP Site 153.

We contend our late Miocene marine records recovered in Western Amazonia are best explained by a Venezuelan seaway (e.g., Lundberg et al., 1998); i.e., a connection between the Caribbean Sea and the Pebas system via Venezuela (Fig. 3) (e.g., Boonstra et al., 2015). Regional paleogeographic settings also support a Venezuelan seaway in the Miocene (e.g., Hovikoski et al., 2010; Albert et al., 2018), given that major physiographic barriers (e.g., the Central Andes, Purus Arch, Michicola Arch) may have prevented marine incursions through alternative routes (the Peruvian Pacific seaway, Amazon River seaway, and Rio de la Plata–Paraná seaway). Moreover, the only possible barrier to a Venezuelan seaway, the Cordillera de Mérida, uplifted in the Pliocene (for further details on the Western Amazonia paleogeographic setting, see the Supplemental Material).

Furthermore, considering the paleogeographic setting of northern South America and the Caribbean Sea (e.g., Lundberg et al., 1998; Albert et al., 2018) and assuming the Orinoco

drainage system as the likely source of continental sediment supply to DSDP Site 153 (Edgar et al., 1973), we interpret the significant increase in the percentage of reworked dinocysts and P/G ratio in the late Miocene (9.9–9.0 Ma) at Site 153 as the result of enhanced riverine input from northern Venezuela to the Orinoco drainage basin and the Caribbean Sea (Fig. 2). We propose that lower sea level at the final stage of the LMI may have shifted the base level of the main drainage system back to its initial conditions, which would have implied increased erosion and terrigenous nutrient input to surface waters in the continental shelf.

Implications for the Global Climate System

The Miocene encompassed CO₂ levels usually within the ~300–600 ppm range, deep-sea temperatures ~5–8 °C warmer than modern (Steinthorsdottir et al., 2021, and references therein), and major warming events such as the Miocene Climate Optimum (ca. 17.0–14.0 Ma) and the Tortonian thermal maximum (TTM; ca. 10.8 Ma) (Westerhold et al., 2020). Despite limited ice-proximal records, recent advances in general circulation modeling (Gasson et al., 2016) attempted to reconcile this scenario with a dynamic cryosphere (Foster et al., 2012), suggesting sea level may have varied in the early and middle Miocene (Levy et al., 2016).

Another approach to reconstructing the timing and magnitude of eustatic sea-level rise is from direct analysis of marine-indicative records in ancient epicontinental seas. Considering the sub-tectonic time scale (10⁴–10⁵ yr) of the short-lived peaks in the LMI, our marine records are more reasonably explained by glacio-eustatic sea-level changes. We propose that increased global temperatures and orbital variability in the late Miocene may have

triggered transient events of deglaciation, substantial eustatic sea-level rise, and worldwide flooding of lowlands. Based on the age-depth model provided by this study for the onshore studied sites, we contend the LMI (Western Amazonia) is linked to the TTM (Westerhold et al., 2020). Our study raises questions on the cryosphere stability in the late Miocene, a time period usually considered an appropriate analog for future climate scenarios.

Future research efforts should target refining the age calibration of onshore study cores in Western Amazonia. In addition, for a better understanding of the relationship between the Neogene marine incursions to Western Amazonia and the global climate system, there is a great need for higher-resolution geochemical data.

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