

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

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## **S1. Geological settings**

### **The Solimões Basin**

The Solimões Basin is an intracratonic, dominantly E-W striking volcano-sedimentary basin in the Western Amazonia, Brazil. It lies over the Archean and Proterozoic belts of the Central Amazonian Province (Wanderley-Filho et al., 2007), and is bounded to the west by the Acre Basin, through the Iquitos Arc, to the east by the Amazon Basin, through the Purus Arc, and to the north and south by the Guyana and Brazilian shields, respectively (Barata and Caputo, 2007). The Carauari Arc splits the basin into two sub-basins: Jandiatuba (west) and Juruá (east) (Eiras et al., 1994; Wanderley-Filho et al. 2007) (Fig. S1).

Within the depocenter, it contains a succession of Ordovician through Pleistocene strata that is as much as ~3 km thick (Lisboa et al., 2013). Tectonic cycles of subsidence and uplift resulted in five depositional supersequences (Wanderley Filho et al., 2007): [1] Meso-Ordovician, [2] Silurian-Eo Devonian, [3] Mesodevonian-Eocarboniferous, [4] Neocarboniferous-Eopermian, and [5] Cretaceous-Tertiary. Our work focus on the Neogene sequences of the Jandiatuba Sub-basin – the homonym Solimões Formation.

### **Neogene Andean orogeny and the Solimões Formation**

The Solimões Formation sediments were deposited alongside the Andean orogeny in the Neogene, in a fluvio-lacustrine cycle with episodic marine incursions during the Miocene, due to rising global sea level (Haq et al., 1987; Hoorn, 1993; 2010a). Tectonic changes triggered by the Andean orogeny led to intense environmental shifts in the Western Amazonia, which preconditioned the development of the Amazon Biota ever since (Lundberg et al., 1998; Whatley et al., 1998; Lovejoy et al., 2006). The lacustrine system of the Solimões Formation covers most of the Western Amazonia with a narrow connection to the sea, and the rivers that

flowed from the Andes during its uplifting drained into this system from the west (Räsänen et al., 1998).

Rich and well-preserved fossil record of the Solimões Formation includes plant fossils, pollen grains and spores (Hoorn, 1994a,c; Silva-Caminha et al., 2010; Kachniasz and Silva-Caminha, 2016; Sá and Carvalho, 2017; Jaramillo et al., 2017; Leandro et al., 2019), ostracods (Purper, 1977, 1979; Ramos, 2006; Gross et al., 2011, 2013, 2014, 2015; Linhares et al., 2011; 2017), fish scales and fragments, bird fragments, and reptile and mammal teeth and bones (Santos et al., 1991; Monsch, 1998). Microfossil-based studies assigns Neogene age (Miocene–Pliocene: 23–2.6 Ma) to the Solimões Formation.

### **Evidence of Miocene marine incursions in the Western Amazonia**

A pioneer study about marine incursions in the Solimões Formation highlights the occurrence of marine palynomorphs (dinoflagellate cysts, acritarch, and foraminiferal linings) (Hoorn, 1993). Other studies also interpreted the region as a large lacustrine system with freshwater predominantly conditions and episodic marine incursions (Hoorn, 1994a,b; Hoorn et al., 1995; Boonstra et al., 2015). This environmental context is represented by intervals with mixture of marine, transitional and non-marine taxa (Linhares et al., 2011), condition widely observed in estuarine zones (Miranda, et al., 2002). These Miocene marine incursions are related to intense tectonic events that occurred in northern South America during the Neogene, allowing the establishment of low-land areas and thus marine flooding in the Western Amazonia (Rincón et al., 2014).

More recent work proposed two marine incursion events based on palynological data from the Western Amazonia (Jaramillo et al., 2017): early (18.0-17.2 Ma), and middle Miocene (14.1-13.7 Ma). Based on palynomorphs and calcareous microfossils, other authors recognized three marine incursions between the early and late Miocene (Linhares et al., 2017, 2019).

Despite paleontological, ichnological, and geochemical evidence for early and middle Miocene marine flooding events in the Western Amazonia (Gingras et al., 2002; Hovikoski et al., 2010; Antoine et al., 2016), relatively little is known on late Miocene incursions (e.g., Räsänen et al., 1995; Linhares et al., 2017; Sá and Carvalho, 2017). The Pliocene marine record here (1AS-105-AM) included the occurrence of cysts dinoflagellate, Foraminiferal lining, scolecodonts, and rare planktonic foraminifera (*Globigerinoides* sp.). S/TOC, TOC/TN and  $\delta^{13}\text{C}$  data (1AS-105-AM) demonstrated lower paleosalinity data, yet the data are limited and require further deepening. However, previous studies also recorded marine evidence (microfossils) during the Pliocene (Kachniasz and Silva-Caminha, 2016; Silveira and Souza, 2017; Espinosa et al., 2021).

### **Source and pathway of Miocene marine incursions in the Western Amazonia**

Three major phases of paleogeographic reconfiguration resulted in high mountain ranges surrounding the Amazon drainage basin (for overview see Albert et al., 2018). These regional events created paleogeographic barriers that restricted the marine incursions on at least three potential seaway routes (for overview see Hovikoski et al., 2010; Fig. S1):

(1) Peruvian Pacific Seaway - the central Andes was already uplifted, and the paleoaltitude was ~2.0–2.5 km at ~20.0–17.0 Ma (early Miocene) in the Central Andes, and ~2.0 km at ~15.0–10.0 Ma (middle–late Miocene) in the Western Andes (Sundell et al., 2019);

(2) Rio de la Plata-Paraná Seaway - through the separation of the Paraná and Amazon drainage basins since the rise of the Michicola Arc (~43.0–30.0 Ma) and still by the emergence of Chapare Butress (~30.0–20.0 Ma) (Lundberg et al., 1998). Besides, there are no comparative micropaleontological studies that allow verifying the similarity between the assemblages of the two areas.

3) Amazon River Seaway (Albert et al., 2018) - the Purus Arch was already a geographic barrier since the Cretaceous and most of the Cenozoic (~145.0-10.0 Ma).

Structural archs played an important role in driving these potential seaways, although it is not a consensus when and how these acted in the evolution of the Amazonian landscape. According to Mora et al. (2010) the Iquitos, Carauari, and Purus archs were not geographic barriers to the eastward flow of the Amazonian drainage. However, in the late Miocene the Purus Arch might have acted as a geographic barrier separating the Solimões from the Amazon basin (Albert et al., 2018). The establishment of the transcontinental Amazon River occurred as late as the late Miocene, when drainage was able to circumvent the Purus Arch (Hoorn et al., 2017).

Dating this shift in the drainage system has been challenging, with estimates varying between late Miocene (Figueiredo et al., 2009; Hoorn et al., 2010a,b; 2017), Pliocene (Espurt et al., 2007), and even Pleistocene (Latrubesse et al., 2010). This is further supported by the orogeny in the Venezuelan Andes (Mérida Andes), whose mountains acted as an effective physical barrier from the Pliocene onwards (Backé et al., 2006; Egbue and Kellogg, 2010).

We argue the Miocene marine records found in Western Amazonia are compatible with a connection between the Caribbean Sea and the Pebas System through Venezuela, as proposed by studies based on fish phylogeny (e.g., Lovejoy et al., 1998). This Venezuelan Seaway has also been proposed as a source of early-to-middle Miocene marine records (e.g., McDermott, 2021). Moreover, the only possible barrier would be the Merida Mountain Ranges, uplifted in the Pliocene (Egbue and Kellogg, 2010).

Considering the paleogeographic setting of northern South America and the Caribbean Sea, we assume the Maracaibo Basin drainage system was the likely source of continental sediment supply to the DSDP Site 153. 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 the Site 153 as

enhanced riverine input from the northern Venezuela to the Maracaibo Basin and the Caribbean Sea. We propose that post-LMI sea-level fluctuations may have shifted the base level of the main drainage system back to its initial conditions, which would have implied in increased erosion and terrigenous-derived nutrient input to surface waters in the continental shelf.

### **Dinocyst assemblages from nearby ocean basins**

Based on the regional paleogeographic settings of the Brazilian Western Amazonia during the Miocene, we compiled dinocyst assemblage data of nine offshore sites from three nearby ocean basins in order to reconstruct the potential source of the marine incursions observed in this study (Table S1). This compilation suggests that dinocysts were scarce in Equatorial Atlantic and Eastern Pacific waters. Some authors (Sangiorgi et al., 2018) suggest that sea-surface temperature (SST) make an essential role in the distribution of modern dinoflagellate associations, and this might have been the case of Quaternary associations in the Peruvian region (DSDP Leg 34, 321: Wiseman, 1979; DSDP Leg 112, sites 683, 684, 685: Lewis et al., 1990). However, proxy-based SST reconstructions show little or even no temperature change across latitudes during the late Miocene (Steinthorsdottir et al., 2021 and references therein), which shows that Equatorial Atlantic and Eastern Pacific water masses were substantially poorer in dinocysts than the Caribbean Sea.

**Table S1.** Location, geographic coordinates and association of dinocysts from offshore locations near the study area.

<b>Ocean basin</b>	<b>Coordinates</b>	<b>Site name</b>	<b>Dinocyst assemblage composition</b>	<b>Reference</b>
Caribbean Sea	13°58.33'N 72°26.08'W	DSDP Site 153	<i>Apectodinium</i> spp. - 2% <i>Operculodinium</i> spp. - 1%	Leandro et al., 2020

			<i>Selenopemphix</i> spp. - 17% <i>Spiniferites</i> spp. - 11% <i>Trinovantedinium</i> spp. - 1% <i>Tuberculodinium</i> spp. - 2% Other genera - 67%	This study
Caribbean Sea	16°33.223'N 79°52.044'W	ODP Site 1000	<i>Hystriocholpoma</i> spp. - 1% <i>Lingulodinium</i> spp. - 3% <i>Operculodinium</i> spp. - 60% <i>Selenopemphix</i> spp. - 10% <i>Spiniferites</i> spp. - 1% <i>Tuberculodinium</i> spp. - <1% Other genera - 25%	Mahdvijourshari, 2014
Caribbean Sea	10°42.366'N 65°10.179'W	ODP Site 1002	<i>Lingulodinium</i> spp. - 18% <i>Operculodinium</i> spp. - 2% <i>Selenopemphix</i> spp. - 12% <i>Spiniferites</i> spp. - 36% <i>Tuberculodinium</i> spp. - <1% Other genera - 32%	Mertens et al., 2009
Equatorial Atlantic Ocean	05°53.95'N 44°11.78'W	DSDP Site 354	<i>Spiniferites</i> spp. - <1%	This study
Eastern Pacific Ocean	12°01.29'S 81°54.24'W	DSDP Site 321	Other genera	This study
Eastern Pacific Ocean	09°01.69'S 80°24.40'W	ODP Site 683	Barren	Lewis, et al., 1990

Eastern Pacific Ocean	08°59.49'S 79°54.35'W	ODP Site 684	Barren	Lewis, et al., 1990
Eastern Pacific Ocean	09°06.78'S 80°35.01'W	ODP Site 685	Barren	Lewis, et al., 1990
Eastern Pacific Ocean	Not available	Buenaventura 1-ST-P	<i>Hystrichokolpoma</i> spp. - 1% <i>Lingulodinium</i> spp. - 6% <i>Operculodinium</i> spp. - 1% <i>Selenopemphix</i> spp. - 57% <i>Spiniferites</i> spp. - 7% <i>Trinovantedinium</i> spp. - 4% <i>Tuberculodinium</i> spp. - <1% Other genera - 23%	Duque-Herrera et al., 2018



## S2. Materials and methods

### Study area

Here we studied nine boreholes: six from the Solimões Basin, Western Amazonia drilled by the Brazilian Geological Survey (CPRM) for the “Coal in the Solimões Rise” project; and three near-field Deep Sea Drilling Project (DSDP) cores drilled in the Atlantic and Pacific oceans (SM6-SM14, Table S2, Fig. S1).

**Table S2.** Location and geographical coordinates of study sites.

Site	Location	Coordinates
1AS-7D-AM	Nearby the Araras River (Quixito River), Amazonas State, Brazil	04°34'S 70°41'W
1AS-8-AM	Nearby the Itacuaí River, Amazonas State, Brazil	04°36'S 70°16'W
1AS-31-AM	Nearby the Ituí River, Atalaia do Norte city, Amazonas State, Brazil	05°18'S 71°02'W
1AS-51-AM	Left banks of the Japurá River, Amazonas State, Brazil	01°51'S 69°02'W
1AS-52-AM	Right banks of the Içá River, Amazonas State, Brazil	02°47'S 69°29'W
1AS-105-AM	Nearby the Solimões River, Tabatinga city, Amazonas State, Brazil	04°15'S 69°56'W
DSDP Leg 15 Site 153	Southernmost Beata Mountain range and nearby the Aruba Gap, Caribbean Sea, Atlantic Ocean	13°58.33'N 72°26.08'W
DSDP Leg 34 Site 321	Eastern Nazca plate, Peru Basin, Pacific Ocean	12°01.29'S 81°54.24'W
DSDP Leg 39 Site 354	Westernmost Ceará Rise, Atlantic Ocean	05°53.95'N 44°11.78'W

### Sampling

Overall, we generated 553 organic carbon  $\delta^{13}\text{C}$ , total nitrogen (TN), sulfur/total organic carbon (S/TOC) ratio, bulk sediment carbonate content (%  $\text{CaCO}_3$ ), and calcareous and organic-walled microfossil data (SM5-SM14) that were combined with 278 published microfossil data (Linhares et al., 2011, 2017, 2019; Jaramillo et al., 2017). All samples, slides, and residues produced by this study are stored at the Technological Institute of Micropaleontology (itt Fossil, UNISINOS), under the curatorial numbers (ULVG-13130 to ULVG-13429).

### **Calcareous microfossil processing techniques**

Ostracods and foraminifera were extracted following the standard methodology for calcareous microfossils. Samples were washed through standard sieves (0.5 mm; 0.250 mm; 0.180 mm; 0.125 mm). Wet sieve residue was dried at 60 °C and the residuals  $\geq 63 \mu\text{m}$  in size were separated using a stereo microscope for identification. Scanning Electron Microscope (SEM) images have been taken at the Museu Paraense Emílio Goeldi (LEO 1450VP), SEM laboratory at itt Fossil (EVO MA15 Zeiss), at Geological Survey of Brazil (office of Belém), and at “Technological Institute of Micropaleontology” (itt Fossil, UNISINOS), Brazil. Ostracods identification was based in Purper (1979), Purper and Pinto (1983, 1985), Purper and Ornellas (1991), Muñoz-Torres et al. (1998), and Gross et al. (2013, 2014; 2015). Generic-level identification of foraminifera followed Treatise on Invertebrate Paleontology, Part C, Protista, Moore (1964). Specimens figured have been deposited in the Micropaleontology Collection at Museu Paraense Emílio Goeldi, Pará, and in the microfossil collection of LAVIGEA (Laboratório da História da Vida na Terra), Rio Grande do Sul.

### **Organic-walled microfossil processing and counting techniques**

The preparation of organic walled microfossils followed the Palynological procedures adapted by Wood et al. (1996). The process involved the use of hydrochloric (HCl 32%) and hydrofluoric (HF 40%) acids to remove all mineral constituents. With a transmitted-light microscope (Zeiss-Imager A2 at 200, 630, and 1000x magnification), at least 300 palynomorphs were counted in each sample at the Technological Institute of Micropaleontology (itt Fossil), UNISINOS, Brazil. When necessary, incident blue light (ultra-violet fluorescence mode) was applied. Pollen grains, spores and dinoflagellate cysts were identified to the genera (qualitative/quantitative) and/or species (qualitative) levels. For statistical analysis, we used only samples with more than 100 palynomorphs.

Using the program PAST (v. 3.15; Hammer et al. 2001), we used a comparison of Mann–Whitney test (5% significance level) to evaluate the equality of means to compare the number of marine elements for the marine intervals versus continental intervals for the core 1AS-51-AM. In addition, we performed a cluster analysis to determine the similarity among the marine samples and no marine samples. We used the coefficient of Euclidean distance and the Unweighted Pair Group Method using Arithmetic Averages (UPGMA) strategy considering a data matrix including the micropaleontological data found in the 1AS-51-AM also (Appendix). We selected the core 1AS-51-AM because it is the closest to the likely source area and has the entire Miocene range and a good representation of marine palynomorphs. The marine intervals showed a significant increase of marine microfossils compared with the continental interval within the core 1AS-51-AM (Mann-Whitney  $U=7.5$ ,  $p=0.0002$ ).

### **Stable isotope geochemistry**

All sedimentary organic matter samples were analyzed at the University of California, Riverside. All samples were dried and ground until fine before being homogenized. Samples prepared for carbon isotope analysis were decarbonated by acidifying ~0.1 g of ground sediment sample in a 10% HCl bath for 24 h three times followed by decantation in deionized water to rinse away acid residue.

For organic carbon isotope analysis, 50-100 mg sample powders were acidified using 6N HCl in 50 mL centrifuge tubes. Magnetic stir bar was spun at 150 rpm during acidification to prevent formation of carbonate crust, and vials were periodically vortexed to ensure complete decarbonation. Decarbonated and dried insoluble residue of samples were weighed into  $9 \times 10$  mm tin weigh boats for organic carbon isotope analysis. An aliquot of 5 mg of decarbonated sediment for %TOC and  $\delta^{13}\text{C}$  analysis and 10 mg of non-decarbonated sediment for %N analysis was compacted in  $5 \times 9$  mm tin capsules.

The  $\delta^{13}\text{C}$  were measured using the Costech EA 4010, Thermo-Finnigan Delta V Advantage mass spectrometer, and Conflo IV open-split interface system. Two calibration standards, NBS18 and NBS19, were utilized in the same run and the precision of  $\delta^{13}\text{C}$  was 0.1‰.

All isotope data are expressed as delta notation ( $\delta\text{‰}$ ), using the following equation:

$$\delta R = [(R_{\text{sample}} - R_{\text{standard}})/R_{\text{standard}}] \times 1000,$$

where  $R_{\text{sample}}$  is the ratio of the heavy to light isotope in the sample and  $R^{\text{standard}}$  is the ratio of the heavy to light isotope in the standard (Coplen, 2011). The  $\delta^{13}\text{C}$  data are reported in permil vs. Vienna Pee Dee belemnite (VPDB).

### **Biostratigraphy and age controls**

We defined palynological zones at most Western Amazonia study sites following the scheme proposed by Lorente (1986). This includes five biozones defined by first and last occurrence (FO, LO) of sporomorph taxa (Table S3, Fig. S2): *Verrutricolporites* (lower Miocene), *Psiladiporites-Crototricolpites* (lower–middle Miocene), *Crassoretitritetes* (middle Miocene), *Grimsdalea* (middle–upper Miocene), *Asteraceae* (upper Miocene), and *Fenestrites longispinosus* (upper Miocene–Pliocene). We used FO *Grimsdalea magnaclavata* as datum to correlate the study sites (Fig. S3). We defined ostracod biozones at the core 1AS-31-AM following regional scheme (Linhares et al., 2011, 2019). We calibrated FO/LO *Cyprideis* species with sporomorph biozones (Lorente, 1986; Hoorn, 1993). Age-calibrated assignments (Bolli and Saunders, 1985; Gradstein et al., 2012) and depths at Western Amazonia study cores are provided (Fig. S2).

**Table S3.** Sporomorph zonation scheme used in this study.

Biozone	Base definition	Top definition	Correlation with planktonic foraminifera (PF) or calcareous nannofossil (CN) zonation schemes (Bolli and Saunders, 1985)
<i>Fenestrites longispinosus</i> Zone ( <i>Ladekhipollenites?</i> <i>caribbiensis</i> Subzone)	Occurrence of <i>Podocarpidites</i> sp., <i>Fenestrites garciae</i> , <i>Malvacipollis spinulosa</i> , <i>Polyadopollenites mariae</i> , <i>Psilatricolporites maculosus</i> , and <i>Striatricolporites catatumbus</i>		NN12-NN15 Zones (CN)
<i>Asteraceae</i> Zone	FO <i>Echitricolporites spinosus</i>	FO <i>Stephanocolpites evansii</i>	NN10 Zone (CN)
<i>Verrutricolporites</i> Zone	FO <i>Verrutricolporites rotundiporus</i>	FO <i>Psiladiporites minimus</i>	FAD of <i>Globorotalia kugleri</i> (PF)
<i>Grimsdalea</i> Zone	FO <i>Grimsdalea magnaclavata</i>	FO <i>Echitricolporites spinosus</i>	<i>Globorotalia fohsi robusta</i> Zone (PF)
<i>Crassoretitriletes</i> Zone	FO <i>Crassoretitriletes vanraadshoovenii</i> , FO <i>Bombacacidites baculatus</i>	FO <i>Grimsdalea magnaclavata</i>	From the <i>Globotalia barisanensis</i> Zone ( <i>peripheroronda</i> ) to the <i>Globorotalia fohsi robusta</i> Zone (PF; Falcon Basin); base as young as the <i>Globorotalia fohsi lobata</i> (PF; Eastern Basin of Venezuela)
<i>Psiladiporites-Crototricolpites</i> Zone	FO <i>Psiladiporites minimus</i> (accessories at 1AS-51-AM, 1AS-105-AM: FO <i>Crototricolpites annemariae</i> , FO <i>Retitricolporites guianensis</i> )	FO <i>Crassoretitriletes vanraadshoovenii</i> (accessory at 1AS-51-AM, 1AS-105-AM: FO <i>Bombacacidites baculatus</i> )	<i>Globigerinatella insueta</i> / <i>Praeorbulina glomerata</i> Zone (PF)

The age-depth models for the Neogene interval of the Western Amazonia study cores are based on FO/LO sporomorph events and constraints (Lorente, 1986). These were correlated with planktonic foraminifera and calcareous nannofossil zonation schemes (Bolli and Saunders, 1985), and adjusted to the geological timescale (Gradstein et al., 2012) (Table S4; Fig. S4). The resulting age models suggest that the average sedimentation rates increase substantially from ~10.8 Ma.

The age of DSDP Site 153 was obtained through planktonic foraminifera (Edgar and Saunders, 1973), based on the stratigraphic scheme from the Caribbean (Bolli and Premoli-

Silva, 1973), and correlated to the global zonation scheme (Bolli and Saunders, 1985). Besides, we confirm the age established through dinoflagellate zones (Leandro et al., 2020). The age of DSDP Site 321 was obtained from Radiolarian zones (Yeats and Hart, 1976), and DSDP Site 354 was dated with foraminifera and calcareous nannofossils zones (Perch-Nielsen, et al., 1977). In these last two sites, it was not possible to propose a palynological biozonation due to the absence of index fossils.

Figure S5 shows the broad array of proxy-based data from our studied sites against calibrated ages.

**Table S4.** Spormorph datum events from the Neogene of the Western Amazonia. Key: \* = events used as age constrains; <sup>A</sup> = spormorph bioevents adjusted through ostracod biozonation scheme.

Event	Depth (m)						Published age (Ma)
	1AS-7D-AM	1AS-8-AM	1AS-31-AM	1AS-51-AM	1AS-52-AM	1AS-105-AM	
LO <i>Ladekhipollenites? caribbiensis</i>			174.53	9.40*	9.35*	101.20	3.82
LO <i>Stephanocolporites evansii</i>			287.15	116.30	42.35	187.60	5.53
FO <i>Stephanocolpites evansii</i>	14.80*						8.19
FO <i>Echitricolporites spinosus</i>	125.00	32.00*	138.20 <sup>A</sup>	121.50	55.30	192.00	9.96
FO <i>Grimsdalea magnaclavata</i>	184.00	141.00	230.00 <sup>A</sup>	149.60	74.65	289.90	10.79
FO <i>Crassoretitritetes vanraadshoovenii</i>		246.76		155.30	86.30*	360.00	14.86
FO <i>Psiladiporites minimus</i>	296.00*	323.40		166.75*		370.00*	21.11
FO <i>Verrutricolporites rotundiporus</i>		368.00*					22.96

**Figure S1.** Paleogeography and geological setting of Western Amazonia during the middle and late Miocene and location of the studied cores (adapted from Hoorn et al., 2017; Albert et al. 2018).

**Figure S2.** Regional spormorph biozones by Lorente (1986) and correlation with planktonic foraminiferal and calcareous nannofossils zonation schemes (Bolli and Saunders, 1985), and regional ostracod biozones by Linhares

et al. (2019). Age-calibrated assignments (Gradstein et al., 2012) and depths at Western Amazonia study cores are provided (Gradstein et al., 2012).

**Figure S3.** Stratigraphic correlation of the three marine incursions during the Neogene in the Solimões Basin in drill cores DSDP Leg 15 Site 153, 1AS-51-AM, 1AS-52-AM, 1AS-105-AM, 1AS-8-AM, 1AS-7D-AM and 1AS-31-AM, in addition DSDP Leg 34 Site 321 and Leg 39 Site 354. The red line indicates the datum used to correlate the six drill cores (the first occurrence of *Grimsdalea magnaclavata*).

**Figure S4.** Age-depth plot for the Western Amazonia study sites against the Geologic Time Scale (Gradstein et al., 2012). Solid line, correlation is unambiguous; dashed line, correlation is inferred.

**Figure S5.** Multi-proxy records from Solimões Basin, the Caribbean Sea and correlation with global records. Solimões Basin (A-G): regional palynological zones (A; Lorente, 1986); absolute abundance of salinity-indicative palynomorphs (B) and calcareous microfossils (C); bulk sediment % CaCO<sub>3</sub> (D); S/TOC ratio (E);  $\delta^{13}\text{C}_{\text{org}}$  record (F); TOC/TN ratio (G). From elsewhere (H, I; Westerhold et al., 2020): high-resolution benthic carbon (H) and oxygen (I) isotope records. From the Caribbean Sea (J, K): reworked dinocysts (J); dinocyst P/G ratio (K).

### S3. References

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## Plates

**Plate 1.** Foraminiferal lining: 1. (1AS-51-AM; 160.40 m). 2–3. (1AS-52-AM; 42.35 m). 4. (1AS-52-AM; 55.30 m). 5. (1AS-51-AM; 143.50 m). 6. (1AS-7D-AM; 90.00 m). 7. (1AS-52-AM; 55.30 m). 8. (1AS-52-AM; 86.30 m). 9. (1AS-51-AM; 150.00 m). 10–11. (1AS-52-AM; 86.30 m). 12. (1AS-51-AM; 27.90 m). Scale: 20  $\mu$ m.

**Plate 2.** Scolecodont (1AS-51-AM): 1–4. (145.00 m). 5. (150.00 m). 6–8. (143.50 m). 9. (160.40 m). Scale: 20  $\mu$ m.

**Plate 3.** Dinocysts: Undetermined: 1, 1A. (1AS-51-AM; 162.00 m). 2, 2a. (1AS-51-AM; 159.80 m). 3, 3a. (1AS-51-AM; 158.00 m). Dinocysts: 4, 4a. *Spiniferites* spp. (1AS-51-AM; 158.00 m). 5, 5a–6, 6a. *Spiniferites mirabilis* (1AS-51-AM; 155.00 m). Undetermined: 7, 7a. (1AS-8-AM; 323.40 m). 8, 8a. (1AS-51-AM; 155.30 m). Scale: 20  $\mu$ m.

**Plate 4.** 1, 1a–2, 2a. Dinocysts: *Spiniferites* spp. (1AS-51-AM; 155.30 m). 3, 3a. Prasynophytes, *Leiosphaeridia* spp. (1AS-7D-AM; 115.50 m). Dinocysts: 4, 4a. *Operculodinium giganteum* (1AS-51-AM; 149.60 m). 5, 5a. *Spiniferites* spp./*Cleistosphaeridium* sp. (1AS-51-AM; 149.60 m). 6, 6a. *Operculodinium* spp. (1AS-51-AM; 158.00 m). 7, 7a. *Operculodinium centrocarpum* (1AS-51-AM; 149.60 m). 8, 8a. *Operculodinium giganteum* (1AS-51-AM; 149.60 m). Scale: 20  $\mu$ m.

**Plate 5.** Dinocysts: 1, 1a. *Spiniferites dentatus* (1AS-51-AM; 149.60 m). 2, 2a. *Spiniferites* spp. (1AS-52-AM; 155.30 m). 3, 3a. *Spiniferites pachydermus* (1AS-51-AM; 149.60 m). 4, 4a. *Spiniferites* spp. (1AS-8-AM; 323.40 m). 5, 5a. *Spiniferites ramosus multiplicatus* (1AS-51-

AM; 149.60 m). 6, 6a. *Spiniferites speciosus* (1AS-51-AM; 149.60 m). 8, 8a. Undetermined (1AS-31-AM; 173.60 m). Scale: 20 µm.

**Plate 6.** Dinocysts: 1, 1a. *Impletosphaeridium prolatum* (1AS-105-AM; 76.20 m). 2 Undetermined (1AS-7D-AM; 1115.50 m). 3–6. *Cleistosphaeridium* sp. (1AS-51-AM; 149.60 m). Acritarch: 7, 7a. *Quadrina? Conditia* (1AS-7D-AM; 76.50 m). Dinocysts: 8, 8a. *Spiniferites ramosus* (1AS-51-AM; 155,30 m). *Spiniferites miralilis* (1AS-51-AM; 27.90 m). Scale: 20 µm.

**Plate 7.** Dinocysts (DSDP Leg 15 Site 153): 1. *Bitectatodinium tepikiense* (304.10 m). 2. *Brigantedinium cariacense* (204.00 m). 3. *Brigantedinium simplex* *Brigantedinium simplex* (204.00 m). 4. *Hafniasphaera* sp. (404.90 m). 5. *Impagidinium patulum* (307.00 m). 6. *Impagidinium striatum* (302.50 m). 7. *Lejeunecysta hyalina* (305.70 m). 8. *Lejeunecysta tenella* (215.00 m). 9. *Lingulodinium machaerophorum* (302.00 m). 10. *Nematosphaeropsis labyrinthus* (304.80 m). 11. *Operculodinium centrocarpum* (301.00 m). 12. *Palaeocystodinium miocaenicum* (403.50 m). Scale: 20 µm.

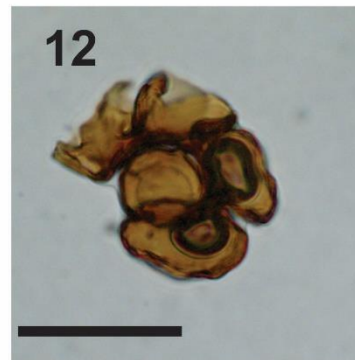
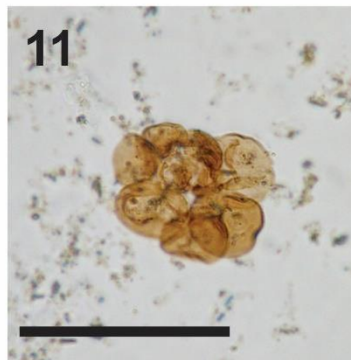
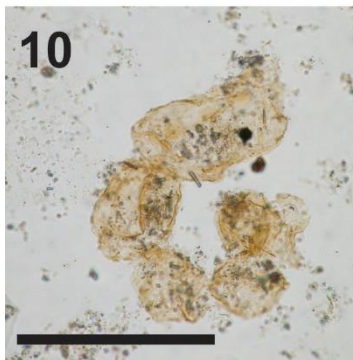
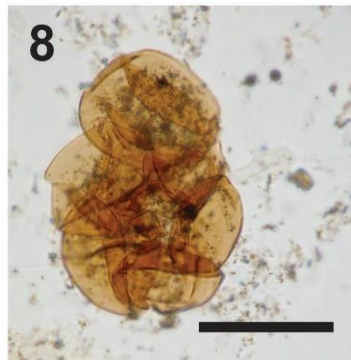
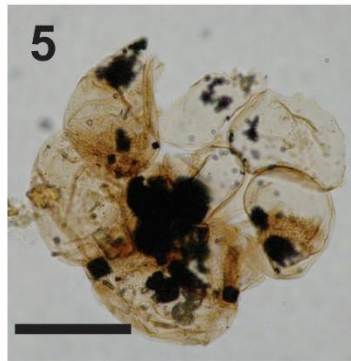
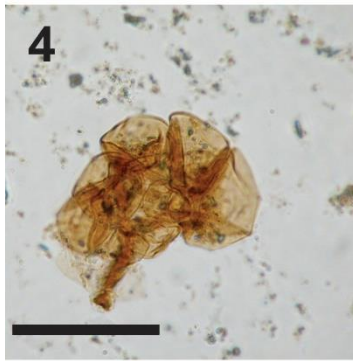
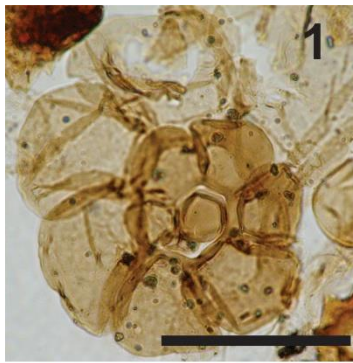
**Plate 8.** Dinocysts (DSDP Leg 15 Site 153): 1. *Polysphaeridium zoharyi* (307.00 m). 2. *Selenopemphix armageddonensis* (204.00 m). 3. *Selenopemphix armata* (207.00 m). 4. *Selenopemphix brevispinosa* (302.50 m). 5. *Selenopemphix nephroides* (207.00 m). 6. *Spiniferites bulloideus* (302.50 m). 7. *Spiniferites mirabilis* (307.50 m). 8. *Spiniferites pachydermus* (215.50 m). 9. *Spiniferites pseudofurcatus* (305.70 m). 10. *Spiniferites ramosus multiplicatus* (304.70 m). 11. *Tectatodinium pellitum* 304.80 m). 12. *Tuberculodinium vancampoe* (216.00 m). Scale: 20 µm.

**Plate 9.** Foraminifera (1AS-31-AM): 1, 1a. *Amphistegina* sp.1 (170.90 m). 2. *Amphistegina* sp. 2 (170.90 m). 3, 3a. *Planorbulina* spp. (170.90 m). 4. *Quinqueloculina* spp. (171.40 m). 5, 5a. *Textularia* spp. 1 (170.90 m). 6. *Textularia* spp. 2 (172.40 m). 7. ?*Cibicides* spp. (170.90 m). 8, 8a. *Globorotalia* spp. (170.90 m). 9. *Globigerinoides* spp. (170.90 m). 10. *Globigerina* spp. (170.90 m). 11. *Globigerina* spp. (170.90 m). Scale: 100  $\mu$ m.

**Plate 10.** Foraminifera: 1–6. Morphotype of *Ammonia tepida* (1AS-7D-AM; 50.00 m). 7–10. Morphotype of *Ammonia tepida* (1AS-7D-AM; 73.60 m). 11. Undetermined (1AS-7D-AM; 50.00 m). 12. Undetermined (1AS-7D-AM; 73.60 m). 13–15. *Miliammina fusca* (1AS-8-AM; 323.40 m). Scale: 100  $\mu$ m.

**Plate 11.** Foraminifera: 1. *Globigerinoides* spp. (1AS-8-AM; 137.45 m). 2. *Globigerina* spp. (1AS-7D-AM; 155.00 m). 3. Undetermined (1AS-7D-AM; 140.50 m). 4. Undetermined (1AS-7D-AM; 155.00 m). 5. Morphotype of *Ammonia tepida* (1AS-31-AM; 177.60 m). 6–7. Undetermined (1AS-51-AM; 149.60 m). 8. Undetermined (1AS-105-AM; 41.45 m).

**Plate 1**



**Plate 2**

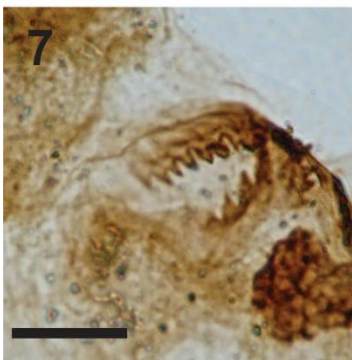
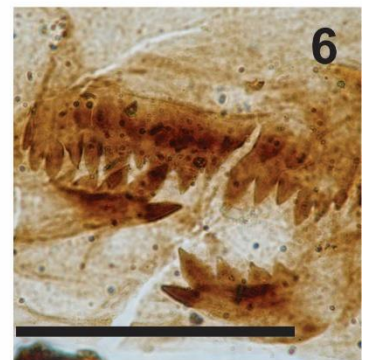
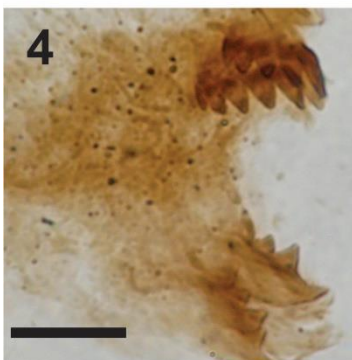
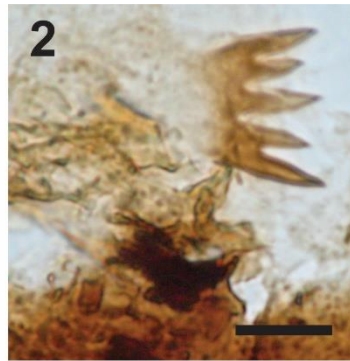
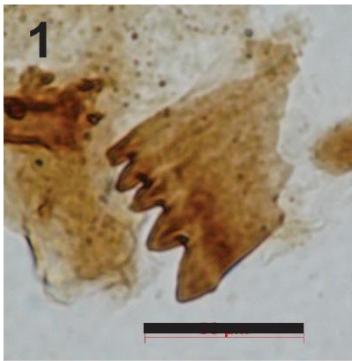
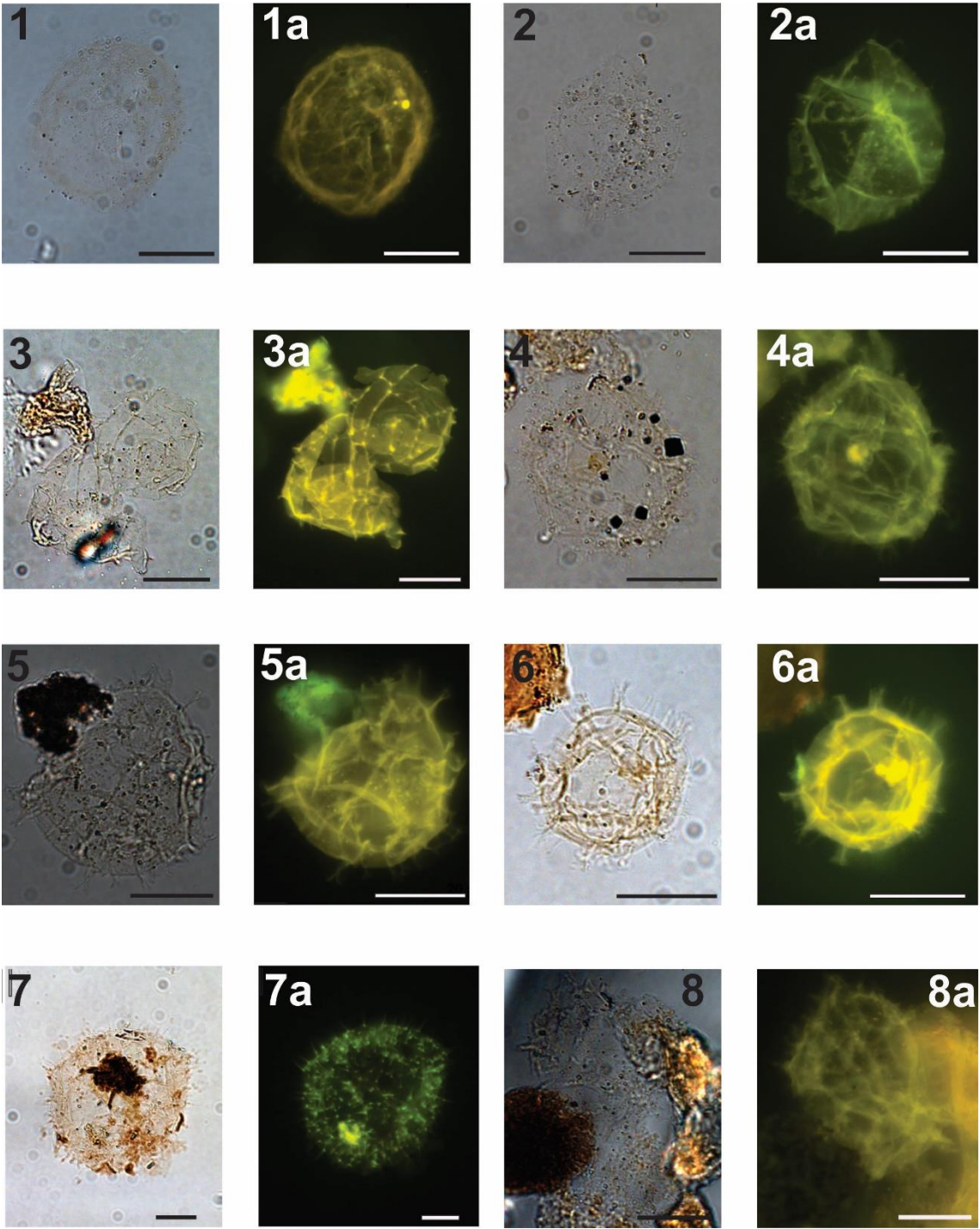


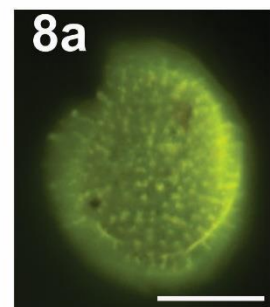
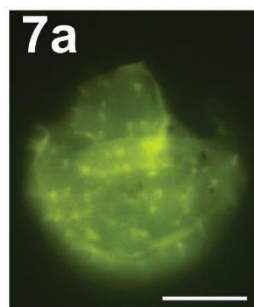
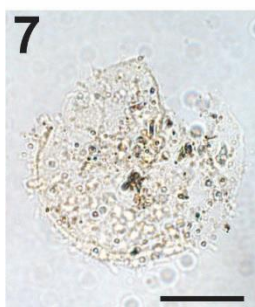
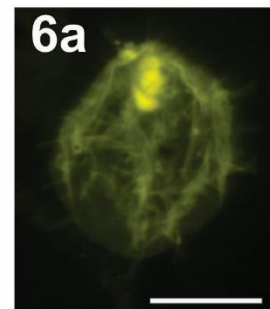
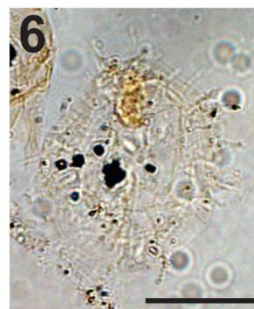
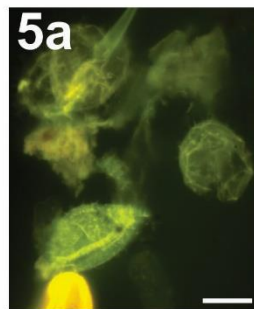
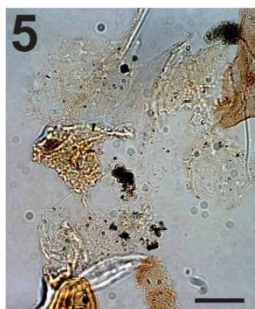
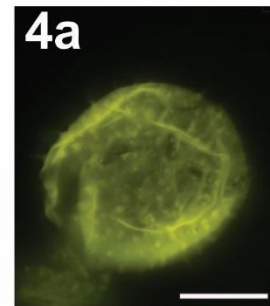
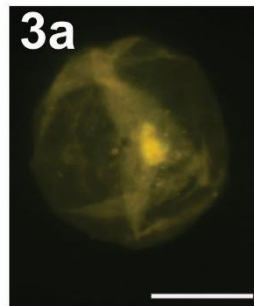
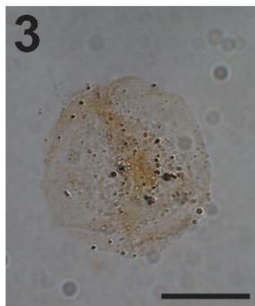
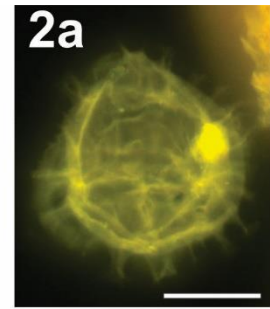
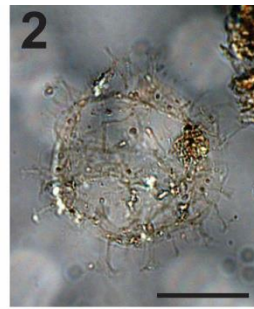
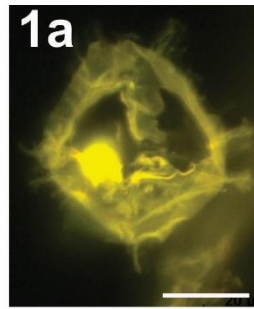


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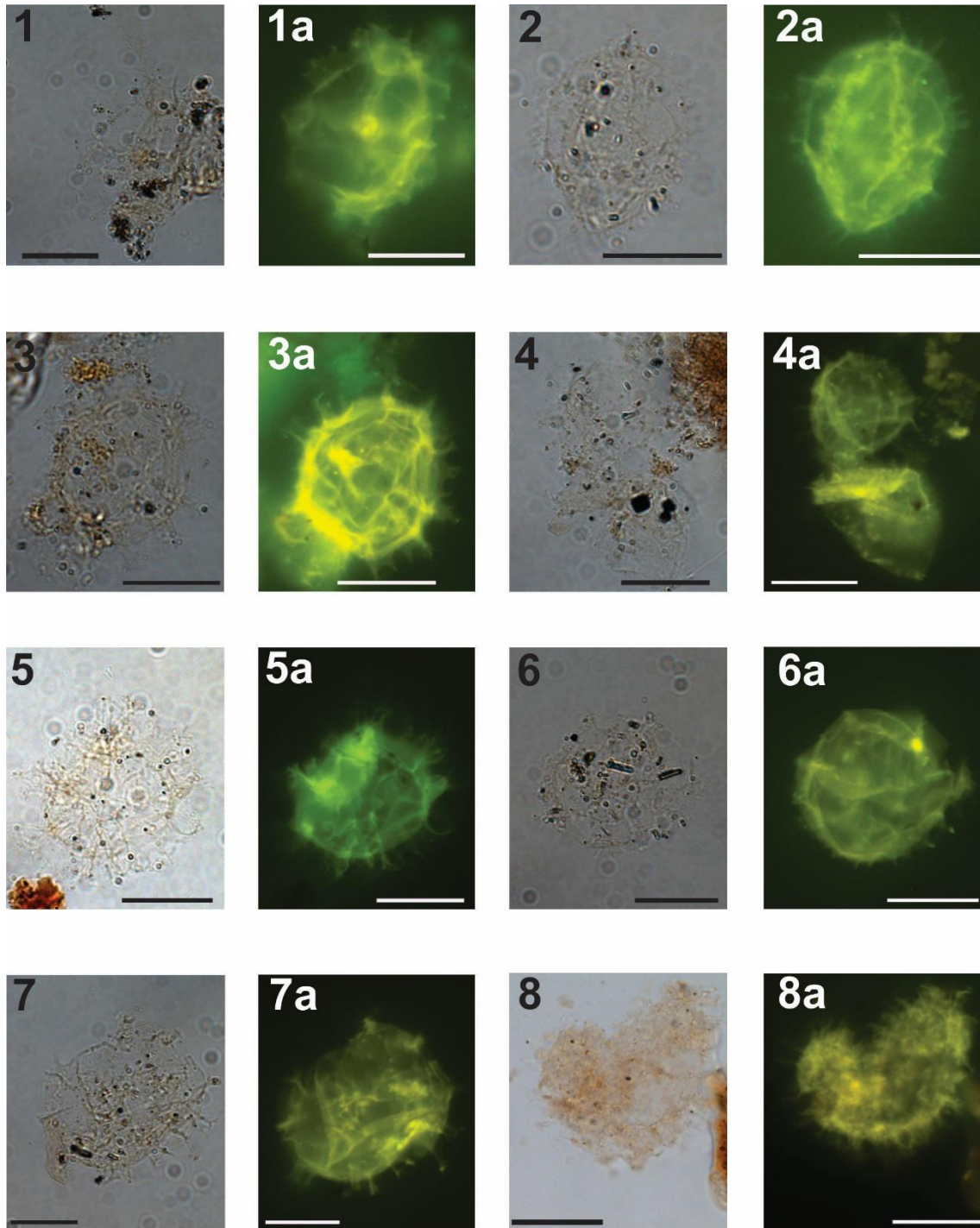




**Plate 4**



**Plate 5**



**Plate 6**

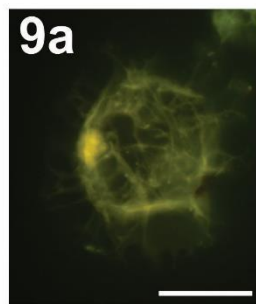
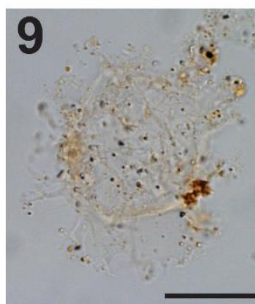
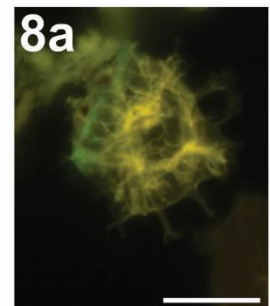
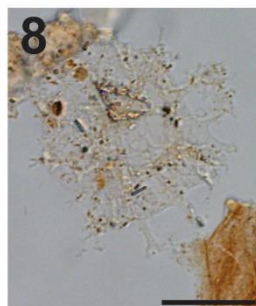
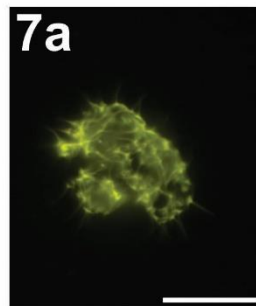
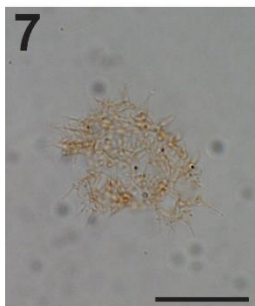
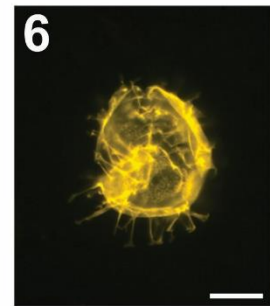
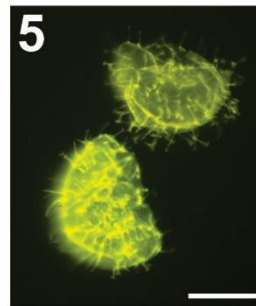
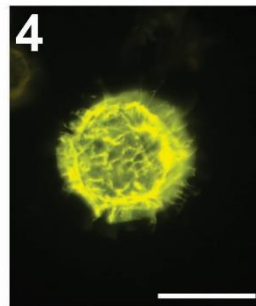
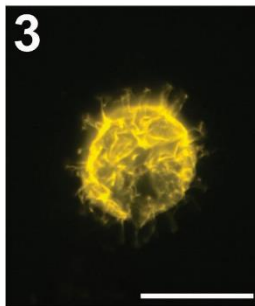
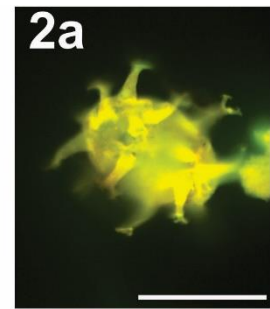
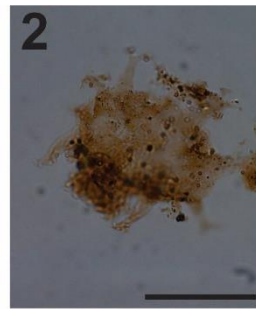
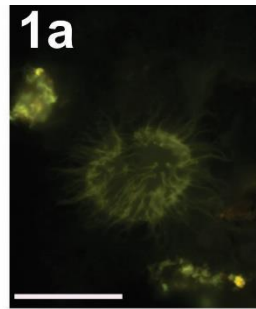
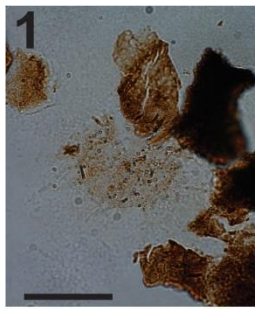




Plate 7

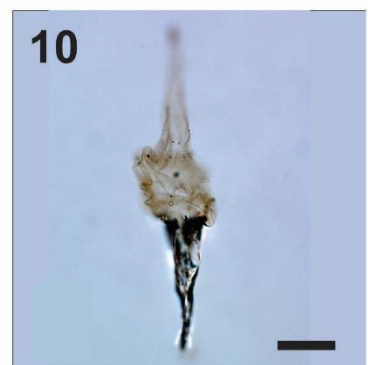
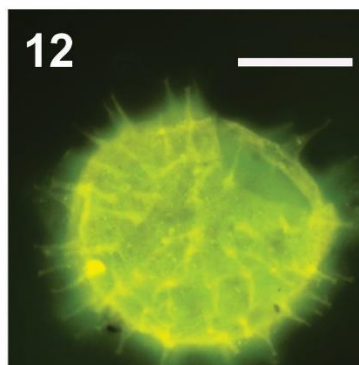
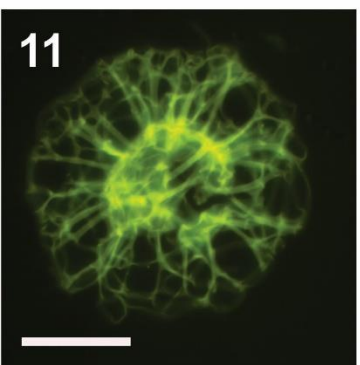
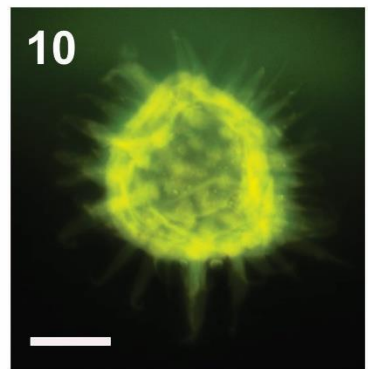
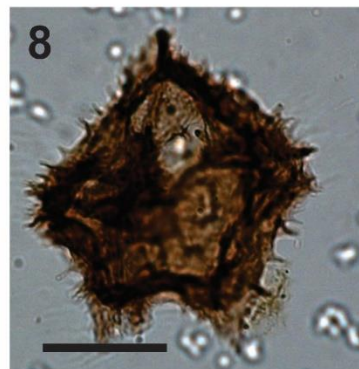
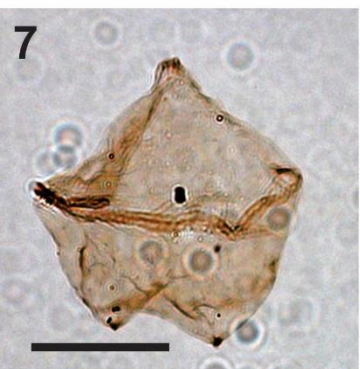
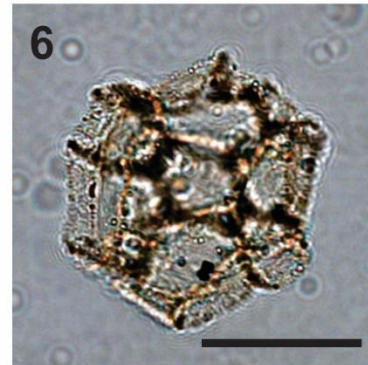
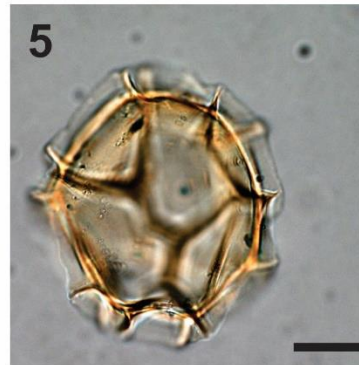
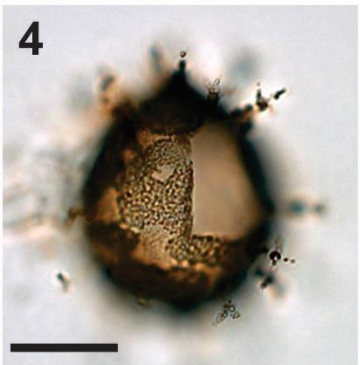
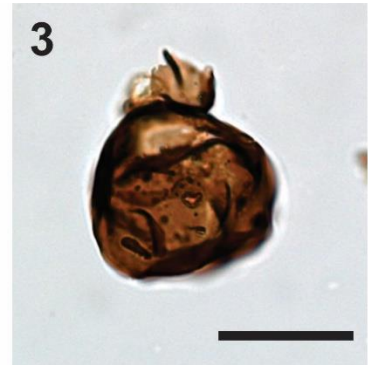


Plate 8

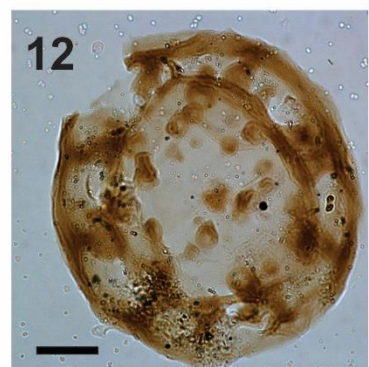
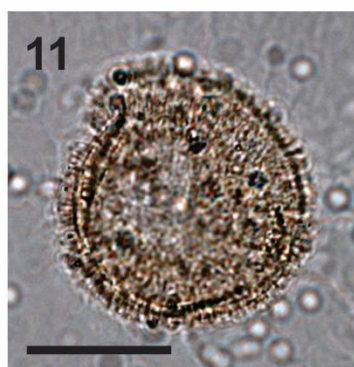
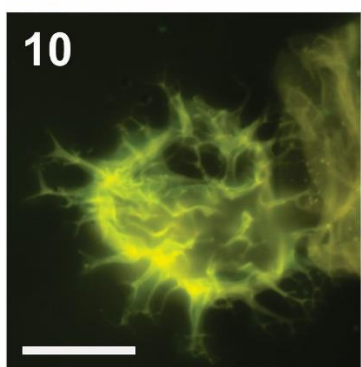
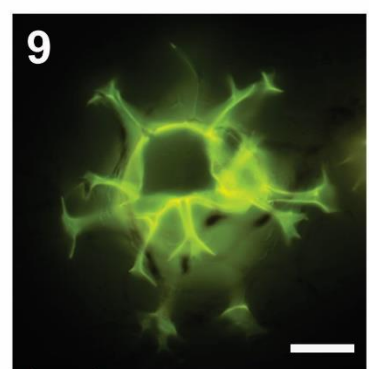
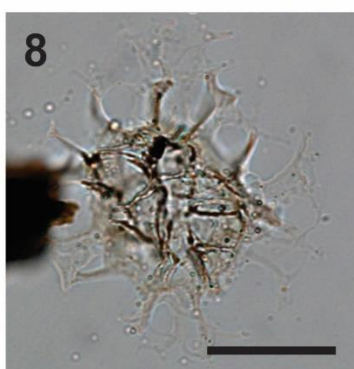
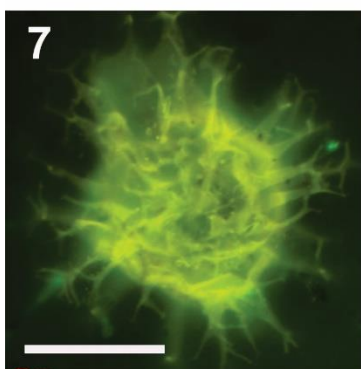
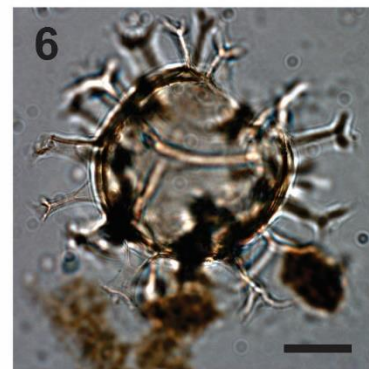
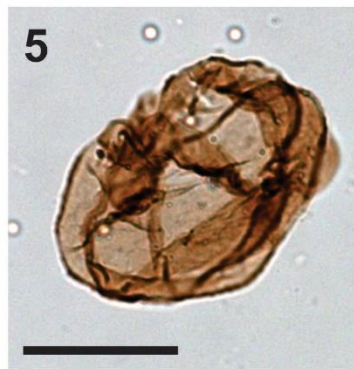
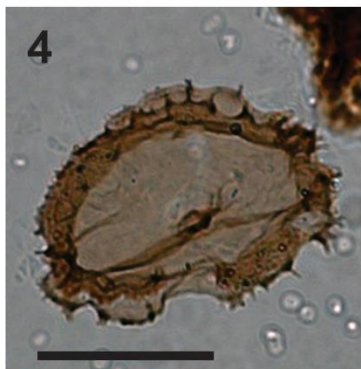
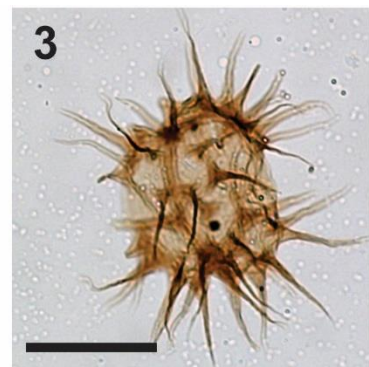
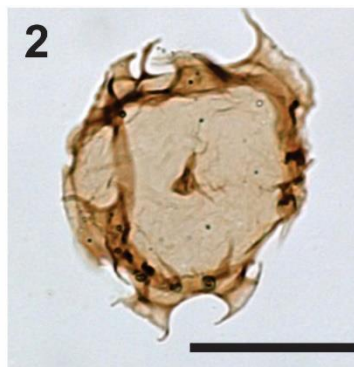
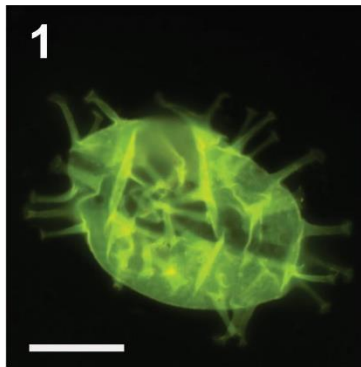


Plate 9

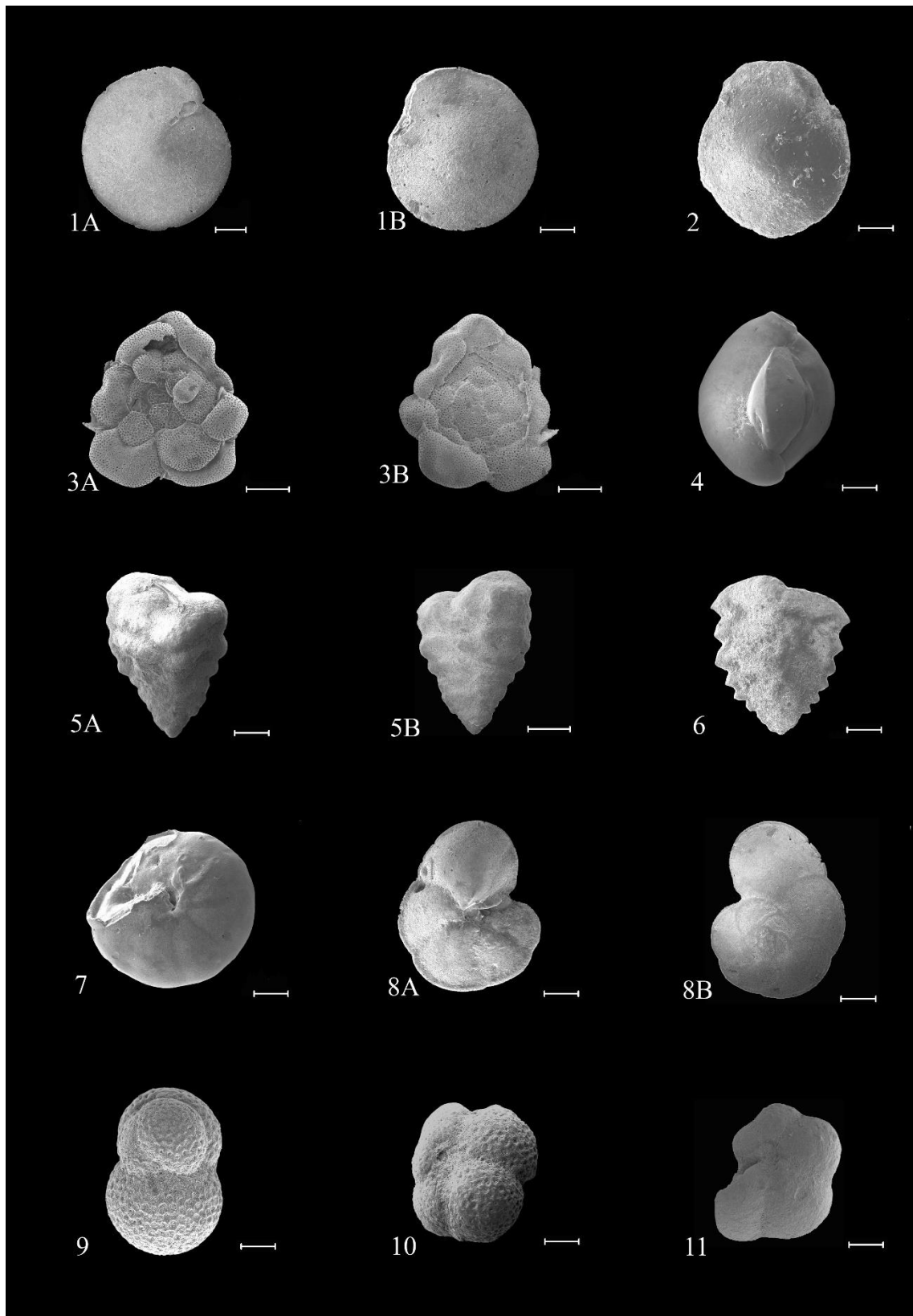




Plate 10

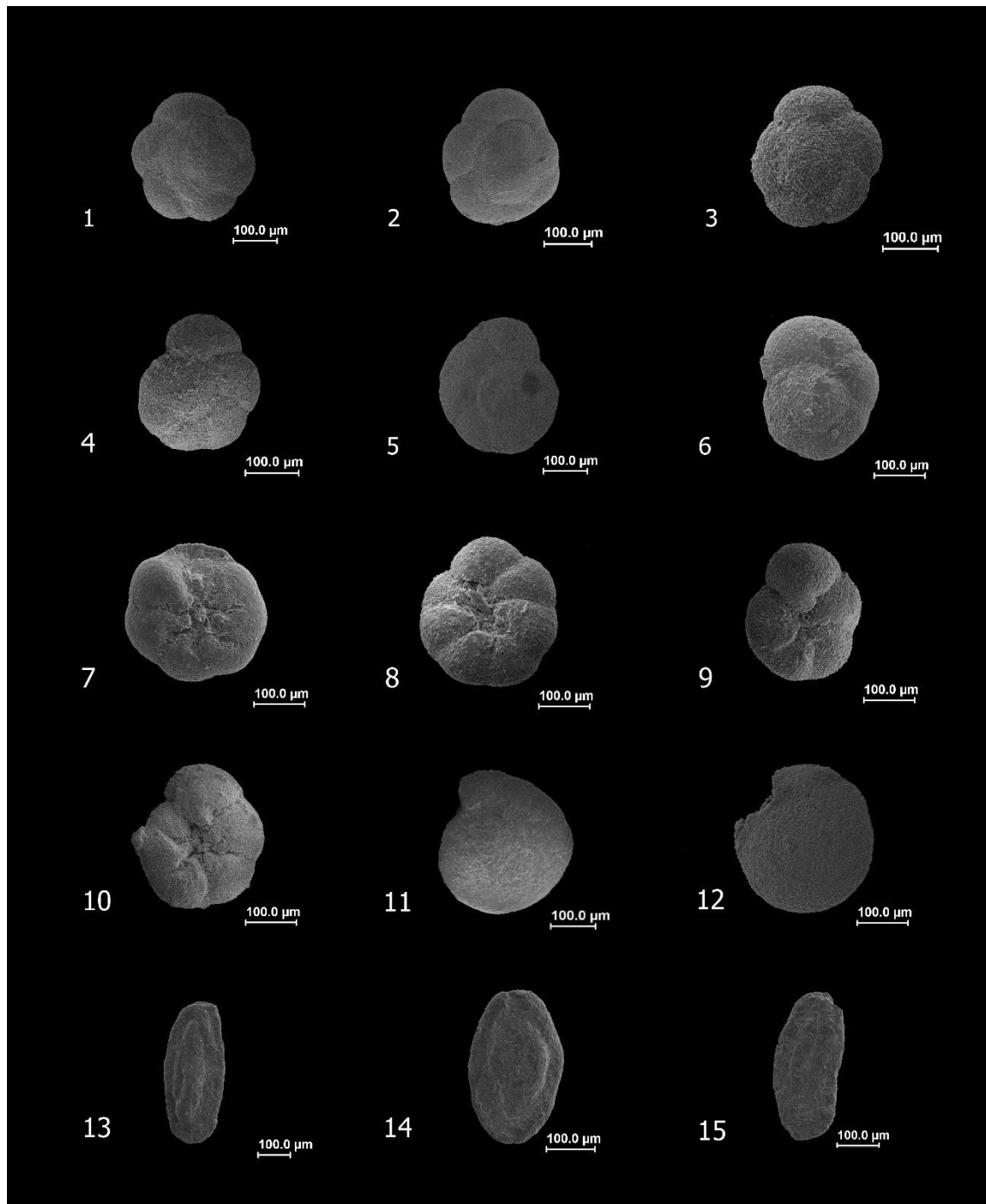
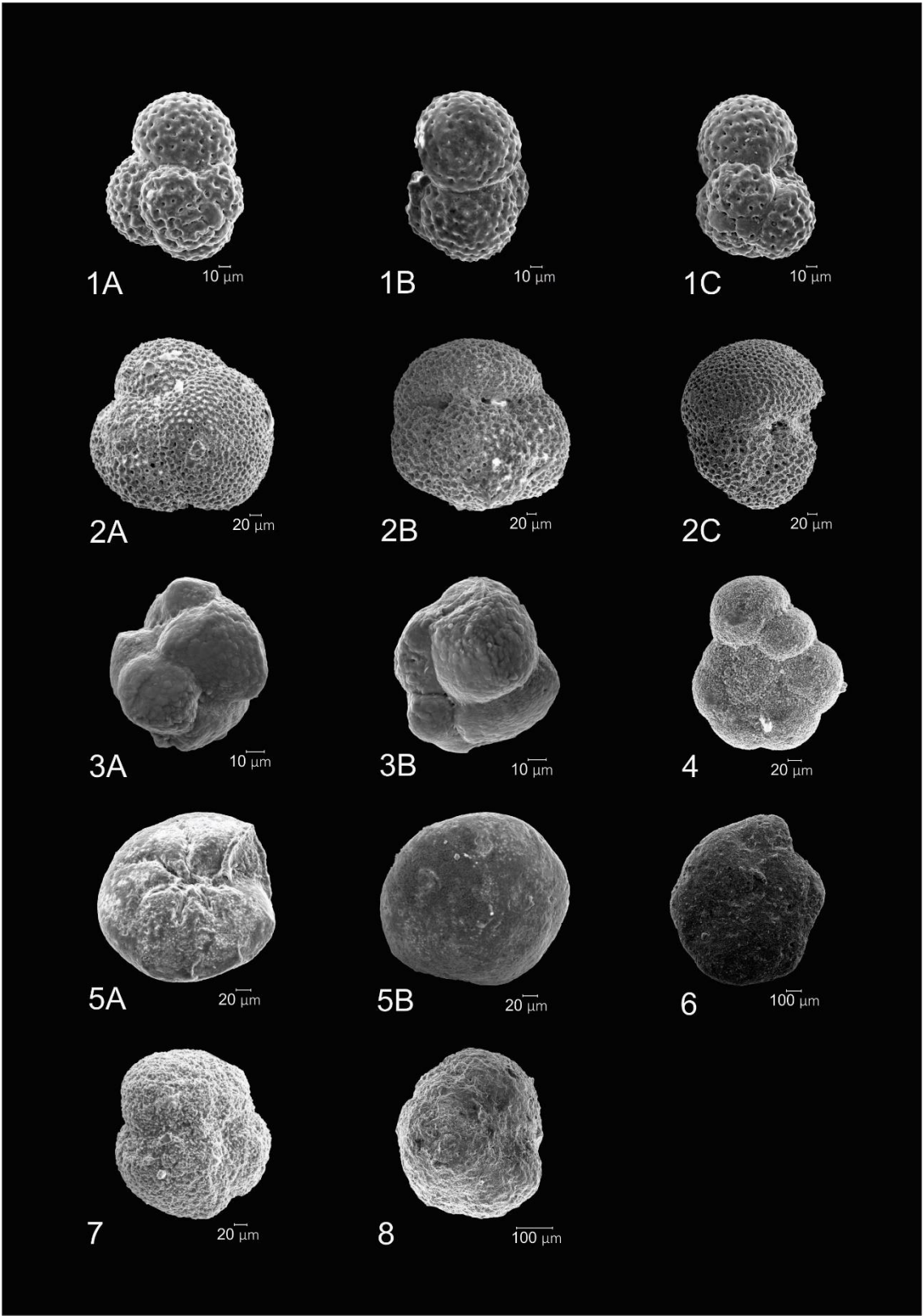


Plate 11





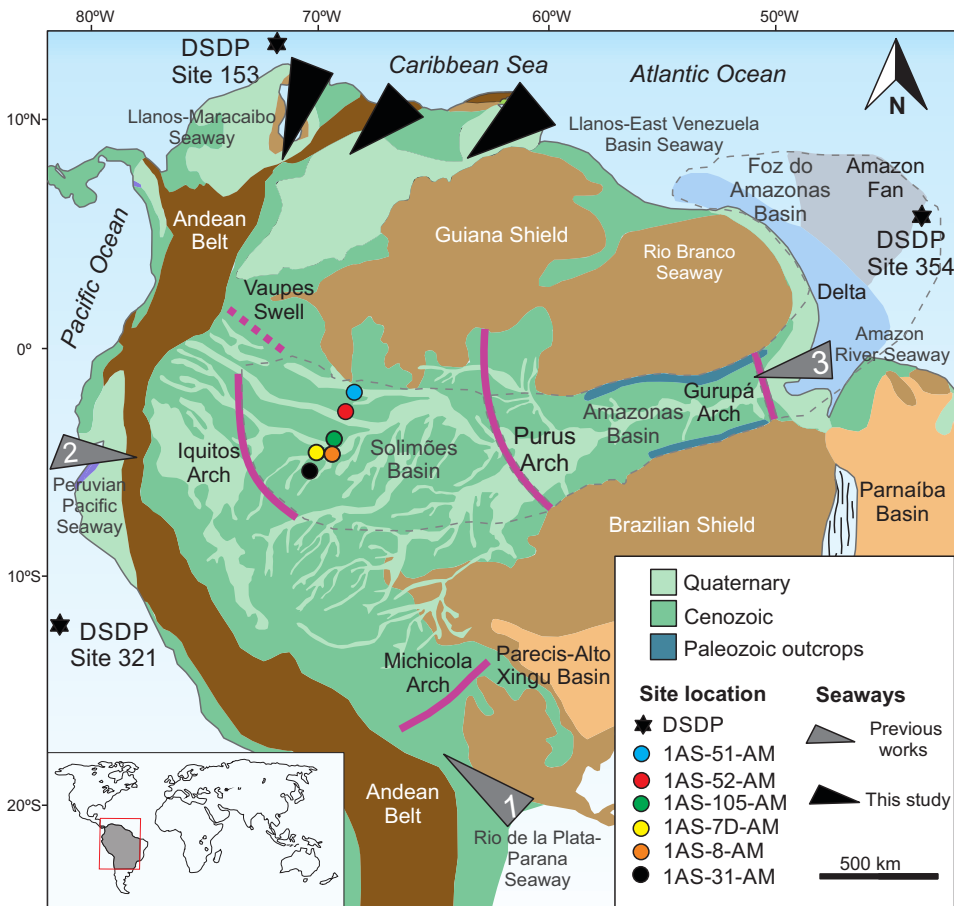
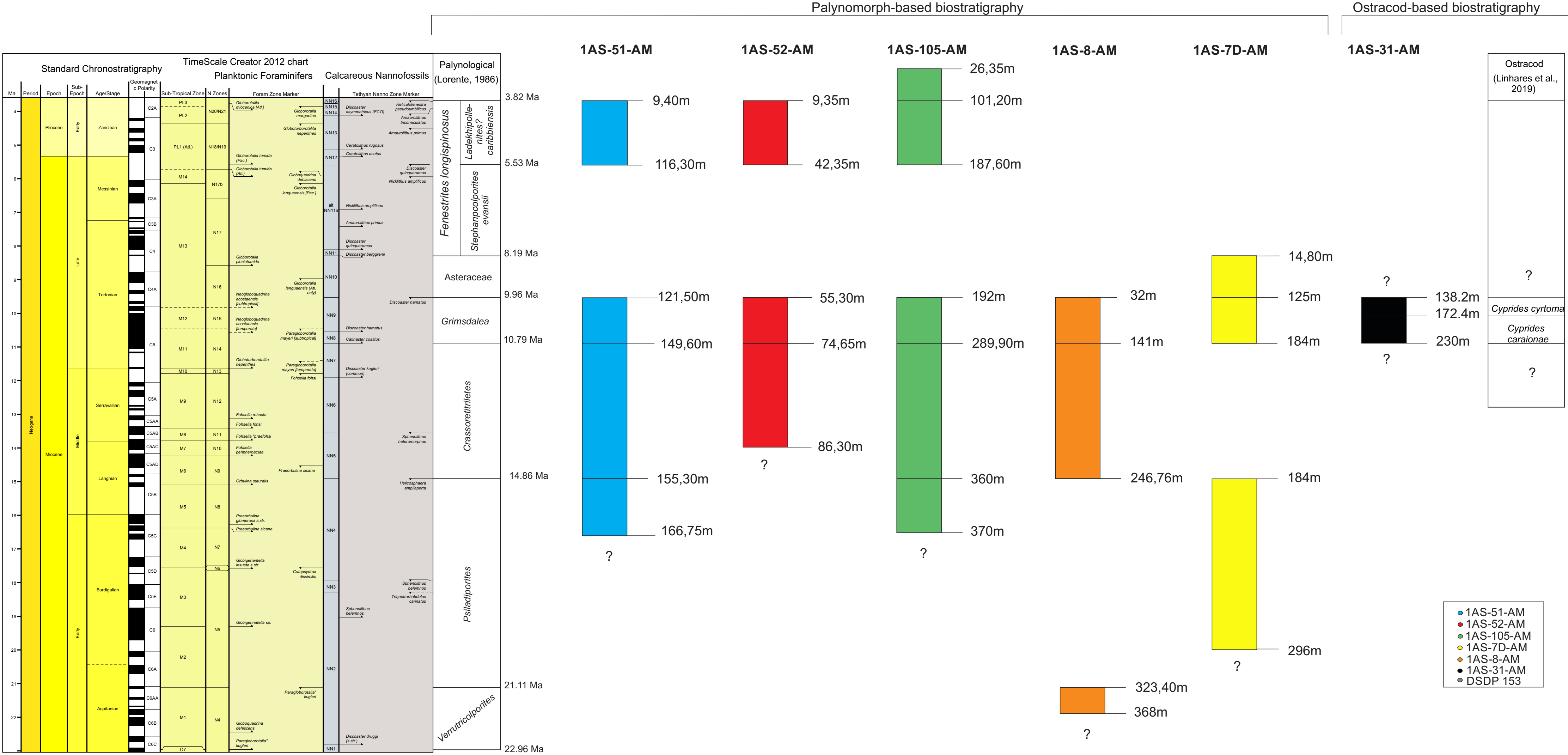


Figure S1





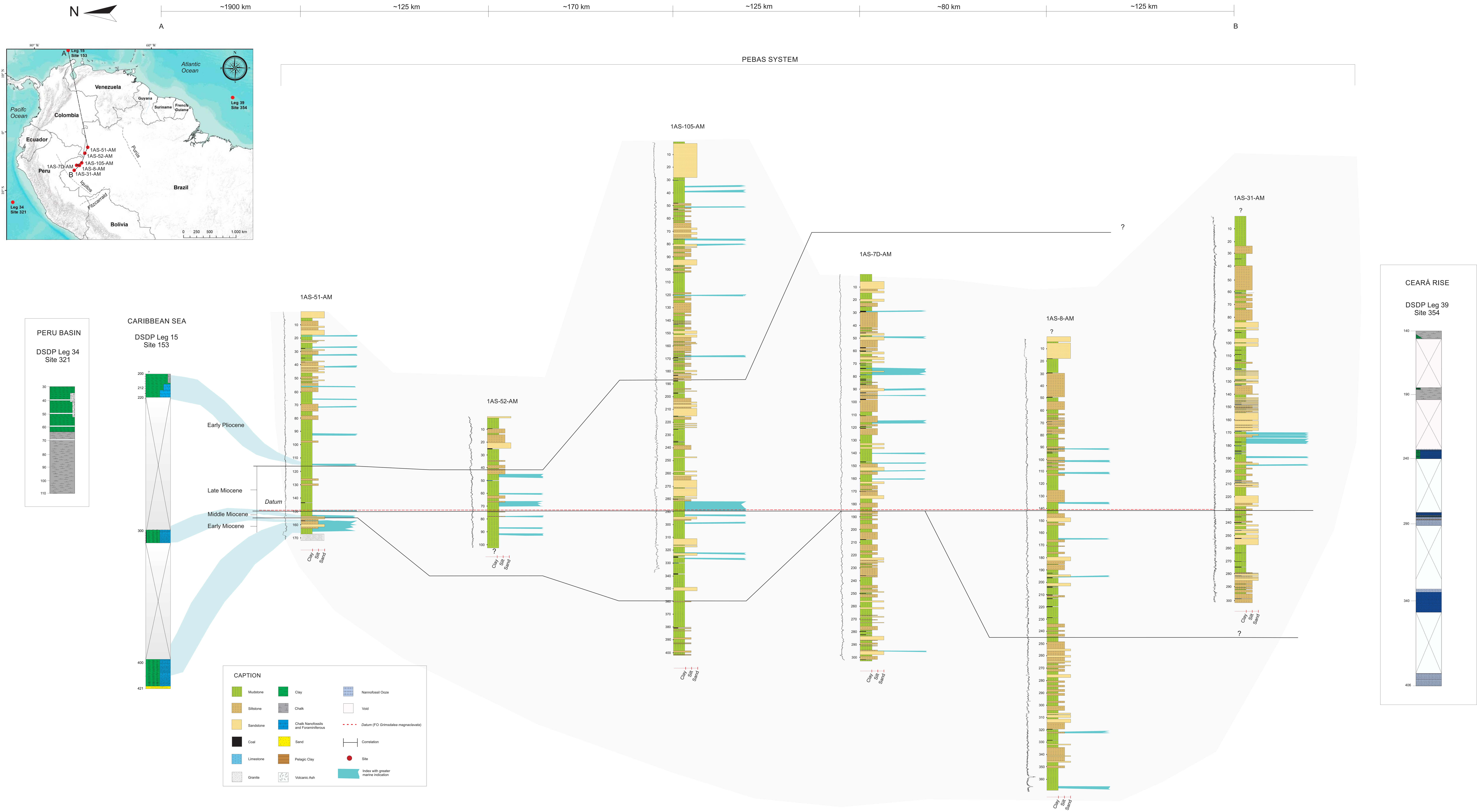


Figure S3





